Market-Based Coordination of Thermostatically Controlled Loads—Part I: A Mechanism Design Formulation

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Abstract—**This paper focuses on the coordination of a population of thermostatically controlled loads (TCLs) with unknown parameters to achieve group objectives. The problem involves designing the device bidding and market clearing strategies to motivate self-interested users to realize efficient energy allocation subject to a peak energy constraint. This coordination problem is formulated as a mechanism design problem, and we propose a mechanism to implement the social choice function in dominant strategy equilibrium. The proposed mechanism consists of a novel bidding and clearing strategy that incorporates the internal dynamics of TCLs in the market mechanism design, and we show it can realize the team optimal solution. This paper is divided into two parts. Part I presents a mathematical formulation of the problem and develops a coordination framework using the mechanism design approach. Part II presents a learning scheme to account for the unknown load model parameters, and evaluates the proposed framework through realistic simulations.**

Index Terms—**Demand response, market-based coordination, mechanism design, thermostatically controlled loads.**

I. INTRODUCTION

DEMAND response has attracted considerable research attention in recent years, and is regarded as one of the most important means to improve the efficiency and reliability of the future smart grid. A natural way to achieve demand response is through various pricing schemes, such as real time pricing (RTP), Time of use (TOU), and critical peak pricing (CPP) [1], [2]. Many validation projects [3] have been carried out to demonstrate the performance of these pricing schemes in terms of payment reduction, load shifting, and peak shaving. These price-based methods either directly pass the wholesale energy price to end-users [2] or design pricing strategies in heuristic ways [4]. It is thus hard to achieve predictable and reliable aggregated response, which is essential in various demand response applications, such as energy capping, load following, frequency regulation, among others.

To achieve accurate and reliable load response, aggregated load control has been extensively studied in the literature. A simple form of aggregated load control is the direct load control (DLC), where the aggregator can remotely control the operations of residential appliances based on the agreement between customers and the utility company. While traditional DLC is mainly concerned with peak load management [5], [6], recent research effort focuses more on the modeling and control of different kinds of aggregated loads, such as data center servers [7], [8], hybrid electrical vehicles [9], [10], and thermostatically controlled loads [11]–[14], to participate in various demand response programs. Some of these DLC methods require fast communications between the aggregator and individual loads. The communication overhead can be reduced using advanced state estimation algorithms [15], [16] that can accurately estimate load state information without frequently collecting measurements from the loads.

Another important paradigm of aggregated load control is the market-based coordination. It borrows ideas from economics [17] to coordinate a group of self-interested users to achieve desired aggregated load response [18], [19]. Different from DLC, the market-based coordination affects the load response indirectly via an internal price signal. The internal price can be dramatically different from the wholesale price due to specific group objectives. For instance, in [20] and [21], a market-based approach is proposed to efficiently allocate thermal resources among offices only based on local information. In [22] and [23], a multi-agent-based control framework is proposed to integrate distributed energy resources for various coordination objectives. A distributed algorithm is developed in [24] and [25] for the utility company and users to jointly determine optimal prices and demand schedules via an iterative bidding and clearing process. In [26], a group of smart buildings are coordinated through an internal price signal to provide frequency regulation services to the ancillary market. In addition, the Pacific Northwest National Laboratory launched the GridWise® demonstration project to validate the market-based coordination strategies for residential loads [27]. The demonstration project involved 112 residential houses in Washington and Oregon, and showed that the market-based coordination strategies could reduce the utility demand and congestion at key times.

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Although the aggregated dynamics of thermostatically controlled loads (TCLs) may significantly affect the performance of the control strategies, many existing market-based coordination strategies either neglect this internal dynamics or use a simplified model to characterize it. In this paper, we consider the coordination of a group of TCLs to maximize the social welfare subject to a peak energy constraint, where the internal dynamics of TCLs are taking into account. This coordination problem poses several challenges. First, the user utilities are private information, making it rather challenging for the coordinator to achieve group objectives with incomplete information. Second, many existing works adopt the Nash equilibrium concept [28], [29], which requires multiple iterations between the agents and the coordinator to achieve the optimal social outcome. The real time implementation of such coordination algorithms requires considerable communication resources. Third, a lot of existing literature assumes accurate load models with known parameters. However, the Gridwise® demonstration project [27] suggests this is not always the case. In practice, the information each user sends to the coordinator can only depend on local measurements, such as room temperature and “on/off” state. Therefore, an estimation scheme is needed for the users to compute their bids only based on online measurements.

The key contribution of this paper lies in the development of a market-based coordination framework for residential air conditioning loads with a systematic consideration of all the aforementioned challenges. In this paper, we formulate the coordination problem as a mechanism design problem [17], [30]. The price-responsive loads are modeled as individual utility maximizers, while the group objective is encoded in the social choice function, which is to maximize the social welfare subject to a peak energy constraint. We propose a mechanism and show it can implement the social choice function in dominant strategy equilibrium. Such solution concept does not require iterative information exchanges between the coordinator and the individual loads, and can be implemented with limited communication resources. The proposed mechanism contains a novel bidding and clearing strategy that incorporates the internal dynamics of the TCLs into the market mechanism design, and we show that it can realize the team optimal solution.

Different from many existing works [25], [27], the problem is addressed with a systematic consideration of various practical factors, such as heterogeneous load dynamics, private information of individual users, unknown parameters of the load model, communication resources for the information exchange, etc. All these factors are brought up based on the observations in the GridWise® demonstration project [27]. They are important not only for customer privacy protection and the end user engagement, but also for the cost-effective implementation of the real-time control strategies. Once our framework is properly implemented, it can accurately achieve the desired load responses, and improve the operational efficiency of the distribution system in an economically feasible way.

The rest of the paper proceeds as follows. A motivating example based on a real-world demonstration project is presented in Section II, followed by a problem formulation in Section III. A mechanism is constructed in Section IV to implement the optimal energy allocation. Simulation results and the joint state-parameter estimation framework are presented in the companion paper [31].

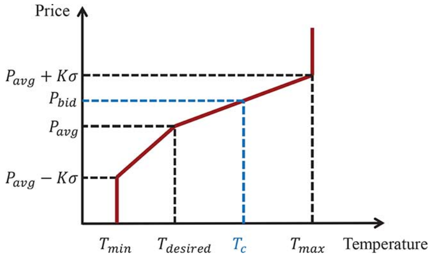

Fig. 1. Controller measures its current temperature T_c and submits a bid P_{bid} to the coordinator using this curve.

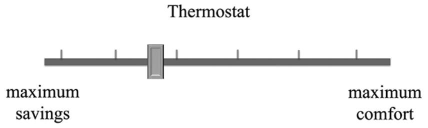

Fig. 2. User interface used in the GridWise® demonstration project [27].

II. MOTIVATING EXAMPLE

The framework proposed in this paper is largely motivated by the Pacific Northwest GridWise® demonstration project [27], where a 5-min double-auction market is created to coordinate a group of TCLs to cap the aggregated peak energy. Each device is equipped with a smart thermostat that can measure the room temperature and communicate with the coordinator. Before each market period, the device measures its room temperature, T_c, and submits a bid to the coordinator. The bid should consist of the load power and the bidding price. Since the rated power of the load is different from its actual power due to environmental disturbances, in practice each device is required to bid the measured average power of the most recent market period during which the load is on. The bidding price is determined by a bidding curve shown in Fig. 1, where P_{avg} is the average clearing price of certain price history (e.g., 24 h), σ is the standard variation of the clearing prices during the given history, and $T_{\min}$, T_{desired}, and $T_{\max}$ are user-specified minimum, desired, and maximum temperature, respectively. We denote the bidding power and price as Q_{bid} and P_{bid}, respectively. In addition, each user can specify energy use preferences through a smart thermostat interface (see Fig. 2). This user preference will affect the slope of the bidding curve.

The coordinator collects all the bids and orders the bids in a decreasing sequence, $P_{\mathrm{bid}}^1, \ldots, P_{\mathrm{bid}}^N$. With the associated power sequence, $Q_{\mathrm{bid}}^1, \ldots, Q_{\mathrm{bid}}^N$, a demand curve can be constructed to map the clearing price to aggregated power. Fig. 3 illustrates how the demand curve is constructed. This curve is then used to determine the market clearing price that respects the feeder capacity constraint: when the total demand is less than the feeder capacity, the market clearing price is equal to the base price, P_{base} (Fig. 4), which is the wholesale energy price plus a retail modifier as defined by the tariff of American Electric Power (AEP) [32]; otherwise, the market price, P_c, is determined by

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