Policy-Based Energy Management in Smart Homes

T. K. Anandalakshmi, S. Sathiakumar and N. Parameswaran

Abstract This paper proposes the use of policies in smart homes to manage energy efficiently and reduce peak energy demand. In peak hours, demand increases and supply providers bring additional power plants online to supply more power, which results in higher operating costs and carbon emission. In order to meet peak demand, utility companies have to build additional power plants, which may be operated only for short period of time. Therefore, reducing peak load will reduce the need for building additional power plants and decrease carbon emission. Our policy-based framework achieves peak shaving so that power consumption adapts to available power while ensuring the comfort level of the inhabitants and taking device characteristics into account at the same time. Our simulation results on Matlab indicate that the proposed policy driven homes can effectively contribute to demand side power management.

Keywords Agents · Policy · House agent · Energy management · Policy-based modeling

Introduction

Global demand for energy is increasing fast as the population increases and the number of household appliances also increases as the technology improves. The international energy agency says the world's energy needs could be 50% higher

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in 2030. Thus, there is a need to use less energy or use energy more efficiently and smartly. To opt out of more power generation, smart energy management is required.

Instead of managing energy at the supply side only which is expensive, it may also help to have control on energy consumption at the distribution side. For a given amount of power generation with insignificant energy storage options, whatever energy is generated must be transmitted and consumed by the consumers at once. If power generation is not equal to power consumption, then the stability problem arises. In order to overcome peak demand and power system stability problems, we propose in this paper an approach where the power consumption behavior of the household appliances in a smart home are controlled and managed by a set of policy rules such that the average power consumption of the house is always less than the available power for that house over a period of time and that the average comfort level of the residents is not excessively compromised.

Traditional energy management techniques and studies always ignore social behavior or treat it as a single parameter describing the society as a whole. Consumers' choice and interests on energy use is one of the main factors which affects energy demand and should be considered in power management. Policy-based simulation technique views electric appliances as agents whose behaviors are controlled by policy rules. The agents react to the changes in their social and physical environments.

Policy-based management is acknowledged as a promising approach for dealing with automated management of large-scale distributed systems and networks. Policies which are sets of rules can alter the behavior of objects within the system [1]. Policy-based approach attempts to model specific behaviors of a given individual whereas the traditional macro simulation techniques, which are based on mathematical models, attempt to capture the overall characteristics of a given population. Thus, policy-based modeling is appropriate for domains characterized by a high degree of localization and distribution whereas equation-based modeling is suitable for systems that can be modeled centrally in which the dynamics are dominated by physical laws rather than using information processing [2].

This paper is organized as follows: In Section "Related Work", we review the existing energy management techniques. We discuss the user behavior with regard to energy consumption in Section "User's Behavior and Energy Management". In Section "Power Consumption Management and Policies", we explain power consumption management and policies. In Section "Power System Model", we discuss how our policy-based model works in different situations using simulation results. Concluding remarks are given in Section "Conclusion".

Related Work

Smart home refers to a home where energy is managed smartly and efficiently while ensuring the comfort level of the inhabitants. Several research efforts have focused on energy saving through intelligent management of house appliances. In

[3], the authors present a Multi Agent Home Automation System (MAHS) which allows the agents to cooperate and coordinate their actions so that power is managed efficiently. Tabu search algorithm is used to reduce the complexity of the problem by dividing into independent sub problems. In [4], the authors propose an agent-based approach to reduce energy consumption and carbon emission. They mainly focus on how to reduce energy wastage and to develop “good” habits and life style toward energy saving and CO2 reducing. Simulation results demonstrate how energy consumption and CO2 emission can be calculated. In [5], the authors propose a hybrid social model for accurate power demand estimation which extends traditional models by adding a social simulation layer to capture social responsiveness on power conservation policies. In this, they develop a simulator called Residential Power Demand Simulator for evaluating power-pricing policies, in which a consumer’s behavior and social interactions are considered. They run a variety of scenarios and observe the impact of how policies may affect total demand. In [6], the authors propose a demand side management system for a household by using Keiko University Network oriented Intelligent and Versatile Energy System (KNIVES) and a smart circuit breaker box. It controls electric power by using a distributed and cooperative power control algorithm. In this paper, we focus our research on how to reduce peak energy demand by managing the household appliances using policy while taking care of device characteristics. We also evaluate the user satisfaction factor while executing policies for the appliances and make sure that their comfort level is maintained.

User’s Behavior and Energy Management

Household appliances account for 30% of the total energy consumption. White goods such as refrigerators, washing machines, and dish washers are the largest contributors to household energy use consuming 34% of all energy consumed by household appliances as shown in Fig. 1.

An average household in Australia supposedly uses around 15–20 kWh electricity per day[7]. For most utilities, electricity demand peaks between 3 p.m. and 8 p.m. when people come home from work and start cooking dinner, washing clothes, running dishwasher, and turning on their big screen TVs. Thus, targetting household appliances will be a useful strategy in residential energy management.

The total energy savings from all appliances (which could amount to several millions typically in a city) could be significant and can effectively contribute to substantial energy savings if consumers learn to manage their energy consumption behavior (which may also help reduce the peaks in the power consumption curve).

Consumer behavior changes may be achieved by incentives such as vouchers, tax credits, and utility rebates. Consumers may have preferences in their usage of electricity and their appliances. They also have the authority and responsibility for device level management within their homes. Consumers have the right to employ any instruments and tools to manage energy.

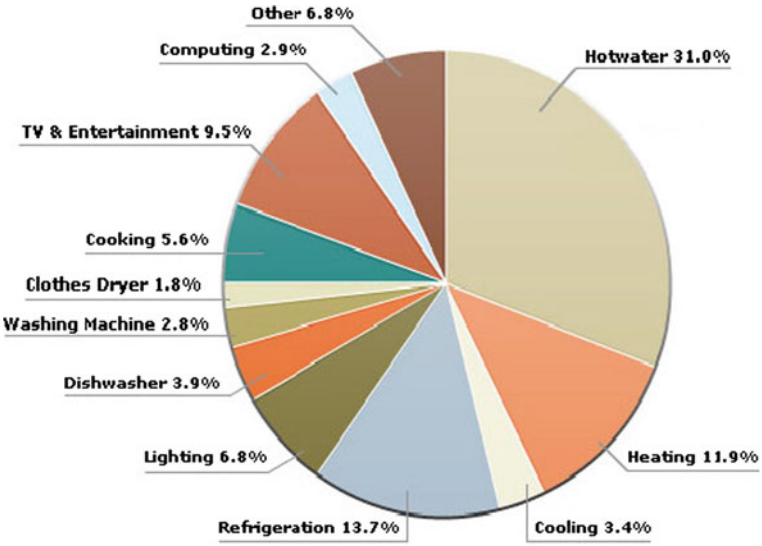


Fig. 1 Energy use within an average NSW household [7]

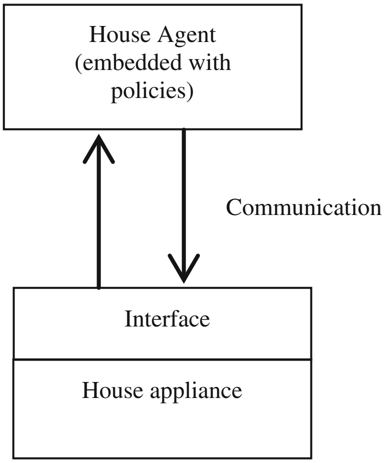
Using policies to control electric appliances is one of the ways of managing the overall power consumption behavior of a consumer. Policies are set of rules that turn on or off an appliance depending on a set of conditions. In general, rules in a policy can examine the current state of an appliance and decide upon the next state to which the appliance can be switched to depending on the current situation. Policies can be modified dynamically thus offering flexibility. Policies also allow communications with other appliances using standard protocols over a network (Wi-Fi, Ethernet, and Home area networks such as Zigbee, Z-Wave, and Homeplug) and are leveraged to support grid applications such as meter reading, DR, and energy management [8].

Power Consumption Management and Policies

Our power consumption management framework consists of a house agent that monitors and controls the electric appliances in the house using a policy implemented using a set of rules. (See Fig. 2.) Communication between the house agent and the appliance is implemented using existing power lines. The house agent accesses the states of the appliances using a standard Zigbee protocol, and decides upon the new state to which the appliance must be taken to depending on the time and total power consumption at that time.

Let us consider an example. Suppose the air conditioners (A/Cs) in a house are permitted to be switched on between 10:00 a.m. and 4:00 p.m. in summer

Fig. 2 Communication between house agent and appliance



according to a policy. During this time, the A/Cs will be on if the user wants them on and if the total power consumption does not exceed the available power; otherwise they will be off.

Let t be the sampling time of a day and RonAC is the request time of the user to turn on the A/C. Then, the following rules denote a policy specifying when the A/Cs can be on or off:

if (t = RonAC & $10 \leq t \leq 16$ & total power $\leq$ available power) **then** turn on AC;
if (t = RonAC & $10 \leq t \leq 16$ & total power $\geq$ available power) **then** turn off A/C;

When a home agent receives a request to turn on the A/Cs from the consumer, the home agent invokes the policy rules. Policy rules which reside in the home agent propose an action for the appliance depending upon the time, the state of the appliance and actual power consumption at that time. Action is sent to the interface using an agreed upon protocol. The Interface upon receiving the action name and the parameters, passes the action to the appliance and the appliance executes the action after which the state changes.

Power System Model

Electricity distribution is a complex process where demand fluctuates quickly and loads that are responsive in real time can be highly valuable to retailers and networks. This domain is ideal for the adoption of policy-based power consumption management. Fig. 3 shows the power system from generating station to household appliances.

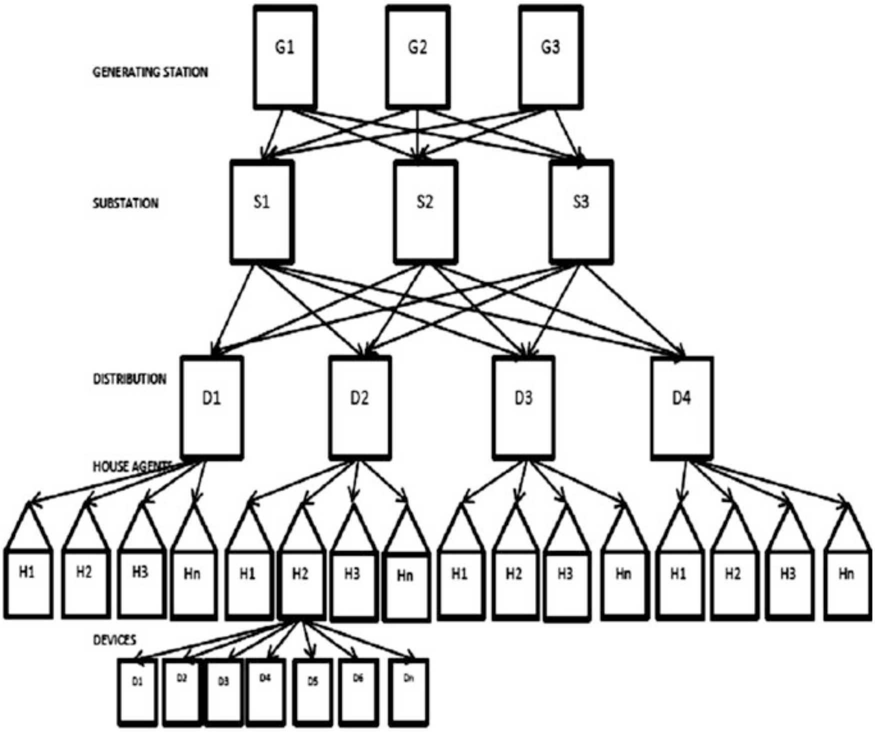


Fig. 3 Electric power system model from generation to appliances

Hierarchy in Power System

- Generating station

Electricity is produced close to supplies of energy such as coal and water, which are used to drive equipment used to generate power.

- Substation

The electric power carried over the extra high voltage transmission lines is delivered to regional and neighborhood substations where the electricity is stepped down from high voltage to a voltage that can be used in homes and offices.

- Distribution

This is the last stage in the delivery of electric power to the users. Distribution circuits start from a transformer located in the electrical distribution substation.

- Home agents

Each home has an “electrical service” connection and a meter for billing. The home agent monitors and manages energy effectively throughout the day by controlling the appliances and ensures that the total power does not exceed the available power while maintaining the comfort level of the user.

- Appliances

Appliances are the real consumers of electricity in the houses. Power produced at the generating plant finally goes to the appliances so that the inhabitants benefit from the services provided by the appliances. In this paper, we assume that the appliances do not interact amongst themselves and they can only share information with the home agent.

Policy-Based Implementation

We assume that the house agent wants to maintain total energy consumption below an available power of 5,000 W.

Power Consumption Behavior without Policies

Figure 4 shows the overall power consumption of appliances in a typical home where the consumption is not monitored or managed. Note that it has peaks exceeding over 5,000W line. The appliances are turned on any time any number of times and any longer. Since appliances like refrigerators, although appear to be on all day, are actually running between 12 and 15 h a day, we assume that on an average a refrigerator is on for 10 h a day. The peaks in Fig. 4 are due to many appliances being turned on during the same interval.

Fig. 4 Actual power consumption curve

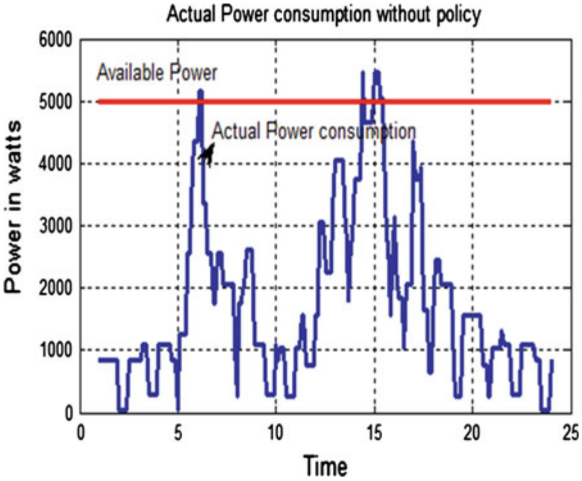


Table 1 Classification of appliances

Grade 1 (essential appliances)	Grade 2 (entertainment appliances)	Grade 3 (optional appliances)
Microwave (1,000 W)	Air conditioner (1,000 W)	Washing machine (800 W)
Computer (250 W)	Nintendo (500 W)	Clothes dryer (1,000 W)
Water heater (1,000 W)	TV (500 W)	Dish washer (1,200 W)
Lights (200 W) 4 rooms	Music (400 W)	Vacuum cleaner (1,000 W)
Iron box (1,000 W)		
Coffee maker (800 W)		
Fridge (800 W) (permanent service)		

Power Consumption with Monitoring Policies

The appliances are categorized according to their importance to the inhabitants. A typical classification of appliances is given in Table 1.

(a) *Grade 1 appliances*

These appliances are essential to sustain the day-to-day activities of the inhabitant. Agents or policies should not turn them off while the inhabitant is using them.

(b) *Grade 2 appliances*

These appliances are turned on most of the time, and yet not considered essential.

(c) *Grade 3 appliances*

The operation of these appliances is required only rarely.

Modeling Appliances

When the inhabitant tries to operate an appliance, the maximum available power is the first constraint. Thus, the policy rules need to ensure that the power consumption does not exceed the available power while following the device characteristics.

Device characteristics can be specified using states along with their attributes. Some important attributes are: time constants and power consumption. Some of the important time constants are: τ_{on}, $\tau_{\text{min-on}}$, τ_{off}, and $\tau_{\text{min-off}}$,
where

τ_{on} is the time required by the appliance to go from OFF state to ON state;
τ_{off} is the time required by the appliance to go from ON state to OFF state;
τ_{minoff} is the time duration for which the appliance stays in its OFF state before it goes to ON state; and

τ_{minon} is the time duration for which the appliance stays in its ON state before it goes to OFF state.

These time constants are important since they can determine how quickly the system can move from one state to another. State diagram is used to describe the dynamic behavior of a device or an appliance. When a rule operates on a particular appliance, it consults the state diagram of that appliance before the rule fires.

Figure 5 describes the simple state diagram of a light. We model this device with two states: light on (s0) and light off (s1). The arrows between the states are called transitions and will happen when the switch is flipped.

A more general state diagram of an appliance with multiple states is shown in Fig. 6. The states are s0 (On), s1 (turning off), s2 (Off), and s3 (turning on).

Once the appliance is switched on, it goes to warming up state, and after τ_{on} units of time, it goes to the ON state. The appliance then stays in the working state at least for τ_{minon} period. During the ON state, if a policy rule says that the appliance should be turned on, the appliance is turned on to which event the

Fig. 5 State diagram of a light

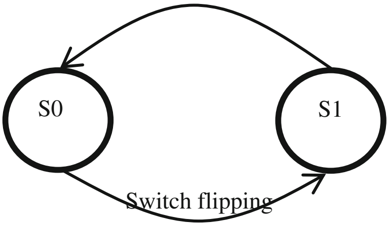
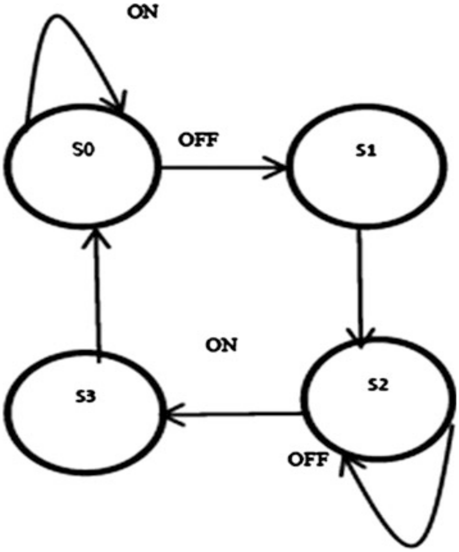


Fig. 6 State diagram of an appliance with multiple states



appliance responds by continuing to stay in the ON state. When it is switched off, it starts the shutting down operation and after τ_{off} it goes to the OFF state. It stays in the OFF state for at least τ_{minoff} period. During the OFF state, if the rule requires it to turn off, the appliance continues to stay in the OFF state.

Rules for the House Agent

Before defining a set of rules for the house agent to monitor and control the appliances, we define a term called *on-time* which denotes the interval over which we need the appliance to remain ON once it is turned on. For example, the customer may need for an A/C appliance, a minimum on-time of 4 h, say between 10 a.m. and 4 p.m. A rule that uses the on-time notion may look like:

```
if RontimeAC $\geq$ 10 & $t \leq 16$
then

  Turn off fridge and turn on A/C for the first five sampling periods;
  Turn off A/C and turn on fridge for next five sampling periods;
  Repeat this until A/C is on;
```

This will help reduce peak demand during, for example, hot summer. Figure 7 shows the duty cycle of a fridge before policy is implemented.

Figure 8 shows that the demand for energy suddenly increases from 800 to 1,800 W when A/C (1,000 W) is turned on and when there is no policy executed.

Figure 9 shows that the power consumption by the A/C and the fridge when operated together with the policy above is only 1,000 W. If the duty cycle is not adjusted, then the power during the A/C time would have reached 1,800 W.

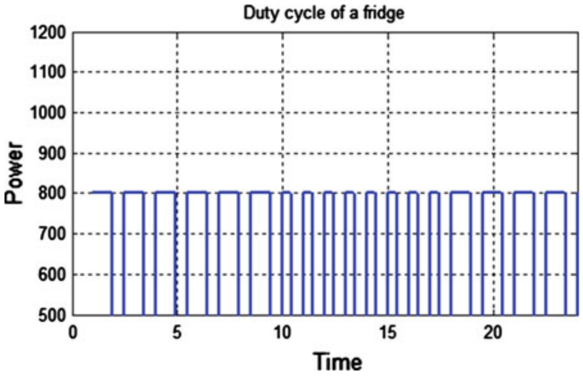


Fig. 7 Duty cycle of a fridge

Fig. 8 A/C and fridge working together without policy

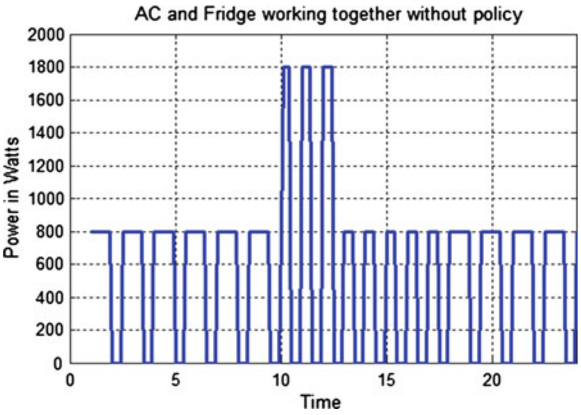
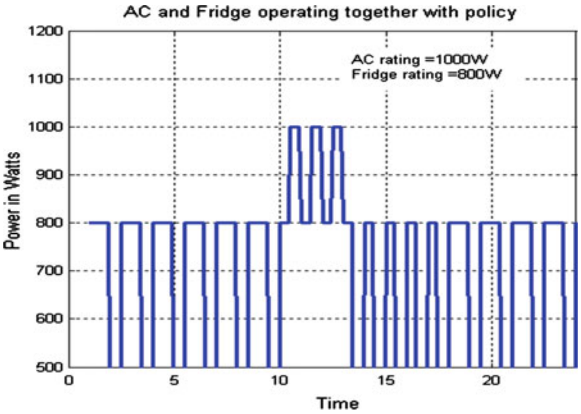


Fig. 9 Duty cycle of Fridge and A/C during the operation of A/C



Rules for House Agent

```
t =sampling time starts at 0 and incremented by 0.1;
ontime(wash) = requestontime for washing machine from user;
durationwash  = operation time for washingmachine;

// only one grade3 appliance will be allowed to operate at any time.
R1: ontime(wash)= ontime(dish)=ontime(vacuum)   →
              ontime(dish)=ontime(wash)+durationwash+0.1,
              ntime(vacuum)=ontime(wash)+durationwash+0.3;

//once a grade 3 appliance is on, then no other grade 3
//appliances can be operated until that appliance is off.
R2:  t ≥  ontimegrade3appliance          →
              turn off other grade3  appliances

// postpone grade 3 appliances
R3: t = ontimegrade1 appliance         →
              turn on grade1 appliance;

R4:  power > available power
     &  t=ontimegrade3appliance        →
              ontimegrade3appliance =
              ontimegrade1appliance+durationgrade1appliance;

    t=ontimewaterheater &  t = ontimewash or ontimedish
    or ontimevacuum       →
              postpone grade 3 appliances;

//to prevent power consumption to go high when A/C is
// ON, the iron box is turned off
R5:  t = ontimeironbox &  t = AC time   →
              turn off Iron box;

//TV and Nintendo are not operated together.
R6: ontimeTV = ontimeNintendo      →
              turn off TV and turn on  Nintendo;

//Nintendo is not allowed before  school hours.
R7: ontimeNintendo <15 →
              turn off Nintendo;

//if total power exceeds available power music is turned off.
R8: total power >available power →
               turn off Music;

//to ensure  quality of the process once  grade 3 appliance is turned on it will run
until the process(washing, drying, dish wash) is completed.
R9:  t >ontimegrade 3 appliances →
              grade 3 appliances cannot  be turned off;
//TV is preferred than music when there is a power constraint.
R10:  t=ontimeTV=ontimemusic
      & power>available  power →
               turn off music;
//if lights are on during the day and if actual power exceeds    //available power
then lights will be turned off.
R11:  t = ontimelights &  10≤t≤16
      & power >available power →
              turn  off lights.
R12: if t<10 &t>16 turn on fridge for 10 sampling periods and
       turn off for 5 sampling periods.
  //Outside AC time fridge will work normally.
R13: If t <10 or t>16 &  if    power>available power →
       turn off AC.
//Outside AC time if A/C is on and if power
//exceeds the available power then A/C will be switched off.
R14:  total power consumption < available power
       & t<6 & t<22 &  available power-actual power >500 →
              turn on music
        available power-power >1200  →
              turn on AC;
```

Entertainment appliances like music and AC are turned on depending upon the remaining power and the actual time to enhance the comfort level of the inhabitant.

(For simplicity reasons, we did not write rules to check the time constants of appliances each time.)

Performance with Policy

Figure 10 demonstrates the fact that the rules in the house agent make sure that the total power does not exceed the available power and at the same time they try to satisfy the inhabitant by postponing the operation of grade 3 appliances later in the day. By repeating the simulation several times, we realized that our policy-based framework works well in other scenarios as well.

Figure 11 shows the status of appliances before and after the rules were applied. Since the power goes above the available power level, the on-time of the

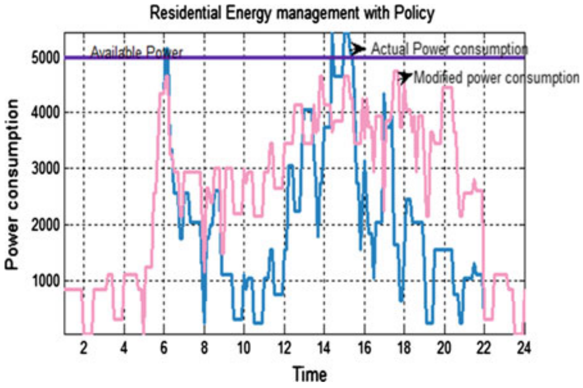
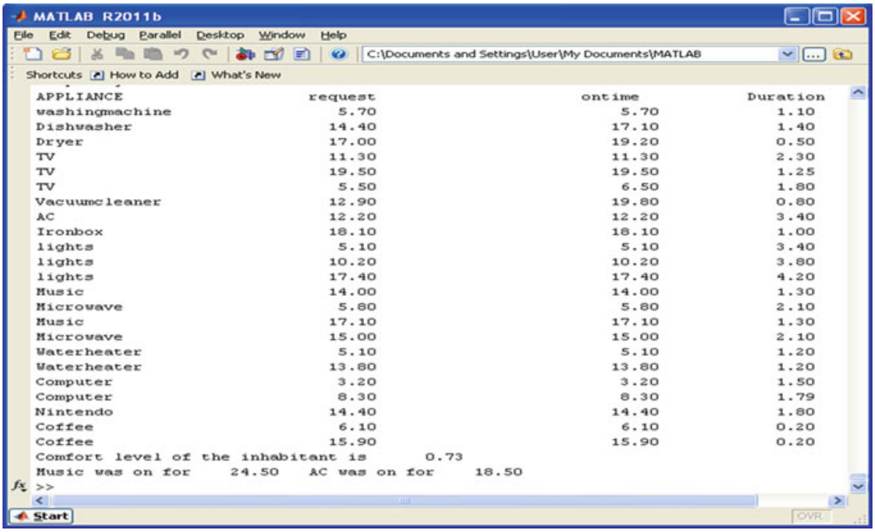


Fig. 10 Residential energy management with policy



```
APPLIANCE                    request                      ontime          Duration
washingmachine                  5.70                        5.70              1.10
Dishwasher                     14.40                       17.10              1.40
Dryer                          17.00                       19.20              0.50
TV                             11.30                       11.30              2.30
TV                             19.50                       19.50              1.25
TV                              5.50                        6.50              1.80
Vacuumcleaner                  12.90                       19.80              0.80
AC                             12.20                       12.20              3.40
Ironbox                        18.10                       18.10              1.00
lights                          5.10                        5.10              3.40
lights                         10.20                       10.20              3.80
lights                         17.40                       17.40              4.20
Music                          14.00                       14.00              1.30
Microwave                       5.80                        5.80              2.10
Music                          17.10                       17.10              1.30
Microwave                      15.00                       15.00              2.10
Waterheater                     5.10                        5.10              1.20
Waterheater                    13.80                       13.80              1.20
Computer                        3.20                        3.20              1.50
Computer                        8.30                        8.30              1.79
Nintendo                       14.40                       14.40              1.80
Coffee                          6.10                        6.10              0.20
Coffee                         15.90                       15.90              0.20
Comfort level of the inhabitant is      0.73
Music was on for     24.50    AC was on for     18.50
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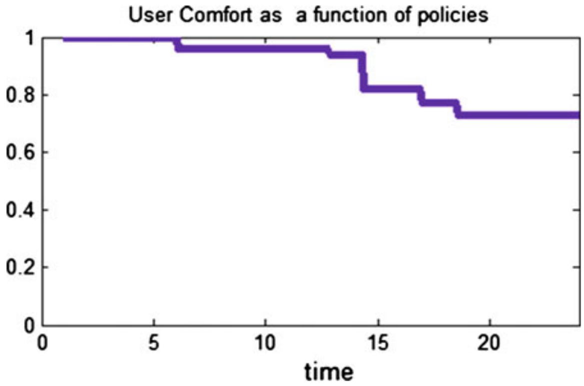
Fig. 11 Status of appliances (on-time request and actual on-time)

Fig. 12 User comfort model



dishwasher is postponed to 17:10 h. Further, TV was postponed from 5:50 to 6:50 h and the on-time of the dryer is postponed from 17:00 to 19:20 h.

User’s Satisfaction Model

To estimate the customer’s satisfaction, we assume that the actual power consumption behavior “b” of the customer as, for example, shown in Fig. 4 above is a reasonable model of his satisfaction behavior over time. Any deviation from this behavior is interpreted as a measure of dissatisfaction. When a policy is used to manage the power consumption behavior, deviations are measured and plotted as shown in Fig. 12. When the deviation exceeds a threshold, say 0.5, the user may require a change in the policy. Figure 12 illustrates that inhabitant’s comfort level is 0.72 which is acceptable.

Conclusion

In this paper, we have proposed a policy-based smart home energy management approach to monitor and control the state of appliances to consume only the available power and manage energy efficiently throughout the day. Simulation results demonstrate that policy-based smart home can perform peak shave effectively taking electrical characteristics of appliances into account. Since peak energy demand is minimized in this approach, there is no need to operate additional power plants and therefore carbon emission can be significantly reduced. In our future work, we plan to extend our approach to a community of agents where agents cooperatively perform energy management.

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