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Residential power scheduling for demand response in smart grid

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ABSTRACT

This paper studies the power scheduling problem for residential consumers in smart grid. In general, the consumers have two types of electric appliances. The first type of appliances have flexible starting time and work continuously with a fixed power. The second type of appliances work with a flexible power in a predefined working time. The consumers can adjust the starting time of the first type of appliances or reduce the power consumption of the second type of appliances to reduce the payments. However, this will also incur discomfort to the consumers. Assuming the electricity price is announced by the service provider ahead of time, we propose a power scheduling strategy for the residential consumers to achieve a desired trade-off between the payments and the discomfort. The power scheduling is formulated as an optimization problem including integer and continuous variables. An optimal scheduling strategy is obtained by solving the optimization problem. Simulation results demonstrate that the scheduling strategy can achieve a desired tradeoff between the payments and the discomfort.

Introduction

Smart grid is an intelligent power network that integrates with advanced information, control, and communication technologies. In smart grid, the consumers can adjust the load with demand response (DR) program. There are two types of DR programs. The first type is the incentive-based DR program with which the service provider can remotely shut down the consumer appliances with a short notice when needed [1,2]. The second type is the price-based DR program [3], where the consumers are encouraged to individually manage their power consumption in response to the price.

This study focuses on the price-based DR program with an advanced metering infrastructure (AMI), which supports the collection of meter readings and the announcement of price. According to the announced price, the residential consumers can regulate the operations of the appliances. For example, An energy management method was proposed to implement the energy storage and the appliance scheduling [4]. A simulation platform was developed to optimize the operations of the household appliances [5]. The power scheduling problem was formulated for multiple residences to maximize the social welfare [6]. An optimal residential power scheduling strategy was developed to achieve a trade-off between the payments and the waiting time [7]. The scheduling problem was formulated by the noncooperative game in [8], the Stackelberg game in [9], the punishment mechanism in [10], and the contract design in [11]. The scheduling problem under the real-time price was considered in [12], which only considered a single type of schedulable appliances. The motivation of this work is to achieve the tradeoff between the discomfort and the payments by scheduling two types of appliances. The challenges of this work are twofold: First, we need to model the discomfort cost of the two types of appliances. Second, we should formulate the optimization problem that can achieve the tradeoff between the discomfort and the payments by tuning the value of the parameter. Comparing with the existing works, one contribution of this work is modeling the discomfort cost by the Taguchi loss function [13], which transforms the power deviations to the economic cost, the other contribution is achieving the tradeoff between the discomfort cost and the payments by using a tradeoff parameter. Specifically, we consider three operation modes that are corresponding to three parameter settings and compare the scheduling strategies under the three operation modes.

In this study, the consumers are assumed to be equipped with energy control systems (ECS), and the ECS devices are deployed inside the smart meters and connected to a communication network. When the electricity prices are announced ahead of time, the consumers can regulate the operations of appliances to reduce their payments. We assume each consumer has two types of appliances. The first type of appliances can be delayed to operate, and the second type of appliances can be operated with a reduced power level. Both of the two operations will incur discomfort to

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the consumers. Therefore, the optimal power consumption scheduling is needed to achieve a desired trade-off between the discomfort cost and the payments.

The rest of the paper is organized as follows. The system model is given in Section "System model". In Section "Optimization problem formulation and solution", we formulate the power scheduling problem as an optimization problem and obtain the optimal scheduling strategy. Simulation results are given in Section "Simulation results", and the paper is summarized in Section "Conclusions".

System model

We consider a smart power system composed of one service provider and several consumers, as shown in Fig. 1. Each consumer is equipped with an ECS device in the smart meter to schedule the power consumption of the appliances. The ECS devices are connected to the service provider through a communication network such as a local area network (LAN) [14] (dashed line in Fig. 1). The service provider announces the price p^t at specific time slots $\mathcal{T} = \{1, \ldots, T\}$ over the LAN. Each time slot in the scheduling horizon represents one hour and the period with $T = 24$ corresponds to one day. The appliances include non-schedulable appliances and schedulable appliances. The non-schedulable appliances operate with the fixed power and time horizon (*e.g.*, refrigerator). The schedulable appliances have certain flexibilities to be scheduled (*e.g.*, air-condition). In this study, we consider two types of schedulable appliances. Let $\mathcal{A}_1$ and $\mathcal{A}_2$ denote the sets of the two types of schedulable appliances. The scalar x_a^t denotes the power consumption of appliance *a* in time slot *t*. For appliance *a*, α_a and β_a ($\beta_a > \alpha_a$) refer to the starting time and the end time, respectively. We assume $x_a^t = 0$ for any $t < \alpha_a$ or $t > \beta_a$ because the power consumption is not needed outside the scheduling horizon $[\alpha_a, \beta_a]$. Next, we formulate the two types of appliances in detail.

(1) The first type of appliances have flexible starting time. The starting time is denoted as t_a^b and can be delayed in the scheduling horizon. The appliance operates continuously with a fixed power r_a for T_a hours. For example, a clothes washer continuously working with fixed power during the operation time.
(2) The second type of appliances operate with a flexible power x_a^t in the scheduling horizon $[\alpha_a, \beta_a]$ and stop working outside the scheduling horizon $[\alpha_a, \beta_a]$. The appliance can operate with the power between the minimum power denoted by $r_a^{\min}$ and the maximum power denoted by $r_a^{\max}$. For example, the lights and air conditioners can regulate their power consumption from the minimum power $r_a^{\min}$ to the maximum power $r_a^{\max}$.

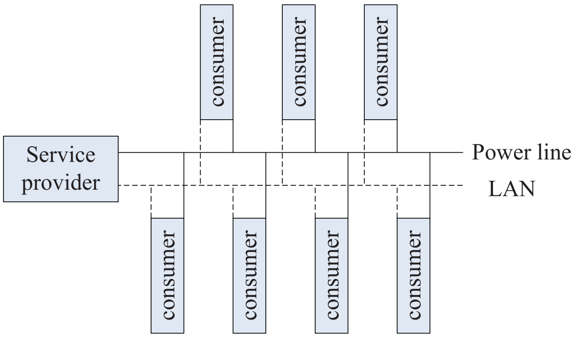

Fig. 1. Smart power system.

A feasible scheduling set χ for the power consumption of appliances is defined as

$$\begin{aligned}
\chi = \{x \mid & x_a^t = r_a, \forall t \in \{t_a^b, \ldots, t_a^b + T_a - 1\} \subset [\alpha_a, \beta_a], \forall a \in \mathcal{A}_1, \\
& x_a^t = 0, \forall t \in \mathcal{T} \setminus \{t_a^b, \ldots, t_a^b + T_a - 1\}, \forall a \in \mathcal{A}_1, \\
& r_a^{\min} \leqslant x_a^t \leqslant r_a^{\max}, \forall t \in [\alpha_a, \beta_a], \forall a \in \mathcal{A}_2, \\
& x_a^t = 0, \forall t \in \mathcal{T} \setminus [\alpha_a, \beta_a], \forall a \in \mathcal{A}_2\}.
\end{aligned} \tag{1}$$

The selection of χ depends on the electricity price announced by the service provider and the character parameters of the appliances $(\alpha_a, \beta_a, r_a, T_a, r_a^{\min}, r_a^{\max})$. The ECS device determines the optimal scheduling strategy for the appliances. The scheduling strategy is then applied to control the appliances via commands. These commands specify the power level and the starting time for each appliance and transmit over a wired or wireless home area network. For example, a wireless home area network (WHAN) is shown in Fig. 2. The in-home wireless communications can be implemented by ZigBee transceivers afforded by the ZigBee appliance. Interested readers can find more details about a variety of home area network technologies in [15].

Optimization problem formulation and solution

The electricity price in a scheduling horizon is assumed to be published to the consumers one day ahead. Then, the consumers will schedule the power consumption of the appliances in response to the day-ahead price. For example, the consumer selects $\alpha_a = 6$ pm and $\beta_a = 7$ am (the next day) for the clothes washer to finish the washing by early morning. The consumer may choose to delay the operation of the clothes washer to the time slots with lower electricity prices in order to reduce the payments, however, postponing the operation of the appliance will result in discomfort. For lights and air conditioners, the consumer may select lower power level in the interval $[r_a^{\min}, r_a^{\max}]$ to reduce the electricity payments, and this also induces the discomfort. In general, the consumers need to make a tradeoff between the electricity payments and the discomfort. Next, we formulate an optimization-based power scheduling problem.

Since the price is known to the consumers, the electricity payments within the scheduling horizon can be denoted as

$$V_p = \sum_t p^t \times \left(\sum_{a \in \mathcal{A}_1 \bigcup \mathcal{A}_2} x_a^t \right). \tag{2}$$

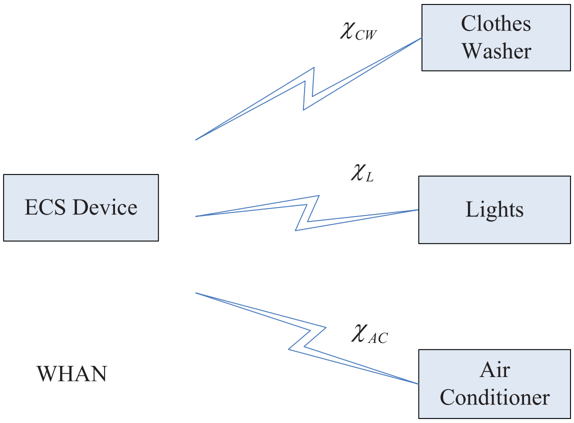

Fig. 2. The power consumption scheduling strategy selected by the ECS device can be applied to the appliances with commands over the WHAN using ZigBee transceivers.