Insights on the Resilience and Capacity of AMI Wireless Networks

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***Abstract*—The Advanced Metering Infrastructure (AMI) is a fundamental component of the Smart Grid architecture. The AMI consists of a collection of Neighborhood Area Networks (NANs), which interconnects the smart meters to the utility company. In this paper, we address two important performance metrics regarding the NAN design, the topology's resilience and the network capacity. We propose an analysis methodology in order to determine the appropriate transmission power and the required number of gateways for wireless-enabled mesh-connected architectures. We employ a graph-theoretic approach for the analysis. Furthermore, we assume wireless NANs based on the new IEEE 802.15.4g standard. A planning tool has been implemented using software Mathematica in order to automate our approach. Simulation results show interesting tradeoffs between the performance metrics and the network design parameters, thus providing useful insights for the NAN designer.**

***Index Terms*—NAN; AMI; Smart Grid; Resilience; Capacity**

I. Introduction

The Smart Grid concept improves the robustness and efficiency of the electrical systems by adopting the cutting-edge information and communication technologies. These technologies allow us to modernize the way we generate, transmit, distribute and consume electricity through the use of innovative functionalities for sensing, communication, and control [1]. The Advanced Metering Infrastructure (AMI) provides the network communication between utilities and smart meters. The Neighborhood Area Network (NAN) plays an important role in the deployment of the smart grid because it connects the smart meters to the gateways. Wireless communication technologies have been widely used for NAN due to the low cost and ease of deployment. Among all available wireless standards, those enabling mesh architectures are more appropriated because smart meters can dynamically establish ad-hoc communication with neighbors and find alternative paths to communicate with the gateways.

The design and deployment of reliable and efficient NANs is an important research problem. These networks may be composed of hundreds of resource-constrained embedded devices usually interconnected with communication technologies that can provide only low-bandwidth and unreliable links [2]. The prior knowledge of the resilience and of the network transmission capacity can guide the specification and development of new applications and services which will be provided by the utility company.

In this paper, we propose an analysis methodology aiming to determine how the transmission power and the number of gateways affect the resilience and capacity of the NAN. In order to evaluate the resilience, a faithful representation of the network topology is required [3]. The topology can be defined based on the locations of smart meters and gateways, and the radio transmission range. Therefore, we use a topology generation strategy that meets certain characteristics imposed by the deployment environment. Afterwards, we define a methodology for resilience analysis which can be applied to determine the necessary transmission power of the nodes and the required number of network gateways. Moreover, we address the network capacity. The smart meters can communicate with the gateway using multihop paths, what affects the capacity due to the contention and collision domains. We analyze how the capacity is modified for a different number of gateways and radio transmission parameters. In our analysis, we assume that the network nodes are equipped with radios compatible with the new IEEE 802.15.4g standard [4] and operates at the 902-928MHz unlicensed ISM band. Simulation results show interesting tradeoffs between the performance metrics and the network design parameters, thus providing useful insights for the NAN designer when determining the number of gateways, gateway's positions and the radio transmission power.

The rest of this paper is organized as follows. In Section II we present the related work. Section III describes the NAN topological model employed in the simulations. The proposed methodology for resilience and capacity analysis is presented in Section IV. A study case is discussed in Section V. Finally, this paper is concluded in Section VI.

II. Related work

An efficient design and analysis of the AMI architecture require a precise and realistic topological model for the NAN. There are few studies on the topological models for NAN and many researchers usually employ random and grid topologies [5]. A recent study developed in [3] proposes an interesting strategy for NAN topology generation based on a real map that creates topologies from buildings of an urban geographical area. Inspired by their model and aiming not to use specific geographical map information, we present in Section III a simple strategy to generate NAN topologies.

Given that we have a more realistic topological model for NAN, it is possible to study the network resilience in a more precise way. Several studies have proposed the use of graph metrics to better predict network resilience, network faults and survivability against attacks [6]. In [7] the authors investigate the reliability of an IEEE802.11-based AMI network in terms of end-to-end delay and round-trip time for a different number of nodes in the network. They propose the use of a hybrid single-hop and multihop architecture in order to increase the network resilience. In [8] the authors investigate how to enhance the reliability of a wireless mesh NAN, focusing on a specific routing protocol which includes fast link recovery capability. However, from the perspective of the NAN designer, it would be very useful to define the resilience in terms of the number of gateways and transmission power of the nodes. In Section IV, we propose the methodology which maps the resilience in terms of node's transmission power and a number of gateways.

The network capacity is another important topic covered in this paper. In [9] the authors theoretically evaluate the AMI network capacity, however, their study is restricted to linear chain multihop wireless communication architectures. In [10] the authors perform a theoretical and simulated capacity analysis for the AMI with emphasis on WiFi-based architectures. In this paper, we also evaluate the NAN capacity using the proposed topological model. We implemented a software tool to compute the network capacity using the well-established model presented in [11]. Given the topology and the set of active nodes, the model provides exact upper bounds on the network throughput.

III. Topological Model

Typically, in real NAN deployments, the smart meters are positioned on the border of the blocks and near the street. Therefore, inspired by the model presented in [3], we define a new topology generation strategy in which the nodes are randomly placed in restricted regions, based on practical deployment observations.

Consider a street divided into blocks with dimensions (l, l) and a maximum distance c from the border of the block. This defines a peripheral region of a block, where we assume that the NAN elements (smart meters, repeaters, and gateways) can be deployed. In order to create a more embracing topology, we can define a street width r and create topologies with more blocks. An example of this structure considering four street blocks is presented in Figure 1.

The dashed areas define the possible regions where nodes can be deployed. The NAN elements are positioned in these areas using a uniform random distribution. Figure 2 illustrates an example of the topology generated using this model for a scenario with four gateways. The results presented in Section V assume NAN topologies generated according to this model.

IV. Proposed Methodology

In this section, we present the proposed methodology for resilience and capacity analysis. Consider a network topology

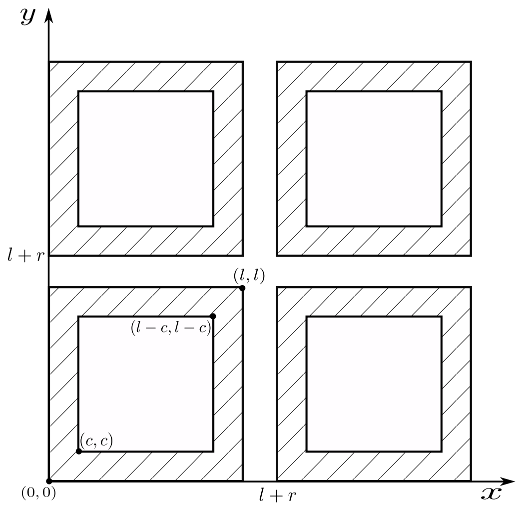

Figure 1. NAN deployment area.

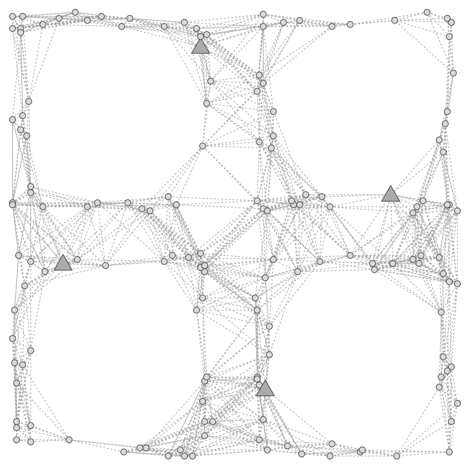

Figure 2. Example of generated NAN topology.

with $N = N_g + N_s$ nodes represented by a graph G, with N_g gateways and N_s smart meters. A path in G with length $(l - 1)$ hops can be described by a subgraph P, where V=$\{p_0, p_1, \ldots, p_l\}$ is the set of vertexes and E=$\{(p_0, p_1),$ $(p_1, p_2), \ldots, (p_{l-1}, p_l)\}$ is the set of edges. The vertexes p_0 and p_l denote the source and destination nodes, respectively. Two paths between (p_0, p_l) are independent if they do not have intermediate vertexes in common. The existence of independent paths is directly related to the resilience of the network. In case of node failure or link fault, the source node has alternative paths to reach the gateway. The NAN capacity is also investigated because it can limit the performance of the applications that can be implemented using the wireless network. The proposed methodology is shown in Figure 3. The five initial steps are common for both resilience and capacity analysis.

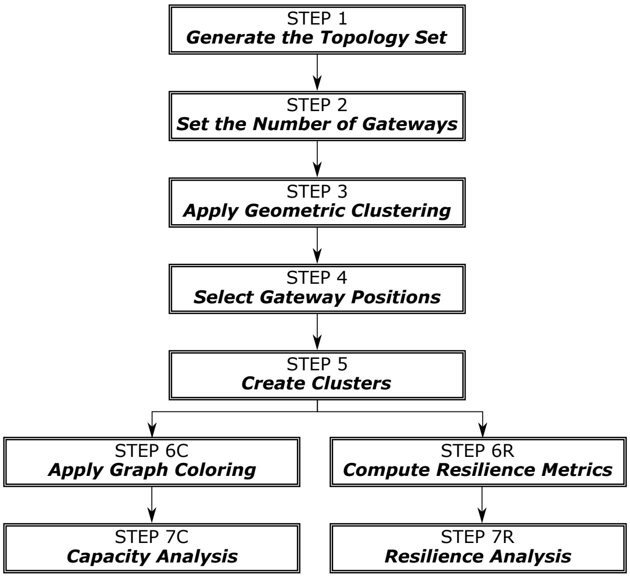

Figure 3. Proposed methodology.

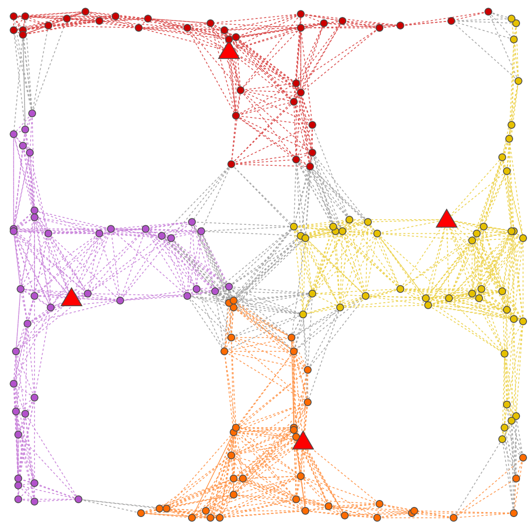

Figure 4. Example of clusterized topology.

A. Resilience Analysis

In wireless NAN deployments, nodes are often vulnerable to attacks and natural hazards while being susceptible to faults that could disrupt its normal operation. A resilient network has the ability to maintain global communication in the face of these challenges and this is a central concern for network designers [12]. The goal is to evaluate the resilience as a function of the number of gateways and transmission power of the nodes. The steps for resilience analysis are described as follows:

- **Step 1:** Generate a random set of topologies.
- **Step 2:** Define the target number of gateways, N_g.
- **Step 3:** Group the network nodes in N_g clusters using the geometric clustering strategy. We apply the k-means algorithm [13] in this step.
- **Step 4**: Select the position of the gateway nodes. The gateway node is defined as the network node which has the nearest position to the cluster's geometric center.
- **Step 5:** Effectively create the NAN clusters. The initial clusterization procedure executed in Step 3 indicates the nodes that would be associated with each cluster based on a distance criterion. In step 4 there is a high probability that the chosen gateways are not positioned exactly at the center of each cluster. Therefore, there is a possibility that some nodes have no connection due to the radio transmission range. Thus, an additional procedure is necessary to conclude the clusterization. We apply the shortest path criteria to assign each network node to the respective gateway in order to create the final clusters. An example of the final clusterization process is shown in Figure 4.
- **Step 6R:** Compute the intra-cluster and inter-cluster resilience metrics. For intra-cluster analysis, we compute the average number of hops and the number of independent paths to reach the gateway. The inter-cluster analysis addresses the node's capability to connect to other gateways in case it loses the connectivity to the default gateway. For each network node, we define a list of candidate gateways, based on the shortest path metric. The candidate gateways are ordered by distance, from the nearest to the farthest one. Then, compute the number of independent paths from the node to all gateways. We select independent paths whose path length is limited to a maximum of L hops, which is a tuning criterion that can be defined based on delay constraints.
- **Step 7R:** Analyze the intra-cluster and inter-cluster metrics. From intra-cluster metrics, we analyze how the average number of independent paths and hops are affected by the number of gateways and the transmission power of the nodes. Therefore, given a target number of gateways, from this analysis we can obtain the minimum transmission power that enables the smart meters to reach its gateway, using a path limited to L hops. For a more resilient network architecture, it is important that a smart meter has many independent paths to the gateway inside its cluster but also that it has independent paths to other gateways in the network. We evaluate the inter-cluster metrics as well.

The inter-cluster resilience is evaluated by using the proposed metric defined by equation (1). The parameter I_{ij} is the number of independent paths from node i to gateway j. We assume that j represents the index for the ordered list of candidate gateways for node i. The list is ordered by distance, from the nearest to the farthest one.

$$R_{inter} = \frac{1}{R_{ref}} \frac{1}{N_s N_g} \sum_{i=1}^{N_s} \sum_{j=1}^{N_g} I_{ij} \cdot j, \quad (1)$$

The multiplier j represents a weighting factor related to the number of gateways that a node can reach. Nodes that can reach a higher number of gateways with a higher number of independent paths present a higher resilience. The parameter R_{ref} is a normalizing factor which represents the resilience obtained in the case of using the maximum allowed transmission power and number of gateways of a given scenario.

B. Capacity Analysis

The network capacity is directly related to the bottleneck collision domain. Additionally, the interference domain affects the received signal quality and degrades the communication link performance. By increasing the node's transmission power we increase the node's coverage range, but at a cost of increasing the collision and interference domains. The goal is to investigate how the NAN capacity is affected by the topology parameters. The methodology follows the same initial steps of resilience analysis. The specific steps are described as follows:

- **Step 6C:** Apply a graph coloring strategy [14] to allocate channels to the different network clusters, in order to minimize the co-channel and adjacent channel interference. Each cluster is represented by a vertex in the graph coloring procedure. Estimates the NAN capacity using the model in [11].
- **Step 7C:** Analyze how the network capacity is affected by the transmission power of the nodes and the number of network gateways.

V. Study Case

We consider a wireless NAN whose smart meters and gateways are equipped with IEEE802.15.4g AVR radios [15] [16], operating in the 902-928MHz ISM band. We employ the binary multi-rate frequency shift keying (MR-FSK) modulation scheme with transmission rates of 50 and 200kbps. Table I summarizes the radio parameters, where f is the operating frequency, S_{rx} is the receiver sensitivity, R is the transmission rate and N_F is the receiver noise figure. The radio transmission power is adjustable between -12 and 15 dBm. The physical layer frame structure is shown in Figure 5. The preamble size is 8 bytes for a transmission rate of 50kbps and 16 bytes for 200kbps. The start of frame delimiter (SFD) and the physical header (PHR) have both 2 bytes length. The physical service data unit (PSDU) has a maximum length of 250 bytes.

Table I
AVR Radio Parameters

Scenario	f (MHz)	R (kbps)	S_{rx} (dBm)	N_F (dB)
1	914	50	-109	4.5
2		200	-102	

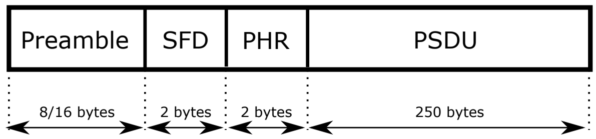

Figure 5. Physical Layer Frame Structure

We employ the log-distance propagation model [17]

$$P_L^{\mathrm{dB}} = P_L^{\mathrm{dB}}(d_0) + 10\ n\ \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma, \quad (2)$$

where d is the transmitter-receiver distance, d_0=1m is the reference distance, $P_L^{\mathrm{dB}}(d_0)$ is the free-space path loss computed at the reference distance and $X\sigma$ is a random variable with Gaussian distribution, standard deviation σ in dB and zero mean. We assume a path loss exponent $n = 3.7$ which is a reasonable value for modeling path loss in urban areas. The receiver power is computed as

$$P_{rx}^{\mathrm{dBm}} = P_{tx}^{\mathrm{dBm}} + G_t^{\mathrm{dB}} + G_r^{\mathrm{dB}} - P_L^{\mathrm{dB}} - N_F^{\mathrm{dB}}, \quad (3)$$

where G_t^{dB} and G_r^{dB} are the transmitter and receiver antenna gains, respectively. Two nodes are connected in the network graph if $P_{rx}^{\mathrm{dBm}} \geq S_{rx}$. We assume $G_t^{\mathrm{dB}} = G_r^{\mathrm{dB}} = 0$.

Furthermore, we consider NAN topologies covering four square street blocks, where each block has dimension (l, l)=$(100, 100)$ meters. The distance of the border of the block where the smart meters can be deployed was set to c=10m and the street width to r=20m. An example of a topology generated using these parameters is shown in Figure 2, with a density of 40 nodes per block and transmission power of -5 dBm for all nodes. We assume a maximum number of gateways $N_g = 10$, a set of possible transmission powers $\{-10, -5, 0, 5, 10\}$ dBm and a maximum length for the independent paths of $L = 10$ hops. An ensemble of 100 topologies was generated for the analysis. The goal is to investigate the resilience and the capacity as a function of the selected number of gateways and the transmission power used by nodes.

A. Resilience Analysis

First, we present the intra-cluster results. Figure 6(a) shows the average number of independent paths inside the cluster for different number of gateways. For transmitting powers between -10 dBm and 0 dBm, the number of independent paths is insensible to the number of gateways because the low topology connectivity. When nodes operate with higher transmit powers (+5 and +10 dBm), we obtain a significant gain in terms of independent paths due to the high intra-cluster connectivity. When the number of gateways increases the number of independent paths reduces as a consequence of the reduced cluster size. The number of hops shown in Figure 6(b) presents a similar behaviour. For a great number of gateways, the nodes are able to reach the gateway in one hop due the reduced cluster size.

Based on the results shown in Figure 6(b) we can determine the minimum transmission power and number of gateways

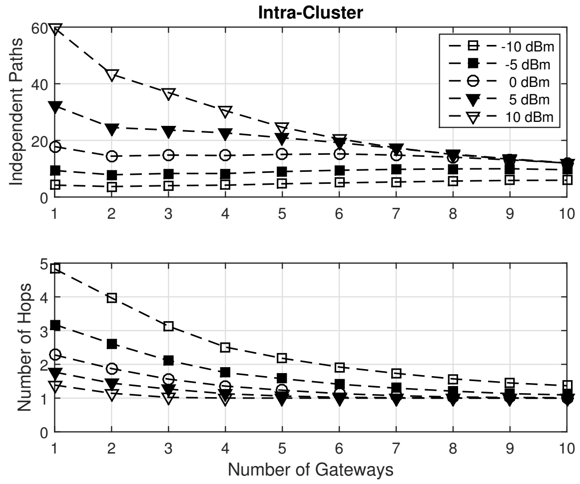

Figure 6. Average number of independent paths (a) and hops (b).

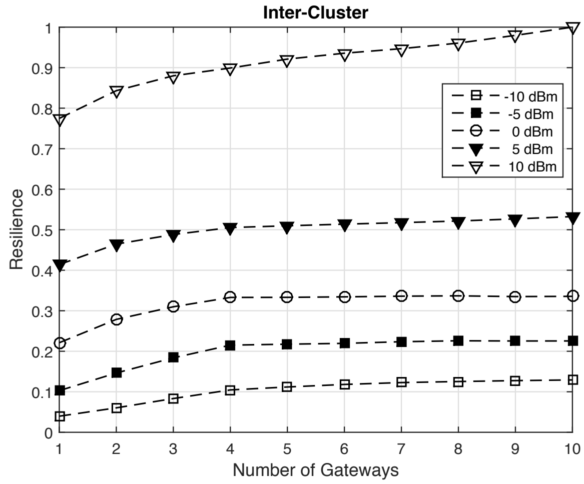

Figure 8. Inter-cluster resilience.

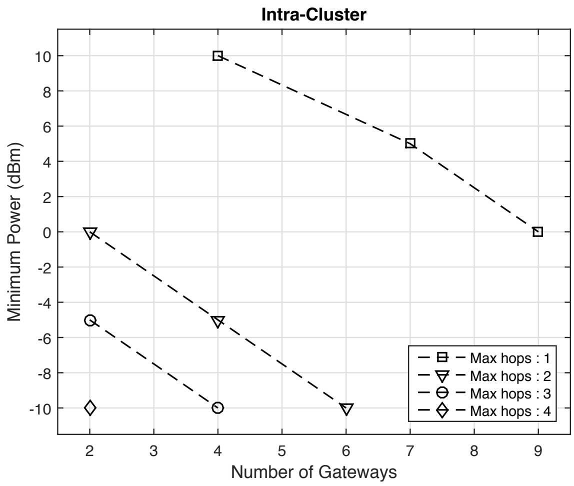

Figure 7. Maximum number of hops to the gateway.

required to restrict the maximum number of hops that smart meters require to reach the gateway. This result is presented in Figure 7 for a target maximum number of hops between 1 and 4 hops. For example, to reach the gateways with at most 4 hops it is necessary to configure the smart meters with a minimum transmission power of -10 dBm and a minimum of two gateways. Similarly, in order to obtain a NAN deployment where nodes have a direct connection with the gateways (one hop), we have three possible configurations. We can set the transmission power to 0 dBm with 9 gateways, 5 dBm with 7 gateways or 10 dBm with 4 gateways. These parameters represent minimum values that should be assumed for practical NAN configuration.

Regarding the inter-cluster analysis, Figure 8 presents the results using the resilience metric defined by equation (1), where R_{ref} is the normalizing factor, which represents the resilience for a transmission power of 10 dBm and 10 gateways. Note that when the number of gateways increases, the resilience tends to saturate with approximately five gateways for transmission powers between -10 and 0 dBm. This effect is caused by reduced connectivity and by the path length limit (L) defined in Step 6. For example, for a transmission power of -10 dBm the maximum resilience is achieved with approximately 8 gateways. However, with a transmission power of 0 dBm the maximum resilience is obtained with only 4 gateways in the NAN coverage area. For the scenarios with higher transmission powers (5 and 10 dBm) we have a tendency of increasing the resilience with the number of gateways due to the high connectivity.

Figure 9(a) shows the resilience for different node densities in the topology (40, 60 and 80 smart meters per block), all configured with a transmission power of -10 dBm. As expected, for a higher node density we have an increased number of independent paths to the gateways. However, the gains tend to saturate for NAN scenarios with more than five gateways.

In Figure 9(b) we investigate the effect of the maximum length for the independent paths (L) for a scenario with transmission power of -10 dBm. By setting a higher target value for L we achieve a better resilience due to the greater number of available paths. The drawback is that the communication delay increases for long multihop routes, which can be a restriction for time constrained services in the AMI architecture.

B. Capacity Analysis

We investigated the network capacity for the two configuration scenarios shown in Table I. In scenario 1 the radio employs a lower transmission rate, but it has a better receiver sensitivity than scenario 2. Figure 10(a) shows the network capacity using the configuration scenario 1, where the radio transmission rate is 50 kbps. For example, for a transmission power of -10 dBm and 5 gateways, the average capacity is around 400 bps. For transmission powers of 0 and 10 dBm, the capacity behaviour is similar for different number of gateways. The reason is that network is highly connected for these power

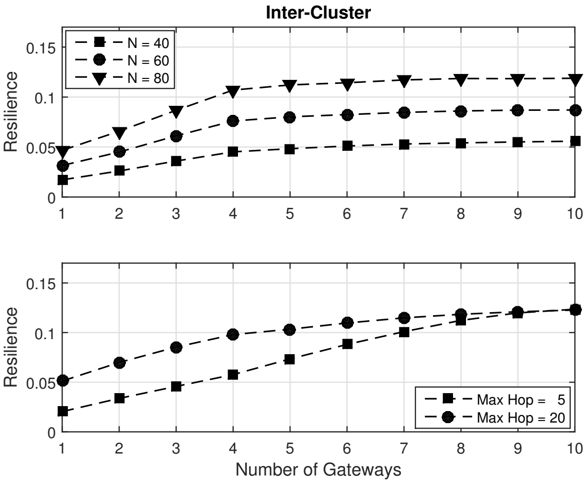

Figure 9. Effect of node density and max hops (-10 dBm).

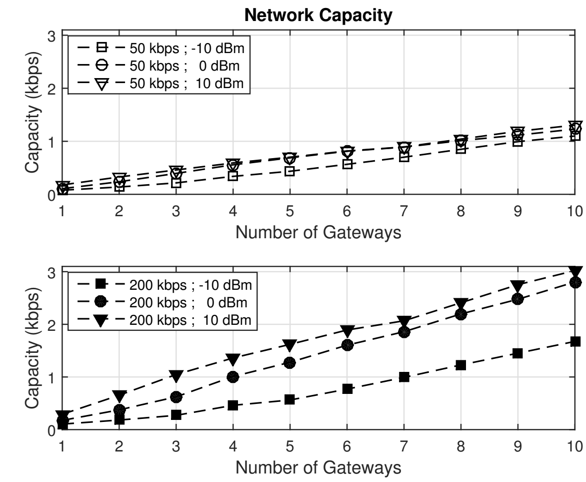

Figure 10. Network capacity: Scenario 1 (a) and Scenario 2 (b).

values due to the better receiver sensitivity and consequently nodes require fewer hops to reach the gateway.

Figure 10(b) shows the capacity for configuration scenario 2. In this case, for a transmission power of -10 dBm and 5 gateways, we achieve a capacity around 600 bps because the higher radio transmission rate. Unlike scenario 1, by increasing the transmission power and number of gateways we significantly improve the capacity. The lower receiver sensitivity reduces the network connectivity when compared to scenario 1, for the same transmission power. In this case, the network capacity is improved due to the use of more clusters (gateways) and due to the channel selection procedure implemented in Step 6C.

VI. Conclusions

The NAN is a very important component in a smart grid while wireless architectures based on the IEEE 802.15.4g standard have been often used in the NAN deployments. In this paper, we investigated the topological aspects and the resilience of the NAN. We proposed a novel topology generation strategy that meets certain characteristics imposed by the deployment environment of a NAN. In addition, we defined a methodology for resilience analysis that evaluates the network resilience in terms of independent paths and average number of hops to reach the gateways. The methodology allows us to determine the appropriate transmission power of the nodes and the number of gateways in a geographical region, in order to meet performance design criteria for NAN deployments.

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