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Transmission Power Allocation for Cooperative Relay-Based Neighborhood Area Networks for Smart Grid*

Kai Ma, Guoqiang Hu, and Costas J. Spanos

Abstract—**This paper studies cooperative relay-based neighborhood area networks in smart grid, where the building gateway with better channel condition will forward the energy consumption information originated from the congested building gateways to the data aggregator unit, in order to improve the accuracy of energy consumption information gathered at the data aggregator. This can make the consumers reserve accurate energy from the public utility with a low price, and further reduce the electricity cost. Relay power allocation is important to the efficiency of the cooperative relaying in cost reduction. The paper is motivated by these two interesting questions: How the relay building gateway allocates transmission power between relaying and its own transmission and what is the optimal relay power allocation strategy among the other buildings gateways? In order to answer the questions, we formulate the power allocation problem as a Stackelberg game and prove that it has a unique equilibrium point, which is the optimal power allocation solution for the building gateways. Numerical results show that relaying can dramatically reduce the cost of consumers in a building.**

I. INTRODUCTION

Smart grid is a large-scale cyber-physical system, which integrates modern communication, control and power technologies. The major feature of smart grid is the real-time information exchange, which relies on the advanced communication network technologies [1].

There are several works on communication system in smart grid [2-4]. A. Zaballos *et al.* proposed a heterogeneous communication architecture and management method for smart grid [2]. The work in [3] gave a hierarchical communication network architecture, which is composed of home area networks (HAN), neighborhood area networks (NAN) and wide area networks (WAN). Then, a multi-gate communication network was designed for HAN and NAN in [4]. Further, R. Yu *et al.* considered the application of cognitive radio techonology to the hierarchincal communication network in smart grid, and presented the spectrum sharing and management methods [5].

Recently, cooperative relaying has been proposed for communications in smart grid. The basic idea of cooperative relay is to use relays to help mobile users to transmit data to the destination, in order to combat the impact of fading and improve the transmission rates [6]. In [7], cooperative relay is proposed for HAN in smart grid, in order to combat fading without considering the cost reduction problem. In [8], D. Niyato *et al.* proposed a cooperative relay-based meter data collection networks in smart grid, in order to reduce the electricity cost for consumers in the community.

In this paper, we aim to apply cooperative relaying to NAN in smart grid, in order to reduce the electricity cost. The motivation for this work is as follows. In general, the operation of an electricity market consists of two stages due to the uncertain electricity demand and supply [8, 9]. In the first stage, consumers reserve the electricity supply with a lower price from the public utility. To implement the reservation, the building gateways should forward the reservation information from the consumers to the data aggregator unit (DAU), which sends the reservation information to the control center to reserve the electricity supply from the electricity market. Unfortunately, some building gateways may suffer from congestions due to simultaneous data transmissions for consumers in the buildings. Thus, the reserved electricity supply is less than the actual electricity demand due to data packet loss from congestions. To meet the electricity demands, consumers purchase additional electricity from the public utility with a higher price for immediate use in the second stage. This increases the electricity cost for the consumers in the buildings. This paper will address the following question: *How to improve the accuracy of electricity reservation so as to reduce the electricity cost?*

In this paper, we will design a more efficient electricity reservation strategy by improving the transmission rates of the building gateways. Cooperative relay is a desirable method to improve the transmission rates, which we will leverage to design a cooperative relay-based NAN for smart grid, in order to mitigate the congestion and reduce the electricity cost. However, the performance of cooperative relay relies on the transmission power allocation of the relay. It is important to allocate the relay power in order to minimize the electricity cost. In practice, the infrastructure cost involved in the deployment of a relay station is very large. It is reasonable to select the building gateway in each community with better channel condition as the relay (RBG), which not only forwards the data originated from other congested building gateways (CBG), but also transmits its own data to the DAU. Thus, the cost of the RBG consists of two parts: the relaying cost and the electricity cost. This paper will also address the following questions: *How should the RBG determine the power allocation for relaying and the direct transmission of its own data? How to allocate the relay power for CBGs?*

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This paper will shed some lights on the above questions and present an optimal relay power allocation strategy based on the Stackelberg game, which is suitable for dealing with the multi-stage decision making problem in communication networks. The main contribution of the proposed method is to reduce the electricity cost of consumers in smart buildings, and also balance the reserved electricity and supply for public utility.

The rest of the paper is organized as follows. In section II, we describe the system model and formulate the power allocation problem as a Stackelberg game. In section III, the equilibrium analysis is given and the Stackelberg equilibrium is obtained. Simulation results are shown in section IV. Finally, concluding remarks are given in section V.

II. System Model and Problem Formulation

A. Electricity Cost

We assume a power system consists of N buildings and one DAU. As given in [8], the packet loss rate due to congestion at the CBG i , $i \in N$ can be denoted by

$$L_i = \begin{cases} \dfrac{\bar{R}_i - R_i}{\bar{R}_i}, & R_i < \bar{R}_i \\ 0 & , \ R_i \ge \bar{R}_i \end{cases} \tag{1}$$

where L_i is the packet loss rate of CBG i , and $\bar{R}_i$ is the total number of packets generated from consumers in building i . R_i denotes the transmission rates of CBG i . According to [8], we have the electricity cost of consumers in building i ,

$$V_i = L_i D_i c_h + (1 - L_i) D_i c_l = D_i (c_h - c_l) L_i + D_i c_l \tag{2}$$

In (2), D_i denotes the total electricity demand of building i , c_l and c_h are the electricity price in the reservation stage and immediate use stage, respectively, and $c_h > c_l$. The term $(1 - L_i) D_i c_l$ denotes the electricity cost due to electricity reservation, and $L_i D_i c_h$ denotes the electricity cost for immediate use. Substituting (1) into (2), we have

$$V_i = -\frac{(c_h - c_l) D_i}{\bar{R}_i} R_i + D_i c_h \tag{3}$$

From (3), we see that V_i is decreasing with the transmission rate R_i . In general, the total load and the number of generated packets are proportional to the number of apartments or offices, since the average energy consumption of an apartment or office is approximately the same in case that one building consists of huge number of apartments or offices. Thus, we assume that the electricity demand of one building is proportional to the number of generated packets, *i.e.*, $D_i / \bar{R}_i \approx k$. From (3), we see that the CBGs can reduce the electricity cost by improving the transmission rates, *e.g.*, selecting the building gateways with better channel conditions as relays.

B. Cooperative Relay modeling

As shown in Fig. 1, we consider a neighborhood area network in smart grid, consisting of several building gateways and one DAU. The building gateways are organized into different cooperative groups, in which we select the building gateway with better channel condition as the relay. The grouping is out of the scope of our paper, for a lot of grouping algorithms has been proposed in cooperative relay networks [10-12]. Some of them can be applied to our problem directly. In the following, we only consider the cooperative relaying in one group.

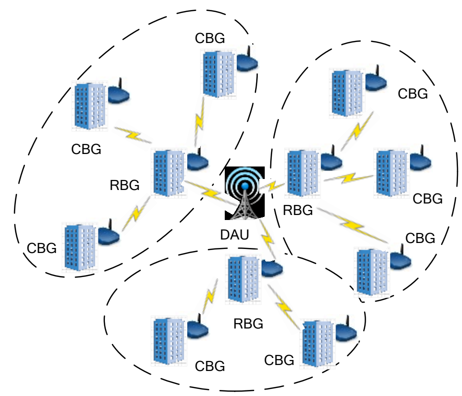

Figure 1. Neighborhood area netowrks in smart grid.

The network is based on frequency division multiple access (FDMA) and each building gateway is allocated W Herz bandwidth for transmission. Without the loss of generality, we employ the decode-and-forward (DF) cooperation protocol in our system model. The relaying is composed of two scheduled time slots: within the first time slot, the CBG broadcasts its signal to the DAU and the RBG while the RBG decodes this signal and then transmits it in the second time slot.

In the first sub-time slot, the received signal at the RBG and DAU is denoted by $y_{i,r}$ and $y_{i,d}$, respectively,

$$y_{i,r} = \sqrt{p_i} g_{i,r} x_i + \eta_{i,r} \tag{4}$$

$$y_{i,d} = \sqrt{p_i} g_{i,d} x_i + \eta_{i,d} \tag{5}$$

where x_i is the symbol transmitted by CBG i and p_i is the corresponding transmission power. The channels are modeled as independent proper complex Gaussian random variables, invariant within each slot, but generally varying over the slots (i.e., Rayleigh block-fading channels). The instantaneous fading channels in each block are denoted by the notations as follows: $g_{i,d}$ denotes the channel gain between CBG i and DAU; $g_{i,r}$ denotes the channel gain between CBG i and the RBG; $\eta_{i,r}$ and $\eta_{i,d}$ denote the zero-mean circular symmetric complex Gaussian noise with variance N_0 at the RBG and

DAU, respectively. In the second sub-time slot, the RBG transmits $x_{i,r}$ to DAU, and the received signal at DAU is

$$y_{r,d} = \sqrt{p_{i,r}}\, g_{r,d} x_{i,r} + \eta_{r,d} \quad (6)$$

where $p_{i,r}$ and $g_{r,d}$ represent the transmission power of the RBG for CBG i and the channel gain from the RBG to the DAU, respectively. $x_{i,r}$ is the RBG's transmitted symbol, which has been normalized to have unit energy. $\eta_{r,d}$ is the received noise at DAU, which is also a zero-mean circular symmetric complex Gaussian variables with variance N_0. The signals received in the first sub-time slot and the second sub-time slot are combined together by the DAU. According to [6], the achievable rates of CBG i at the output of the maximal ratio combining (MRC) detector is given by

$$R_i^C = \frac{W}{2}\min\{\log_2(1+p_i h_{i,d} + p_{i,r} h_{r,d}), \log_2(1+p_i h_{i,r})\} \quad (7)$$

where $h_{i,d} = |g_{i,d}|^2 / N_0$, $h_{r,d} = |g_{r,d}|^2 / N_0$, $h_{i,r} = |g_{i,r}|^2 / N_0$ are the respective effective channel-to-noise ratios (CNRs).

Here, we denote $R_i = R_i^C \tau$, where τ is the gap between the achievable rates and the transmission rates. For convenience, let $W = 2$ MHz and $\tau = \ln 2$. Then, the transmission rate of CBG i can be reduced to

$$R_i = \min\{\ln(1+p_i h_{i,d} + p_{i,r} h_{r,d}), \ln(1+p_i h_{i,r})\} \quad (8)$$

The maximum rate constraint in (8) is due to the fact that the individual capacity of relay-assisted CBG should not exceed the capacity of the CBG to the RBG for reliable decoding of the signal at the RBG. If the direct link (from the CBG to the DAU) is better than the relay link (from the CBG to the RBG), the CBG, which is constrained by the maximal relay capacity, will not be assisted by the RBG. Thus, the individual power constraints can be obtained from the maximum rate constraint (8),

$$p_{i,r} \le \frac{p_i\left(h_{i,r} - h_i\right)}{h_r} \quad (9)$$

Here, each RBG also has the total power constraints denoted by p_r.

C. Problem Formulation

We assume that all of the building gateways are rational and selfish. The RBG is willing to share portions of its transmission power with the CBGs, and earn revenue paid by CBGs so as to compensate the electricity cost. It has the rights to decide the fraction of transmission power leased to the CBGs. Whereas, the CBG, which is competitive with other CBGs for the transmission power, decides only the price it is willing to pay for the RBG, in order to minimize the electricity cost without making too much payments. According to the actions of the CBGs and the RBG, we employ a Stackelberg-game-based scheme as follows:

1 CBG/Follower. Let $I_t = \{1, 2, \ldots, N_t\}$ denotes the whole set of CBGs in the system. Each CBG i is willing to minimize the electricity cost under a reasonable payment c_i. Therefore, the total cost of CBG i is defined to be its electricity cost plus the payments it makes for the RBG

$$C_i = -\omega \ln(1 + p_i h_{i,d} + \frac{c_i}{\sum_{j\in I} c_j}\alpha p_r h_{r,d}) + D_i c_h + c_i \quad (10)$$

where $\omega = (c_h - c_l)k$ is the parameter that transforms the transmission rate to the electricity cost, and $I = \{1, 2, \ldots, N\}$ is a set of CBGs selected by the RBG to participate in the cooperative transmission. It is noted that the relay power fraction α is zero when all of the payments are zero, *i.e.*, the RBG will not relay for any CBG. Then, the electricity cost of CBG i is denoted by

$$C_i^0 = -\omega \ln(1 + p_i h_{i,d}) + D_i c_h \quad (11)$$

2 RBG/Leader. The RBG will transmits its own energy reservation information to the DAU with the remaining transmission power $(1-\alpha)P_r$. It can get the revenue from CBGs in order to compensate for the increased electricity cost, which is incurred by relaying for CBGs. Therefore, the total cost of the RBG is defined to be the electricity cost minus the revenue it collects from the CBGs

$$C_r = -\omega \ln(1 + (1-\alpha) p_r h_{r,d}) + D_r c_h - \sum_{j\in I} c_j \quad (12)$$

where D_r is the electricity demand generated from consumers in the RBG.

Here, minimizing the total cost is equivalent to maximize $u_i = -C_i$ and $u_r = -C_r$, which are defined as the utilities of the CBG i and RBG, respectively. For convenience, we will maximize the utilities of CBGs and RBG instead of minimize the cost of them.

III. GAME ANALYSIS

In this section, we use the backward induction method to analyze the performance of the Stackelberg game.

A. Payment Selection Game

The CBGs in the cooperative set I will compete with each other to minimize the total cost *i.e.*, maximizing its own utility. Then, there is the following non-cooperative payment selection game (NPS).

Definition 1: A non-cooperative payment selection game G *is defined as a triple* $G = \{I, (S_i)_{i\in I}, (u_i)_{i\in I}\}$, *where* I *is the set of selected players (CBGs) participating in cooperation, CBG* i *'s (*$i \in I$*) strategy (payment selection) is*

$$S_i := \{c_i \mid c_i \in [0, \bar{c}]\} \quad (13)$$

and the payoff function (utility) is

$$u_i\left(c_i,\mathbf{c}_{-i}\right)=\omega\ln(1+p_i h_{i,d}+\frac{c_i}{\sum_{j\in I}c_j}\alpha p_r h_{r,d})-c_i \qquad (14)$$

where $\mathbf{c}_{-i}=(c_1,c_2,\ \dots\ ,c_{i-1},c_{i+1},\ \dots\ c_N)$ *denotes the set of strategies selected by all the other CBGs and the strategy profile is denoted by* $(c_i,\mathbf{c}_{-i})=(c_1,c_2,\dots,c_{i\text{-}1},c_i,c_{i+1},\dots c_N)$.

We now analyze the equilibrium of the non-cooperative payment selection game G. The solution we use is the Nash equilibrium [13], which is based on the concept of a best response correspondence defined as follows.

Definition 2: For the non-cooperative payment selection game $G=\left\{I,(S_i)_{i\in I},(u_i)_{i\in I}\right\}$ *, the best response correspondence* $r_i(c_{-i})$ *is defined as*

$$r_i(c_{-i})=\left\{c_i\in S_i \middle| u_i\left(c_i,c_{-i}\right)\geq u_i\left(c_i',c_{-i}\right),\ \textit{for all}\ \mathbf{c}_{-i}\in S_{-i}\right\}$$

Then, a vector of payment selection $\mathbf{c}^*=(c_1^*,c_2^*,\dots,c_N^*)$ *is a Nash equilibrium of the non-cooperative payment selection game if and only if* $c_i^*\in r_i(c_{-i}^*)$ *for all CBGs* $i\in I$*, that is to say,* $u_i(c_i^*,\mathbf{c}_{\text{-}i}^*)\geq u_i(c_i,\mathbf{c}_{\text{-}i}^*)$ *for all* $c_i\in S_i$*, where* $u_i(c_i,\mathbf{c}_{\text{-}i})$ *is the resulting payoff for the CBG i given the other CBGs' payment selection result* $\mathbf{c}_{\text{-}i}$.

The Nash equilibrium is a set of strategies for which no player has an incentive to change unilaterally. In the following, we will analyze the existence and uniqueness of the NE of the non-cooperative payment selection game. To prove the existence of NE, we first give the following lemma:

Lemma 1 [14]: A Nash equilibrium exists in game $G{:}=\left\{I,(S_i)_{i\in I},(u_i)_{i\in I}\right\}$*, if for all* $i\in I$ *:*

(1) S_i *is a nonempty, convex, and compact subset of some Euclidean space* $\Re^N$.

(2) $u(\mathrm{c})$ *is continuous in* $\mathbf{c}$ *and quasi-concave in* c_i.

Based on *Lemma 1*, we have the following theorem.

Theorem 1: There exists a Nash equilibrium for non-cooperative payment selection game G [1].

Let $\mathbf{c}$ denote the Nash equilibrium in G. By *definition* 2, the Nash equilibrium is the fixed point of the equation $\mathbf{c}=r(\mathbf{c})$, where $r(\mathbf{c})=(r_1(\mathbf{c}),r_2(\mathbf{c}),\ \dots\ ,r_N(\mathbf{c}))$ and $r_i(\mathbf{c})$ is the best response function of player i. The best-response correspondence is achieved when the first derivative of u_i with respect to c_i equals to 0. Thus

$$\frac{\partial u_i}{\partial c_i}=h_i(\mathbf{c})=\frac{\omega B\alpha\sum_{j\in I,j\neq i}c_j}{A_i(\sum_{j\in I}c_j)^2+B\alpha c_i\sum_{j\in I}c_j}-1=0 \qquad (15)$$

[1] The proofs of the theorems are omitted throughout the paper to fit within page limits.

From (15), we have a quadratic function of c_i.

$$\begin{aligned}&(A_i+B\alpha)c_i^2+(2A_i\sum_{j\in I,j\neq i}c_j+B\alpha\sum_{j\in I,j\neq i}c_j)c_i\\&+A_i(\sum_{j\in I,j\neq i}c_j)^2-\omega B\alpha\sum_{j\in I,j\neq i}c_j=0\end{aligned} \qquad (16)$$

And the best-response correspondence is calculated as

$$r_i\left(\mathbf{c}\right)=\frac{-(2A_i+B\alpha)\sum_{j\in I,j\neq i}c_j+\sqrt{\Delta}}{2(A_i+B\alpha)} \qquad (17)$$

where,

$$\Delta=B^2\alpha^2(\sum_{j\in I,j\neq i}c_j)^2+(4\omega B^2\alpha^2+4\omega A_i B\alpha)\sum_{j\in I,j\neq i}c_j \qquad (18)$$

Here, another solution of equation (16) is omitted for $r_i(\mathbf{c})>0$, which brings about the following constraints

$$A_i\sum_{j\in I,j\neq i}c_j<\omega B\alpha \qquad (19)$$

It is shown in [15] that the fixed point $\mathbf{c}=r(\mathbf{c})$ is unique for a standard function. Therefore, we can show the uniqueness of the game G by proving that the best response function $r(\mathbf{c})$ is a *standard function*, which is defined as follows.

Definition 3: A function $r(\mathbf{c})$ *is standard if for all* $\mathbf{c}\geq 0$*, the following properties are satisfied:*

- Positivity: $r(\mathbf{c})>0$.
- Monotonicity: If $\mathbf{c}\geq\mathbf{c}'$, then $r(\mathbf{c})\geq r(\mathbf{c}')$.
- Scalability: For all $\beta>1$, $\beta r(\mathbf{c})>r(\beta\mathbf{c})$.

Then, we give the condition on uniqueness of Nash equilibrium in the following theorem.

Theorem 2: The non-cooperative payment selection game G has a unique Nash equilibrium point with the constraints,

$$\sum_{j\in I,j\neq i}c_j<\omega\frac{\sqrt{4(A_i^2+A_iB\alpha)^2+(A_i^2+A_iB\alpha)B^2\alpha^2}-2(A_i^2+A_iB\alpha)}{A_iB\alpha} \qquad (20)$$

We obtain the expressions of the unique equilibrium point for the non-cooperative payment selection game as

Theorem 3: The unique equilibrium point for the non-cooperative payment selection game G is given by

$$c_i^*=\frac{\omega B\alpha(N-1)(A+B\alpha-A_i(N-1))}{(A+B\alpha)(A+NB\alpha)} \qquad (21)$$

Substituting (21) into (6), we have

$$\alpha\leq\frac{p_i\left(h_{i,r}-h_i\right)}{B}\frac{\omega\left(A+NB\alpha\right)}{A+B\alpha-A_i\left(N-1\right)\omega} \qquad (22)$$

According to constraints (22), we can select the optimal subset I^* for CBGs participating in cooperation.

B. Minimizing RBG's Utility

Based on the analytical results of the CBG's payment selection game, the leader of the Stackelberg game, the RBG, can optimize its strategy (I,α) in order to minimize its total cost in (12) *i.e.*, maximizing the utility u_r. Substituting (21) into (12), the utility of the RBG is given by

$$u_r = \omega\ln(1+(1-\alpha)B) - D_r c_h + \frac{(N-1)\omega B\alpha}{A+B\alpha} \tag{23}$$

Here, $\alpha = 0$ denotes that the RBG will not cooperate with CBGs, and the non-cooperative utility of the RBG is

$$u_r^0 = -c_r^0 = \omega\ln(1+B) - D_r c_h \tag{24}$$

where c_r^0 is the non-cooperative cost of the RBG. Then, we give the optimal strategy selection of the RBG as follows:

Theorem 4: The RBG maximizes its utility if and only if α^* is set to be the following optimal values,

$$\alpha^* = \begin{cases} 0 & \text{if } \alpha_0 \le 0 \\ \alpha_0 & \text{if } 0 < \alpha_0 < 1 \\ 1 & \text{if } \alpha_0 \ge 1 \end{cases} \tag{25}$$

where,

$$\alpha_0 = -\frac{A(N+1)}{2B} + \frac{\sqrt{A^2(N-1)^2 + 4(N-1)(1+B+A)A}}{2B} \tag{26}$$

IV. Numerical Results

In this section, we give some numerical results to illustrate the performance of power allocation strategy based on Stackelberg game. As illustrated in Fig. 2, we consider a neighborhood area network composed of several CBGs and one RBG. The DAU is located at (200, 0) and CBGs are located in the region with $-100 \le X \le 0$ and $-100 \le Y \le 100$, randomly. The coordinates of the RBG are denoted by (Rx,0). The total transmission power of each building gateway is 10W. The channel gain of any transmission pair in networks consists of a small-scale Rayleigh fading component and a large-scale path loss component with path loss denoted by $0.097/d^4$. The noise plus interference level is assumed to be 10^{-9} W.

Fig. 3 shows the optimal power allocation fraction α^* versus the positions of the RBG. As shown in Fig. 3, the RBG will not forward any data for CBGs at first, since relaying can't reduce the cost. When the distance between the RBG and the DAU is below some threshold, the RBG will start to forward data for CBGs since relaying can reduce the total cost of the RBG. There exists a maximal power allocation fraction $\alpha^{\max}$ when $\mathrm{Rx} = \mathrm{Rx}^*$. When Rx approaches to Rx^*, the revenue obtained from CBGs is larger than the increasing electricity cost incurred by relaying. Thus, the RBG will increase power allocation for relaying in order to reduce the total cost as much as possible. When Rx approaches to Rx^*, the transmission rate from the RBG to the DAU is increased.

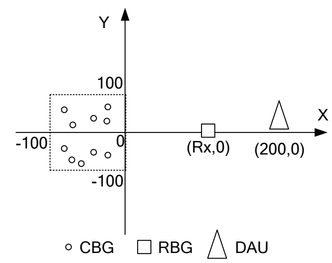

Figure 2 The simulation topology

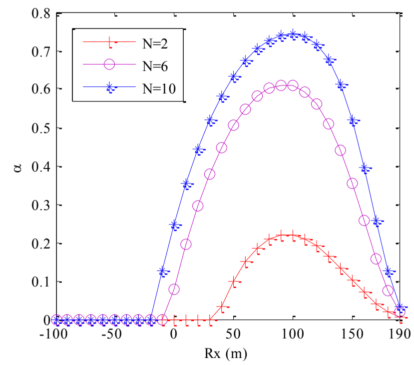

Figure 3 Relay power allocation fraction versus the locations of the RBG

Therefore, the RBG will allocate more power for the direct transmission in order to reduce the electricity cost, *i.e.*, the optimal power allocation strategy α^* will be decreased as Rx approaches to Rx^*. From Fig. 3, we can also see that cooperation will start earlier and α^* becomes larger when the number of CBG increases. This is because the relaying plays a more important role in the total cost of the RBG, which has more willingness to cooperate with CBGs and allocate more power for relaying.

Fig. 4 shows the total cost of RBG versus Rx, when power allocation fraction α is α^* and 0, respectively. Here, $\alpha = \alpha^*$ denotes the optimal power allocation based on Stackelberg game. $\alpha = 0$ indicates no power allocation for relaying. It can be seen that $\alpha = \alpha^*$ brings about the lowest total cost, because relaying can make appropriate tradeoff between the increase of electricity cost and the revenue obtained from the CBGs. Fig. 4 also indicates that the total cost is decreased when the RBG approaches to the DAU due to the improved direct transmission rate.

We give the payment strategies of different CBGs in Fig.5, CBGs will pay more to the RBG, in order to make RBG cooperate with them when the RBG approaches to the DAU. However, the price will get saturated finally, because CBGs will not increase their payments when relaying can't reduce the cost. Fig. 6 shows the cost of CBGs versus the locations of the RBG. It can be seen that all the CBGs can reduce the cost by relaying.

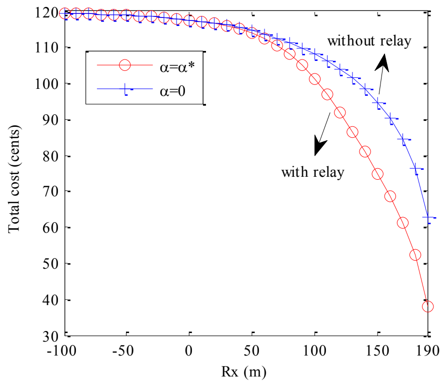

Figure 4 Total cost of the RBG versus the locations of the RBG

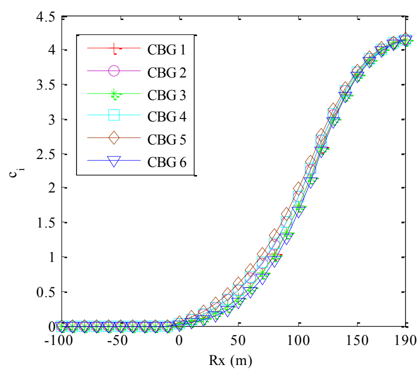

Figure 5 CBG price versus the locations of the RBG

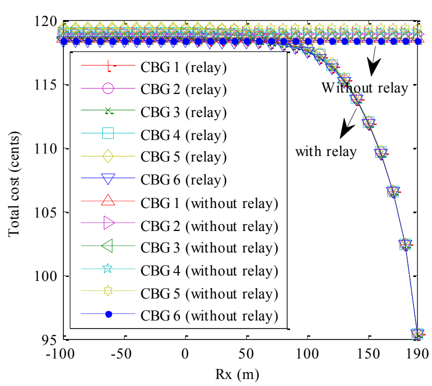

Figure 6 Total cost of CBGs versus the locations of the RBG

V. CONCLUSIONS

This paper presents an optimal power allocation scheme for cooperative relay-based neighborhood area networks in smart grid. By formulating the power allocation problem as a Stackelberg game, where the congested building gateways act as the followers and the relay building gateway acts as the leader, we derive an optimal power allocation solution. Numerical results illustrate that the relaying with optimal power allocation can reduce the total cost of consumers in smart buildings.

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