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Reliability Analysis and Redundancy Design of Smart Grid Wireless Communications System for Demand Side Management

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Abstract

To ensure efficient, continuous, and secure operation of the next generation smart power grid, the reliability of its data communications system, and in particular, the wireless communications system will be crucial. In this paper, we present a reliability analysis of the wireless communications system in the smart grid to support demand-side management (DSM). The availability performance, which is the probability that the wireless connectivity between a smart meter to the meter data-management system (MDMS) is available, is obtained given the random failure of the system devices. This availability measure is then used to calculate the cost of power-demand estimation error and damage of power distribution equipment if its failure cannot be reported. To this end, redundancy design approaches are presented to minimize the cost of failure as well as the cost of deployment of the wireless communications system in the smart grid.

I. INTRODUCTION

The smart grid is emerging as the future generation “energy network” by improving the conventional electrical grid network to be more cooperative, responsive, economical, and organic. Information and communications technology (ICT), and in particular, wireless communications will be integrated into the power grid to enable automation, active operation, and efficient demand response in the smart grid. The wireless communications system in the smart grid will play an important role in sensing/measuring the status (e.g., energy-consumption, alarm, voltage-fluctuation, and damage to power equipment) from different devices (e.g., substations, smart meters, and sensors). The wireless communications system will
be also used to transfer control signals to the different system components to support continuous, reliable and secure operation of the smart grid. The smart grid will use and integrate different available wireless communications technologies, standards, and protocols to allow the electrical grid to operate smoothly and robustly.

The smart grid wireless communications system must be able to operate under the failure of some of its components so that the impact of this failure on the performance of the electrical grid is minimized. In this context, reliability analysis of this system quantifies whether and how long the power generation, transmission, distribution, and consumption in the smart grid will perform efficiently given the target performance requirements. Also, reliability analysis can be used to optimize the smart grid wireless communications system. Reliability analysis has been applied to wireless networks [1], [2], [3], conventional control and information networks for power system [4], [5], and wide-area measurement system (WAMS) in smart grid [6], [7]. However, the reliability analysis of the smart grid wireless communications system to support demand-side management (DSM), which is generally implemented by a public utility company, as part of the advanced metering infrastructure (AMI) was not studied. Also, the cost due to the unavailability and that due to the redundancy design of such a system were not investigated before.

**Fig. 1. Communications system model for demand-side management in smart grid.**

This paper presents a reliability analysis of the smart grid wireless communications system to support DSM. The system has a hierarchical structure consisting of home-area network (HAN), neighborhood-area network (NAN), and wide-area network (WAN) as shown in Fig. 1. A service area is divided into multiple subareas. In each subarea, there are multiple houses using electric appliances. A smart meter is installed in each house to estimate and schedule the power-consumption of appliances [9], [10]. In this case, appliances and the smart meter communicate with each other through the HAN. Wireless technologies such as the IEEE 802.15.4 ZigBee can be used for communications in a HAN. A HAN gateway is connected with each of the smart meters. The smart meter sends the power demand information to the HAN gateway. Then, the HAN gateway forwards this meter data to a data forwarder of a subarea. The network connecting the HAN gateways of the houses in a subarea is the NAN, and the data forwarder is referred to as the NAN gateway. Wireless technologies such as the IEEE 802.11 technologies can be used to implement the NANs. To manage the power supply in a service area, the power demand information from the houses is then forwarded by the NAN gateways to the data aggregator unit (DAU), and from the DAU to a meter data-management system (MDMS). The network connecting the NAN gateways is the WAN for which wireless technologies such as the 3G cellular network technology can be used.
A reliability analysis for the smart grid communications system described above can be used to quantify the availability of the connectivity from a smart meter through the HAN gateway, the NAN gateway, the DAU to the MDMS. Next, given the availability performance, the cost incurred to the public utility company due to the power-demand estimation error is obtained. Also, the damage cost due to the power distribution equipment failure is considered. As an application of the analysis, different redundancy design approaches for NAN gateways are introduced. The performance evaluation results show that the failure of the network devices can affect the cost of power-demand estimation error and the damage cost. With redundancy design, these costs could be minimized. The contributions of this article are: 1) a reliability analysis model for the smart grid communications system, 2) formulation of a cost function related to the availability of the smart grid communications system, and 3) application of the reliability analysis to optimize system design given the smart grid communications requirements.

The rest of the article is organized as follows. We first present a review of the existing literature on the reliability analysis and operation of power system. The demand-side management based on the smart grid wireless communications system is then described. Then the reliability analysis and the redundancy design for the smart grid wireless communications system are presented. The performance evaluation results are reported next. To this end, the conclusions are stated. A list of the acronyms used in this article is given in Table I.

**Table 1. List of Acronyms**

II. RELIABILITY ANALYSIS OF SMART GRID WIRELESS COMMUNICATIONS SYSTEMS AND RELATED CHALLENGES

In this section, the related work on reliability analysis for wireless communications systems and data communications for smart grid in particular are reviewed. Then several research challenges related to reliability analysis of smart grid data communications are discussed.

A. Reliability Analysis of Wireless Communications Systems

Reliability analysis has been applied to many fields including data communications and networking. A few examples are briefly discussed here. In [1], the reliability analysis for UMTS (Universal Mobile Telecommunications System) network is introduced. The hierarchical architecture of the UMTS network is modeled using a Markov chain to determine the reliability properties, and a reliability block diagram is used in the analysis. The number of blocked calls due to hardware and software failures can be calculated which
indicates the revenue loss to a service provider. In addition, a fault-tolerant design is considered to increase the network reliability. In [2], a reliability analysis is presented for wireless multihop networks. Based on a random graph, the analysis is performed for both static and dynamic topologies which correspond to the planned and random mesh networks, respectively. In particular, $k$-terminal reliability, which is the probability that a path is available and can connect $k$ nodes in a network, is calculated. In addition, given a link failure, redundant nodes can be optimally deployed to improve the availability performance. Apart from reliability, the survivability issue is also important for wireless communications systems. [3] provides a comprehensive survey of various works for protection and restoration mechanisms to improve survivability (i.e., ability of the network to operate and survive even when a failure happens) of multihop wireless networks. In a protection mechanism, a redundant network is used to prevent a failure to affect the network performance. On the other hand, to save cost incurred due to redundancy, a restoration mechanism introduces the recovery method (e.g., rerouting) to quickly solve the problem from failure.

B. Reliability Analysis of Smart Grid Data Communications

The supervisory control and data acquisition (SCADA) is used widely in conventional electrical grid for transferring sensor and control data among different systems. In [4], a reliability analysis is performed for the SCADA system for an electrical grid. The analysis focuses on the power generation and transmission systems with centralized and distributed architecture. A model based on Monte-Carlo simulation and the IEEE reliability test system (RTS) is applied to the analysis. In addition, a damage cost function is defined to determine the annual cost measure of SCADA system reliability. This cost is incurred if the power is not supplied properly due to the lack of measurement information from SCADA failure. The analysis shows that the centralized architecture could cost 5.5 times higher than that of a distributed one when failure occurs. In [5], an information architecture is proposed for a power system and a reliability analysis is performed for such an architecture. The proposed architecture is based on a distributed hierarchical structure to achieve the fault-tolerant and scalability requirements of an electrical grid. The layered model is applied to provide an abstraction of a control center, power plant, transmission and distribution substations. In this way, the communication and computation load can be relieved from the higher layer (i.e., control center) due to data aggregation and processing. The reliability performance of the proposed architecture is derived and the evaluation results show that a fully redundant system (e.g., using backup control centers) can improve the reliability of the system significantly.

Wide-area measurement system (WAMS) is used in the smart grid to provide efficient data communications between different parts of an electrical grid. WAMS is used to connect a synchronized phasor
measurement unit (PMU) and a phasor data concentrator (PDC) to monitor the power quality. WAMS provides the capability for public utility to achieve security and stability of power delivery. Therefore, reliability of WAMS is an important issue. In [6], a reliability analysis is performed for hierarchical WAMS with PMU and PDC. A fault tree analysis (FTA) is applied to the IEEE 14 bus system. In this case, WAMS can be divided into three parts. The first part is for the high-voltage nodes for which a mesh network is used. The second part is the fiber-optic communication network to connect all regional networks. The third part is a regional communication network (i.e., backbone) for public utility. In [7], for the reliability analysis, the WAMS is divided into two subsystems, i.e., monitor center subsystem and the data acquisition subsystem. A Markov chain model is developed for the central monitoring subsystem. For the data acquisition system, both series and parallel system models are considered to obtain the reliability performance. A network based on the IEEE 14 nodes is considered for the analysis.

C. Research Challenges

The major research challenges in the reliability analysis of smart grid data communications can be summarized as follows.

- **Reliability analysis of advanced metering infrastructure (AMI):** AMI is a system used to monitor, collect, and analyze power production and usage. The main component of an AMI is the network supporting two-way communication among sensors (e.g., smart meter) and the business entities. For effective deployment and operation of AMI, its reliability analysis will be essential.

- **Availability and cost analysis:** In the smart grid, there will be cost related to the failure and unavailability of the communications system. For example, if meter data cannot be transferred to public utility, an extra cost would incur due to suboptimal power delivery. Also, if the sensor and actuator network cannot operate properly, severe damage can happen to the power grid. Therefore, it is important to study the impact of the availability and the related cost structure in the smart grid.

- **Network and redundancy design:** Based on the reliability analysis, the smart grid communications system can be designed accordingly. Such a design has to take the redundancy into account to improve the reliability and the availability. Reliability and availability analysis enable us to determine the network setting which achieves the best performance under cost constraints, or minimizes the cost under given performance constraints.

- **Reliability under security attacks:** Security is another critical issue in the smart grid. Denial of service (DoS) attack can lead to the loss of resource available for transferring data and information. Also,
various data and information in the smart grid is sensitive to eavesdropping and alteration. The reliability analysis has to be be performed under these threats and used in optimization of protection.

- **Risk management:** Failure can be treated as a risk of an electrical grid. Therefore, it is important to identify, assess, and prioritize the sources of failure and their impact on system performance. These sources of failures are, for example, natural disaster, cyber attack, device and equipment damage. The methods to prevent failures and recover the system from failures need to be optimized.

### III. Demand-Side Management (DSM) in the Smart Grid

A public utility can implement the DSM to optimize the power supply in the smart grid. The public utility is an organization to manage the infrastructure for an electrical grid and to integrate all infrastructure of power generation, transmission, distribution, and consumption to provide smooth electric power delivery. The public utility collects the power usage information from the consumers and estimates the power demand. This power demand is used to determine the amount of power supply to be generated by different generators, transmitted by transmission lines and distributed by substations to the power consumers. However, due to the uncertainty of power-consumption, the power demand may not be determined precisely. As a result, *power under-supply* can occur in which the generated, transmitted, and distributed power cannot meet the demand in a particular area at a particular time. This power under-supply can incur cost to the public utility (e.g., due to penalty charged by a government).

To address the uncertainty issue, the operation of a power system is divided into two stages [8], i.e., unit commitment and economic dispatch stages. In the unit commitment stage, the public utility makes a reservation for power supply from a generator according to the estimated power demand during a time period (e.g., one hour). To acquire the power supply, a forward contract would be made in advance between public utility and a generator. Then, the public utility observes whether or not the power supply from the unit commitment stage meets the actual demand from consumers. If the power supply is not sufficient, in the economic dispatch stage, the public utility will buy additional power from a generator to avoid the under-supply situation. Since the power supply in the unit commitment stage is reserved in advance, the public utility can obtain this supply from a slow-start but cheaper source (e.g., coal generator). On the other hand, power supply in the economic dispatch stage must be able to meet the actual demand, and hence this power supply is usually from a quick-start and more expensive source (e.g., diesel generator). In this case, through the power market, the power supply in the unit commitment stage is reserved with a *forward price*, while the power supply in the economic dispatch stage is bought with an *option price*. The forward price is cheaper than the option price. By dividing the operation of a power system into two
stages, the public utility can efficiently schedule the electric supply to the consumer under uncertainty. Also, the public utility can avoid a penalty from not being able to supply enough power to the consumers.

For the smart grid communications system shown in Fig. 1, the MDMS computes the aggregated power demand of a service area by summing power demand from all houses in that service area. However, if the power demand of any house is not received by the MDMS (e.g., due to failure of the HAN gateway, the NAN gateway, or the DAU), the MDMS uses historical data to compute the aggregated power demand. In this case, the $x\%$ of mean power-consumption\(^1\) of those houses is used as the estimated demand. This mean power-consumption for a house can be calculated statistically from historical data of power usage of the house. Once the aggregated demand is obtained, the MDMS reserves power supply from the generators in the unit commitment stage. The power is delivered to the houses in a service area. Then, the MDMS checks whether the power supply is sufficient or not (e.g., from voltage drop). If the power supply is not sufficient, additional power supply will be bought in the economic dispatch stage to meet the actual demand.

In addition to the use of data communications network to support DSM, the network can also be used to transfer the monitoring data from power distribution equipment (e.g., transformer) to the MDMS. In this case, if an abnormal event is detected from the equipment (e.g., too high temperature inside a transformer), the alarm message will be transmitted to the NAN gateway, and then forwarded to the DAU and then to the MDMS. The MDMS will initiate necessary actions (e.g., maintenance) so that the distribution equipment is not damaged.

IV. RELIABILITY ANALYSIS AND REDUNDANCY DESIGN OF SMART GRID WIRELESS COMMUNICATIONS SYSTEM

We consider the availability performance measure from the theory of reliability analysis. The availability is measured at the steady state of the operating network which takes the time period of failure and repair of component, device, and system into account so that it becomes meaningful for the cost analysis.

A. Availability Performance

The availability of a component/device/system is the probability that the component/device/system has not failed or repaired and it can operate normally. The availability of each component in a system can be computed from: \( \text{Availability, } A = \frac{\text{Uptime of component}}{\text{Uptime of component} + \text{Downtime of component}} \). Here, the uptime

\(^1\)Note that $x \geq 100\%$ to reduce a chance of power under-supply.
is also known as the mean time between failure (MTBF), and the downtime is known as the mean time between repair (MTBR). The failure rate can be obtained a 1-Availability (i.e., $1 - A$). Here, availability is the probability that the smart meter can send power demand to the MDMS.

**Fig. 2. Dependence diagrams for HAN gateway, NAN gateway, and UMTS networks [1].**

Fig. 2 shows the dependence diagram (DD) which is used to analyze the availability of the wireless communications system for DSM. A DD determines the contribution of each component to the availability of the system. The components can be connected in parallel and/or series. For the components connected in series, all of them must work properly so that the system operates normally. On the other hand, for the components connected in parallel, the system can operate if not all of the components fail. For DSM, the components in the communications system, which are considered for the reliability analysis, include the HAN gateway, the NAN gateway, and the DAU. Their availability performance can be obtained as follows.

- **HAN gateway:** A HAN gateway and a smart meter can be integrated into a single device. The availability of a HAN gateway is computed from $A_{\text{HAN}} = \text{availability of metering engine} \times \text{availability of control unit} \times \text{availability of power module} \times \text{availability of radio interface}$. In this case, the radio interface is used for communicating with home appliances through the HAN and the NAN gateways.

- **NAN gateway:** The availability of a NAN gateway is computed from $A_{\text{NAN}} = \text{availability of radio interface} \times \text{availability of single board computer} \times \text{availability of adaptor} \times \text{availability of software} \times (1 - (1 - \text{availability of power module})^2)$. In this case, $(1 - (1 - \text{availability of power module})^2)$ is the availability of the redundant power supply module. Note that the radio interface is used for communicating with the HAN gateways and the DAU.

- **DAU:** A 3G cellular base station is assumed to have the DAU functionality. The availability of a DAU is computed from: $A_{\text{DAU}} = \text{availability of node B} \times \text{availability of radio network controller (RNC)} \times \text{availability of service gateway support node (SGSN)} \times \text{availability of GPRS gateway support node (GGSN)}$. Note that, in each component, there are different modules (e.g., radio interface, controller, and Ethernet) and the reliability analysis of a UMTS network can be found in [1].

The availability of the connection between a HAN gateway of a house and a DAU can be obtained from $A_{\text{HAN}} \times A_{\text{NAN}} \times A_{\text{DAU}}$ which considers the failure of the HAN gateway, the NAN gateway, or the DAU.

Note that although there is another method to analyze the reliability of the system, i.e., fault tree analysis [11], dependence diagram can be simply applied, since there are only two events in the system.
(i.e., failure and repair). Also, calculating availability of HAN gateway, NAN gateway, and DAU follows the method as described in [12].

B. Cost of Network Unavailability

When the connection between a HAN gateway and a DAU is unavailable, the MDMS cannot collect the actual power demand from a smart meter, and the estimated demand will be used instead. This can incur cost due to power-demand estimation error which results in power over- and under-supply. The power over-supply occurs when the MDMS reserves power in the unit commitment stage more than the actual demand. On the other hand, the power under-supply occurs when the MDMS reserves power in the unit commitment stage less than the actual demand, and as a result, additional power supply has to be bought in the economic dispatch stage.

Given the availability of the connection between a HAN gateway and the DAU, the cost of power-demand estimation error can be analyzed based on the power demand distribution. The power demand distribution here refers to the probability density function (PDF) of the actual power demand. The cost of demand-estimation error of individual house \( i \) whose connection to the MDMS is unavailable can be obtained from

\[
\text{Cost}_{\text{house}}(\{i\}) = \underbrace{\int_0^{E_i} (E_i - a) f_A^{(i)}(a) p_{uc} da}_{\text{Cost of power over-supply}} + \underbrace{\int_{E_i}^{\text{Max}_i} (a - E_i) f_A^{(i)}(a) p_{ed} da}_{\text{Cost of power under-supply}}
\]

where \( E_i = x/100 \times \text{Mean}_i \) is the power supply reserved in the unit commitment stage, \( \text{Mean}_i \) is the mean power-consumption of house \( i \), \( \text{Max}_i \) is the maximum power-consumption, and \( f_A^{(i)}(a) \) is the PDF of actual power demand \( a \). \( p_{uc} \) and \( p_{ed} \) denote the power prices in the unit commitment and in the economic dispatch stages, respectively. The first term in (1) represents the aggregated cost due to power over-supply (i.e., the MDMS reserves power of \( E_i \) kWh which is more than the actual demand \( a \), \( E_i > a \)). On the other hand, the second term in (1) represents the aggregated cost due to power under-supply (i.e., reserved power \( E_i \) kWh is less than the actual demand \( a \), \( E_i < a \)). On average, the cost of demand-estimation error of house \( i \) is \( \text{Average Cost}_{\text{house}}(\{i\}) = \text{Cost}_{\text{house}}(\{i\}) \times (1 - A_{\text{HAN},j} \times A_{\text{NAN},k} \times A_{\text{DAU}}) \), where \( A_{\text{HAN},j} \) and \( A_{\text{NAN},k} \) are the availability of HAN gateway \( j \) and NAN gateway \( k \) associated with house \( i \), respectively. Note that this average cost of demand-estimation error is per time period.

The cost of demand-estimation error of two houses denoted by \( i \) and \( i' \) when their connections to the MDMS are unavailable can be calculated in a similar way. In this case, the cost of demand-estimation error of two houses \( i \) and \( i' \) is not equal to the summation of individual costs (i.e., \( \text{Cost}_{\text{house}}(\{i,i'\}) \neq \text{Cost}_{\text{house}}(\{i\}) + \text{Cost}_{\text{house}}(\{i'\}) \).
To calculate the cost of demand-estimation error of two houses, the power demand distribution will become that of the power demand of two houses. For example, if the power demand is normally distributed, the power demand distribution of two houses will be also normally distributed with the mean and the variance given by the sum of the means and the variances for the two houses. Also, the reserved power supply becomes $E_{i,i'} = E_i + E_{i'}$, and the maximum power-consumption becomes $Max_{i,i'} = Max_i + Max_{i'}$. The average total cost of demand-estimation error for a service area can be obtained in a similar way by considering the costs of houses with the unavailability of connections to the MDMS.

Apart from the power-consumption, the communications system is used to monitor the operational condition of the power distribution equipments. The average damage cost due to a malfunctioning power distribution equipment can be calculated from $Average Cost_{equip}(\{k\}) = \sum_{e \in E_k} damage\ cost\ of\ equipment\ e \times probability\ of\ abnormal\ event\ of\ equipment\ e \times (1 - A_{NAN,k} \times A_{DAU})$, where $E_k$ is the set of power distribution equipments to be monitored by NAN gateway $k$. The damage cost is the cost incurred when the problem of power distribution equipment is not fixed due to the lack of monitoring message received by the MDMS. Unlike the cost due to demand-estimation error, the average damage cost of two power distribution equipment is the summation of the individual damage costs.

Note however that even though the above analysis is applied for a wireless communications system, the model can be extended for a system based on wired communications technologies (e.g., broadband power-line communications technology).

C. Redundancy Design

Using the aforementioned analysis, the redundancy design can be optimized by considering the cost of demand-estimation error and damage cost. In particular, the redundancy design is considered for the NAN gateways, but the same approach can be applied for the HAN gateways, the DAUs, and the other parts of network. We consider the average total cost due to the failure of NAN gateway $k$, i.e., $Average Cost_{house}(S_k) + Average Cost_{equip}(\{k\})$, where $S_k$ is the set of houses associated with NAN gateway $k$. These costs are calculated as presented in the previous subsection by taking the redundancy into account. That is, with redundancy of NAN gateway, the availability becomes $A_{NAN,k}^{(R_k)} = 1 - (1 - A_{NAN,k})^{R_k}$, where $R_k$ is the number of redundancy per NAN gateway $k$. $A_{NAN,k}$ is the availability performance measure obtained in the previous subsection.

Three approaches of redundancy design for NAN gateways are considered as follows.
1) Fixed Redundant NAN Gateways: We first consider the case that the total number of redundant NAN gateways is fixed at $R$ (i.e., fixed investment cost). Therefore, the objective is to deploy redundant NAN gateways in subareas such that total cost of NAN gateway failure is minimized. The algorithm for the redundancy design is as follows.

1: Initialize the redundancy of NAN gateway $k$ to be $R_k ← 1$ for $k = 1, \ldots, K$, where $K$ is the total number of NAN gateways in a service area.
2: for $1, \ldots, R$ do
3: Calculate the availability $A_{NAN,k}^{(R_k)}$ of all NAN gateways given redundancy $R_k$ for $k = 1, \ldots, K$
4: Calculate the total cost of failure from $Average \ Cost_{house}(S_k) + Average \ Cost_{equip}(\{k\})$ for $k = 1, \ldots, K$ given availability $A_{NAN,k}^{(R_k)}$
5: Select NAN gateway $k'$ with the largest total cost of failure calculated in step 4
6: Increase redundancy of NAN gateway $k'$, i.e., $R_{k'} ← R_{k'} + 1$
7: end for

2) Meeting the Availability Threshold: In the second case, the redundancy design can be optimized to find the smallest number of redundant NAN gateways such that the availability is larger than or equal to the threshold. The algorithm can be presented as follows.

1: Initialize the redundancy of NAN gateway $k$ to be $R_k ← 1$ for $k = 1, \ldots, K$.
2: repeat
3: Calculate the availability $A_{NAN,k}^{(R_k)}$ of all NAN gateways given redundancy $R_k$ for $k = 1, \ldots, K$.
4: Determine the set $K$ of NAN gateways whose availability is less than the threshold.
5: Increase redundancy of NAN gateway $k' ∈ K$, i.e., $R_{k'} ← R_{k'} + 1$.
6: until the set of NAN gateways whose availability is less than the threshold is empty (i.e., $K = \emptyset$)

Note that the algorithm can alternatively consider the total cost of failure as well. In this case, redundancy will be used for the NAN gateways such that the total cost is less than or equal to the threshold.

3) Cost Minimization: In the third case, the cost of deploying redundant NAN gateways is taken into account. The total cost of failure will be added with the cost of redundancy deployment, and the algorithm to find the minimum of this cost for a service area can be described as follows.

1: Initialize the redundancy of NAN gateway $k$ to be $R_k ← 1$ for $k = 1, \ldots, K$.
2: Calculate the availability $A_{NAN,k}^{(R_k)}$ of all NAN gateways given redundancy $R_k$ for $k = 1, \ldots, K$.
3: Calculate the total cost from
Current total cost = \( \sum_{k=1}^{K} (Average Cost_{house}(S_k) + Average Cost_{equip}(\{k\})) \) given availability \( A^{(R_k)}_{NAN,k} \)

4: loop
5: Calculate the availability \( A^{(R_k)}_{NAN,k} \) of all NAN gateways given redundancy \( R_k \) for \( k = 1, \ldots, K \).
6: Select the NAN gateway \( k' \) with the largest total cost of failure
7: Calculate the availability and then the corresponding new total cost when redundancy is assigned to NAN gateway \( k' \):

\[
\text{New total cost} = \sum_{k=1}^{K} (Average Cost_{house}(S_k) + Average Cost_{equip}(\{k\})) + Cost_{gatew},
\]

where \( Cost_{gatew} \) is the cost of deploying redundancy for NAN gateway \( k' \).
8: if \( \text{New total cost} < \text{Current total cost} \) then
9: \( \text{Current total cost} \leftarrow \text{New total cost} \)
10: Increase redundancy of NAN gateway \( k' \), i.e., \( R_{k'} \leftarrow R_{k'} + 1 \).
11: else
12: Stop
13: end if
14: end loop

V. PERFORMANCE EVALUATION

A. Parameter Setting

We consider a service area with DSM with 500 houses. The power-consumption of each house is random and follows a normal distribution with mean of 3 kWh and standard deviation of 1.5. The maximum power-consumption of each house is 10 kWh. Each house is deployed with a smart meter to measure and determine power demand. The service area is divided into subareas and a NAN gateway is deployed for each of these subareas (i.e., 10 NAN gateways). There is one DAU in the service area. The failure rates for the HAN gateways, the NAN gateways, and the DAU are 2 days per 2 years, 2 days per 3 years, and 2 days per 3 years, respectively.

The MDMS collects and computes the aggregated power demand of a service area and buys power supply in the unit commitment stage at the beginning of each time period. Then, if the power supply is not sufficient, additional power is bought in the economic dispatch stage. If the power demand for any house is not received, the MDMS uses the mean value of the power-consumption (i.e., \( x = 110\% \)) of that house as an estimated demand. The power prices in unit commitment and economic dispatch stages (i.e.,
forward and option prices) are 7 and 10 cents/kWh, respectively. The NAN gateway also receives and forwards a monitoring message from the power distribution equipment to check the abnormal event (e.g., damage due to overloading the transformer). We assume that the abnormal event happens with probability 0.01. If a monitoring message is not successfully sent to the MDMS, the cost due to the damage of power distribution equipment is 1,000 dollars per event.

We assume that there is no congestion in the network under the considered scenario. For example, a smart meter of each house transmits one message with size of few hundred bits containing power demand and other additional data to the HAN gateway, the NAN gateway, and the DAU. If the number of houses per DAU is 500, the amount of data to be transferred is less than 1 Mb per hour. This amount of traffic is considered to be small compared to the available bandwidth of NAN and WAN (e.g., based on WiFi and 3G cellular network, respectively).

### B. Numerical Results

#### Fig. 3. Cost of demand estimation error under different number of houses.

First, we evaluate the availability of the MDMS to collect meter data from HAN gateway. Fig. 3 shows the average cost of power-demand estimation error. As expected, when the number of houses per NAN increases, the cost increases. More interestingly, the cost is a monotonically non-linear increasing function of the number of houses. That is, with a more number of houses, the increase of cost and hence error becomes smaller. Also, the cost increases due to the availability of HAN gateway (inversely the failure rate). As the failure rate decreases, the chance that the smart meter will lose connection to MDMS decreases, the power-estimation error decreases, and the cost decreases.

#### Fig. 4. Cost of estimation error under different number of deployed NAN gateways.

Fig. 4 shows the cost of power-demand estimation error per month under different number NAN gateways in a service area. In this case, each NAN gateway is responsible for collecting meter data from houses in a non-overlapping NAN in a service area. For example, with 3 NAN gateways, a service area is divided into 3 NANs, and each NAN gateway communicates with HAN gateways of houses in each NAN. Interestingly, as shown in Fig. 4, with more number of NANs (i.e., less number of HAN gateways and houses in each NAN), the cost of estimation error increases. This is due to the fact that the power-demand estimation error, which could be due to failure of gateways and DAU, is a concave function of the number of houses (as shown in Fig. 3). This result suggests that from the availability perspective, the number of the HAN gateways in each NAN should be maximized to minimize the cost of estimation error.
Fig. 5. Average total cost under different number of redundant NAN gateway under non-homogeneous NAN.

Next, we consider the non-homogeneous case with 10 NANs. The probabilities of abnormal event of power distribution equipment and the number of houses in NANs 1, 2, …, 10 are 0.02, 0.018, …, 0.002 and 60, 55, …, 15, respectively. The cost of a redundant NAN gateway is $1,000, and a NAN gateway can be used for 5 years. Given the redundancy design for cost minimization, the redundancy will be deployed for NAN 1 first, and then NANs 2, 3, and so on. The reason is that NAN 1 has the largest number of houses and the highest probability of abnormal event. As a result, the total cost is the largest. Fig. 5 shows the average total cost including the cost of redundancy deployment of NAN gateway. When the number of redundant NAN gateways is small, the average total cost decreases, since the gain from redundancy (i.e., reduction of cost of power-demand estimation error and cost of power distribution equipment damage) is larger than the cost of redundancy deployment. However, at a certain point, the average total cost increases, since the cost of redundancy deployment is larger than the gain. In this case, the optimal number of redundancy to be deployed for NAN gateways can be determined which is the basis of developing redundancy design presented earlier.

From the results shown in Figs. 4 and 5, it is clear that the reliability analysis is important which could significantly affect the cost and availability of the smart grid. The reliability analysis should be integrated with the network design for DSM to achieve the lowest overall cost.

VI. CONCLUSION

Demand-side management is a key to optimizing power-consumption and minimizing the cost of power supply. In this article, reliability analysis has been used to analyze the availability of a data communications network (e.g., advanced metering infrastructure [AMI]). The availability performance has then been used to calculate the cost of power-demand estimation error due to failure of wireless communications system components in the smart grid. Three redundancy design concepts have been presented for the smart grid communications system. The performance evaluation results have revealed that the failure of communications devices can incur significant cost to the public utility. Using redundancy designs can minimize the cost of smart grid communications system failure. For the future work, the redundancy design can be based on the channel quality between HAN gateways and NAN gateway (e.g., channel quality must be better than the threshold).
ACKNOWLEDGMENT

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REFERENCES

**TABLE I**

**LIST OF ACRONYMS**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AMI</td>
<td>Advanced Metering Infrastructure</td>
</tr>
<tr>
<td>BPL</td>
<td>Broadband Power Line</td>
</tr>
<tr>
<td>DAU</td>
<td>Data Aggregator Unit</td>
</tr>
<tr>
<td>DD</td>
<td>Dependence Diagram</td>
</tr>
<tr>
<td>DSM</td>
<td>Demand Side Management</td>
</tr>
<tr>
<td>FTA</td>
<td>Fault Tree Analysis</td>
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<tr>
<td>GGSN</td>
<td>GPRS Gateway Support Node</td>
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<tr>
<td>HAN</td>
<td>Home Area Network</td>
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<tr>
<td>MDMS</td>
<td>Meter Data Management System</td>
</tr>
<tr>
<td>MTBF</td>
<td>Mean Time Between Failure</td>
</tr>
<tr>
<td>MTBR</td>
<td>Mean Time Between Repair</td>
</tr>
<tr>
<td>NAN</td>
<td>Neighborhood Area Network</td>
</tr>
<tr>
<td>PDC</td>
<td>Phasor Data Concentrator</td>
</tr>
<tr>
<td>PMU</td>
<td>Phasor Measurement Unit</td>
</tr>
<tr>
<td>RNC</td>
<td>Radio Network Controller</td>
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<tr>
<td>RTS</td>
<td>Reliability Test System</td>
</tr>
<tr>
<td>SGSN</td>
<td>Service Gateway Support Node</td>
</tr>
<tr>
<td>WAMS</td>
<td>Wide-Area Measurement System</td>
</tr>
<tr>
<td>WAN</td>
<td>Wide Area Network</td>
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</table>
Fig. 1. Communications system model for demand-side management in smart grid.
Dependence diagram of smart meter and home area network gateway

Dependence diagram of neighborhood area network gateway

Dependence diagram of UMTS network

Fig. 2. Dependence diagrams for HAN gateway, NAN gateway, and UMTS networks [1].
Fig. 3. Cost of demand estimation error under different number of houses.
Fig. 4. Cost of estimation error under different number of deployed NAN gateways.
Fig. 5. Average total cost under different number of redundant NAN gateway under non-homogeneous NAN.