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Scheduling policies for two-state smart-home appliances in dynamic electricity pricing environments

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ABSTRACT

In this paper we present and analyze online and offline scheduling models for the determination of the maximum power consumption in a smart grid environment. The proposed load models consider that each consumer's residence is equipped with a certain number of appliances of different power demands and different operational times, while the appliances' feature of alternating between ON and OFF states is also incorporated. Each load model is correlated with a scheduling policy that aims to the reduction of the power consumption through the compression of power demands or the postponement of power requests. Furthermore, we associate each load model with a proper dynamic pricing process in order to provide consumers with incentives to contribute to the overall power consumption reduction. The evaluation of the load models through simulation reveals the consistency and the accuracy of the proposed analysis.

1. Introduction

The smart grid is a visionary power system that aims to the transformation of the existing infrastructure to a more consistent, efficient and user-centric power grid [1]. The evolution to this next generation grid is based on the utilization of intelligent controllers and two-way communication between consumers and power utilities, with the aim of providing reliable and cost-effective energy supply [2]. The communication technologies are vital to the future smart grid, as they provide the means for a synergic effort by both parties to manage the energy distribution and consumption, while limiting the cost and the environmental impact of the power generation [3]. This inclination towards a DSM (Demand Side Management) promotes the active participation of consumers to compensate the imbalance of generation and demand, through the change of their power usage preferences [4].

DR (Demand Response) is one of the main DSM activities that aims to provide consumers with motives to change their electric use, in response to changes in electricity prices, as stated by the US Department of Energy [5]. Designing an efficient DR program is an important issue that should target on the modification of the consumers' demand profile. This objective can be realized by either reducing the power consumption of specific loads [6] or controlling the activation time of the requested load [7]. In the former case, power scheduling programs regulate the operation of various appliances, in order to consume less power during system stress periods without affecting their functionality (e.g. air-conditions that can be adjusted to 25 °C, instead of 22 °C, during a summer day) [8]. Alternatively, in task scheduling programs requested loads that are able to be adjusted (e.g. water-heaters or laundry pairs) are shifted to off-peak hours [9]. The decisions related to both scheduling methods (amount of power reduction or duration of the request delay) are taken either offline, based on past or predicted consumption patterns [10], or online, based on real-time observations of the power consumption [11].

The performance of a scheduling program can be further improved by applying an efficient pricing management scheme. A dynamic pricing model provides consumers with incentives to reduce their loads or to shift their power consumption to off-peak hours [12]. At the same time, power utilities receive significant benefits from the application of dynamic pricing, since the reduced power consumption in high-peak hours de-escalates the need to activate expensive-to-run power plants [13]. Moreover, the key features of the applied pricing model should be defined based on the applied scheduling policy, in order to provide a more rational charging policy to customers.

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Nomenclature

a_m	transfer probability from state ON to OFF
B_m	probability of exceeding P after the acceptance of type-m request
B_{m1}	probability of exceeding P after the acceptance of type-m request for the ON-PSP
C_m	re-activation blocking probability of type-m appliance
C_{m1}	re-activation blocking probability of type-m appliance for the ON-PSP
$d_{i,m}^{-1}$	mean operational duration in state i
$(d_{i,m}^{h})^{-1}$	mean operational duration in state i for the ON-PSP
e	predefined blocking probabilities upper bound
$f_{i,m}$	utilization of the i-th state by type-m appliance
H	number of thresholds for the online policies
j_1	total number of p.u. in the real system
j_2	total number of p.u. in the fictitious system
M	number of appliances
n_m^i	number of type-m appliances in state i
P	maximum number of supported p.u. in the real system
P^h	power threshold for the online policies
P^t	power threshold for the offline policies
P^{fict}	maximum number of supported p.u. in the fictitious system
$q(\overrightarrow{j})$	distribution of occupied p.u. $\overrightarrow{j} = (j_1,j_2)$
Q	distribution normalization constant
r_m	power demand of type-m appliance
r_m^h	compressed power demand for the ON-PSP
T	number of thresholds for the offline policies
$y_{i,m}$	mean number of type-m appliance in state i
r_m	power demand of type-m appliance

Greek symbols

λ_m	type-m power request arrival rate
ω_m^t	power demand compression factor
ξ_m^t	operation duration increase factor
δ_m^t	request delay duration
φ_m	control function for the ON-PSP
γ_m^h	control function for the ON-PSP

Subscripts

m	appliance type
i	appliance state (ON or OFF)
s	system type (real or fictitious)
t	threshold for the offline policies
h	threshold for the online policies

The performance evaluation of either power or task scheduling policies has been extensively studied in the literature, mainly through simulation [9,14,15], or optimization methods [16,17]. However, only a few analytical models have been proposed; power demand control policies are proposed and analyzed in Refs. [18,19]. They take the current power consumption pattern into consideration so as to immediately activate or postpone a power request. In addition, a number of analytical models have been developed for the performance evaluation of electric vehicle charging infrastructures [20,21]. In all cases, the power requirement of each power request equals to 1 power unit, which is constant for the entire operating time of the device.

In this paper, we aim to develop analytical models for the performance evaluation of both power and task scheduling policies. The target of each analytical model is the mathematical derivation of the peak demand in a residential area, as a function of critical parameters of the appliances that are installed in each residence, while also considering the parameters that are related to the applied scheduling method. In comparison to time-consuming simulations, the utilization of analytical models is a fast, resourceful and cost-effective solution that could be used by power utilities in order to evaluate the effectiveness of a scheduling policy, to derive the optimum set of parameters that will guarantee particular objectives, and predict the grid's performance under extreme power-demand conditions.

The contribution of this paper can be summarized in the following 5 points:

- We present the baseline policy and we develop an analytical model for the determination of the upper bound of the maximum power consumption in a residential area.
- We study both the power and task scheduling policies by presenting and analyzing two offline and two online scheduling policies that aim to reduce the maximum power consumption in the under study residential area. The baseline policy and the scheduling policies are applied to a residential area, where each residence is equipped with a specific number of appliances with different power demands, operational times and arrival rates of power requests.
- Moreover, we assume the more realistic case, where the power requirements of a number of appliances are not constant for their entire operation period. On the contrary, we consider that an appliance transits between two states of operation; an ON state, where the appliance operates under its nominal power and an OFF state where no power consumption occurs. The parameters related to the duration of ON and OFF periods and the transition probability from ON to OFF state and vice versa are also incorporated in our analysis.
- We also associate the proposed scheduling policies with a proper dynamic pricing scheme by providing different cost functions for each policy and we present analytical results for the total average cost.
- Finally, we compare analytical results from the proposed scenarios with corresponding analytical results from Ref. [19]. We demonstrate that the proposed analytical models achieve better performance regarding the total power consumption, while being more realistic since they consider multiple power requests of ON–OFF type with diverse power requirements.

The remainder of the paper is organized as follows. In Section 2 we introduce the background for the analysis of the baseline policy that is also the basis for the analysis of the proposed scheduling policies. In Sections 3 and 4 we present and analyze the two proposed offline and the two online power demand policies, respectively. Section 5 investigates the effect of a dynamic electricity pricing function to the total average cost for the proposed power demand policies. In Section 6 we evaluate the proposed analysis by comparing analytical and simulation results. The conclusions of our paper are stated in Section 7.

2. Background and preliminaries

In this section we present the general features of the baseline policy; these features are also used to describe the basic modeling