Relay Placement Problem in Smart Grid Deployment

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Abstract. In this paper, we give an overview of power grid, smart grid, Advanced Metering Infrastructure (AMI), and the deployment cost analysis step by step. The importance between Relay Placement Problem (RPP) and the deployment cost in an AMI system is highlighted. Additionally, a decision supporting system in a pilot AMI system funded by National Science Council (NSC) is briefly described where RPP is solved by an approximation algorithm.

1 Introduction to the Power Grid

The power grid is an interconnected network for delivering electricity from suppliers to consumers. Three processes are involved in the electricity delivery within the grid. That is,

- Electricity generation
- Electric power transmission
- Electricity distribution

As shown in Fig. 1, the initial step is to generate sufficient electricity in the generation station. After that, generated electricity is ready to be transmitted through transmission lines. The electricity of 765 kV, 500 kV, 345 kV, 230 kV, and 138 kV are sent out. In the final process, the electricity with high voltages is then distributed to sub–transmission customers with 26 kV and 69 kV, to primary customers with 13 kV and 4 kV, and to secondary customers like houses in residential areas with 120 V and 240 V.

For the traditional electrical grid mentioned above, there are some energy issues:

- Reliability
- Economy
- Efficiency
- Affordability
- Environmental Impacts

In the reliability aspect, blackout usually takes place in unexpected situations suddenly. The unstable power supplies could put heavy impact on the economy. According to the Electric Power Research Institute (EPRI) report in June 2001,

T. Margaria and B. Steffen (Eds.): ISoLA 2010, Part I, LNCS 6415, pp. 411–424, 2010.

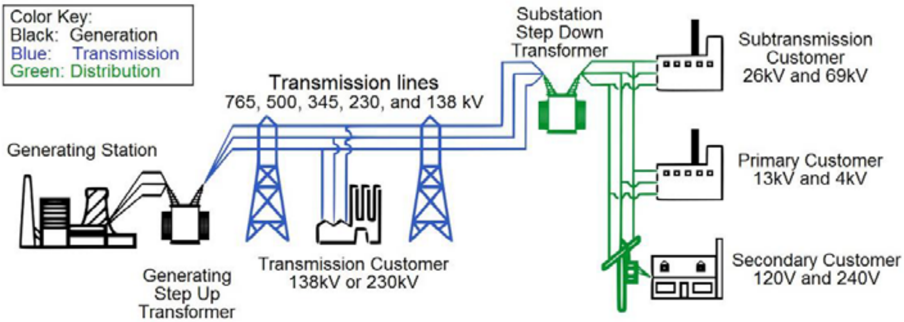

Fig. 1. Simple Diagram of Power Grid in North America [10]

"The Cost of Power Disturbances to Industrial & Digital Economy Companies" estimated that the annual direct cost of power outages and power quality disturbances for all sectors was between $120 billion and $188 billion. In its 2003 report, the Department of Energy (DOE) noted that "it is estimated that power outages and power quality disturbances cost the economy from $25 to $180 billion annually." [2]

There are some technical reasons which could be imputed to slow mechanical switches that cannot endure heavier load, no automated analysis for situational awareness, and so forth. Moreover, the electricity outage actually results from the overburdening since people need more and more electricity in life. However, it can be easily understood that electricity demand is not always the same during twenty–four hours in a day. According to the Pareto principle (also known as the 80–20 rule), about 80 percents of the total required electricity are consumed in 20 percents of time in one day. In other words, a large part of electricity is consumed in specific 4.8 hours. The power plant works hard merely in 0.2 day and relaxes in the remaining 0.8 day. Because of it, the efficiency of the power grid is extreme low.

Even worse, the cost of electricity goes up as the price of fossil fuel rises. When people work hard to earn money, factories increase their output. At the same time, more electricity is needed. Currently most electricity is generated by burning coals, which will emit a great deal of greenhouse gas (GHG) that traps heat in the atmosphere. It can be seen that the temperature on Earth's surface will go up and up because of producing too much GHG.

Therefore, to improve energy utilization efficiency and further improve our lives, a better power grid is desired. That is why the smart grid was proposed for efficiently utilizing the limited resources in generating electricity.

2 Smart Grid

Like the power grid, the smart grid also delivers electricity from suppliers to consumers. However, it uses two–way digital technology to support communication between consumers and suppliers. It combines power systems, telecommunications, smart energy devices, information technology, and digital control (Fig. 2).

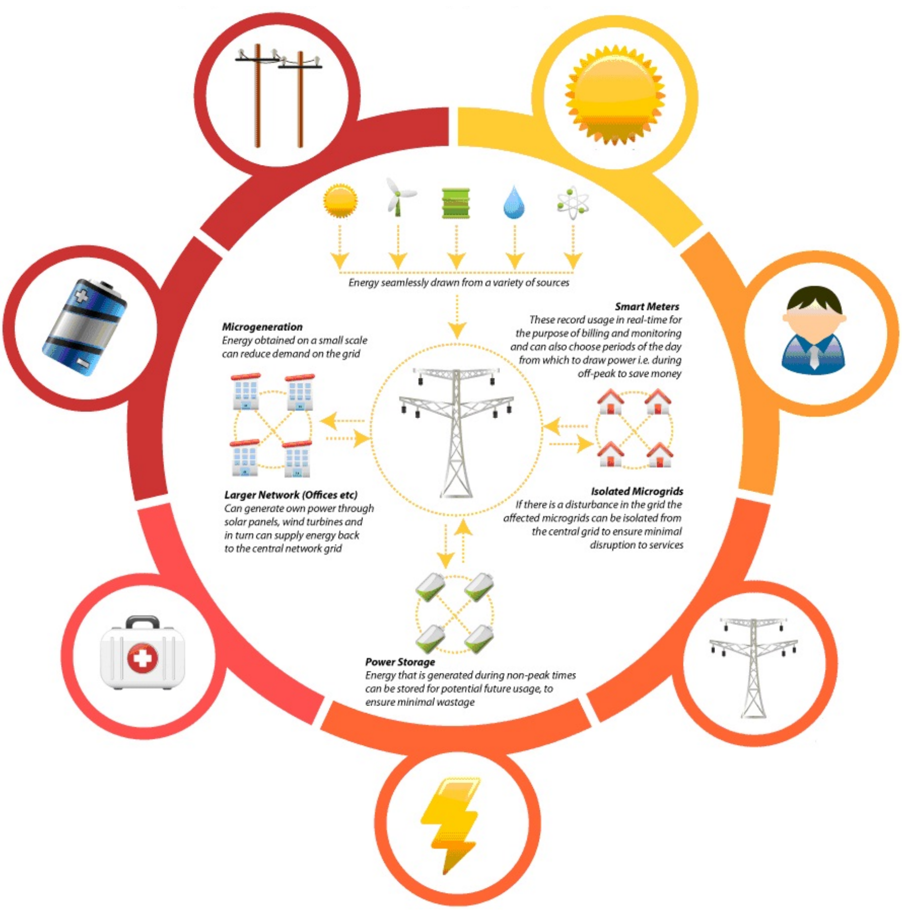

Fig. 2. Smart Grid [11]

There are some characteristics about the smart grid [3]:

- Sensing and Measurement
- Integrated Communication
- Improved Interfaces and Decisions Support
- Advanced Components
- Advanced Control Methods

First of all, through intelligent devices like electricity meters, all suspicious behaviors can be detected in real time via sensing and measurement, such as consuming large amount of electricity at night when no electrical equipment is expected to be powered on. Secondly, it contains an integrated two–way communication network which allows consumers to monitor all electricity flowing in the system and even control smart components such as intelligent washing machines. Intelligent machines like these can run at scheduled time. Since the policy of Critical

Peak Pricing (CPP), where higher price for electricity is charged in peak hours in contrast with off-peak periods, is used for charging electricity, and intelligent machines can be turned off in peak hours and turned on while the electricity price is least expensive, this system can surely bring economical benefits to consumers. Similarly, suppliers can also communicate with consumers to check whether people agree to turn off some appliances in peak hours; people who agree to do so will be rewarded with some "credit points." Besides that, there are many advanced components in a smart grid, such as superconductivity transmission lines and storage facilities. Suppose each consumer has a large–size battery in his/her house, which can store electricity during off–peak time. Then during peak time, consumers can get the electricity directly from the battery, or even sell it back to suppliers. This would significantly reduce the demand of electricity from suppliers during the peak hours. Finally, advanced control methods would be designed to handle the whole smart grid system through integrated communications.

Foreseeing the importance of this new technology, many countries including Italy, Sweden, Holland, and England are developing nation–wide smart grid projects. Some other countries are carrying out smaller–scale regional smart grid plans. In America, President Obama put $3.4 billion into the research and deployment of smart grids in October, 2009. Fig. 3 shows the location of these

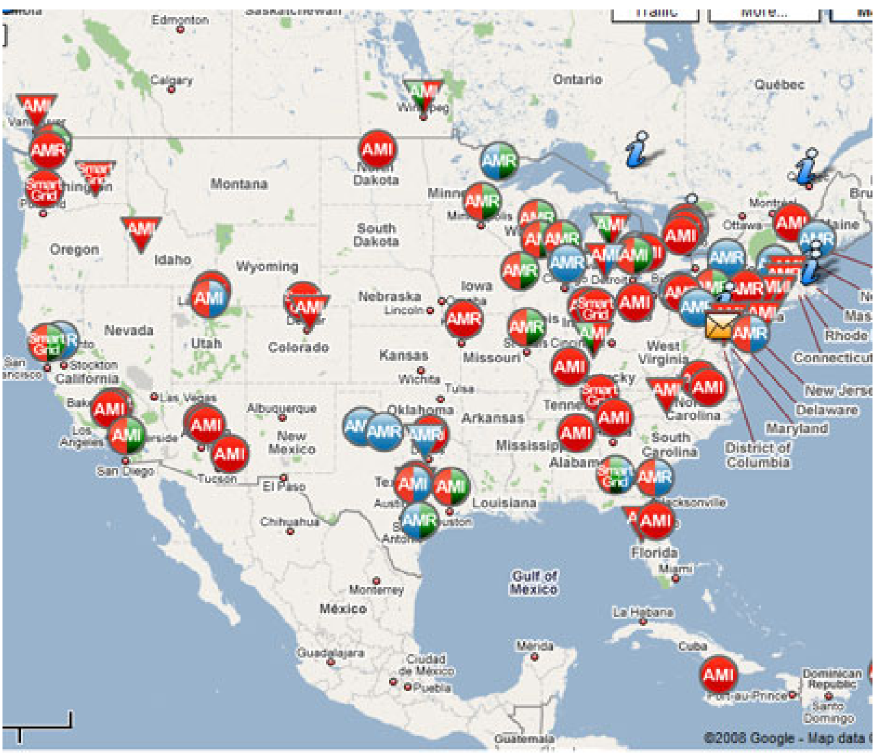

Fig. 3. AMI/AMR Deployment around U.S.A. [12]

pilot projects of automatic meter reading (AMR) and advanced metering infrastructure (AMI).

3 Advanced Metering Infrastructure (AMI)

To build a smart grid system, an advanced metering infrastructure (AMI) is required to actively measure, collect, and analyze energy consumption data. AMI has the interface to interact with advanced devices such as electricity meters, heat meters, gas meters, water meters, and any other intelligent appliances. In this section, we shall introduce how AMI works and the architecture of its communication networks. A pilot AMI project funded by National Science Council (NSC) in Taiwan will be demonstrated as a real example.

3.1 How AMI Works

Generally, an AMI system consists of four components (Fig. 4) – the smart meter, the energy display and controller, the communication network, and the meter data management application (MDMA).

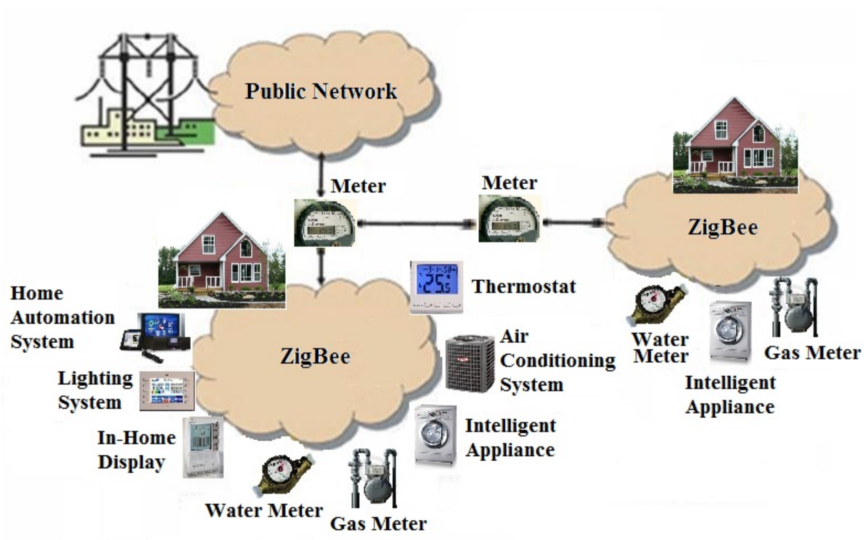

Fig. 4. An Illustration of AMI

The smart meter is an electricity meter with additional capacity to record energy usage and receive messages from suppliers. Besides, it can be turned on and off via remote controllers. Data cumulated by smart meters would be shown on the smart meter directly (Fig. 5) or on controllers such as the in–home display (IHD) device (Fig. 6). Consumers could interact with suppliers or check energy usage data through this device. The success of an AMI system would rely on a reliable communication network to connect smart meters with the display and controllers, so that the MDMA can manage collected data to make wise decisions.

Fig. 5. Smart Meter [13]

Fig. 6. In-Home Display [14]

3.2 National Science Council Program in Taiwan

To foster the AMI technology in Taiwan, National Science Council (NSC) funded some universities to run a pilot project inside the campus. The NSC project consists of four subprojects:

- Smart Power–saving Outlets
- Small–scale Energy Storage System
- Network and Communication Technology
- Smart Energy Management Application Service Platform

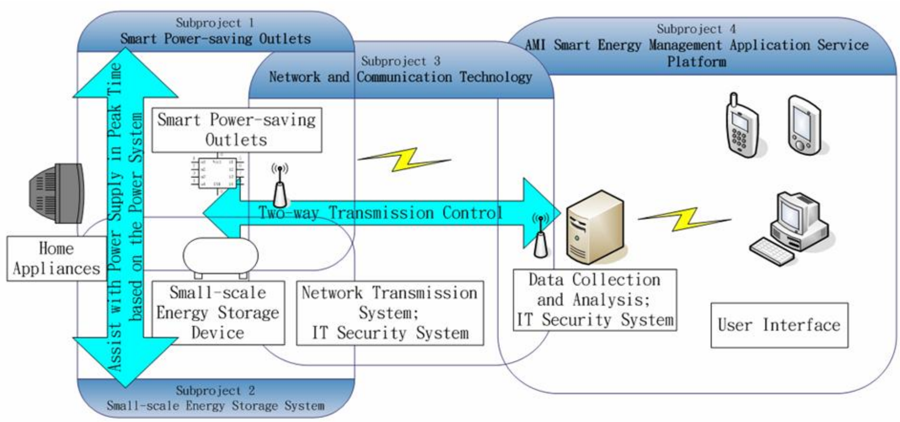

Fig. 7. Subprojects in the NSC AMI project in Taiwan

Fig. 7 shows the relationship between four subprojects of an AMI system. In the 1^{st} subproject, smart outlets will be designed which can intelligently record the electricity usage and then transmit the data to the management application of the 4^{th} subproject, where electricity usage data are stored and analyzed. According to the received data, the management application can monitor and control the overall electricity usage and even detect abnormal situations such as the excessive consumption of electricity on the outlet. Besides, to efficiently utilize the power and balance the electric output of power suppliers, a small–scale energy storage system for consumers is developed in the 2^{nd} subproject. This allows consumers to charge electricity in the off–peak time. During the peak time, consumers can get electricity directly from the storage system (usually some batteries) without demanding electricity from suppliers, and this can reduce the load of power suppliers in the peak time. As data transmission, the 3^{rd} subproject is responsible for making a two–way communication between management application and smart devices, smart outlets, and energy storages. Through the technology of the two–way communication, consumers can acquire data from smart devices, and put commands to control them, too.

3.3 Factors That Affect Deployment Cost

No matter how intelligent and wonderful the smart grid is, the cost of deployment and maintenance will be a key factor which will determine whether this new technology will be successful and widely adopted. As shown in Fig. 8, facility hardware and network hardware are the major cost of an AMI deployment, which are 45% and 20%, respectively.

Many AMI communication networks adopt the ZigBee wireless technology because of its low power and low cost characteristics. However, as every wireless technology, ZigBee suffers from the signal decay problem. Therefore, we need a relay which is the device used to strengthen the received signal and then re–transmit it

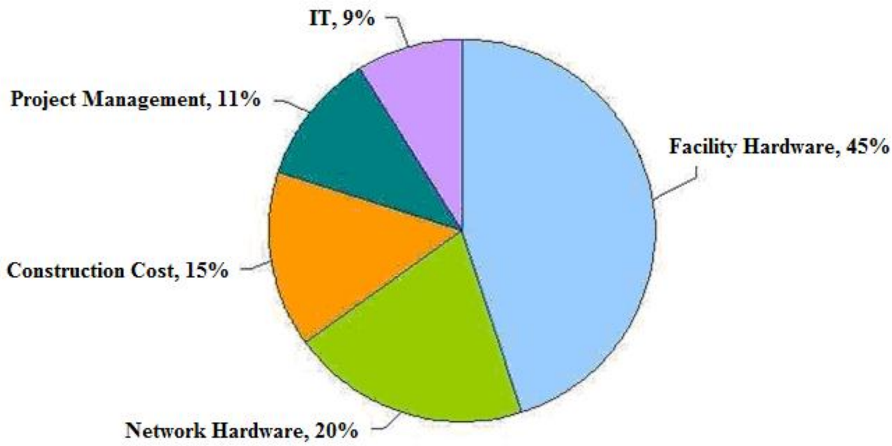

Fig. 8. AMI Deployment Cost Analyzing Illustration [15]

to the destination. Because of the limited range for radio communication, usually many relays must be added to form a connected stable network. Suppose the main facilities like smart devices, storages, and management applications are fixed, one factor that can affect the cost of the communication network is the number of relays. If the relays are not wisely deployed, quite a large number of relays must be deployed to form a connected network, which will significantly increase the cost of the AMI communication network. In next section, we shall formally define the Relay Placement Problem and illustrate the algorithms to solve it.

4 Relay Placement Problem (RPP)

The problem of finding positions of minimum number of relays in a smart grid system is called RPP. The problem definition, evaluation criterion of approximation algorithms, variations of RPP, and related algorithms are explained below.

4.1 Problem Definition

The definition of RPP is shown as follows: On a Euclidean plane, given a set of N sensors, which have the effective communication range 1, and a fixed number $R \geq 1$, which is the effective communication range of a relay. RPP is to place a minimum number of relays so that between every pair of sensors there is at least a path through relays such that the consecutive vertices of the path are within distance R if both vertices are relays and within distance 1 otherwise, forming a connected network. Fig. 9 shows a connected network with smart devices and relays.

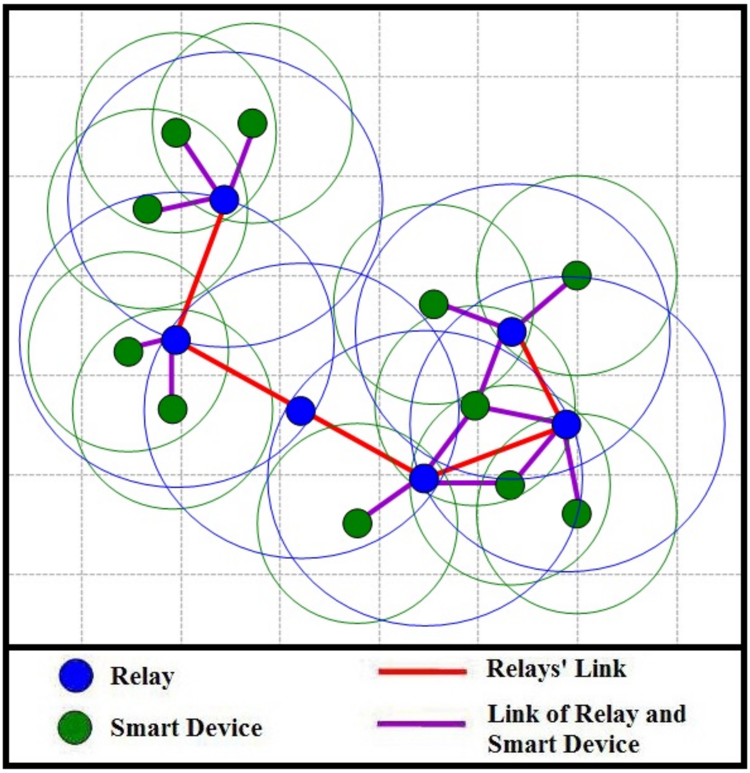

Fig. 9. Relay Placement Problem

4.2 The Worst Situation of Deployment

This subsection demonstrates some bad situations when relays are not deployed wisely. Assume that there are N sensors, and the effective communication rage of a relay is R. Those $N-1$ sensors form a standard circle where the distances of consecutive sensors are D, where $1 < D \leq 2$. The remaining sensor is placed in the center of the circle. Therefore, the distance between the central sensor and each outside sensor is approximately $\frac{(N-1)D}{2\pi}$.

To make the whole N sensors connected, relays can be placed between the central sensor and each of the $N-1$ outside sensors. Since the distances between central sensor and other sensors are all $\frac{(N-1)D}{2\pi}$, $(N-1)\lceil\frac{(N-1)D}{2\pi R}+1\rceil$ relays are needed to form a connected communication network. (Fig. 10)

However, there is another approach to deploy relays in this case. Suppose we place a relay in the middle of consecutive outside sensors. Totally $N-1$ relays will be deployed at this step. After that, we connect the central sensor to one another sensor arbitrarily via $\lceil\frac{(N-1)D}{2\pi R}\rceil+1$ relays. Through this way, all sensors become connected by only $N+\lceil\frac{(N-1)D}{2\pi R}\rceil$ relays, as shown in Fig. 11.

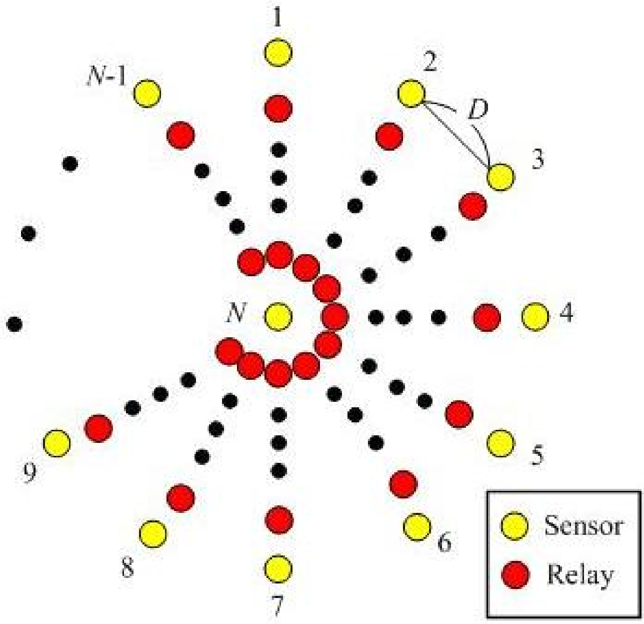

Fig. 10. A Bad Deployment of Relays

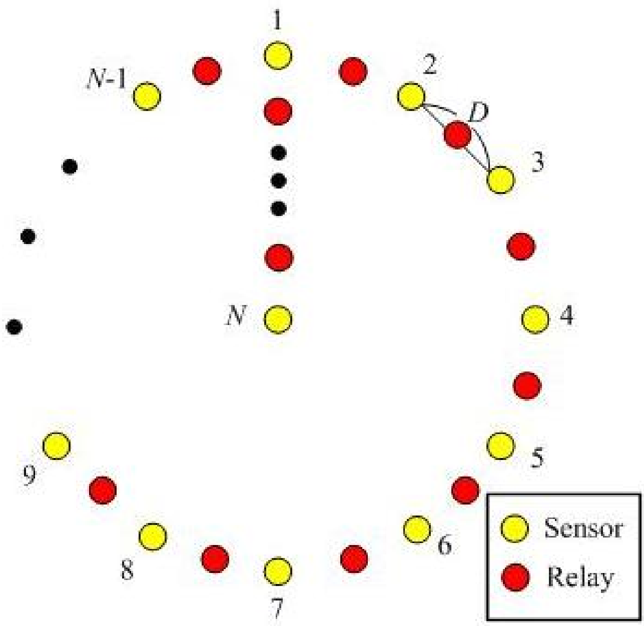

Fig. 11. A Wise Deployment of Relays

The above two deployment approaches are extremely different. They will require $(N-1)\lceil\frac{(N-1)D}{2\pi R}+1\rceil$ and $N+\lceil\frac{(N-1)D}{2\pi R}\rceil$ relays, respectively. Assume $N = 1000$, $D = 2$, and $R = 4$. The required number of relays for the first approach is approximately 80919; however, the second approach only needs 1080 relays. That is to say, people who adopt the first approach to deploy relays must spend nearly 75 times higher cost than those who choose the second approach.

4.3 The Evaluation Criterion – Approximation Ratio

Since Minimum Geometric Disk Cover (MGDC) problem is a special case of RPP, and MGDC is known to be NP–complete [9], RPP is an NP–hard problem. That is, it is unlikely for us to find a polynomial–time algorithm which returns the optimal solution. Therefore, many approximation algorithms for solving RPP were proposed.

It is important to define an evaluation criterion to judge which approximation algorithms perform better. If an approximation algorithm A guarantees to return a solution bounded by α multiplies by the optimal solution, then A is said to be an α–approximation algorithm and has an approximation ratio of α. Therefore, the approximation algorithm which has the smaller approximation ratio is desired here since RPP is expected to deploy fewer relays in a communication network.

4.4 Approximation Algorithms and Variations of RPP

For the simplest RPP problem, forming a connected network is enough. However, considering higher reliability in the communication network of a smart grid, one variation of RPP, namely 2–connected RPP, which is to form a 2–connected network where there exist two disjoint paths between any two sensors, was also proposed.

Table 1. Approximation Ratio Comparisons

	LWJ2006 [4]	THS2006 [5]	LX2007 [6]	EFGMPS 2008 [7]	CDWX 2008 [8]
RPP	$6+\epsilon$	8 and 4.5	7	3.11	3 and 2.5
2–Connected RPP	$(24+\epsilon)$ and $(\frac{6}{T}+12+\epsilon)$	6 and 4.5			

To the original RPP, [4,5,6,7,8] proposed $(6{+}\epsilon)$–approximation, 8–approximation, 4.5–approximation, 7–approximation, 3.11–approximation, 3–approximation, and 2.5–approximation algorithms respectively, as shown in Table 1. Fig. 12 depicts an example that runs the 8–approximation algorithm in [5] to deploy relays.

To the 2–connected RPP, [4] proposed a $(24+\epsilon)$–approximation and a $(\frac{6}{T}+12+\epsilon)$–approximation algorithm, in which T is the ratio of the number of relays placed in its RPP to the number of sensors, while [5] proposed a 6–approximation and a 4.5–approximation algorithm.

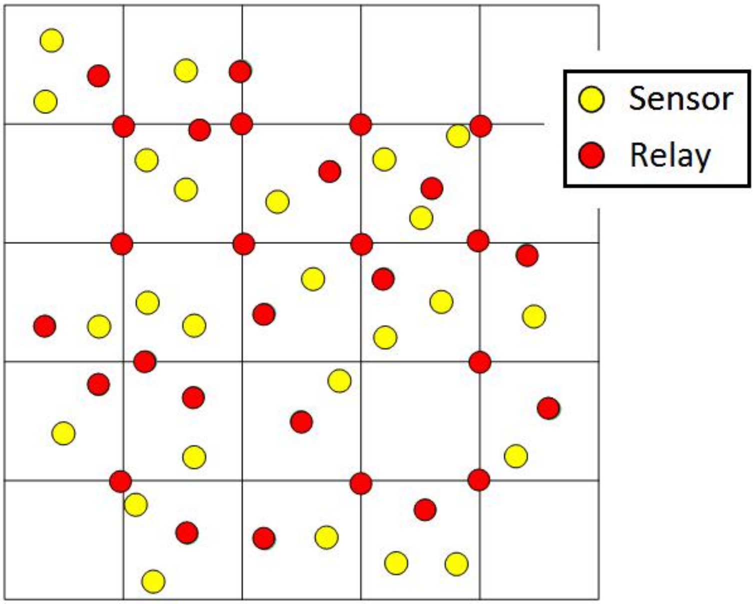

Fig. 12. An Example of [5]'s 8–approxiamtion Algorithm

4.5 Decision Supporting System in NSC Program

In our NSC AMI project, a 4.5–approximation algorithm of 2–connected RPP in [5] is selected to serve the decision supporting system for relay deployment because of the easy practice and reliability. The steps are described briefly below.

Algorithm 1. A 4.5–Approximation Algorithm for RPP

Step 0. Divide the region into cells with side length 4. For each cell, find all P–positions for relays (where position Y is called a P–position if there exist two sensors which are one unit away from Y). Move those P–positions outside the cell to the nearest border on its cell.

Step 1. Inside each cell, exhaustively search all 1 through 21–subsets of the P–positions inside (or on) the cell, to find a subset with smallest order which can cover all sensors in the cell at least twice. For each cell B_i, Let H_i be the set of relays found for B_i (note that each H_i has at least two relays).

Step 2. Inside each cell B_i, if the relays in H_i are connected but not 2–connected, add a relay on the horizontal mid–line of B_i, 4 units away from the left–top corner of B_i. If they are not connected, then add one more relay on the vertical mid–line of B_i, 4 units away from the left–top corner of B_i.

Step 3. Now, we make the set of the chosen relays to be connected.

Step 3.1. Connect each row of the H_i's.

Let H_{i+1} be the set of relays to the right of H_i. If H_i and H_{i+1} are not connected, add a relay, q_i, on the horizontal mid–line of B_i, 4 units away from the left–top corner of B_i, and set $H_i = H_i \cup q_i$. If they are still not connected, add a relay, q_{i+1}, on the horizontal mid–line of B_{i+1}, 4 units away from the left–top corner of B_{i+1}, and set $H_{i+1} = H_{i+1} \cup q_{i+1}$ (notice that we only make them connected here, instead of 2–connected).

Repeat **Step 3.1**, until every row of H_i's is connected.

Step 3.2. Connect each column of the H_i's.

For each H_i, let $LEFT_{B_i}$ denote the set of relays in H_i, which are connected to some relays in the set to the left of H_i, i.e., $LEFT_{B_i} = \{q \in H_i | q$ is connected to a node in the set to the left of $H_i\}$; let $RIGHT_{B_i}$ denote the set of relays in H_i, which are connected to some relays in the set to the right of H_i, i.e., $RIGHT_{B_i} = \{q \in H_i | q$ is connected to a node in the set to the left of $H_i\}$.

If $|LEFT_{B_i} \cup RIGHT_{B_i}| > 1$, then $H_i' = H_i$. Otherwise, $H_i' = H_i - LEFT_{B_i} \cup RIGHT_{B_i}$.

Let H_{i+x} be the set of relays directly under H_i. If H_i' and H_{i+x}' are not connected, then add a relay, q, on the vertical mid–line of B_i, 4 units away from the left–top corner of B_i, and set $H_i = H_i \cup \{q\}$. If they are still not connected, add a relay, q', on the vertical mid–line of B_{i+x}, 4 units away from the left–top corner of B_{i+x}, and set $H_{i+x} = H_{i+x} \cup \{q'\}$.

Repeat **Step 3.2**, until every column of H_i's is connected.

Suppose the optimal deployment of a RPP problem requires N relays. Mathematically, it can be shown that the above algorithm can always give a deployment with at most $4.5N$ relays. [5]

5 Conclusions and Future Works

The deployment cost of a smart grid system is crucial to its success. This paper illustrated the Relay Placement Problem, which significantly affects the cost of an AMI system when ZigBee is adopted in its communication network. To solve the Relay Placement Problem, we demonstrated a decision supporting system in our NSC project, which adopted intelligent algorithms to minimize the number of relays in question. When deploying larger networks, where significant amount of relays are needed, an efficient RPP algorithm would be very important to control the deployment cost.

Acknowledgments

This work was supported in part by National Science Council in Taiwan under grants NSC98-2218-E-029-004 and NSC99-2221-E-260-012.

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