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Peak shaving through real-time scheduling of household appliances

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ABSTRACT

The problem of limiting the peak load of the power consumed by a set of electric loads has been largely addressed in over 5 decades of research on power systems. The motivation of such attention arises from the benefits that a smoother load profile brings to the management of power systems.

This paper illustrates an approach to the peak shaving problem that leverages the real-time scheduling discipline to coordinate the activation/deactivation of a set of loads. The real-time scheduling is an active research topic in the field of computing systems. The innovative idea proposed in this paper is to apply existing real-time scheduling algorithms and analysis methods to the management of power loads. This solution requires an adequate modeling of considered devices in order to derive a representation in terms of timing parameters. The modeling approach enables the handling of a set of heterogeneous loads in a coordinated manner. In particular, this paper focuses on the modeling and management of household appliances. For this purpose, a set of the most common appliances is modeled and their activation is controlled by the proposed scheduling policy. Realistic assumptions are made on the daily usage of each device. The derived results show an effective and predicable reduction of the peak load while guaranteeing the user comfort associated with the load operation. The peak load of a single apartment is reduced by the 8% in the average case and by the 41% w.r.t. the worst-case. Considering the coalition of several apartments, the scheduling approach achieves a peak load reduction up to 46%.

1. Introduction

The problem of limiting the peak of power consumed by a set of electric loads has been widely studied in the field of power systems [1]. The advantage of achieving a limited peak load is both on the energy provider and user side. The coordination of electric loads is often addressed in the context of *smart grids* under the so-called Demand-Side Management (DSM) [2]. The DSM addresses techniques targeted to the regulation of the demanded electric power.

This paper describes a method to coordinate a set of electric loads to limit the peak load of power usage. The proposed method leverages the real-time scheduling discipline to coordinate the activation/deactivation of the load set. Real-time scheduling is an active research field in the computer science domain, where it is studied to manage the concurrent execution of processing tasks on a set of processors under timing constraints [3]. The innovative idea proposed in this paper is to adapt some existing real-time scheduling and analysis methods to coordinate the activation of activations power loads. This solution requires an adequate modeling of the considered loads to derive a representation in terms of timing parameters. Suitable parameters can be found applying the so-called Real-Time Physical System (RTPS) model [4]. The most remarkable features of a power load management based on real-time scheduling algorithms are:

- predictability: the behavior of a real-time scheduling pattern is a-priori guaranteed in a mathematically strong form [3];
- robustness: real-time scheduling algorithms are concerned with worst-case working conditions [3];
- reusability: there are several modeling and control methodologies that can be adapted and applied to the load management [5];
- automatization: the derivation of load priorities is based on the characteristics of both the load and the underlying physical process, without the need of the empirical intervention of a system designer [6];
- scalability: thanks to low-complexity algorithms, large sets of heterogeneous loads can be effectively managed and analyzed [7].

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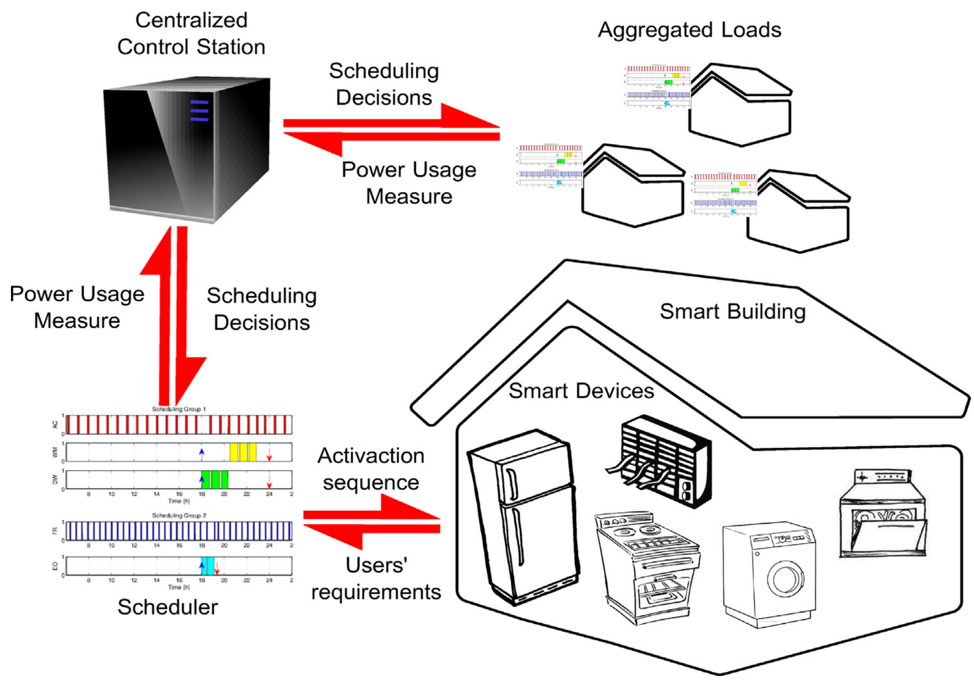

Fig. 1. The Home Energy Management system based on real-time control techniques.

Although the proposed method can handle a set of heterogeneous loads, including industrial loads [8,9], this paper focuses on the modeling and the management of household appliances. Fig. 1 depicts a Home Energy Management (HEM) infrastructure that allows to manage the appliances of several houses/apartments in a coordinated manner. This aggregated organization is known as *coalition*, and the set of users are seen as a Virtual Electricity Consumer [10].

For this purpose, a set of the most common appliances is modeled and real-time scheduling algorithms are applied to their coordination. The considered loads are classified as *time-triggered* (TT) or *event-triggered* (ET) loads. A TT load generated a periodic sequence of activation requests. The TT loads considered in this paper are refrigerators and Heating, Ventilating and Air Conditioning (HVAC) systems. On the other hand, the activation of ET loads is triggered by the user. In this case, the automatic coordination system schedules the load activity within a given time interval. The considered ET loads are washing machines, dishwashers, and electric ovens. The type of loads to model has been selected considering two parameters: its penetration rate, i.e., the percentage of the population that purchased the appliance, and its controllability. The former allows to neglect those appliances that are not widely spread. Only appliances having a penetration rate above 50% have been considered. The penetration rate has been evaluated on the Italian market, based on the information reported in [11]. The controllability refers to those loads that can be suitably managed by a centralized controller, i.e., loads that can be freely turned on/off without affecting the user comfort. For this reason, non-controllable loads such as televisions and the lighting systems have been excluded.

For each considered load a simple but accurate thermodynamic model has been derived. The model is used to determine the values of timing parameters required to perform an active control using real-time scheduling techniques. The derived profiles have been validated against real measured ones. The sources of measured profiles are [12], a report developed in collaboration with the European Committee of Domestic Equipment Manufacturers (CECED), and [13]. Realistic assumptions are made on the daily usage of each load.

The derived results show an effective and predictable reduction of the peak load while guaranteeing the user comfort associated with the load operation. In particular, when the proposed approach is applied in the context of a single apartment, simulation results show that the peak load can be reduced from 8% up to 41%, for some load activation patterns. Moreover, when a group of users forms a coalition the benefits increase: the reduction is up to the 46% w.r.t. worst-case conditions.

1.1. Paper organization

The paper is organized as follows. Section 2 provides a short introduction to the state of the art of electric load management. In Section 3 the physical models of the processes controlled by the considered electric devices are presented. Section 4 illustrates the proposed Home Energy Management strategy, describing the adopted algorithms and the timing characterization of loads. Since some of the evaluated appliances, like washing machines and ovens, are activated by the user, considerations on the user behavior are reported in Section 5. In Section 6, an example of application is provided on a single apartment, while Section 7 derives simulation results on a coalition. Finally, Section 8 states our conclusions.

2. Related works

This section focuses on existing modeling and coordination approaches targeted to peak load management.

Several papers propose physically based load models of electric loads and appliances [14–16]. However, such models are either uselessly detailed for our purposes or they simply neglect loads that are considered in this paper. We have tailored the complexity of our proposed models to address the modeling in terms of timing parameters.

Over the decades, approaches based on optimization techniques as linear programming [17] and linear control methods [18] have been proposed. Another class of approaches is based on artificial intelligence techniques, such as neural networks [19], self organizing agents [20], fuzzy logic [21,22], and expert systems [23]. Those methods do not provide any predictable forecasting on the