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Energy-on-Demand System Based on Combinatorial Optimization of Appliance Power Consumptions

Naoyuki Morimoto[1,a)]

Abstract: In this paper, the author proposes an Energy-on-Demand (EoD) system based on *combinatorial optimization* of appliance power consumptions, and describes its implementation and evaluation. Recently, efficient usage of limited amount of electrical energy has been an important issue. EoD is a novel power network architecture of demand-side power management, whose objective is to intelligently manage power flows among power generations under the limitation of available power resource. In an EoD system, the importance of each appliance is explicitly parameterized, and the amount of power consumption of appliances is measured by power sensors. When total power consumption exceeds the limit of power resource, a power allocation manager deployed in the system decides the optimal power allocation to all the appliances based on their parameters, and controls the amount of power supplied to the appliances in a way that causes minimum undesired effect to quality-of-life (QoL) of users. Therefore, one of the most crucial factors in an EoD system is the strategy for deciding the optimal power allocation. From a mathematical viewpoint, the power allocation management in an EoD system can be considered as an optimization problem of appliance operation modes. In the developed system, power allocation is based on the *multiple-choice knapsack problem* (MCKP), a kind of combinatorial optimization problem. The system measures power consumption of appliances, computes the optimal power allocation based on an algorithm for the MCKP, and realizes computed power allocation by controlling IR-controllable appliances and mechanical relays. Through experiments, the developed system is confirmed to work properly as an EoD system by observing system behaviors when the total power consumption exceeds the upper limit of the available power resource.

Keywords: Energy-on-Demand, Power Allocation Management, Multiple-Choice Knapsack Problem.

1. Introduction

In recent years, efficient usage of limited amount of electrical energy has been an important issue. For example, in the so-called "demand-response" system, consumers are requested to save electricity usage to balance the amount of power demand and supply for improving power network stability. Thus it is crucial to utilize the limited amount of available power in an efficient manner. Various approaches have been taken to support consumers to do their power-saving activities. Typically, the "energy usage visualization" system, which collects power consumption data of appliances in a home and visualizes them to consumers in some graphical ways, has certain helpful effect for consumers [1]. On the other hand, even if visualized data are presented, actual power-saving activities still require manual operations by users, which makes it not always easy to keep the activity in daily life. Though decision-making on controlling the amount of power to appliances is crucial to power-saving in user's daily life [2], [3], it is not always properly done by ordinary users since their awareness on the amount of power consumption of appliances or their electricity bills is not necessarily high [4], [5]. If users do not have sufficient knowledge on the amount of power consumption of appliances they use, there is no guarantee to achieve their power-saving goals.

1 Kyoto University, Yoshida Ushinomiya, Sakyo, Kyoto 606-8302, Japan
a) nmorimoto@icems.kyoto-u.ac.jp

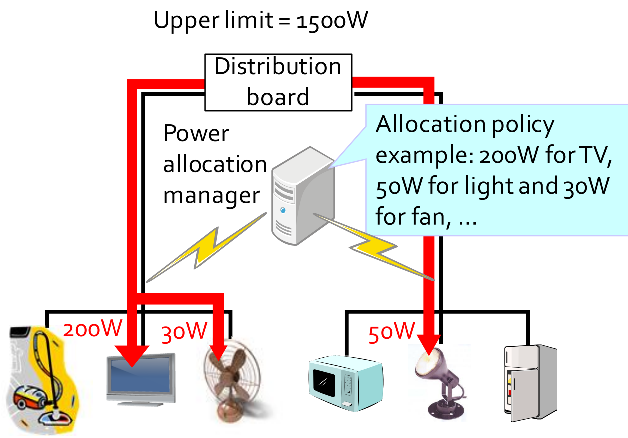

Fig. 1 Optimizing power allocation to appliances.

Energy-on-Demand (EoD) [6] is a recently-proposed novel power network architecture of demand-side power management, whose objective is to intelligently manage power flows among power generations under the limitation of the amount of available power resource. In an EoD system, the importance of each appliance is explicitly parameterized, and the amount of power consumption of appliances is measured by power sensors; then, if total amount of power consumption exceeds the limitation of power resource, a *power allocation manager* deployed in a home makes a decision on power allocation for appliances based on the parameters, capacity of the power source and various factors such as users lifestyles etc., and controls the amount of power supplied to the appliances in a way that minimizes undesired effect on quality-of-life (QoL) of users. Therefore, one of the most crucial factors in an EoD system is the strategy for deciding the optimal power allocation to appliances [7]. For optimizing power allocation, the power management system optimizes power allocation (e.g. up to 200W for a TV, 30W for a fan) considering user's QoL, and when total power consumption exceeds a threshold value the system automatically controls power allocation based on control policies suited for users, assuming situations that total usable power is limited in demand-response scheme or for reducing peak load. Fig. 1 shows the concept of optimal power allocation.

From a mathematical viewpoint, the power allocation management in an EoD system can be considered as an optimization problem; the problem where the goal is to choose the power allocation to appliances optimized for users from various possible combinations of appliance statuses, keeping total consumed power under the limitation. In real environments, many appliances have various operational modes in addition to simple on/off states, and it is not easy to find the most optimized combination of operation modes from many possible candidates. Also, the problem cannot be easily solved by linear programming methods since the importance of an appliance for users is not in proportion to the amount of power consumption, and since the amount of power consumption of many appliances varies in a step-wise manner with the change of operation modes. Moreover, for realizing the decided power allocation, the system should be able to flexibly and properly change operational modes of appliances, since most appliances do not work properly if the system simply reduces the amount of power supplied to them.

In this research work, we propose power allocation management is considered as *combinatorial optimization* of appliance power consumptions as an alternative approach than the priority-based ones, and discuss the design, implementation and evaluation of an EoD system based on the combinatorial optimization. Power allocation schemes in existing EoD systems are priority-based, not based on the combinatorial optimization, where *priority* parameter is associated with each appliance, and the power allocation manager reduces the amount of power allocated to the appliance with lowest priority among the appliances [6], [8], [9], [10]. We formulate the power allocation as the *multiple-choice knapsack problem* (MCKP) [11], a kind of combinatorial optimization problem. The MCKP is an extended version of the simple knapsack problem; in the MCKP, *class* (an appliance) is a set of *items* (operation modes). Each item has parameters of *size* (power consumption) and *profit* (the importance to user's life). A *knapsack* corresponds to a power source, and its *capacity* is the limit of available power resource. The objective of the problem is to find the optimal set of items packed into the knapsack that maximizes total obtained profit. Here exactly one item should be chosen from a class and should be packed into the knapsack in a way that the total size of packed items does not exceed capacity of the knapsack. The system is implemented utilizing a smart outlet network, where the power consumption of all the appliances is frequently (every one second) measured by power sensors. When the total amount of consumed power exceeds the upper limit, the power allocation manager deployed in the system computes the new optimal allocation using an algorithm for the MCKP, and sends control messages to appliances. To control ordinary IR-controllable appliances with various operation modes other than simple on/off states, we have adopted a programmable IR control unit controllable from the manager via Wi-Fi, which enables the system to flexibly control the operation modes of IR-controllable appliances by sending pre-recorded IR signal patterns. Through experiments, the developed system is confirmed to work properly as an EoD system by observing system behaviors when the total power consumption exceeds the upper limit of the available power resource.

This paper is consisted as follows; Section 2 refers related work. Section 3 presents a basic concept of Energy-on-Demand and formulation of power allocation as a combinatorial optimization problem. In Section 4, we discuss our implementation of the developed power allocation system. Section 5 describes experiments and considerations. Section 6 concludes this paper.

2. Related Work

As described in the previous section, power allocation schemes in existing EoD systems are priority-based, not based on the combinatorial optimization, where *priority* parameter is associated with each appliance, and the power allocation manager reduces the amount of power allocated to the appliance with lowest priority among the appliances [6], [8], [9], [10]. The major difference between the combinatorial optimization based approach and the priority-based approach lays in their power reduction schemes, especially when the total amount of power consumption exceeds an upper limit; a basic scheme of the priority-based algorithms is to repeatedly reduce the amount of supplied power for an appliance with lowest priority until total power consumption becomes less than the limit. The beneficial aspect of the combinatorial optimization based algorithm is that the power allocation can be done based on specific measures by setting an appropriate objective function, and the decision of the optimal modes of multiple appliances is completed by a single calculation. On the other hand, in the priority-based approach, configuring parameters might be relatively simple since only one appliance is controlled in a single operation. In general schemes of power management in Automated Demand Response or Home Energy Management System, priority-based methods are commonly used [12]. There have been other research work where optimization problems are considered in diverse formulation, and various simulational and theoretical studies have been conducted [13].

There have been noteworthy studies on optimizing power consumption in homes by quantifying the relationship between the importance of an appliance and the amount of power consumption. Sianaki et al. formulated the optimal power allocation as the knapsack problem (in a different approach compared to our formulation), proposed a method for parameterizing the importance of each appliance by applying the analytic hierarchy process, and presented results obtained by numerical simulations [14]. Kempton and Montgomery proposed a "folk quantification" method [15] to quantify the importance of appliance use in homes. Kumaraguruparan et al. formulated a scheduling problem based on

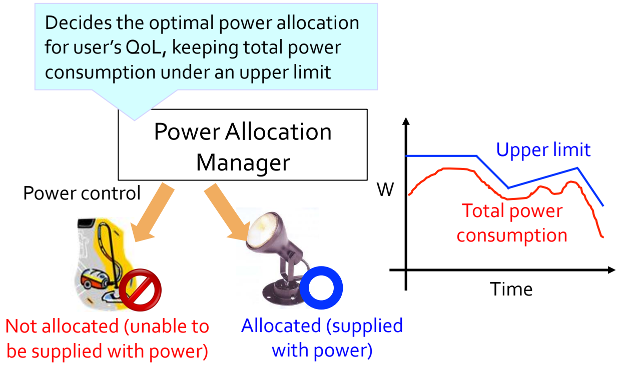

Fig. 2 Energy-on-Demand concept.

the multiple knapsack problem, in which daily power-consuming tasks are allocated to time slots with different electricity bills to minimize total electricity bills, and made a simulation-based evaluation [16].

3. Concept and Formulation

This section describes the EoD concept and problem formulation of power allocation in EoD.

3.1 EoD Concept

In a conventional power network in homes, power consuming devices (appliances) can be supplied with power if only they are connected to power sockets and are turned on. Therefore, to achieve power-saving goals, users are required to have sufficient knowledge on how much power is consumed by each appliance, and should take careful and manual work to save electricity. Energy-on-Demand (EoD) [17] is a novel power network architecture for automated power-saving with minimum undesired effect to users' QoL, targeting ordinary homes and offices as well as plants or buildings. In an EoD system, the importance of each appliance is explicitly parameterized, which corresponds to the strength of "power demand" from each appliance, and the amount of power consumption of appliances are measured by power sensors; then, if the total amount of power consumption exceeds the limitation of power resource, a *power allocation manager* deployed in the system makes a decision on power allocation for appliances based on the parameters, the amount of power consumption, varying capacity of the power source and various factors such as users lifestyles etc., and controls the amount of power supplied to the appliances in a way that causes minimum undesired effect to QoL of users and total power consumption does not exceed the limit. Fig. 2 presents an overview of an EoD concept. In this example, there are two power-requiring appliances (cleaner and light). The power allocation manager decides the power allocation optimized to users life, based on parameters (power consumption, profit, upper limit of available power), and controls the amount of power supplied to the appliances (in this example, the light is supplied with power, while the cleaner is not).

3.2 Formulation as a Combinatorial Optimization Problem

Setting an objective function is a crucial factor in the formulation of an optimization problem, and there are many reasonable candidates of the objective function in modeling power allocation in an EoD system. In this research work, we set the objective function as maximization of user's benefit, which is gained by use of appliances with various operation modes; Fig. 3 shows an example situation where each appliance has its operational modes such as "high", "mid" or "low", associated with parameters of *profit* and *power consumption*. The task of the power allocation manager is to decide the optimal combination of the operational modes of the appliances, which maximizes total profit gained by selected modes.

In the simple knapsack problem, we are given a knapsack with capacity and set of items with profit and size, and our objective is to find a subset of items that maximizes total profit of items and total size does not exceed the capacity of the knapsack. The multiple-choice knapsack problem (MCKP) [11] is a natural extension of the knapsack problem; the items are classified into *class*, and the constraint is added that exactly one item must be packed into the knapsack from each class. The objective is the same as the simple knapsack problem.

Here we define some mathematical symbols for problem formulation; the number of classes (appliances) is denoted by m, and a class i ($1 \leq i \leq m$) is a set consisted of n_i items (operational modes) j ($1 \leq j \leq n_i$). For each item j, profit (importance for its user) p_{ij} and size (power consumption) w_{ij} are associated. A knapsack (a power source) has capacity (upper limit of total power usage) c. Exactly one item must be packed into the knapsack, which means that an appliance cannot work with multiple modes at the same time (here operational modes contain the "off" status). A decision variable $x_{ij} \in \{0, 1\}$ means whether item j is chosen from class i; namely, if $x_{ij} = 1$, appliance i works with operational mode j, and $x_{ij} = 0$ means i works with some other mode than j.

The formulation of the MCKP is presented below (here $N_i$is a set of items in class i). The first constraint means that the total size of packed items should not exceed capacity of the knapsack. The second and third constraints mean that exactly one item should be chosen from each class and packed into the knapsack.

$$\max \sum_{i=1}^{m} \sum_{j \in N_i} p_{ij} x_{ij} \tag{1}$$

$$\text{subject to} \sum_{i=1}^{m} \sum_{j \in N_i} w_{ij} x_{ij} \leq c, \tag{2}$$

$$\sum_{j \in N_i} x_{ij} = 1, \; i = 1, ..., m, \tag{3}$$

$$x_{ij} \in \{0, 1\}, \; i = 1, ..., m, \; j \in N_i. \tag{4}$$

4. System Design and Implementation

The design of the system is an extension of the former prototype system [18], which was based on an algorithm for the simple knapsack problem and was capable of on/off control utilizing smart outlets, which are the power strips with functions of power measurement, communications and power control with mechanical relays. Fig. 4 presents the overview of the developed system, which we assume is suitable for ordinary homes. The system ar-

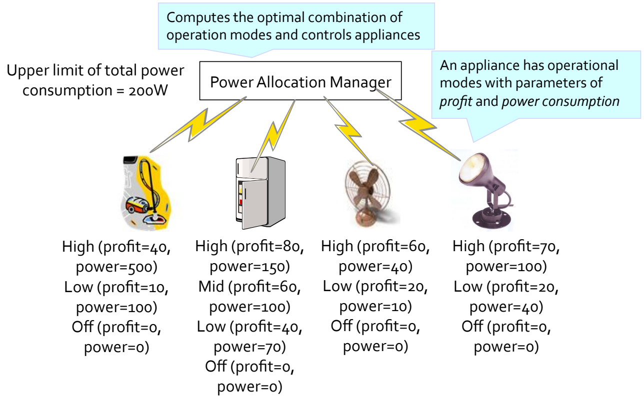

Fig. 3 Combinatorial optimization of appliance operation modes in an EoD system.

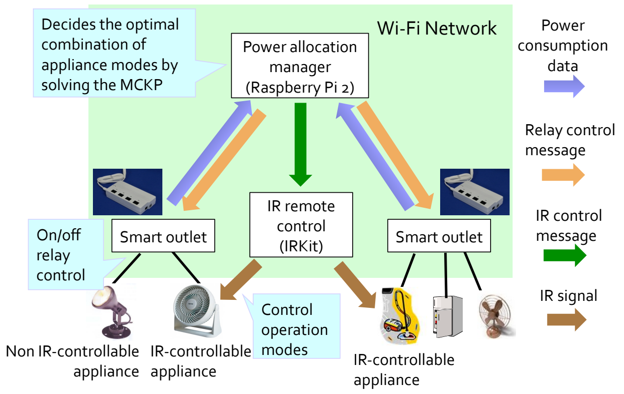

Fig. 4 System overview.

chitecture is designed in a centralized manner, where the power allocation manager takes all the crucial decisions. The manager stores data of possible operational modes of each appliance, values of parameters (profit and size) of each mode, control methods available for each appliance (IR-controllable or relay-only). The manager also collects real-time data of power consumption of each appliance (every one second), and when the total amount exceeds the upper limit it calculates optimal power allocation utilizing a dynamic-programming algorithm for the MCKP. Finally, the manager sends control messages to realize calculated power allocation; if the appliance to be controlled is IR-controllable, the manager first sends the corresponding control message to the Wi-Fi capable IR remote control, then the control sends IR signals to the appliance. Otherwise i.e. the appliance is not IR-controllable hence no direct mode control method is available, the manager sends a control message to the smart outlet to which the appliance is connected, and the outlet turns on or off the corresponding socket. Table 1 shows the list of data stored and maintained by the manager.

4.1 Design and Implementation of Hardware and Software

4.1.1 Power Allocation manager

In hardware aspects, the system consists of the power allocation manager, the smart outlets and the IR remote control, all of which are deployed in an IEEE802.11n Wi-Fi network. We assumed that, in realistic environments, the power allocation manager is not expected to have rich computational resources compared with personal computers such as laptop/desktop PCs, and it likely has similar specifications as embedded computers such as home controllers. Therefore, we adopted Raspberry Pi 2 model B [*1], a microcomputer with sufficient specifications and programmability, as the hardware of the power allocation manager. Table 2 shows its specifications.

Table 1 Data stored and maintained by the manager

Items	Remarks
Appliance IDs	Name of appliances
Operational modes	Possible operational modes
Available control methods	IR-controllable or relay-only
IR control messages	For IR-controllable appliances
Relay control messages	For relay-only appliances
Parameters of each operation mode	Profit and power consumption
Current power consumption	Measured by smart outlets
Capacity of the power source	Current upper limit
Current modes of appliances	For proper control of the system

Table 2 Specifications of the power allocation manager.

Items	Specs
CPU	ARM Cortex-A7 900MHz Quad-Core
RAM	1GB
Communication media	IEEE802.11n Wi-Fi
Interface	USB 2.0
OS	Raspbian (Debian-based Linux)

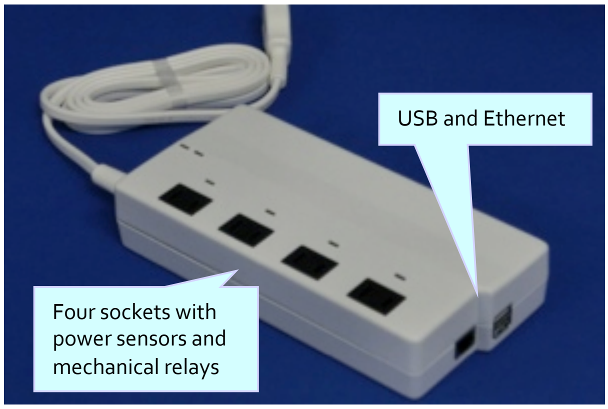

Fig. 5 An outward appearance of the smart outlet.

4.1.2 Smart Outlet

The smart outlet used on the developed system is the extended version of the one formerly developed [19]; we have improved the outlet to be more compact and practically designed, and have extended computational resources. Fig. 5 is an outward appearance of the smart outlet, and Table 3 shows its specifications. It has four sockets, and has functions of power sensing (voltage, current and power) and controlling relays for each socket. The Raspberry Pi Model B is used as the application board; an ARM-based microcomputer with CPU (ARM1176JZF-S 700MHz) and RAM (256MB or 512MB), enabling implementation of various software and control policies on the outlet. It has a built-in Ethernet interface and a Wi-Fi interface installed via USB. It communicates power consumption data and control messages via Wi-Fi and TCP/IP communications with outer devices such as a controller, a server or other smart outlets. Rated voltage and current is 100V and 15A, respectively. A/D conversion of measured amount of power is done with 20kHz sampling frequency and 12bit resolution.

[*1] `http://www.raspberrypi.org`

Table 3 Specifications of the smart outlet.

Items	Specs
Measurement	Instantaneous power, integrated power, current and voltage
Sampling frequency	20kHz
Resolution	12bit
Error	Under 2%
Power control	On-off control for each socket
Number of sockets	Four
Rated voltage	AC 100V
Rated current	15A (in total of all the four sockets)
CPU	ARM1176JZF-S 700MHz
RAM	512MB
Storage	8GB
Communication media	IEEE802.11n Wi-Fi and Ethernet
Interface	USB 2.0
OS	Raspbian (Debian-based Linux)

We adopted IRKit [*2] to control IR-controllable appliances from the power allocation manager, which is a Wi-Fi-capable IR remote control. We can record IR signals of ordinary appliances using a receiver equipped in the IRKit and though its HTTP-based API, and the recorded signal data is able to be stored in the allocation manager. When the manager takes control of an IR-controllable appliance as a result of calculation, the manager first sends a text-based control message to the IRKit via Wi-Fi, then the IRKit transforms the message into IR signals and sends it to the appliance, realizing the decision made by the manager.

4.1.3 Software

The software in the system has been developed using the standard C language. Since there is no straightforward method to grasp current operation modes and statuses of ordinary appliances from outer devices, the system has to keep the current operation modes of appliances by tracking the variation of modes from the initial state. The manager also stores data of IR control messages for changing modes of IR-controllable appliances, relay-control messages for controlling non IR-controllable appliances, and values of (pre-measured) power consumption and profit parameters associated to each operation mode of appliances. The communication in the Wi-Fi network among the manager, smart outlets and the IR control is done via standard TCP/IP socket protocols.

4.2 Network

The Wi-Fi used in the network is IEEE 802.11n with maximum bandwidth of 300Mbps using 2.4GHz of frequency and is protected with WPA encryption for easier coordination with ordinary information devices such as PC, tablets or smartphones. As a transport layer protocol, we have chosen TCP for reliability, dependability and safety, because the system does control electricity actively, not only gathering data on power consumption.

4.3 Data Formats

Measured power consumption data and relay control messages are formatted in XML-like manners as follows, considering the extendibility, versatility and easier handling [19].

- Measured Power Consumption Data:
  The below is an example of `notice_wattmeter`, which is used for sending measured power consumption data (approximately 540 bytes). This example means that integrated power on socket #2 is 64Wh, instantaneous voltage is 100.585V, current is 0.831A, instantaneous effective power is 48.8W, and the relay at the socket has been turned on.


```
<root><info>
<kind>notice_wattmeter</kind>
<time>20160509213008175</time>
</info><data>
<socket1><wh>0</wh><volt>100.519</volt><
    current>0.002</current><watt>0.8</watt><
    state>OFF</state></socket1>
<socket2><wh>64</wh><volt>100.585</volt><
    current>0.831</current><watt>48.8</watt><
    state>ON</state></socket2>
<socket3><wh>4</wh><volt>100.561</volt><
    current>0.005</current><watt>2.0</watt><
    state>OFF</state></socket3>
<socket4><wh>57</wh><volt>100.568</volt><
    current>0.511</current><watt>33.7</watt><
    state>ON</state></socket4>
</data></root>
```


- Relay Control Message: The below is an example of `command_socket`, a message for controlling relays (approximately 250 bytes). In this example, relay #1 and #4 should be turned on and #2 and #3 should be off.


```
<root><info>
<kind>command_socket</kind>
</info><data>
<socket1><state>ON</state></socket1>
<socket2><state>OFF</state></socket2>
<socket3><state>OFF</state></socket3>
<socket4><state>ON</state></socket4>
</data></root>
```


4.4 Dynamic-programming Algorithm for MCKP

When all the classes have only one item, the MCKP corresponds to simple knapsack problem. Therefore the MCKP is NP-hard, since it includes the knapsack problem as a special case and the knapsack problem is NP-hard [20]. However, it has been shown that there is a dynamic-programming algorithm for the MCKP that obtains an optimal solution in pseudo-polynomial time [21]. Hereafter, we treat the power capacity and the amount of power consumption as integers (note that the smart outlet is able to measure the power consumptions to one decimal place and the algorithm is able to handle real numbers by increasing the number of digits, though there is trade-off between accuracy and computational time).

We have implemented the dynamic-programming algorithm in the system. Algorithm 1 presents its formal description. As defined before, the number of appliances is denoted by m, and the number of operation modes of appliance i is denoted by n_i. $P(i, d)$ denotes an optimal solution of the subproblem with classes of $1, ..., i$ $(1 \leq i \leq m)$ and a knapsack with capacity of d $(1 \leq d \leq c)$. Generally, a dynamic-programming algorithm is based on *principle of optimality*; the algorithm first obtains the optimal solution of an instance with smaller size, then constructs the optimal solution for a larger instance in a step-by-step manner. In the case

*2 `http://getirkit.com/en/`

of the MCKP, the dynamic-programming based algorithm first treats the instance with limited capacity and a subset of items. Then, by using solutions for smaller instances and the recursions $P_j(i,d) = P(i-1, d-w_{ij}) + p_{ij}$ or $P_j(i,d) = P(i-1,d)$, we can obtain the optimal solution of the instance with classes $1, ..., i$ and the knapsack with capacity d, based on the optimal solutions of the smaller instance with limited classes $1, ..., i-1$ and the knapsack with capacity smaller than d. Through the algorithm execution, the system records the set of selected appliance modes that achieves the optimal profit $P(i,d)$ for each subproblem so that it is able to control the modes in a way that realizes the final optimal solution.

Algorithm 1 Dynamic-programming Algorithm for the Multiple-Choice Knapsack Problem [21]

```
for d = 0 to c do
  P(0, d) = 0
end for
for d = 1 to c do
  for i = 1 to m do
    for j = 1 to n_i do
      if d ≥ w_ij then
        P_j(i, d) = P(i − 1, d − w_ij) + p_ij
      else
        P_j(i, d) = P(i − 1, d)
      end if
    end for
    P(i, d) = max_j{P_j(i, d) | j = 1, ..., n_i}
  end for
end for
```

5. Experiments and Considerations

This section descibes observations of the system behavior when the upper limit of an available power resource is periodically changed, shows required time for communication/calculation of power allocation/power control, and presents some considerations.

5.1 Experiments

For presenting the result clearly, here we describe behavior of the system with a small number of appliances. Fig. 6 presents an example configuration of the developed system, which includes an IR-controllable fan (with modes of "off", "low" and "high", an IR-controllable light (with modes of "off" and "on"), a laptop (not IR-controllable) and a battery charger (not IR-controllable). In this example configuration, the profit parameters of appliances are manually set based on user's preference. The power consumption parameters of the appliances are set as 50W for the laptop, 18W for the fan with "low mode" and 35W for "high" mode, 3W for the light and 5W for the battery charger, based on pre-measured power consumption of each appliance. The power allocation manager checks whether the total power consumption exceeds the limit every one second, and when exceeding the limit it calculates the new power allocation based on the pre-measured power consumption values.

We have observed how the developed system controls appli-

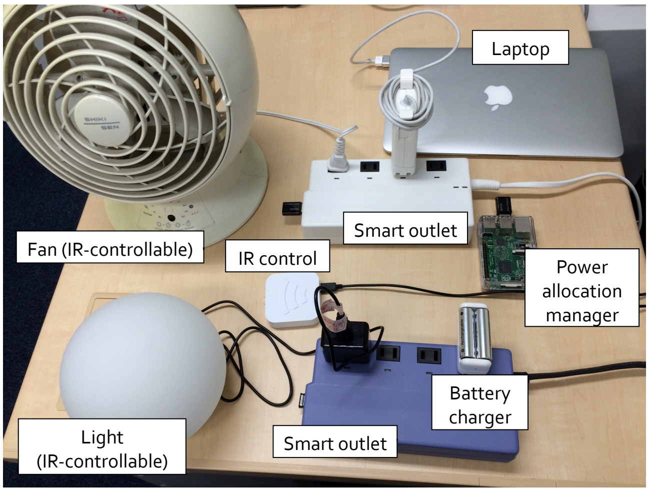

Fig. 6 Example configuration.

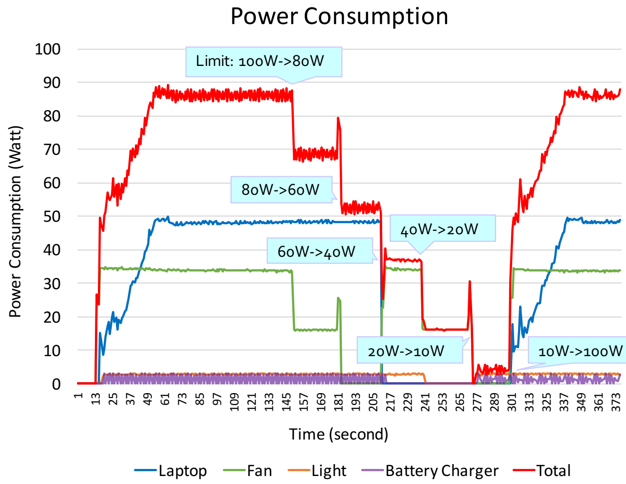

Fig. 7 Power consumption of each appliance and their summation.

ance operation modes by recalculating the optimal power allocation, with the upper limit being changed over time. Fig. 7 shows the variations of total power consumption and power consumption by each appliance over time, where the X axis represents time (second), and the Y axis represents power consumption (W). The experiment was conducted in the following scenario;

(1) From the zeroth second to around 150th seconds, the upper limit is set to be 100W; therefore, the fan works with its "high" mode and the other appliances are turned on with no limitation.

(2) The first power control taken by the system can be observed around 150th seconds when the upper limit is set as 80W. Since the total power consumption exceeds the limit, the power allocation manager computes the new optimal power allocation. As a result, the fan is set to be "low" mode by a control message sent by the manager, and total power consumption became less than the limit. Hereafter, the upper limit changes periodically (every 30 seconds).

(3) The second power control is observed around 180th seconds when the upper limit is set as 60W. A the result of the new optimal power allocation, the fan is turned off, while the allocation to other appliances are unchanged. Note that,

at around the 180th seconds, the power consumption of the fan temporarily increased and immediately dropped, because the manager should control it to be turned off via temporal "high" mode due to the specification of the fan.

(4) Next, we set a new upper limit of 40W around 210th seconds. The decision by the manager is that the laptop and the battery charger should be turned off since 40W of available power is not sufficient to supply power to them, instead the fan is controlled to be "high" mode.

(5) Similarly, when the limit is changed to 20W at the 240th seconds and 10W at the 270th seconds, the new power allocation is recalculated as optimized for each new setting.

(6) When the limit is recovered to 100W around 300th seconds, the power resource is sufficient and all the appliances are fully allocated with power, i.e. the fan works with "high" mode and all the other appliances are turned on.

These observations through the experiment indicate that the system works properly as an EoD system. By deploying the system in a real-life environment and changing the upper limit, we also have confirmed that the system is able to handle other ordinary appliances such as an IR-controllable air conditioner, a TV, audio systems, a coffee maker or a hair dryer, etc., some of which consume the larger amount of power than the appliances used in the example configuration.

We have measured time required to compute the optimal power allocation by using the algorithm for the MCKP. The calculation of the optimal allocation is completed less than one second on the power allocation manager (Raspberry Pi 2), when example instances have 24 appliances with five modes and the upper limit is set as 3000W (and less than 100 milliseconds when four appliances with three modes). Therefore, the time needed for the calculation is sufficiently short. In the experimental environment, to control an appliance required at most around six seconds when multiple IR signals should be sent to an IR-controlable fan. It is shown that relay control by the smart outlet can be done in averagely 29.3 milliseconds after receiving a relay control message, using Wi-Fi 802.11n as a communication media and the standard TCP/IP socket communication [18]. Hence, in a real-world environment, the implemented system is also expected to work as a circuit breaker and is beneficial for avoiding damage caused by overcurrent, overload or short circuit, though the main purpose of the system is optimizing power allocation.

5.2 Considerations

In the experiments, sending IR-control messages requires marginal time, since IR-controllable appliances sometimes failed to receive the control signals if they are sent fast and continuously. Also, since the calculation of power allocation is done using pre-measured power consumption of each appliance, sometimes there appears some unintentional deference between assumed power consumption and actual power consumption, which causes inefficiency in utilizing available power resources. In addition to that, as long as the power allocation and control is done in periodically, it should be inevitable that sometimes total power consumption temporally exceeds the upper limit, which is a common issue in EoD systems [6]. Frequency of data collection and power control should be optimized for real-life situations, considering various factors such as the variation of appliances' power consumption, trade-off between control precision and computational load, etc.

Some of the limitations of the developed system depend on functional restrictions of today's ordinary appliances; there is no straightforward method to grasp their current operation modes or internal statuses from outer devices such as the power allocation manager. Therefore, the system should properly manage statuses of all the appliances, which is not always possible in a real-life environment since the appliance operation modes can be manually changed by users and it is not easy for the system to precisely detect or handle manual mode changes. After the system fails to detect the manual operation, the control by the system does not work properly since the actual modes differ from the modes assumed in the system.

Though the estimation methods for recognizing operation modes of appliances from power consumption [22] should be useful, the complete solution for these technical problems can be achieved only by utilizing so-called smart appliances, which are capable of communicating the internal statuses with other devices based on communication standards for smart appliances such as ZigBee Smart Energy Profile [*3] , Apple HomeKit [*4] or ECHONET Lite [*5]. Therefore, we are considering to extend the developed system being capable of handling these protocols, and conduct real-life experiments. In this context, the noteworthy feature of USB Power Delivery (USB PD) [*6] is its smart power supplying scheme; a USB PD ready power consuming device communicates with the power source, negotiates about the amount of power it is allowed to consume, and is able to adapt its mode best suited for available power amount. For developing a more sophisticated and flexible EoD system, it is strongly desired that the appliances have similar smart functions.

6. Conclusion and Future Work

In this paper, we have considered the power allocation management in an EoD system as a combinatorial optimization of appliance power consumptions, and have discussed the design and implementation of an EoD system using the dynamic-programming algorithm for the multiple-choice knapsack problem. The system finds the optimal combination of appliance operation modes under the limitation of available amount of power, and controls the amount of power supplied to appliances using the IR control and mechanical relays in smart outlets. Time required for calculating the optimal allocation is sufficiently short when we consider instances with realistic size (24 appliances with five modes, upper limit set as 3000W). We have confirmed that the developed system works properly as an EoD system by observing system behaviors when the total power consumption exceeds the upper limit of the available power resource.

In the developed system we focused on keeping restrictions on instantaneous power, however there are other reasonable factors to be considered as well; for example, assuming the Time-

[*3] http://www.zigbee.org/
[*4] http://www.apple.com/ios/homekit/
[*5] http://www.echonet.gr.jp/english/index.htm
[*6] http://www.usb.org/developers/powerdelivery/

of-Use pricing in demand response systems, it is reasonable to control power consumption to minimize the electricity cost, not only considering restrictions of instantaneous power. Since the combinatorial-based approach we have taken can be extended to other objective functions (the total energy consumption, electricity cost, CO_2 emission, etc.), we are planning to additionally implement a scheduling scheme in the developed system, where the parameter setting is based on real-life power consumption data and patterns measured over one year [19]. In developing scheduling strategies, it should be of importance and interesting to consider uncertain factors such as price uncertainty [23].

Another future research direction is to make experimental comparisons of two power allocation approaches (the combinatorial optimization based approach and the priority-based approach) in real-life environments, since they have different characteristics; the combinatorial optimization based algorithm decides all the operation modes in a single calculation, while the priority-based algorithm repeats to select an appliance based on its priority parameter and reduce the amount of supplied power for it until total power consumption decreases to be less than the upper limit.

One of the important future work topics for applying the developed system in real-life situations is to pursue a method to decide the profit parameters of appliances. The methods for systematically parameterize the importance of appliances are the common challenging problem in EoD systems (e.g. [24]). The profit parameters of appliance modes should dynamically change over time, depending on various factors such as temperature value. We are considering to apply the methods for quantifying user's preference such as analytic hierarchy process [14] or folk quantification [15], based on patterns of user's behavior and power consumption data in a real-life environment, which can be grasped by the smart outlet network for energy-aware services utilizing various sensor information (motion, temperature, humidity, etc.) [19]. We expect the developed system works as a test-bed for real-life application of the other optimization methods which have been studied in theoretical or simulational manners. Also we are considering to pursue more sophisticated system with a smart rule-based scheme which realizes EoD by determining the power requests from policies and the appliances specification [9], since the computational resource of the smart outlet and the power allocation manager is sufficient for the rule-based power management system [19].

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