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Cooperative Transmission for Meter Data Collection in Smart Grid

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Abstract

Smart grid will become the next generation electrical power system to provide reliable, efficient, secure, and cost-effective energy generation, distribution, and consumption. To achieve these goals, communications infrastructure and wireless networking will play an important role in supporting data transfer and information exchange in smart grid. In this article, the application of cooperative transmission for the meter data collection in smart grid is introduced. In a service area of smart grid, there are multiple communities composed of power consumption nodes (e.g., houses). The power consumption demand from the nodes is measured by smart meter and transmitted to meter data management system (MDMS) through the data aggregator unit (DAU) using wireless broadband access. The community invests and deploys relay station to perform relay transmission to improve the transmission rate and to avoid the congestion at DAU. As a result, MDMS will have the complete and correct power demand data which can be used to make a better decision of power supply. Since the communities in a service area of smart grid are rational, they will optimize the relay transmission strategy so that the total cost (i.e., power cost and transmission cost) is minimized. To analyze the relay transmission strategy of the community, the noncooperative game model is formulated and the Nash equilibrium is considered as the solution. The proposed network architecture and analysis will be useful for the design and optimization of wireless network for smart grid.

I. INTRODUCTION

Smart grid has been introduced to be the next generation electrical power grid by integrating modern information, communications, and electronic technologies. Smart grid will introduce a distributed and user-centric system that will incorporate consumers into its decision process to provide cost-effective and reliable power supply. The modern communications infrastructure will play an important role in managing, controlling, and optimizing different functional and smart devices and systems in a smart grid. Wireless technologies can be used in different parts of smart grid to achieve flexible and low-cost data communications and networking. However, since the radio resource of wireless network is limited, the

maximum efficiency must be achieved by using the advanced technique (e.g., cooperative transmission) so that the optimal decision about power management can be made.

In this article, we explore the application of the cooperative transmission to the wireless network for smart grid. Specifically, we consider the optimal cooperative transmission of meter data in smart grid. The cooperative diversity achieved in cooperative transmission helps to improve the transmission rate of the data aggregator unit (DAU) transmitting the meter data collected from the nodes with smart meter to the meter data management system (MDMS). Since in a service area of smart grid, there are multiple rational communities with power consumption nodes (e.g., houses), the communities can invest and deploy relay stations to perform relay transmission for DAU. With relay transmission, the congestion at DAU can be avoided and, consequently, the MDMS will have complete and correct power demand data for the decision making on electrical power allocation. However, at the same time, communities have to minimize the cost (i.e., power cost and transmission cost). Noncooperative game model is formulated and the Nash equilibrium is obtained as the solution for the relay stations of communities to perform relay transmission.

The rest of this article is organized as follows: Section II presents an overview of smart grid and the role of data communications and wireless networking. Section III introduces the cooperative transmission of meter data in smart grid. The network model and optimal strategy of relay stations are also discussed. Finally, Section IV concludes the article. Table I provides the list and description of abbreviations used in this article.

Table I: List of abbreviations.

II. DATA COMMUNICATIONS AND WIRELESS NETWORKING FOR SMART GRID

In this section, a brief overview of smart grid is presented. The role of data communications and wireless networking for smart grid is given. Then, the potential application of cooperative transmission to smart grid is discussed.

A. Smart Grid

The existing electrical power grid is evolving to face the new challenges (e.g., increase in demand response, depletion of primary energy resources, generation diversification, climate changes, and reliability) which must be responded to in a vision of the future [1]. Therefore, the concept of smart grid has been introduced with the decentralized infrastructure that provides better demand side management and intelligent power supply. Smart grid will be a user-centric system which improves the flexibility, efficiency,

accessibility, and reliability. Besides the incumbent function of delivering electricity from suppliers to consumers, smart grid will also provide information and intelligence to the power grid to enable grid automation, active operation, and efficient demand response.

Smart grid will use two-way data communications technologies to integrate the electrical power control system with consumers so that the intelligent power generation, distribution, and consumption can be achieved. Moreover, smart grid will allow active participation of users by providing consumer data related to demand and fault report. Smart grid is expected to have the broad capabilities including self-healing, integrated distributed energy resource (DER) (e.g., solar panel), improving grid security, supporting plug-and-play devices, and interoperability.

Fig. 1 shows the components related to data communications and wireless networking for smart grid. The detail of each component is as follows:

- *Home Appliance*: Home appliance is a power consumption device in smart grid. The power consumption of home appliances in the house is measured and collected by smart meter. Alternatively, advanced home appliance can proactively send report to smart meter.
- *Smart Meter*: Smart meter is a device used to collect the power consumption data from home appliances. Smart meter can have the capability of data transmission to report the meter data (e.g., power demand). Alternatively, smart meter may connect with the home gateway with a dedicated function of data transmission.
- *Data Aggregator Unit (DAU)*: DAU is a communication device used to collect meter data from smart meter or home gateway. The meter data will be transmitted by DAU to the control center for managing the power consumption and supply.
- *Power generator*: Power generator is the system to supply the electrical power into the grid. Power generator has to report the status and its capacity to the control center. Also, in the case of open power market, power generator has to inform the price of power to the consumers (e.g., for energy bidding).
- *Power Transmission and Distribution*: Power transmission and distribution are used to transfer electrical power from the generator to the consumers using the network of transmission lines and distribution stations. The status and capacity of transmission line and distribution station have to be reported to the control center. In the case of open power market, the cost of power transmission and distribution has to be informed to the generator and consumers, so that the best power delivery can be achieved.
- *Meter Data Management System (MDMS)*: MDMS is a control center providing the storage, manage-

ment, and processing of meter data for proper usage by other power system applications and services. Also, MDMS collects the status and attribute of the power generator, transmission, and distribution for optimization purpose. The communications of MDMS (e.g., to power generator) can be through IP networks.

It is important that all components in smart grid must have high speed, seamless, and reliable data communications to support full features of power generation, consumption, and management. In the following, the data communications and network infrastructures for smart grid will be discussed.

B. Data Communications and Networking Infrastructure

Different data communications and networking infrastructures (i.e., wired and wireless) are developed to provide functionality for smart grid, i.e., home energy management system (HEMS), wide-area measurement system (WAMS), advanced metering infrastructure (AMI), and sensor and actuator network (SANET).

1) *Home Energy Management System (HEMS)*: One objective of smart grid is to reduce energy consumption in the household. To achieve this, HEMS is developed for the effective energy management at consumer side. HEMS provides the capability of monitoring and controlling different electrical appliances using various communications technologies (e.g., power line communication (PLC), ZigBee, and WiFi). Therefore, the power management services and consumers' end devices such as smart meters, smart appliances, smart sensors, and energy monitoring tools (e.g., thermostats and in-home displays) can be monitored and controlled in real-time fashion. The major HEMS services are based on real-time price-responsive load management and power consumption history analysis (e.g., Google powermeter and Microsoft Hohm). The price and load information is used to control the energy usage of appliances to meet the consumer requirement.

2) *Wide-Area Measurement System (WAMS)*: WAMS is a monitoring and controlling system which can simultaneously acquire variety of information (e.g., phase of voltage, current, rate of change of frequency, and power of the lines) to provide effective security and fault tolerance for the entire power grid. With the main focus on the power generation, transmission, and distribution, WAMS consists of a control center, phasor measurement unit, and phasor data collector to measure the electrical waves on an electricity grid so that the state and performance of the power grid can be analyzed.

3) *Advanced Metering Infrastructure (AMI)*: AMI is the key component in a smart grid to support data communication architecture between the smart meter and MDMS. Additionally, AMI will also provide

an interface to other parts of smart grid (e.g., adaptive electrical supply and transmission and active user interface for information access by consumers). AMI will be used to transfer real-time meter data including fault and outage to the electrical power control center. A hierarchical network or a multi-tier architecture with a variety of communications technologies including PLC, cellular network (e.g., GSM and CDMA), broadband wireless access (e.g., WiMAX), and IP network will be used in AMI, e.g., to support HEMS.

4) *Sensor and Actuator Network (SANET)*: SANET is composed of a number of sensors and actuators, used to monitor and control the operational characteristic and behavior of smart grid devices so that any outage or disturbance can be prevented. The sensors and actuators can be used at multiple sites in smart grid (e.g., at transformer, at distribution substation, or at home). The sensors are used to measure different system parameters (e.g., light intensity, temperature, voltage and current fluctuation, and power of the line). The actuators receive and convert control signal into actions by setting the values of different parameters (e.g., displaying the sensor measurements or status of circuit breaker). SANET is required to provide secure and continuous information transfer among sensors and actuators using wired/wireless links.

C. Wireless Network Architecture

To support data transfer and power management in smart grid, different wireless network architectures can be used. As shown in Fig. 1, three main networks different in sizes and locations used in smart grid are the home area network (HAN), neighborhood area network (NAN), and wide area network (WAN).

1) *Home Area Network (HAN)*: HAN uses the short-range or local area wireless transmission (e.g., WiFi and ZigBee) to support real-time meter data transfer, dynamic pricing, and deterministic direct load control by connecting the devices with sensors and actuators (e.g., SANET), in-home display, smart meter, and HEMS. Wireless technologies become the popular choices for HAN due to their low installation cost and better control and flexibility. For example, ZigBee is a suitable technology for HAN in terms of interoperability. In HAN, the home gateway or HAN gateway is used to transfer data to the external entity (e.g., DAU). HAN gateway can be integrated into smart meter or alternatively be a stand-alone device integrated into some in-home devices such as in-home display or programmable thermostat.

2) *Neighborhood Area Network (NAN)*:

Fig. 1: Meter data collection in smart grid.

NAN connects multiple HANs together. As shown in Fig. 1, HAN gateway transfers meter data to DAU through NAN. The DAU communicates with the HAN gateway using network technologies such as WiFi.

Also, DAU can act as the NAN gateway to transfer data to MDMS.

3) *Wide Area Network (WAN)*: WAN is used to connect remote systems (e.g., MDMS, AMI, and SONET) together in smart grid. Also, WAN is part of the WAMS to collect and manage data transmission for measurement and control purposes. WAN also provides a backhaul for connecting electrical power company to the customer premises, power generators, transmission, and distribution subsystems. In this case, the backhaul can adopt a variety of technologies (e.g., cellular network or broadband wireless access) to transfer the data from NAN (through DAU) to the MDMS at the local offices. A WAN gateway can use broadband connection (e.g., 3G, satellite, and WiMAX) to collect the required data.

D. Cooperative Transmission in Smart Grid

Cooperative transmission based on cooperative diversity technique has been introduced to improve the performance (i.e., reliability and throughput) by taking advantage of the broadcast nature of wireless channels. The signals transmitted from a source to its destination can be overheard by other nodes in the vicinity of the source. Such nodes can act as relays to repeat the transmission, which makes it possible for the destination to receive multiple independent copies of the transmitted information from the source and the relays, respectively. In this way, a virtual MIMO can be formed for users with a single antenna, and cooperation diversity can be achieved. The advantages of using cooperative transmission in the wireless networks for smart grid are as follows:

- *Improving reliability*: In smart grid, wireless networks (e.g., SANET) can be deployed in power generator, transmission, and distribution sites to monitor and perform necessary control action. In those sites, the severe electromagnetic interference can result in high transmission error. Cooperative transmission can be used to improve the bit-error-rate (BER) performance [2] and, hence, the reliability of smart grid.
- *Enhancing transmission rate*: In wireless networks, radio resource in terms of bandwidth (e.g., channel and time slot) is scarce and expensive (e.g., in WAN). With the limited radio resource, the gateway and data aggregator (e.g., to collect meter data from consumption nodes or price information from generators) can be the bottleneck which results in poor decision making of power management due to the lack of complete and timely information. Therefore, cooperative transmission can be used to increase the transmission rate so that the congestion in wireless network for smart grid can be avoided.

Although various issues (e.g., scheduling [3], power allocation [4], and routing [5]) of cooperative transmission have been addressed in the literature, all of them considered traditional networks (e.g.,

Internet). Also, none of them considered the wireless environment for smart grid which has different transmission requirements. In this article, the cooperative wireless transmission is considered in WAN to transfer meter data from DAU to MDMS. Cooperative wireless transmission is suitable for meter data transfer between DAU and MDMS, since the data volume is not high and the delay constraint of the data is not stringent. In the next section, the optimal relay transmission strategy of relay stations is obtained through the noncooperative game formulation.

III. COOPERATIVE TRANSMISSION FOR METER DATA COLLECTION

In this section, the cooperative transmission for the meter data collection in smart grid is introduced. First, the network model is described. Next, the noncooperative game model is formulated for the optimal cooperative transmission strategy of the relay stations. The numerical results are then presented.

A. Network Model

We consider HEMS in a service area of smart grid. In HEMS, the meter data (i.e., power consumption and demand status) is collected from the home appliances using smart meter. The service area is divided into I communities, each community corresponding to a group of houses (e.g., village). Denote the number of nodes in community i as N_i . All communities transfer meter data from smart meter of the nodes through NAN (e.g., single-hop or multi-hop WiFi) to DAU. Then, DAU transfers meter data through WAN (e.g., WiMAX) to MDMS. MDMS performs the demand estimation and allocates the power supply to all communities. Without loss of generality, each community invests and deploys a relay station to perform cooperative transmission for DAU so that the performance of WAN link from DAU to MDMS can be improved (i.e., the higher transmission rate). As a result, the congestion at DAU collecting meter data from a number of nodes can be avoided. Fig. 2 shows an example of aforementioned network model with 3 communities where RS_i is the relay station of community i . Clearly, the relay station can be located at different location of a community (e.g., between DAU and MDMS) to improve the transmission performance of DAU through the relay transmission. Note that the community may not prefer to forward meter data of the nodes to MDMS using relay station since the extra WAN link (e.g., spectrum and time slot) would be required which is more costly than that of NAN.

The two-hop cooperative transmission from DAU to MDMS is considered (e.g., the frame structure as in IEEE 802.16j and 802.16m [6] can be used). Specifically, the relay station of community adopts decode-and-forward (DF) relaying method. Each relay station is assumed to operate on the same channel as that of DAU. First, DAU transmits the packet of meter data to MDMS. At the same time, relay stations

of all communities receive the data transmitted by DAU. If a relay station decides to perform relay transmission (i.e., according to the selected strategy of the community), it will decode the received packet from DAU. Then, the relay station transmits the decoded packet from DAU to MDMS. Let $r(\mathcal{C})$ denote the transmission rate given set $\mathcal{C}$ of the active relay stations. Given the channel qualities, the transmission rate $r(\mathcal{C})$ can be obtained by calculating the spectral efficiency of multiple relay stations with adaptive modulation (e.g., [7, Eq. (5)]).

B. Power Supply and Demand Estimation

Due to the uncertainty (e.g., random electrical power demand), in general, the operational decision of power system is made in two stages [8]. In the first stage, the electrical power company reserves power supply from the generator according to the expected load. This stage is called *unit commitment*, in which a contract is made before the actual operation. Then, in the second stage called *economic dispatch*, after the actual demand is observed, the reserved power is supplied to the consumer. However, if the reserved power is not enough (i.e., under-reservation), additional power will be bought from the available generator. Since the decision in unit commitment stage (i.e., amount of power to be reserved) is made in advance, the electrical power company can choose and buy power with a cheaper *forward price* denoted by p_f than a *option price* denoted by p_o in economic dispatch stage. By having decision in two stages, the electrical power company can efficiently schedule the electrical supply to the consumer under uncertainty.

In HEMS, MDMS first estimates the power demand from all nodes in all communities based on the meter data transmitted by DAU. This estimation is done during the *estimation period*. Then, with the estimated power demand, MDMS makes decision to reserve the power supply in unit commitment stage before the *power consumption period*, and to buy additional power supply in the economic dispatch stage during the power consumption period. For example, for the power consumption period of 7:00-8:00pm, the estimation period could be 6:55-7:00pm. The power supply reservation in the unit commitment stage will be done just before 7:00pm. Then, the additional power supply in the economic dispatch stage will be bought during 7:00-8:00pm if the reserved power supply cannot meet the actual demand.

For the power demand estimation, each node in a service area sends a sample of power consumption (i.e., power demand) to MDMS through DAU during estimation period. The samples are aggregated and the total power demand of a service area for the power consumption period is computed by MDMS. Let the average power demand of node n in community i be denoted by $P_{i,n}$. If there is no packet loss between DAU and MDMS (i.e., no congestion), the estimated total power demand is denoted by $D = \sum_{i=1}^I \sum_{n=1}^{N_i} P_{i,n}$. However, if there is a congestion at DAU, and the packet loss probability (e.g., due

to the lack of buffer space) is denoted by L , the estimated total power demand becomes $\tilde{D}(L) = (1-L)D$, where the packet loss is assumed to be uniform and independent for all nodes. In this case, since the MDMS lacks complete data, the packet loss results in lower estimated power demand. The actual power demand is random with probability density function (PDF) denoted by $f(z)$ for power demand z . The power cost with demand estimation error (i.e., due to packet loss probability L of DAU) can be obtained from

$$C^{\text{pow}}(L) = p_f \tilde{D}(L) + \int_{D_{\min}}^{D_{\max}} p_o \max(0, z - \tilde{D}(L)) f(z) dz, \quad (1)$$

where $D_{\min}$ and $D_{\max}$ are the minimum and maximum power demands, respectively. The power cost with demand estimation error defined in (1) is composed of the reserved power supply cost in unit commitment stage with the forward price (i.e., $p_f \tilde{D}(L)$) and additional power supply cost in economic dispatch stage with option price if the reserved power supply cannot meet the demand (i.e., $\int_{D_{\min}}^{D_{\max}} p_o \max(0, z - \tilde{D}(L)) f(z) dz$). Note that to simplify the calculation of the power cost, the power demand can be discretized into a finite set in which the integration over PDF of the demand in (1) is replaced by the summation over the approximated probability mass function (PMF) [9].

C. Optimal Cooperative Transmission for Meter Data Transmission

Fig. 2: Cooperative transmission for meter data collection in smart grid.

Since the communities in the service area of smart grid can be rational to minimize their own cost, they can act strategically to perform relay transmission for DAU. For example, consider the scenario shown in Fig. 2, the relay station of community 1 always performs relay transmission for DAU. Consequently, due to the higher transmission rate, the packet loss at DAU is reduced, which results in smaller demand estimation error and less power cost (i.e., enough power supply is reserved in the unit commitment stage). In this case, communities 2 and 3 are also beneficial from the relay transmission by relay station of community 1, while there is no cost for them from relay transmission. Since the community 1 is aware of this fact, it may not always perform relay transmission for DAU to reduce its cost due to relay transmission. In this case, as communities 2 and 3 are rational, they have to perform relay transmission for DAU to achieve the low power cost. Therefore, it is important for all communities to obtain the equilibrium strategies of relay transmission for DAU, so that their individual cost is minimized.

According to the aforementioned noncooperative situation among communities in a service area of smart grid, the noncooperative game model can be formulated as follows: The players are the communities in a service area, where the total number of players are I . The strategy x_i of player i is the probability of

relay transmission for the packet from DAU to MDMS. The objective of player is to minimize the total cost. The total cost of player i is defined as follows:

$$C_i^{\text{tot}}(x_i, \mathbf{x}_{-i}) = C_i^{\text{pow}}(L(x_i, \mathbf{x}_{-i})) + C_i^{\text{rel}}x_i, \quad (2)$$

where $\mathbf{x}_{-i}$ is a vector of probabilities of relay transmission by the relay stations of all communities except that of community i . $C_i^{\text{pow}}(L)$ is the power cost of community i obtained from (1) considering only the nodes in community i . C_i^{rel} is the cost due to the relay transmission (e.g., due to power consumption and bandwidth usage of relay station). $L(x_i, \mathbf{x}_{-i})$ is the packet loss defined as a function of probabilities of relay transmission. The packet loss can be obtained from $L(x_i, \mathbf{x}_{-i}) = \frac{\sum_{i=1}^I N_i - R(x_1, \dots, x_I)}{\sum_{i=1}^I N_i}$ where $\sum_{i=1}^I N_i$ is the total number of packets of meter data generated during estimation period and arrived at DAU. $R(x_1, \dots, x_I)$ is the average transmission rate of DAU per estimation period given the relay transmission probabilities of all communities. The transmission rate of DAU can be obtained by considering all cases of communities through the set of $\mathcal{C}$ performing relay transmission. Specifically, the transmission rate of DAU is obtained from

$$R(x_1, \dots, x_I) = \sum_{\forall \mathcal{C} \subseteq \mathcal{I}} \left(\prod_{i \in \mathcal{C}} x_i \right) \left(\prod_{j \in \mathcal{I} \setminus \mathcal{C}} (1 - x_j) \right) r(\mathcal{C}), \quad (3)$$

where $\mathcal{I} = \{1, \dots, I\}$ is a set of all players (i.e., all communities), and $r(\mathcal{C})$ is the transmission rate of DAU when the relay stations of communities in set $\mathcal{C}$ perform relay transmission. Note that the packet loss from each node to DAU in NAN is negligible since the high speed connection (e.g., WiFi) and the QoS-aware routing (e.g., as in [10]) can be used.

The Nash equilibrium [11] is considered to be the solution of the noncooperative game model for relay transmission by multiple communities in a service area of smart grid. First, the best response strategy of community i is obtained as follows: $x_i^* = \min_{x_i} C_i^{\text{tot}}(x_i, \mathbf{x}_{-i})$. Then, the Nash equilibrium is defined by x_i^* for $C_i^{\text{tot}}(x_i^*, \mathbf{x}_{-i}^*) \leq C_i^{\text{tot}}(x_i, \mathbf{x}_{-i}^*) \forall i \in \mathcal{I}$. Specifically, the Nash equilibrium is obtained as follows: $x_i^* = \min_{x_i} C_i^{\text{tot}}(x_i, \mathbf{x}_{-i}^*)$ where $\mathbf{x}_{-i}^*$ is a vector of best response strategies of all communities except that of community i . At the Nash equilibrium, none of the community can change the probability of relay transmission to decrease the individual total cost defined in (2) if other communities keep their strategies unchanged. The numerical method (e.g., simplex algorithm [12]) can be applied to obtain the best response strategy and, subsequently, the Nash equilibrium.

D. Numerical Results

We consider a service area with 3 communities and, hence, 3 relay stations. Each community is composed of 100 nodes. The estimation period is 5 minutes, and the power consumption period corresponding to the estimation period is 1 hour. The power demand of each node is random and follows normal distribution. The mean of power demand of each node is 3kWh with variance 1. The forward price of power reserved in the unit commitment stage is 0.3\$ per kWh and the option price of power acquired in the economic dispatch stage is 0.5\$ per kWh. The relay transmission cost of relay station is 10^{-3} \$. Unless otherwise mentioned, the channel quality (i.e., average SIR) from DAU and relay stations to MDMS is 7dB. Let γ_i denote the channel quality from relay station of community i to MDMS.

Fig. 4: Packet loss probability at DAU under different probability of transmission by relay station 1.

Fig. 4 shows the packet loss probability at DAU given the different probabilities of relay stations to help the transmission from DAU to MDMS. With the limited radio resource at DAU, the packet loss can be reduced if the relay stations perform relay transmission. As the relay stations increase the chance of relay transmission for DAU, the packet loss decreases. As a result, MDMS will have more complete information about the power demand. The reservation of power in unit commitment stage with lower forward price can reduce the power cost. Fig. 3 shows the total cost (i.e., power cost and relay transmission cost) of community 1 under different probabilities of relay transmission. First, the total cost decreases when the relay transmission probability of relay station 1 increases. However, at a certain point the total cost increases since the increase in cost of relay transmission is larger than the decrease in power cost due to relay transmission. Clearly, there is the optimal point for the relay station 1 to minimize its total cost and this is referred to as the best response strategy. Given the different probabilities of relay transmission by the relay stations 2 and 3, this best response strategy of community 1 changes accordingly. In particular, if relay stations of communities 2 and 3 perform more relay transmissions, community 1 will achieve lower total cost when its relay station performs less relay transmission.

Fig. 5: Best responses of relay stations 1 and 2.

Fig. 5 shows the best response strategies of relay stations 1 and 2 (i.e., denoted as BR1,2 in the legend). We observe that the best response strategies of relay stations 1 and 2 overlap on the same curve. When relay station 3 increases probability of relay transmission (i.e., from $x_3 = 0.5$ to $x_3 = 0.6$ for fixed $\gamma_1 = 7$ dB), the best response strategies of relay stations 1 and 2 decrease since they benefit from the

higher transmission rate due to the strategy of relay station 3. In addition, when the channel quality of relay station 1 becomes better (i.e., from $\gamma_1 = 7\text{dB}$ to $\gamma_1 = 10\text{dB}$ for fixed $x_3 = 0.6$), the best response strategies of relay stations 1 and 2 correspond to the smaller probability of relay station 1 performing relay transmission. Since the channel quality of relay station 1 is better in this case, the DAU achieves higher transmission rate per relay transmission by relay station 1. Therefore, relay station of community 1 can reduce the probability of relay transmission to achieve the lowest total cost.

When relay station 3 can optimize its strategy, we again observe that its best response strategy also overlaps with those of the relay stations 1 and 2. Therefore, there could be an infinite number of Nash equilibria. On these Nash equilibria, none of relay stations can deviate by increasing or decreasing the probabilities of relay transmission to achieve the lower total cost. An infinite number of Nash equilibria occur, since the strategies in terms of the probabilities of relay transmission are substitutable. In particular, the power cost can be minimized at a certain transmission rate of DAU. This transmission rate can be the result of an infinite number of combinations of probabilities of relay transmission selected by the communities. For example, if x_1 is small, x_2 and x_3 must be large or if x_1 is large, x_2 and x_3 can be small and both cases achieve the lowest individual total cost. Therefore, if one of these combinations is reached, there is no motivation for all communities to change their strategies which constitute the Nash equilibrium.

Fig. 6: Nash equilibrium under different channel qualities.

However, since there are a number of Nash equilibria, the equilibrium selection will be important. We assume that the relay stations can search along the Nash equilibria and select the solution which yields the lowest total cost for all relay stations. Fig. 6 shows the adaptation of the selected Nash equilibrium for relay station of community 1. As the channel quality improves, the probability of relay transmission of the relay station of community 1 at the Nash equilibrium decreases. The similar effect is observed for relay stations of communities 2 and 3 whose results are omitted for brevity.

From the numerical results, the observations can be summarized as follows:

- Relay stations of multiple communities in smart grid can perform relay transmission to improve the performance of DAU which results in lower total cost.
- The relay stations can strategically adjust the probabilities of relay transmission for DAU to reach their lowest cost. The noncooperative game model is formulated to analyze this situation.
- There could have an infinite number of Nash equilibria, and the equilibrium selection can be applied to reach the best solution.

For the future work, the different equilibrium selection policies can be applied to investigate the behavior of the relay stations.

IV. CONCLUSION

In this article, the application of cooperative communications to smart grid has been introduced. First, a brief overview of data communications and wireless networking in smart grid has been presented. The potential usages of cooperative transmission in smart grid have been identified. Then, we have considered the problem of optimal cooperative transmission for meter data collection for smart grid. The multiple rational communities in a service area of smart grid decide strategically to perform relay transmission for the data aggregator unit (DAU) to transmit meter data to the meter data management system (MDMS) so that their individual total cost (i.e., power cost and transmission cost) is minimized. The noncooperative game model has been formulated and the Nash equilibrium has been considered as the solution. It has been found that there could be an infinite number of Nash equilibria and the simple equilibrium selection policy has been applied to obtain the minimum total cost of all communities.

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TABLE I
LIST OF ABBREVIATIONS.

Abbreviation	Description
AMI	<i>Advanced metering infrastructure</i> is used to collect the meter data from smart meter
DAU	<i>Data aggregator unit</i> collects meter data from smart meters and transmits to control center
DER	<i>Distributed energy resource</i> is a small power generator to provide alternative electrical power to the grid
DF	<i>Decode-and-forward</i> is a technique in cooperative transmission where relay station receives, decodes, and transmits the data from source to destination
HAN	<i>Home area network</i> is a small wired/wireless network connecting sensors and home appliances to the smart meter and gateway
HEMS	<i>Home energy management system</i> is a set of devices, networks, and services to manage the power consumption of consumer
MDMS	<i>Meter data management system</i> is a control center collecting, storing, and processing meter data of power consumption and status of power generation, transmission, and distribution
NAN	<i>Neighborhood area network</i> is a network used to transfer meter data from smart meters or home gateways to data aggregator or concentrator
PLC	<i>Power line communications</i> is a technique for transmitting data over the electrical cable
RS	<i>Relay station</i> is the node which receives data from source and transmits to the destination
SANET	<i>Sensor and actuator network</i> is a collection of sensors and actuators connected to monitor and perform action related to power management
WAMS	<i>Wide-area measurement system</i> is used to connect remote sites of power consumption, generation, transmission, and distribution for collecting data
WAN	<i>Wide area network</i> is a large scale network used to collect different data in smart grid from remote sites of power consumption, generation, transmission, and distribution

Fig. 1. Meter data collection in smart grid.

Fig. 2. Cooperative transmission for meter data collection in smart grid.

Fig. 3. Cost under different probability of transmission by relay station 1.

Fig. 4. Packet loss probability at DAU under different probability of transmission by relay station 1.

Fig. 5. Best responses of relay stations 1 and 2.

Fig. 6. Nash equilibrium under different channel qualities.