A Greedy-based Network Planning Algorithm for Heterogeneous Smart Grid Infrastructures

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***Abstract*—Focus of this paper is the evaluation and optimization of automatic network planning algorithms considering different communication technologies supporting Smart Grid communication infrastructures. Therefore, a performance evaluation and sensitivity analysis of parameters of greedy-based algorithms solving the covering-location problem are implemented and analyzed in a discrete-event simulation environment. Based upon the presented results, an optimization based on the greedy algorithm is introduced considering Smart Grid technology and topology specific parameters. An evaluation for several real-world reference scenarios shows the influence of multi-layered and heterogeneous network topologies, which are typically used in Smart Gird ICT networks, including wired, wireless and Powerline Communication technologies. Depending on the technology, an optimization of the deployment level and number of network entities can be achieved and is presented by a reduction up to 30% for single-technology topologies and up to 10% for heterogeneous topologies.**

***Keywords*-network planning algorithm; covering location problem; heterogeneous infrastructures; smart grid.**

I. INTRODUCTION

Current Smart Grid approaches comprise an actively integration of distributed energy sources and loads into the energy grid in order to enable a more balanced usage of volatile energy sources and movable load systems. In this context, several smart energy management approaches are present like locally managed and self-sustaining Micro Grids [1] and centralized load coordination like Demand Side Management (DSM), Distributed Energy Resources (DER) for example based on dynamic energy prices. At this point, seamless integration of DER and DSM at the customers households are some of the key capabilities of future Smart Grid infrastructures. For this purpose, the underlying communication infrastructure requires a reliable, sufficient dimensioned and demand-oriented network design in order to transport metering data, control information and to provide added-value services with the required Quality-of-Service (QoS). But the challenging task in designing a network infrastructure for these application is caused by the heterogeneity of access technologies (e.g., GPRS, PLC, DSL), combining shared and dedicated infrastructures, integrating existing networks, deploying new networks and providing Home Area Networks (HAN), Neighborhood Area Networks (NAN) and Wide Area Networks (WAN) for different application scenarios [2]. The variety in applicable technologies leads to a heterogeneous infrastructure, which requires detailed and adjustable network planning algorithms considering the different architectural structures for different technologies.

The work in this paper concentrates on the design and evaluation of heterogeneous network infrastructure planning algorithms. Therefore several network planning methologies are discussed in terms of cell size, cell capacity, multi-layered and heterogeneous topologies. A Greedy-based algorithm is evaluated by simulation and enhanced for typical Smart Grid infrastructures.

The paper is structured as follows: Section II introduces related work in terms of ongoing Smart Grid projects and network planning algorithms. The implemented algorithms and the simulation environment are presented in Section III. The performance evaluation of a typical Smart Grid scenario is addressed in Section IV. Finally, the paper is finished with conclusion and an outlook on future work.

II. PROBLEM STATEMENT AND RELATED WORK

An overview on heterogeneous network topologies supporting the Smart Gird by using different technologies for multiple application scenarios is given in the following Section II-A. An approach describing the optimization problem is given in Section II-B, whereas a state-of-the-art review of network planning algorithms is provided in Section II-C.

A. Smart Grid Topologies

Network infrastructures for Smart Grids applications comprise different aggregation levels in HAN, NAN and WAN infrastructures in order to support different ICT and Energy components [3]. Figure 1 shows a multi-layered network topology for integrating large-scale components, like wind

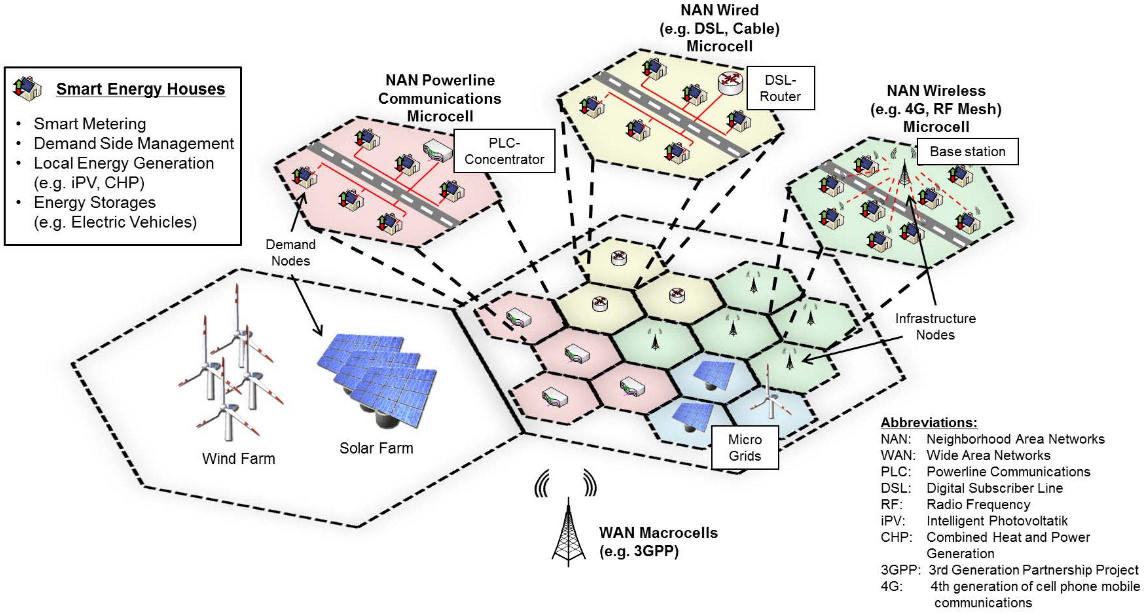

Figure 1. Multi-Layered Network Topologies for Smart Grid Application Scenarios

and solar farms, as well as particular smart energy households and micro grids. In order to provide connectivity to the customers premises equipment, several options has been introduced [4], which mainly base on two scenarios: a *dedicated* network infrastructure and a *shared* network infrastructure. By using a shared network infrastructure, restrictions in terms of Quality-of-Service have to be accepted due to non-exclusive usage of the medium. On the other hand, this solution offers an economic alternative by using existing infrastructures.

Wired preexisting technologies (e.g., DSL, FTTx, GPON) [5] in the Smart Grid context are used for integrating the prosumers (**pro**ducer and co**sumer**) households and sub-, resp. transformer stations into the infrastructure. Since installation costs are higher compared to wireless technologies, the integration of existing infrastructures is widely preferred.

Using the powerline as transmission medium for data has been discussed decades-long and has been established successfully for the transport grid. Concerning the present efforts on integrating new actors like the prosumers, into the Smart Grid, especially Broadband PLC technologies (IEEE P1901, HomePlug 1.0/1.0 Turbo/AV/AV+, DS2, Panasonic HD) become more relevant. Due to new capabilities like larger bandwidth, higher modulation schemes and notching filter, the BPLC technologies offers an economic solution for the communication infrastructure on several levels of the Smart Grid. Furthermore, narrowband PLC technologies are discussed as a last-mile solution due to moderate installation costs and exclusive usage.

Wireless Technologies, like GSM, UMTS as well as LTE and Mobile WiMAX offer a cost-efficient solution for new communication infrastructures due to the saved installation costs for cables. On the other side, wireless technologies are based on a substantiated network design covering resource and frequency allocation. Several Smart Metering projects are based upon wireless low data rate approaches, but for a comprehensive installation of Smart Meters and for offering enhanced services like DSM enhancements, the usage of next generation cellular networks for machine-to-machine (M2M) services is currently evaluated. Especially the usage of lower frequency ranges (e.g., digital dividend after digital television transition) for dedicated services (Smart Metering, DSM, Substation Automation) offers a promising solution for covering rural areas, whereas the development of future network deployments needs to be taken into account.

B. *Covering-Location-Problem*

Deploying and optimizing the previously described networking technologies is related to the *Set-Covering-Location-Problem (SCLP)*, which is one of the most studied NP-hard problems [6]. The goal is to cover a given set of demand nodes $J = \{0, ..., m\}$, e.g., Smart Energy Houses, with the minimum number of required infrastructure nodes, e.g., base stations, which are taken from a set of possible infrastructure node positions $I = \{0, ..., n\}$. A mathematical description of the optimization problem is given by

$$min \sum_{i \in I} y_i \qquad (1)$$

under the condition that

$$\sum_{i \in I} r_{ij} y_i \geq 1 \quad for \quad j \in J \tag{2}$$

with

$$y_i, r_{ij} \in \{0,1\} \quad for \quad i \in I, j \in J \tag{3}$$

whereas y_i is representing the deployed infrastructure node positions and r_{ij} is indicating the according covered demand nodes in range.

The *Maximum-Covering-Location-Problem (MCLP)* is a modification of the SCLP, where the goal is to cover a maximum number of demand nodes with a limited number of infrastructure nodes. In order to priorize the demand nodes an additional parameter b_j for $j \in J$ is introduced and the relation for the optimization problem is given by

$$max \sum_{j \in J} b_j \cdot x_j \tag{4}$$

under the condition that

$$\sum_{i \in I} r_{ij} \cdot y_i \geq x_j \quad for \quad j \in J \tag{5}$$

and

$$\sum_{i \in I} y_i = p \tag{6}$$

and

$$x_j, y_i \in \{0,1\} \quad for \quad i \in I, j \in J \tag{7}$$

Several approaches for solving the optimization problem are discussed in literature and summarized in the next section.

C. Network Planning Algorithms

In general, the following networking algorithms are discussed in the literature [7]: *Exact Algorithms*, *Genetic Algorithms* and *Heuristic Algorithms*.

In order to obtain an optimal solution for the problem, exact algorithms search all potential solutions in the parameter space, which is a time-consuming procedure, in the context of Smart Grid infrastructures, where thousands of nodes are taken into account [8]. Another approach are genetic algorithms based on Darwin theory of natural selection and its class of evolutionary algorithm. The idea behind this algorithm is to start with an initial population and then individuals from the initial population are selected in order to generate new individual solutions [9][10]. Heuristics algorithms are approximated algorithms and provide relatively *optimal* solutions in a reasonable computation time. This is a compromise between solution quality and execution time, which offers a sufficient solution for network planning. There are several approximated algorithms used to solve network planning problems, like Tabu Search [11], Simulated Annealing [12] and Greedy Algorithm [7], which are iterative algorithms calculating stepwise the local optimum.

III. SIMULATION ENVIRONMENT

In order to compare the different optimization approaches and network planning methods, a geo-based simulation environment [13] is used for the conducted performance analysis. Due to the geo-based positions of the communication nodes, close to real world scenarios were investigated in order to analyze the impact of the algorithms on the real-world scenarios.

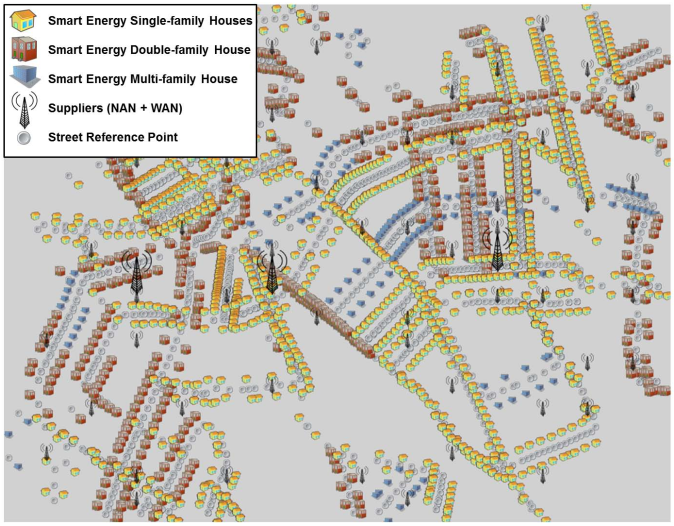

Figure 2. Simulation Scenario with Multi-Layered Infrastructure and Adaptive Cell Size

A. Geo based Scenario Generator

The presented simulation model is based on the discrete event simulator OMNeT++ [14]. The developed geo-position scenario generator acquires the coordinates from different offline sources. This includes own acquired data and governmental/commercial data products, as well as online sources, like the Google Maps API (Premier) or OpenStreetMap. Due to the limitations in requesting data from the online sources, the online procedure is reasonable for smaller scenarios, but in case of a large-scale scenario, the acquisition of the geo-positions can be performed by offline sources. In order to generate a large-scale network with thousands of nodes, a dynamic network creation is necessary. This avoids a

	Broadband NAN Technology		
	Wired	Wireless	PLC
max. Demand Nodes per Cell	96	200	48
min. Demand Nodes per Cell	18	6	6
max. Distance/Range	500 m	200 m	100 m
Infrastructure Node Positions	Streets	Houses	Streets
Coverage Area Calculation	Distance	Channel Model	Distance

Table I
PARAMETERS FOR DIFFERENT APPLICATION SCENARIOS

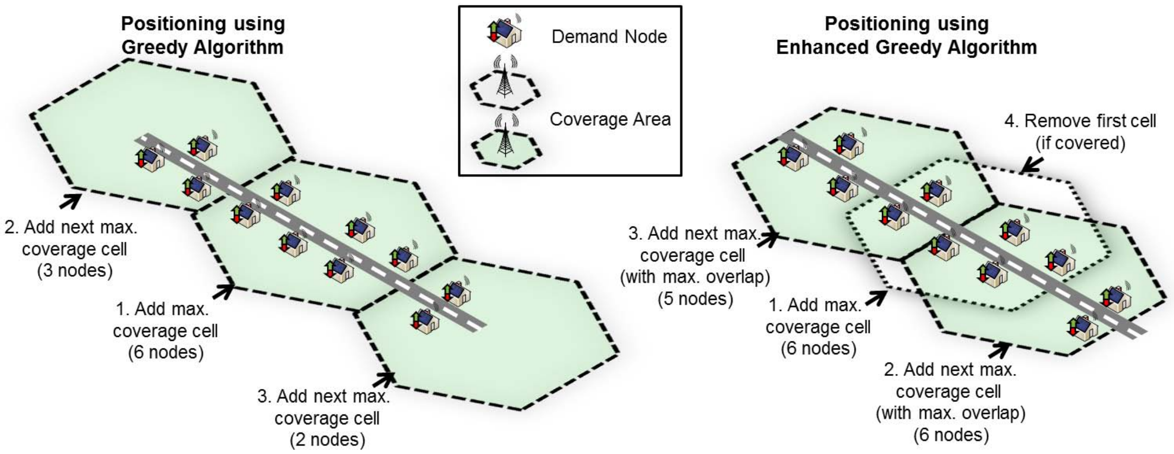

Figure 3. Network Planning based upon Greedy Algorithms and Enhanced Greedy Algorithms

manual, time-consuming static generation and configuration of each node. In our approach, we use geographic positions of real locations, e.g., houses, as input parameters for the automatic network generation. This ensures a close to reality network topology. An exemplary geo-based simulation scenario is presented in Figure 2.

Initialization, generation and configuration of the network are executed by a core simulation [13]. A set of preconfigured geographic positions (north-west and south-east corner coordinates) mark the simulation playground. The core simulation can receive the positions of nodes, which are located within the playground, from an offline source and online from an external SQL database, e.g., the geo-position database *GeoDatabase*. Via a connection between the core simulation and the GeoDatabase [13], all information about existing nodes within the playground and neighbors of particular nodes can be retrieved, including the information listed in Table III-A. The dynamic node creation is based on the received geographic positions. Nodes are placed on the Cartesian positions (x,y), which are calculated using Mercator projection of GPS position data of real locations.

B. Network Planning Algorithms

The network planning algorithm is based upon a *Greedy-Adding Algorithm* [15] with several adjustments in terms of cell size, link budget and multi-layered infrastructures in order to meet the requirements on a communication infrastructure for a Smart Grid. The parameters of implemented different broadband NAN technologies are summarized in Table III-A.

1) Greedy Adding Algorithmic: The Greedy Adding Algorithm offers a powerful approach for solving the CLP, but in some cases a non optimal result is calculated. Especially in areas of high density with a linear placement of communication nodes, which is usually the case for streets or smaller villages, an optimization of the Greedy-Adding algorithm can reduce the overall number of communication cells. Figure 3 shows the comparison of the common and enhanced Greedy Algorithm. The common Greedy Algorithm selects the next best candidate position for an infrastructure node by selecting the position, which covers the maximum number of uncovered demand nodes. This procedure comes along with two disadvantages: On the one hand, two or more equal positions can not be distinguished due to the next best position is chosen from the list. On the other hand, one position with less uncovered demand nodes could have a better coverage due to already covered demand nodes within the area, which are not taken into consideration. The enhanced algorithm adds in a first step an additional condition to the next best candidate selection by choosing the best position with additionally covering already covered demand nodes. In a second step all candidate positions are checked for multiple covered demand nodes and removed if more than one candidate position is available. Finally, the increased overlapping areas of neighbored cells caused by the additional condition are reduced by optimizing the cell radius and threshold adjustment (see Section III-B2).

2) Adaptive Cell Radius: Usually, the initial connectivity range of a candidate point is adjusted by a simple distance calculation. In reality, more parameters are influencing the connectivity range, e.g., transmission power, outdoor-to-indoor transition, fast fading, incident angle, as well as maximum capacity. In order to meet the requirements for a sufficient simulation of the transmission range per cell, the cell radius is adjusted dynamically by increasing the transmission power from a minimum threshold to a maximum threshold until the maximum transmission power or number of traffic nodes is reached.

3) Link Budget: The calculation of the link budget is accomplished by using appropriate analytic channel models, which take into account the distance, incident angle, house type and orientation. In the presented simulations, analytic radio propagation models are used for different topologies described in Section II-A, which enables a large-scale analysis of the topologies and offers extensibility in terms of technologies. For urban areas, the transmission range is calculated by the Okumura-Hata channel model [16][17][18] covering a high density of stationary communication nodes, prevailing Non-Line-Of-Sight connections and smaller communication ranges. In suburban and rural areas, a predominant number of communication nodes are placed in a (Near)Line-of-Sight conditions and usually the communication ranges are increased.

4) Multi-layered Network Topologies: By introducing multi-layered network topologies, e.g., aggregation of *Smart Metering* data by NAN technologies, an overlapping WAN-technology is required for collecting data from the aggregation points. Additionally, nodes, which are not covered due to their secluded position, can also be covered by the overlapping WAN technology and additionally, an economic threshold of minimum numbers of demand nodes per cell can be defined for the network planning process (e.g. min. 6 nodes). The network planning process for the next higher layer uses the same metric as described in Section III-B2 with according parameters for the WAN technology.

IV. PERFORMANCE ANALYSIS

The results from the simulation are presented in this section. In Figure 4, the coverage of demand nodes is shown depending on the number of infrastructure nodes for a single layered topology. Due to the lower capacity of the PLC cells, up to 150 infrastructure nodes are required in order to cover the whole area, whereas the wireless NAN network requires 72 infrastructure nodes and the wired NAN network requires 40 infrastructure nodes. The influence of the transmission range and capacity is shown by the comparison of the wireless and wired NAN technology. Hence, the wireless NAN technology covers more demand nodes during the first planning steps due to the higher capacity, whereas the wired technology shows overall lower number of infrastructure nodes due to the higher transmission range.

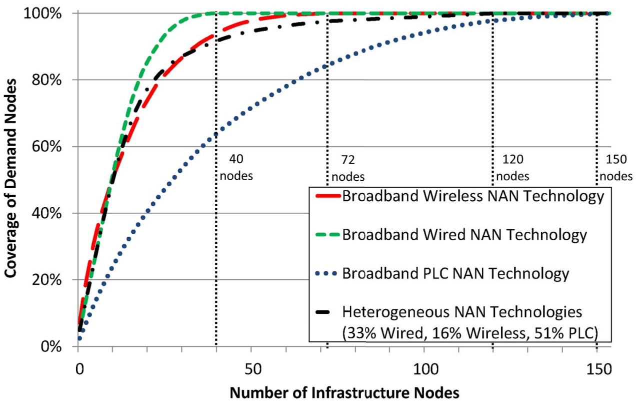

Figure 4. Coverage of Demand Nodes Depending on the Number of Infrastructure Nodes

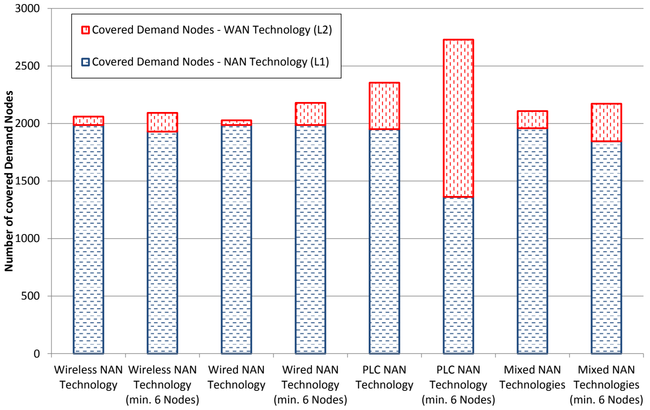

Figure 5. Comparison of NAN Technologies for Multi-Layered Topology Planning

In order to analyze the influence of multiple technologies in one scenario, an additionally heterogeneous network scenario has been analyzed. The results show, that the heterogeneous NAN network shows the same behavior up to a level of deployment of 50% of the wired network, up to a level of deployment of 90% of the wireless network and above 90% of the PLC network. Due to the heterogeneous approach, the number of infrastructure nodes is reduced to 120 together with enhancing the coverage throughout the planning process.

The problem by providing full coverage are secluded nodes (e.g., rural areas). Therefore, a multi-layered infrastructure is introduced by dividing the network into two layers, whereas L1 represents the NAN connectivity and L2 presents the WAN connectivity. The results for a comparison between a single-layered and multi-layered scenarios are shown in Figure 5.

In the multi-layered scenarios, a threshold is defined, which sets the minimum number of demand nodes per NAN cell. All uncovered demand nodes from the L1 are covered in a second planning step (L2) with all L1 infrastructure nodes. The multi-layered planning algorithm shows a better result by reducing the number of infrastructure nodes of up to 30% in the PLC scenario and up to 10% in the mixed scenario.

V. CONCLUSION AND FUTURE WORK

The results presented in this paper show the influence of different parameters and enhancements on greedy based network planning algorithms in order to evaluate the usability for Smart Grid ICT topologies. Based upon a real-world scenario, which has been evaluated by a geo-based simulation environment, the influence of multi-layered topologies where analyzed. Hence, a reduction of infrastructure nodes in the presented heterogeneous scenario of up to 10% could be achieved. The influence of a more detailled model of the actual transmission medium by analytic channel models, link budget calculation and adaptive cell size were analyzed as well.

Future work will focus on the integration of more detailed traffic analysis of the particular network entities in order to optimize the maximum cell size an capacity. Furthermore the performance evaluation of the designed networks within a protocol simulation environment and comparison to established telecommunication networks will give some indications of further optimization approaches in terms of adjusting the multi-layer thresholds and scalability issues.

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