Fair Billing Mechanism for Energy Consumption Scheduling with User Deviation in the Smart Grid

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***Abstract*—In the future smart grid, Demand Side Management (DSM) will be one of the key technologies to facilitate utility companies and customers in order to achieve system optimality such as minimizing energy cost and peak-to-average ratio. While most of the prior works in the literature have reported good results in achieving system optimality, they mostly ignore considering the aspect of system fairness, especially in users' electricity bills. That is, they do not address the important problem of users' commitment and their actual consumption level when calculating the payments. In this paper, we seek to tackle these shortcomings and design an alternative fair billing mechanism that assures the system fairness. The proposed billing considers not only real-time consumption information of the grid but also actual users' consumption level. Thus, each user's payment will be adjusted based on their commitment and contribution to the system. Simulation results show that the proposed billing mechanism ensure fairness in users' payments.**

I. Introduction

Recently, global demand for electricity consumption is increasing due to increase in population and new trends in technology towards electrical usage devices. This rapid advancement emerges new demands, such as electric vehicle (EV), for more electricity consumption, which soon will put the power systems' capacity to its limit [1]–[3]. Furthermore, higher penetration of renewable energy sources in distribution part of the power grid makes balancing supply and demand even more crucial for the reliable operation of the electricity system [4].

With advancement in Information and Communication Technologies (ICT), the power grid is transformed into a smart grid, where information related to demand is gathered and transferred across the grid. Using smart metering technologies and two-way communication in smart grid [5], automate Demand Side Management (DSM) program can be implemented in distribution part of the power grid. Home Energy Management System (HEMS) solution can be deployed in users homes and connect to the utility company via a smart meter. The HEMS can automatically schedule the users' energy consumption based on information received from the utility company.

In literature, various DSM designs have been proposed based on an operation of HEMS to schedule users' load consumption. The main objectives in DSM programs are, for example, total energy generation cost minimization [6], peak load minimization [7] and social welfare maximization [8]. Many of the works in DSM design have been shown to achieve optimality under the assumption that all users contribute and commit to the programs. The assumption is supported by the claim that users have no reason not to participate because of financial benefits. However, in order to have users continue their contribution in the DSM, the system needs to achieve a certain level of fairness. That is, one of the most important factors to motivate a user to contribute to the program is fairness in user's electricity payments. The system is fair if the user who contribute more pay less than others [11].

Some works have been focused on fairness for designing DSM [9]–[13] in many perspectives. In [9], the authors proposed billing mechanism that charges users with a fixed price for their must-run appliances and pricing other appliance's consumption based on a type of users and their income. However, these assumptions are not considered practical in real-world scenarios. In [10], the water-filling method is used to schedule user's loads, and appliance operation delay is considered for fairness. That is, the system tries to assign the same average delay to each user in order to maintain system fairness. A game theory based consumption scheduling and billing mechanisms are proposed in [6], [11], [12]. In [6], the authors initially formulated the energy consumption scheduling of houses in a community as a game. They proposed autonomous DSM scheduling utilizing user interactions. In this system, the billing mechanism is based on consumption averaged over a day. One of the issues in this billing models is that they do not consider user's load profile and contribution to the system, which lead to an unfair in user's payment. Later, [11], [12] proposed hourly proportional billing mechanisms, which address the fairness issues in their previous works. The billing mechanisms charge each user based on their consumption in each period, instead of the whole day. This improves the level of fairness in the user's payment.

However, one of the major drawbacks is that they do not consider the impact on the system fairness when users deviate their consumption from the optimal schedules after being assigned. When user deviates their consumption, the total system load profiles changes, which in turn, affect other user's payments in the community. That is, the billing mechanism applied the same electricity price to all users in each period without considering individual user behavior and commitment regarding the optimal schedules. Although the work in [13]

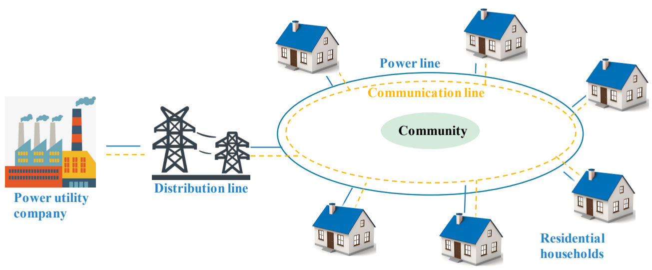

Fig. 1. Overview of the smart grid and residential community model

considered the billing fairness when users violate the optimal schedules, they only considered the case that users increase their consumption from the optimal schedules.

In this paper, we considered the assumption that users may deviate their consumption from the optimal schedules and proposed a fair billing mechanism to address with such users. The objective is to improve the fairness in billing process by taking into account individual user behavior and the actual load profiles.

The rest of this paper is organized as follows: Section II power grid model, energy consumption scheduling game, and billing mechanism are introduced. In Section III, we present the details of the proposed fair billing mechanism. Numerical simulation results and discussion are given in Section IV. The conclusion of the paper is drawn in Section V.

II. System Model

We consider the system model as described in [12], where the interaction of each user is coordinated and formulated an energy consumption game. In this model, a single energy source, provided by a utility company, is shared among a set of $\mathcal{N} = \{1, ..., N\}$ users (houses) forming a residential community. Each user is owning a HEMS capable of scheduling appliances in the home and connected with the utility company via a smart meter. The communication network provides HEMS with two-way communication to the utility company and also among users in the community. Fig. 1 shows the community with power grid system and communication networks. Without loss of generality, we assume that each user has a single flexible appliance such as an EV or a washing machine. A set of scheduling time period $\mathcal{H} = \{1, ..., H\}$ is divided into hourly time slots e.g., $H = 24$ for a day.

A. Users and appliances constraints

Each user n has a single flexible appliance to be scheduled. The user (or HEMS) can set the power x_n^h for the appliance at each time period h in $\mathcal{H}_n = \{\alpha_n, ..., \beta_n\} \subset \mathcal{H}$. Each appliance required a fixed amount of energy to finish its daily operation. The energy constraints are as follow:

$$E_n = \sum_{h=\alpha_n}^{\beta_n} x_n^h. \tag{1}$$

Because of physical limitation, the power assigned to the appliance is bounded from below and above as

$$x_n^{h,min} \leq x_n^h \leq x_n^{h,max}. \tag{2}$$

For the period in which the appliance cannot be used, the energy consumption is set as $x_n^h = 0$ for all $h \notin \mathcal{H}_n$. We denote $\mathcal{X}_n$ as a set of feasible energy consumption x_n^h for user n that respect the constraints in (1) and (2).

B. Electricity generation costs

The utility company is providing electricity to the community. The cost of generating electricity in each period can be represented as a quadratic function denoted as

$$C_h\left(L_h\right) = a_h L_h^2 + b_h L_h + c_h \tag{3}$$

where $a_h > 0, b_h \geq 0$ and $c_h \geq 0$ are the coefficients of the cost function and the total load $L_h = \sum_{n=1}^{N} x_n^h$. Since the marginal production costs increase with demand, we can assume that the cost functions $C_h(\cdot)$ are *increasing* and *strictly convex* [6]. In general, the cost function can also be the actual generation cost or an artificial signal that sent to HEMS for computing schedule optimization problem.

C. Energy consumption game

Each user will seek for consumption vector $\boldsymbol{x}_n$ that minimize his bill $B_n = \sum_{h=1}^{H} b_n^h$ respect to the constraints in (1) and (2) by solving the following optimization problem:

$$\min_{\boldsymbol{x}_n \in \mathcal{X}_n} \sum_{h=1}^{H} b_n^h\left(\boldsymbol{x}_n; \boldsymbol{x}_{-n}\right) \tag{4}$$

where $\boldsymbol{x}_{-n}$ is the consumption vector of all other users except for user n. Since the bill B_n depends on both $\boldsymbol{x}_n$ and $\boldsymbol{x}_{-n}$, we can formulate the problem as an energy consumption game based on the framework of game theory. That is, the payment of one user not only depends on his consumption but also depends on other users' consumption in the community. Thus, the game is stated as

- Players: users $n \in \mathcal{N} = \{1, ..., N\}$
- Strategies: the energy consumption schedule vector $\boldsymbol{x}_n \in \mathcal{X}_n$ for each user
- Payoffs: negative billing for each user $-B_n$

D. Billing functions

The utility company is responsible for designing a billing mechanism for each users participating in the power system. A budget-balance scheme, where the total generation cost is equal to the sum of all users' bills, is assumed in this system. One of the billing mechanisms is hourly proportional billing [12] where the total energy cost is divided between users at each time period, with respect to the energy they consumed. The bill for user n is given by

$$B_n = \sum_{h=1}^{H} \frac{x_n^h}{\sum_{m=1}^{N} x_m^h} C_h\left(L_h\right). \tag{5}$$

This billing mechanism enables to bring each user the real cost of its demand, particularly during peak hours.

III. Proposed Fair Billing Mechanism

In this section, we explain the details of our proposed fair billing mechanism to achieve fairness in user's payment. As described above, each HEMS device schedules load consumption of each user with the optimal energy cost based on the optimization problem in (4). Each user's electricity payment is charged proportionally to their consumption based on billing mechanism in (5). That is, user's bills are calculated using the same price in each period. The price for each period can be expressed as

$$\hat{p}_h = \frac{C_h(\hat{L}_h)}{\sum_{n=1}^{h} \hat{x}_n^h} \tag{6}$$

where $\hat{L}_h$ and $\hat{x}_n^h$ are actual total consumption of the community and user n's actual consumption in period h, respectively. This billing mechanism is considered fair to every user assuming that they consume energy according to the optimal schedules [12]. However, in practice, the assumption rarely holds true because we cannot guarantee that every user will follow the schedules and consumption deviation is possible at any time after the schedules have been assigned. For example, users may change their preferences and thus violate the schedules. With this assumption, the energy cost is changed by the change in consumption, which in turn, affect the user's bills. This would have a negative impact on the system fairness level as the behavior of users are not considered in the billing process.

We propose a fair billing mechanism that taking into consideration each user's actual consumption level in each period h. Thus, the user's bills are calculated individually using different prices depending on their behavior. We define a set $\mathcal{V}_h = \{1, ..., V_h\}$ for a group of users that their actual consumptions are greater than the assigned consumptions $(\hat{x}_n^h > x_n^h)$. Also, we define a set $\mathcal{P}_h = \{1, ..., P_h\}$ for a group of users that their actual consumptions are less or equal than the assigned consumptions $(\hat{x}_n^h \leq x_n^h)$.

We classify electricity prices into three types: *incentive price* (p'_h), *actual price* $(\hat{p}_h)$, and *penalty price* $(\tilde{p}_h)$. The prices are designed such that $p'_h < \hat{p}_h < \tilde{p}_h$. The *incentive price* can be calculated as

$$p'_h = \frac{C_h\left(L'_h\right)}{\sum_{n=1}^{N} x_n'^h} \tag{7}$$

where $x_n'^h = \min[\hat{x}_n^h, x_n^h]$ and $L'_h = \sum_{m=1}^{N} x_m'^h$. The *penalty price* is given by

$$\tilde{p}_h = \frac{\Delta C_h}{\sum_{v=1}^{V_h} \Delta x_v^h} \tag{8}$$

where $\Delta x_n^h = \hat{x}_n^h - x_n^h$ and the cost difference, ΔC_h, is defined as

$$\Delta C_h = C_h(\hat{L}_h) - (\sum_{p=1}^{P_h} \hat{x}_p^h \cdot p'_h) - (\sum_{v=1}^{V_h} x_v^h \cdot \hat{p}_h). \tag{9}$$

The *actual price* is calculated as in (6), where the price is based on the total actual consumption in the community. Based on the defined prices, the proposed billing can be expressed as

$$b_n^{*h} = \begin{cases} \hat{x}_n^h \cdot p'_h & \text{if} \quad \hat{x}_n^h \leq x_n^h \\ \left(x_n^h \cdot \hat{p}_h\right) + \left(\Delta x_n^h \cdot \tilde{p}_h\right) & \text{if} \quad \hat{x}_n^h > x_n^h. \end{cases} \tag{10}$$

Finally, the total daily payment for user n is the sum of all bill in each period as

$$B_n^* = \sum_{h=1}^{H} b_n^{*h}. \tag{11}$$

In the proposed billing functions (10), users that consume less than or equal to the assigned consumption $(\hat{x}_n^h \leq x_n^h)$ are charged with the *incentive price* p'_h. This price is not affected by the increase in cost due to users that increase their consumption during hour h. On the other hand, the reduction in cost due to users that reduce their consumption made the price p'_h lower than the *actual price* $(\hat{p}_h)$. Thus, it motivates users to commit to the optimal schedule or reduce their consumption to prevent demand peak in the grid. For the users that increase their consumption more than the assigned consumption $(\hat{x}_n^h > x_n^h)$, they will be charged with the *actual price* $(\hat{p}_h)$ for the assigned consumption. The exceed energy will be charged by the *penalty price* $(\tilde{p}_h)$ to penalize for their behavior. This would persuade such users not to consume extra energy regularly.

IV. Results and Discussion

In this section, we present and assess the performance of the proposed differential price billing mechanism. We consider a community composes of 20 users sharing a power source provided by a utility company. Each user performs consumption scheduling for their flexible appliances for the next $H = 24$ hours. For simplicity, we assume that each user has one shiftable appliance such as PHEV, washing machine, electric water heater, etc. The users are randomly choose their preference period, $[\alpha_n, \beta_n]$, for their appliances. The costs of generating electricity are assumed as $C_h(L_h) = 0.01L_h^2 + 2L_h$ for $h < 12$ and $C_h(L_h) = 0.03L_h^2 + L_h$ for $h \geq 12$ as in [12]. The total energy, E_n, required for each user is randomly selected between 5 and $40kW$. We assume the budget-balanced system where the total energy cost is equal to the total bills of all users in the community. In our simulation, we choose user 1-10 to deviate their consumption from the optimal schedules and compare our proposed billing mechanism with the conventional hourly proportional billing in [12].

In the first scenario, the deviating users (user 1-10) deviate their consumption by shifting the operation of appliances from the assigned schedules. The amount of energy required for each user remains unchanged, only shifted in time. Fig. 2 (top) shows the daily billing of the *conventional hourly proportional billing* in [12] of each user for the case of no schedule deviation and deviated schedules. The daily payments of non-deviating users are affected by the behavior of deviating users. Some of the non-deviating users' bills are increased despite committing to the assigned schedules. This would have a negative impact on the level of fairness of the system and may lead the users to leave the DSM program. Using the same setting, the bottom figure illustrates daily user payments using our proposed billing mechanism to improve the fairness level in the billing process. The payment of non-deviating users is adjusted with incentive price such that no non-deviating user is charged more than the payment estimated by the optimal schedules. Also, some of the non-deviating users gain financial benefit from being committed to the assigned schedules by receiving an economic incentive.

In the second scenario, we demonstrate our proposed billing when deviating users (user 1-10) violate the consumption schedules by consuming extra energy as assumed in [13]. Fig. 3 (top) shows the impact of deviating users consumption violation. All users' bills are increased due to the increase in energy consumption. Non-deviating users' bills are increased although they committed to the optimal schedules. The users' bills of the proposed billing are shown in the bottom of Fig. 3, where the bills of non-deviating users are adjusted and not impacted by the consumption violation. The billing results of our proposed billing are the same as the billing mechanism in [13] when all deviating user only violates the optimal schedules by consuming extra energy. Thus, the billing in [13] is considered as a special case in our proposed billing mechanism.

The third scenario is assumed that all deviating users (user 1-10) decrease the consumption level. The billing results are shown in Fig. 4. We can see that both conventional billing in [12] (top) and the proposed billing (bottom) provide the same payment for each user. This means that the conventional billing is a special case in our proposed billing when all deviating user only decreases the consumption from the assigned schedules.

In the last scenario, Fig. 5 shows the users' payments, where the behavior of users are mixed. User 1-5 deviate their consumption by consuming extra energy, whereas, user 6-10 deviate their consumption by reducing consumption from the assigned schedules. In this scenario, the conventional billing (top) increases the payment of non-deviating users due to consumption violation. For our proposed billing (bottom), the payment of non-deviating users are not impacted by user 1-5, and some users received economic incentive due to the decrease in consumption by user 6-10.

The proposed billing mechanism calculates user's payment based on their consumption level compared to the assigned schedule in each period. Thus, the proposed billing mechanism improve the fairness level in billing process and motivate the users to remain participating in DSM program by guarantee that the payment of all non-deviating users is not exceeded the estimated payment when calculating the assigned schedules.

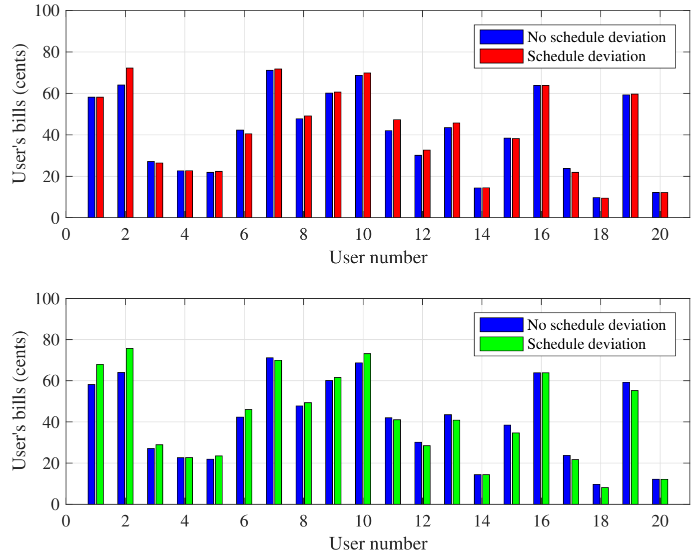

Fig. 2. Daily user's payment in case of time shifted consumption (top) the conventional billing [12] (bottom) the proposed billing in (10).

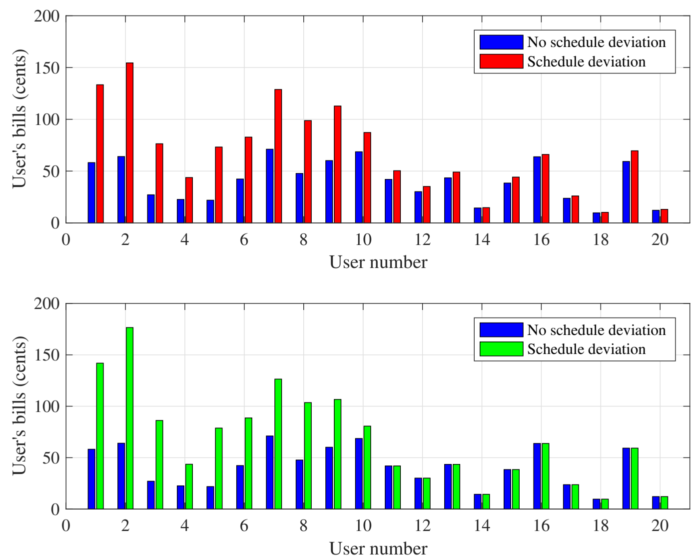

Fig. 3. Daily user's payment in case of consumption increases (top) the conventional billing [12] (bottom) the proposed billing in (10).

V. Conclusion

In this paper, we proposed a fair billing mechanism for energy consumption schedule in DSM programs. The proposed billing utilized different electricity prices based on user's consumption level associated with the optimal schedules. The billing mechanism fairly distributes energy cost to all users in the community. Non-deviating users are protected from the increase in cost due to consumption violation and may receive the economic incentive. This impact is expected to motivate users to keep participating in DSM program and commit to the optimal schedules assigned day-ahead. For users that deviate their consumption, the proposed billing mechanism ensures to calculate each user's payment based on their behavior and actual consumption level. Thus, the proposed billing mechanism improves the level of fairness and increase user's participation to achieve the system objective in minimizing the energy cost. In addition, the proposed billing generalizes the billing in [12] and [13], covering all consumption deviation scenarios. By being able to address

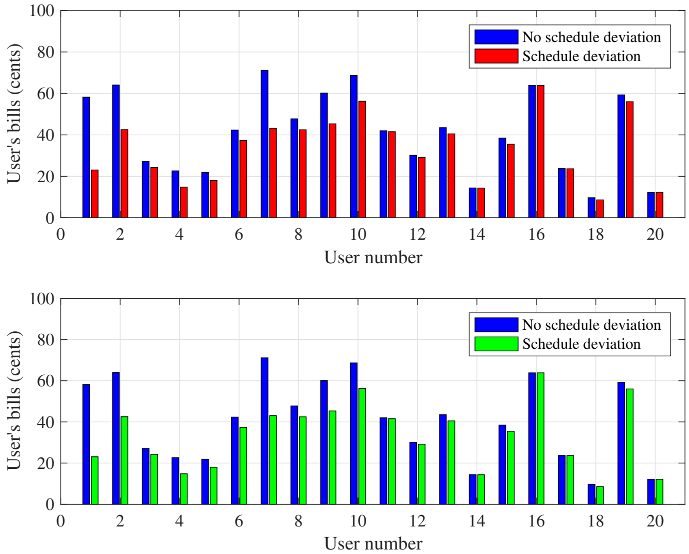

Fig. 4. Daily user's payment in case of consumption decreases (top) the conventional billing [12] (bottom) the proposed billing in (10).

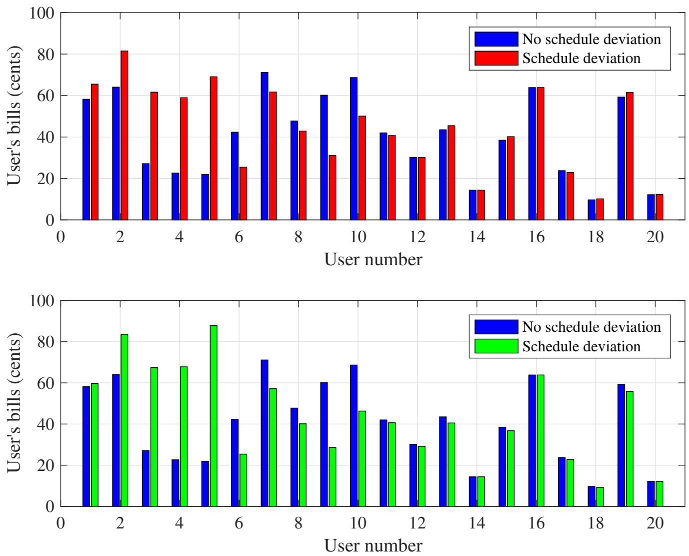

Fig. 5. Daily user's payment in case of mixed consumption deviation (top) the conventional billing [12] (bottom) the proposed billing in (10).

changes in energy consumption and fairly manage user's payments, the proposed billing mechanism will further help DSM programs to achieve a practical deployment in the future smart grid.

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