國立交通大學

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碩 士 論 文

基於遍佈式電表之智慧型電力排程系統

iPM: An Intelligent Power Scheduling System Based on Pervasive Meters

研 究 生：廖家良

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基 於 遍 佈 式 電 表 之 智 慧 型 電 力 排 程 系 統

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摘　　　要

電力的發現是人類史上非常重要的里程碑，它不但推動了後續許多的發明，更豐富了我們的生活，直到今日，我們的生活沒有一天不能不使用到電力。然而，我們常常可以發現每到夏季時，各發電場所輸出的電力往往達到負荷的極限，因此，如何有效率的用電是個十分重要的議題。而對於每位使用者來說，最在意的是如何有效的運用電力，以節省每月用電的開銷，而不同時段的電價，其實並不相同，用電尖峰時段的價格較高，而離峰時段，如深夜，其每度電價較低，故本論文提出一套系統，能將使用者較不急迫使用的電器，排程於電價較低時時段再予以啟動，不僅可有效的節省使用者之用電花費，並可分散電廠尖峰時段的負荷，以達到雙贏的局面。

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Degree Program of Computer Science

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ABSTRACT

Discovery of electricity is an important mile stone of human history. It not only contributes to other investigate and also enriches our life. We can’t live without electricity in our daily life. However, we found that electric companies usually exceed their limit of electric output in summer. Therefore, how to use electricity efficiently is an important subject. For users, what they concern the most is how to use electricity effectively to save electric cost. In fact, the cost of electricity varies in different time. The cost of electric in peak time is higher than Non-peak Time. In this work, we have proposed a system (iPM) which could schedule electric appliance which is not urgent to other time which has lower electric cost. It can not only saves the electric cost for users and also differentiates the loading of electricity company in peak time to get a win-win solution.

誌　　謝

首先，我要由衷的感謝曾煜其棋教授兩年多對我細心的指導以及鼓勵，並給予明確的研究方向。曾老師對於研究的熱情及專注，豎立了學術研究領域中的標竿，並帶給我們對於未來有所新的領悟。曾老師所帶領的實驗室也提供良好的研究環境，和各項所需的開發設備，讓我能充分的獲得硬體環境的支援，以便順利的完成此篇論文研究並且取得碩士學位。

接著我要感謝實驗室組內大博班葉倫武學長，以專業的指導，讓我才有辦法完整建構出此論文作品，研究過程中，組內成員政寬、淑琼、育萱、哲彥、志偉、虹穎都給予許多的幫助及鼓勵，在此感謝 HSCC 實驗室的成員。在這期間有許多美好的回憶及交到許多非常要好的朋友，是研究生兩年生活最大的收穫。

最後感謝家人及朋友，給我支持及動力，好讓我完成這人生的另一個階段，謝謝大家。

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Chapter 1

Introduction

As the standard of living and technological advancements, the electricity consumption of people increases year by year, as shown in Fig. 1.1 [5]. The growing consumption of electricity has put pressure on the power plants to operate at their capacity limit, and thus the consumers would get an expensive electricity bill. In order to prune electricity consumption and lower electricity bill, the smart grid was proposed. The smart grid provides intelligent features for electricity producers and consumers to communicate with one another so as to adjust electricity load. Therefore, one important benefit of a smart grid application is time-based pricing because customers can set their threshold and adjust their usage to take advantage of fluctuating prices. This would depend on the energy management mechanism to control electric appliances and equipment and thus customers could reduce their electricity consumption and save money.

The ZigBee Smart Energy Profile provides the smart grid mechanism for companies and home owners to create a more energy efficient home environment. ZigBee-enabled meters deployed in a home are used to communicate and control ZigBee enabled devices, such as the heating, cooling and air conditioning systems, to enable energy utility programs, including demand response, load control, time of use pricing, etc.. These programs not only reduce the peak load on the utility grid, but help the home users make smart decisions about their energy usage.

In this paper, we propose an intelligent power scheduling system (iPM) based on pervasive meters. Fig. 1.2 shows our system architecture. Each electric appliance connects to a wireless power meter. Through these wireless meters, the current power consumption of electric appliances can be transmitted to the control server. In accordance with the execution characteristics of electric appliances, they can be classified into four types: UC (uncontrollable) type, UM (unmovable) type, MN (movable and non-divisible) type, and MD (movable and divisible) type. Our goal is to dynamically schedule the execution time of each electric appliance in a home to

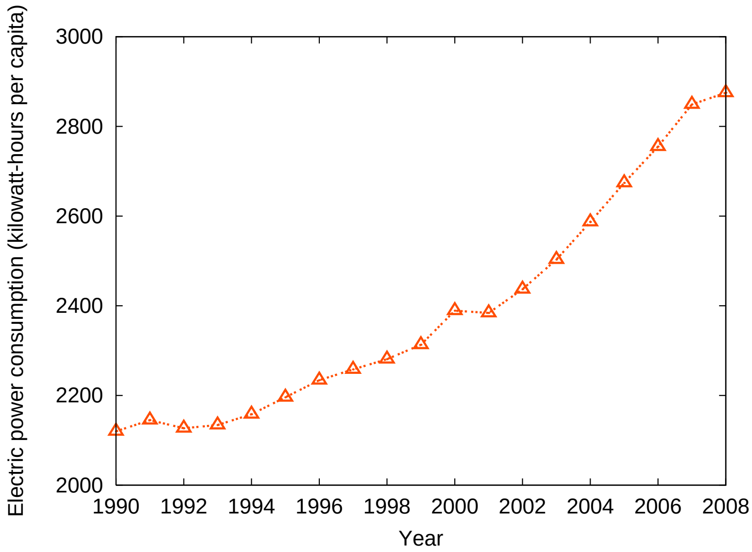


Figure 1.1: Worldwide electricity consumption from World Bank.

minimize the total monetary cost. Still, it poses several challenges: 1) user demand response, 2) load management, and 3) minimizing the monetary cost of electricity consumption.

Hence, we propose a power scheduling algorithm for smart usage of electric appliances in a home dynamically. We verify our results through simulations as well as a real prototype. Specifically, we develop a power scheduling system based on the ZigBee Smart Energy Profile to monitor and schedule the usage of electric appliances. We adopt Jennic JN5148 [4] as our wireless transmission module and adopt FTDI FT232RL [3] to translate UART interface to USB interface from JN5148. So, the control server can get data form electric appliances or send commands to electric appliances via USB interface. A graphical user interface is also implemented to show our functional block of monitoring and scheduling of four electric appliances.

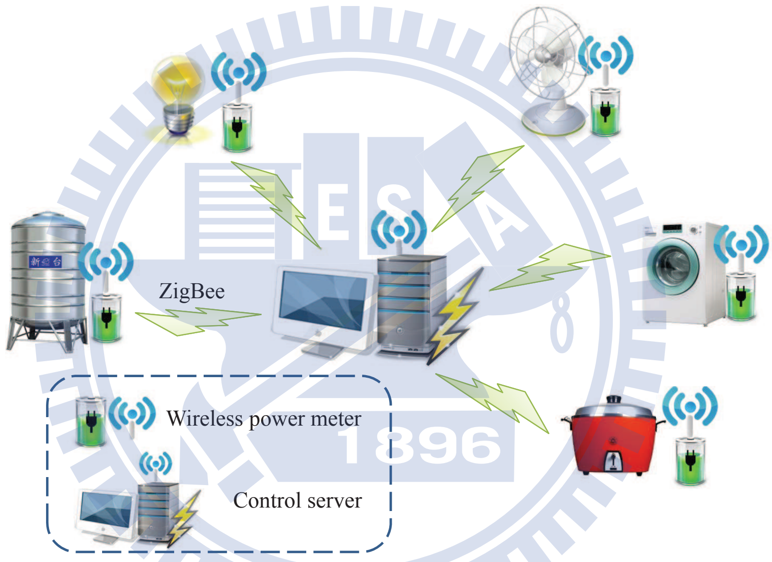


Figure 1.2: The system architecture of iPM system.

Chapter 2

Related Works

The next generation smart grid technology [14][11] will allow customers to make smart decisions about their energy consumption, adjusting both the timing and quantity of their electricity usage.

Electricity demand is the amount of electricity being consumed at any given time. In accordance with people's preferences, there can be considerable variations in electric consumption pattern with time of day, day of week and season of the year. Therefore, energy demand management [7][16], also known as demand side management (DSM), was proposed to encourage consumers to move the time of energy use to off-pick times such as nighttime and weekends instead of peak hours. It offers the promise of cutting costs for commercial customers, saving money for households, and helping utilities operate more efficiently, in turn reducing emissions of greenhouse gases.

Many utilities have load management programs to directly control residential appliances in their service area. Although these programs may be developed for different objectives, two common objectives are the minimization of peak load and production cost [9].

For example, [18] and [17] are two applications to monitor a campus grid using a network of meters. A RFID-based power meter and outage recording system is proposed in [8]. In addition, there are some power monitoring systems for smart home user [12][15].

Systems tied with dynamic pricing [10][19] is implemented to carry out the policy of saving energy and lowering customers'electric bill.

Extracted the essence from previous work, we have developed an intelligent power scheduling system through taking advantage of fluctuating prices to minimize the peak load and electric bill at the same time.

2.1 ZigBee and Smart Energy Profile

ZigBee [6] is a specification for short range wireless communication and targeted at radio-frequency (RF) applications that require a low data rate, long battery life, and secure networking, such as wireless light switches with lamps, remote controller, and several smart home applications. The link and MAC layers of ZigBee are based on the IEEE 802.15.4 standard [13] and the network and application layers are introduced by ZigBee Alliance. Through the ZigBee standard, different manufacturers can design many kinds of wireless network devices to operate together in the same network. Besides, ZigBee Alliance publishes application profiles that allow multiple OEM vendors to create interoperable products, such as Home Automation, Remote Control, Health Care, Telecommunication Services, Smart Energy, etc.

The ZigBee Smart Energy Profile provides the necessary features for companies and home owners to create a more energy efficient home environment, such as advanced metering, demand response, load control, pricing, and customer messaging programs. ZigBee-enabled meters can communicate and control ZigBee enabled devices in the home, such as the heating, cooling and air conditioning systems to enable utility company programs, such as demand response, load control and time of use pricing. These programs not only reduce the peak load on the utility grid, but also help the home owners make smart decisions about their energy usage.

Chapter 3

Design of An Intelligent Power Scheduling System

3.1 System Model

In our system, each electric appliance connects to a wireless power meter. Through the power meter, the current power consumption of electric appliances can be transmitted to the control server. According to their execution characteristic, the electric appliances can be divided into four types: UC (uncontrollable) type, UM (unmovable) type, MN (movable and non-divisible) type, and MD (movable and divisible) type.

- UC type: The electric appliances of UC type are uncontrollable. We cannot schedule their execution time. For each electric appliance of UC type UC_i, $i = 1 \dots w$, we define the constant values γ_i to represent their power consumptions. For example, fluorescent lamps, televisions, and electric fans are electric appliances of UC type.

- UM type: The electric appliances of UM type execute at predefined certain time. For each electric appliance of UM type UM_j, $j = 1 \dots x$, the start time t_j^s, end time t_j^e, and power consumption $p_j^{UM}(t)$ at time t are given. We cannot move or disassemble their execution time. For example, monitors, recorders, and cleaning robots are electric appliances of UM type.

- MN type: The execution time of electric appliances of MN type are movable and non-divisible. For each electric appliances of MN type MN_k, $k = 1 \dots y$, the start time t_k^s, end time t_k^e, deadline d_k^{MN}, and power consumption $p_k^{MN}(t)$ at time t are given. For example, toasters, electric rice cookers, and ovens are electric appliances of MN type.

- MD type: The execution time of electric appliances of MD type are movable and divisible.

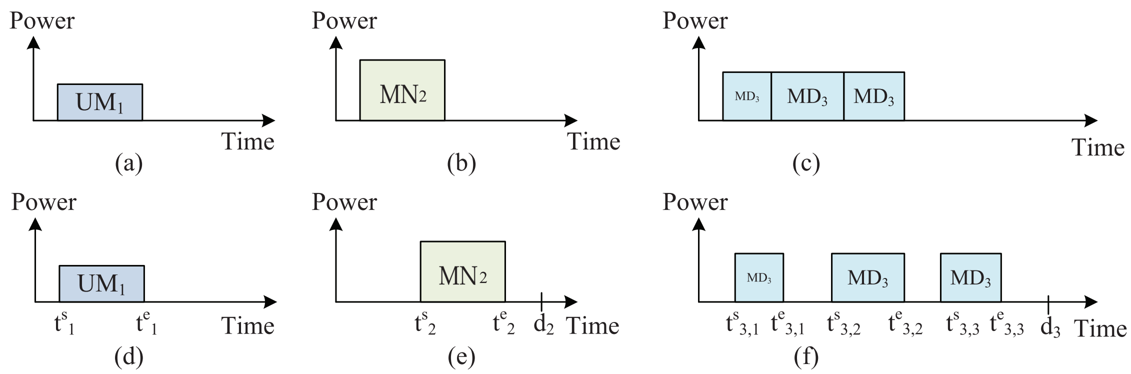


Figure 3.1: An example of electric appliance types. (a), (b), and (c) are three appliances before scheduling. (d), (e), and (f) are three appliances after scheduling.

For each electric appliances of MD type MD_l, $l = 1 \ldots z$, the execution time can be divided into n parts. For $u = 1 \ldots n$, each part start at time $t^s_{l,u}$ and end at time $t^e_{l,u}$. All parts must execute before deadline d^{MD}_l by increasing order. The power consumption of MD_l at time t is $p^{MD}_l(t)$. For example, washers, water pumps, and battery chargers are electric appliances of MD type.

Fig. 3.1 shows an example of these appliances. Fig. 3.1(a), Fig. 3.1(b), and Fig. 3.1(c) are UM type, MN type, and MD type appliances before scheduling, respectively. The execution time of UM_1 can not be moved. As shown in Fig. 3.1(d), the execution time is same as Fig. 3.1(a). The execution time of MN_2 can be moved. As shown in Fig. 3.1(e), after scheduling, the MN_2 starts from t^s_2 to t^e_2. The execution time of MD_3 can divided into three parts. As shown in Fig. 3.1(f), after scheduling, the MD_3 starts from [$t^s_{3,1}$, $t^e_{3,1}$], [$t^s_{3,2}$, $t^e_{3,2}$], and [$t^s_{3,3}$, $t^e_{3,3}$].

The total power consumption of all above electric appliances can not be exceeded the upper bound threshold δ at any time t, i.e.,

$$\Sigma_{\forall i}\gamma_i + \Sigma_{\forall j} p^{UM}_j(t) + \Sigma_{\forall k} p^{MN}_k(t) + \Sigma_{\forall l} p^{MD}_l(t) \leq \delta$$

In our scenario, the cost of power consumption $c(t)$ may be different at different time. Hence, our goal is to adjust the execution time of each appliance to minimize the total cost, i.e.,

$$\min\{\int_{t^s_j}^{t^e_j} f_j(t)c(t)dt + \int_{t^s_k}^{t^e_k} g_k(t)c(t)dt + \sum_{u=1}^{n}\int_{t^s_{l,u}}^{t^e_{l,u}} h_l(t)c(t)dt\}$$

where $t = [t_{now}, d_{max}]$, $d_{max} = \max_{\forall j,k,l}\{t^e_j, d_k, d_l\}$, and t_{now} is current time.

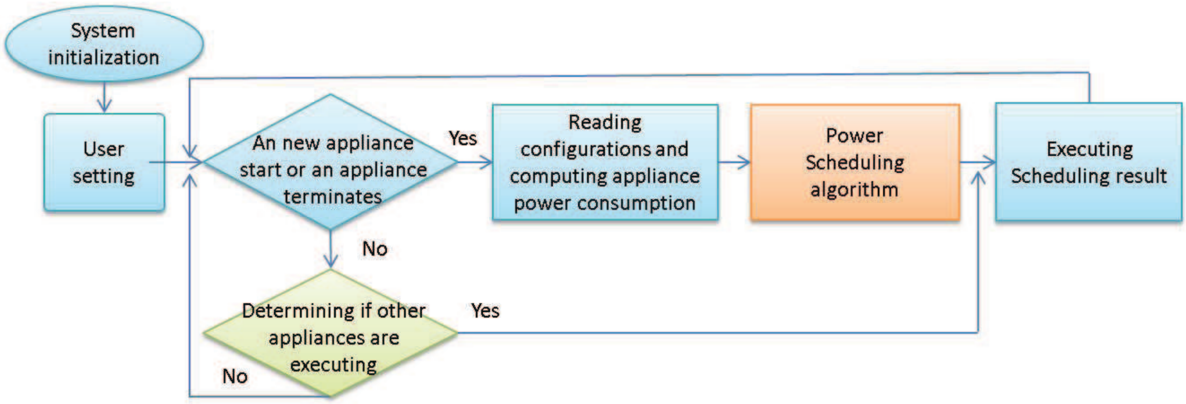


Figure 3.2: The flow chart of iPM system.

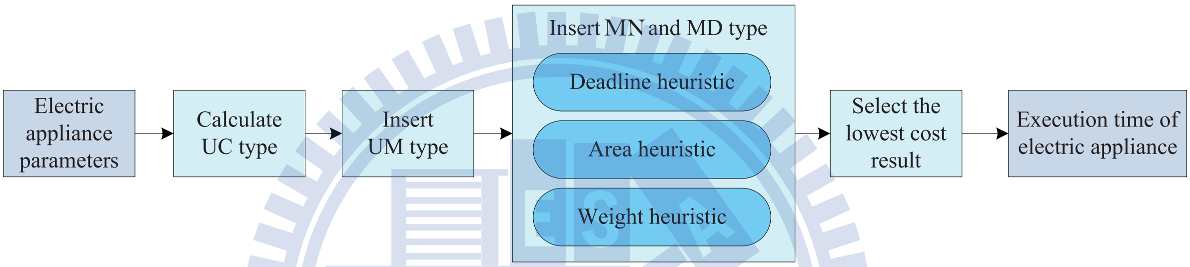


Figure 3.3: The flow chart of iPM scheduling algorithm.

3.2 Power Scheduling Algorithm

Our iPM system can schedule the executing electric appliances dynamically. Fig. 3.2 shows the flow chart of our iPM system. Users should set the parameters about electric appliances, such as start time, end time, deadline, etc. Then, control server will read these configurations and compute these electric appliances power consumption dynamically. According to above parameters of electric appliances, we design a power scheduling algorithm to schedule these electric appliances. Then, these electric appliances will execute by the scheduling result. When an new electric appliance enters the system or an electric appliance terminates, the control server will redo the power scheduling algorithm to guarantee minimizing the total cost for all electric appliances.

Here, we propose a scheduling algorithm for executing electric appliances. Fig. 3.3 shows the flow chart of scheduling algorithm. At first, we consider the electric appliances of UC type. Then, we insert electric appliances of UM type. After that, we propose three heuristic methods to schedule electric appliances of MN and MD types. Finally, we select the lowest cost result

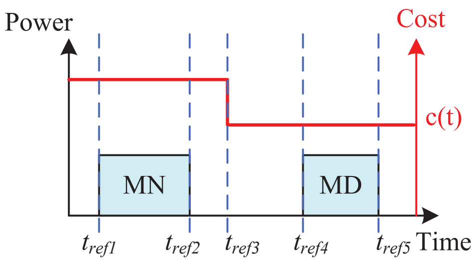


Figure 3.4: An example of the reference points.

from above three heuristic methods. For greedy approaches in heuristic methods, we define two metrics, which are the areas and weighted values of the electric appliances. The area of an electric appliance is the total power consumption while executing. For the electric appliances of MN and MD types, the areas can be denoted as following.

$$area(MN_k) = \int_{t_k^s}^{t_k^e} g_k(t)c(t)dt$$

$$area(MD_l) = \sum_{u=1}^{n} \int_{t_{l,u}^s}^{t_{l,u}^e} h_l(t)c(t)dt$$

Besides, the weighted values are denoted as the area divided by available time, i.e.,

$$weight(MN_k) = area(MN_k)/(d_k - t_{now})$$

$$weight(MD_l) = area(MD_l)/(d_l - t_{now})$$

Before describing the detail of the scheduling algorithm, we define the *reference time point* for inserting the electric appliances of MN and MD types.

Definition 1 *The reference time point t_{ref} is a time point that satisfies one of the following constraints.*

- *The boundary of the cost of power consumption, i.e., $c(t_{ref} + \omega) \neq c(t_{ref})$ and $c(t_{ref} - \omega) \neq c(t_{ref})$, where the ω is a constant.*
- *The start time or end time of electric appliances of UM type, i.e., the $t_{ref} = t_j^s$ or $t_{ref} = t_j^e$ for all $j = 1 \ldots x$ in UM_j.*
- *The start time or end time of electric appliances of MN type, i.e., the $t_{ref} = t_k^s$ or $t_{ref} = t_k^e$ for all $k = 1 \ldots y$ in MN_j.*

- *The start time or end time of electric appliances of MD type, i.e., the $t_{ref} = t^s_{l,u}$ or $t_{ref} = t^e_{l,u}$ for all $l = 1 \dots z$ and $u = 1 \dots n$ in MD_l.*

Fig. 3.4 shows an example of the reference time points. The left and right x-axis are the power consumption of electric appliances and the cost of power consumption, respectively. There are five reference time points in this example. The time point t_{ref1} and t_{ref2} are the start and end time of electric appliances of MN type, respectively. The time point t_{ref4} and t_{ref5} are the start and end time of electric appliances of MD type, respectively. The t_{ref3} is the boundary of cost of power consumption.

Our proposed power scheduling algorithm is composed of the following steps:

SchedulingEA(UC, UM, MN, MD, δ)

1. Subtract the power consumption of UC_i for $i = 1 \dots w$ from δ, i.e., $\delta = \delta - \Sigma_{\forall i}\gamma_i$.
2. Insert UM_j for $j = 1 \dots x$ by their t^s_j and t^e_j.
3. Get current reference time points t_{ref_r}, where $r = 1 \dots m$.
4. Try to schedule all MN_k and MD_l by following three heuristic methods individually and calculate their cost while executing.
   - Deadline heuristic: Sort MN_k and MD_l for $k = 1 \dots y$ and $l = 1 \dots z$ according to d_k and d_l by increasing order into a set EA. Then, do InsertEA(EA) to insert these electric appliances.
   - Area heuristic: Sort MN_k and MD_l for $k = 1 \dots y$ and $l = 1 \dots z$ according to $area(MN_k)$ and $area(MD_l)$ by decreasing order into a set EA. Then, do InsertEA(EA) to insert these electric appliances.
   - Weight heuristic: Sort MN_k and MD_l for $k = 1 \dots y$ and $l = 1 \dots z$ according to $weight(MN_k)$ and $weight(MD_l)$ by decreasing order into a set EA. Then, do InsertEA(EA) to insert these electric appliances.
5. Choose the lowest cost result of above three heuristics to execute.

InsertEA(EA)

1. Traverse each $ea \in EA$ sequentially to check if ea is MD type.

(a) If ea is MD type, greedily and sequentially insert each parts of ea into the t_{ref_r} with the lowest cost, i.e., $\min_{\forall r}\{c(t_{ref_r})\}$ and satisfy the δ and deadline constraints. If multiple t_{ref_r} can be chosen, choose the the latest time first.

(b) Otherwise, greedily insert ea into a t_{ref_r} with the lowest cost, i.e., $\min_{\forall r}\{c(t_{ref_r})\}$ and satisfy the δ and deadline constraints. If multiple t_{ref_r} can be chosen, choose the the latest time first.

Fig. 3.5 shows an example of the power scheduling algorithm. As shown in Fig. 3.5(a), the UC_1 electric appliance with $\gamma_1 = 2$ and UM_1 electric appliance with $t_1^s = 4$ and $t_1^e = 6$. The MN_1 and MN_2 electric appliances with respectively. The MD_1 electric appliance can be divided into two parts with $d_1^{MD} = 16$. At first, we consider the UC_1 and UM_1. As shown in Fig. 3.5(b), the δ is 4 after scheduling the UC_1. By deadline heuristic, we insert MN_2, MN_1, and MD_1 sequentially in Fig. 3.5(c1), Fig. 3.5(c2), and Fig. 3.5(c3), respectively. By area heuristic, we insert MD_1, MN_1, and MN_2 sequentially in Fig. 3.5(d1), Fig. 3.5(d2), and Fig. 3.5(d3), respectively. By weight heuristic, we insert MN_1, MN_2, and MD_1 sequentially in Fig. 3.5(e1), Fig. 3.5(e2), and Fig. 3.5(e3), respectively. In the example, the lowest cost one is deadline heuristic.

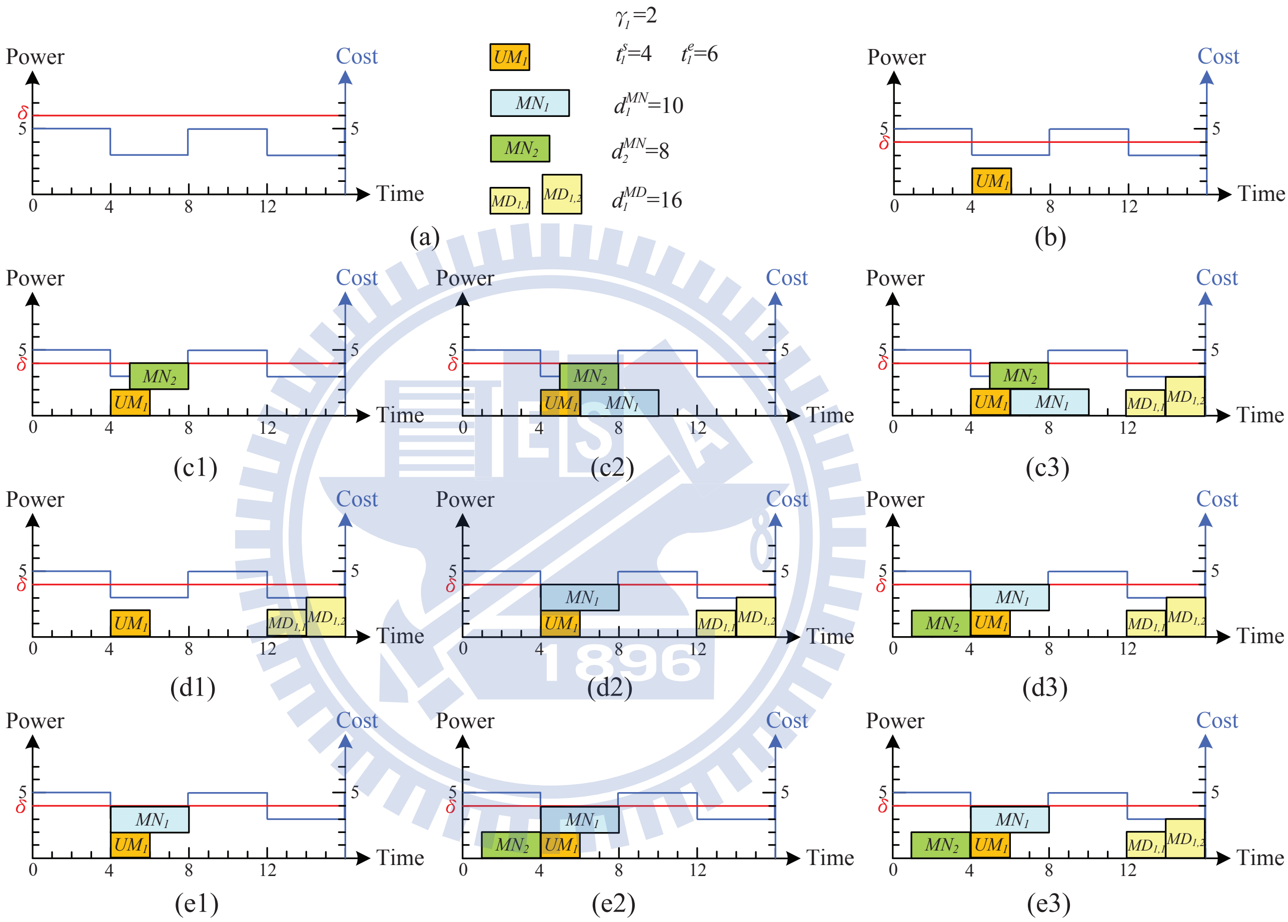


Figure 3.5: An example of power scheduling algorithm. (a) The parameters of the example. (b) Scheduling result after insert UC and UM types. (c) Scheduling results by deadline heuristic. (d) Scheduling results by area heuristic. (e) Scheduling results by weight heuristic.

Chapter 4

Prototyping Results

4.1 Hardware Components

The hardware components of iPM system can be divided into two parts, i.e., wireless power meter and sink receiver. Fig. 4.1 shows our wireless power meter. It is composed of three units:

1. Power sensing unit: We adopt ADE7763 [1] as our energy meter IC to get the energy consumption of electric appliances. As shown in Fig. 4.2, the electric current and voltage can be gotten by current transformer and transformer via channel-1 (CH1) and channel-2 (CH2), respectively. Then, we can get power consumption of electric appliances via SPI (serial peripheral interface).

2. Control unit: Fig. 4.1 shows the control unit of our wireless power meter. We adopt Atmel AVR ATmega128 [2] as our microcontroller which can get power consumption via serial peripheral interface and transmit data via UART interface. Besides, we provide three relay for power control and mode switch.

3. Wireless transmission unit: As shown in Fig. 4.1, we adopt Jennic JN5148 [4], which is a single-chip microprocessor compatible with IEEE 802.15.4 [13], as our wireless transmission module. Through the UART interface, it can get the statuses of electric appliances and transmit to our control server.

Fig. 4.4 shows our sink receiver. We adopt Jennic JN5148 [4] as our wireless transmission module and adopt FTDI FT232RL [3] to translate UART interface to USB interface from JN5148. So, the control server can get data form electric appliances or send commands to electric appliances via USB interface.

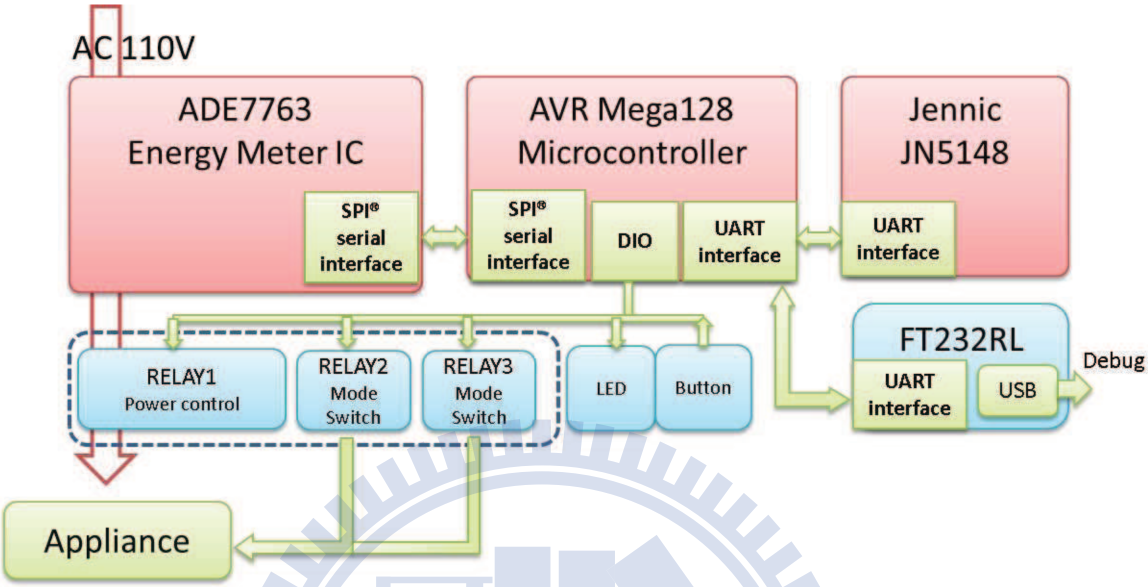


Figure 4.1: The hardware components of our wireless power meter.

Figure 4.2: Our implemented wireless power meter.

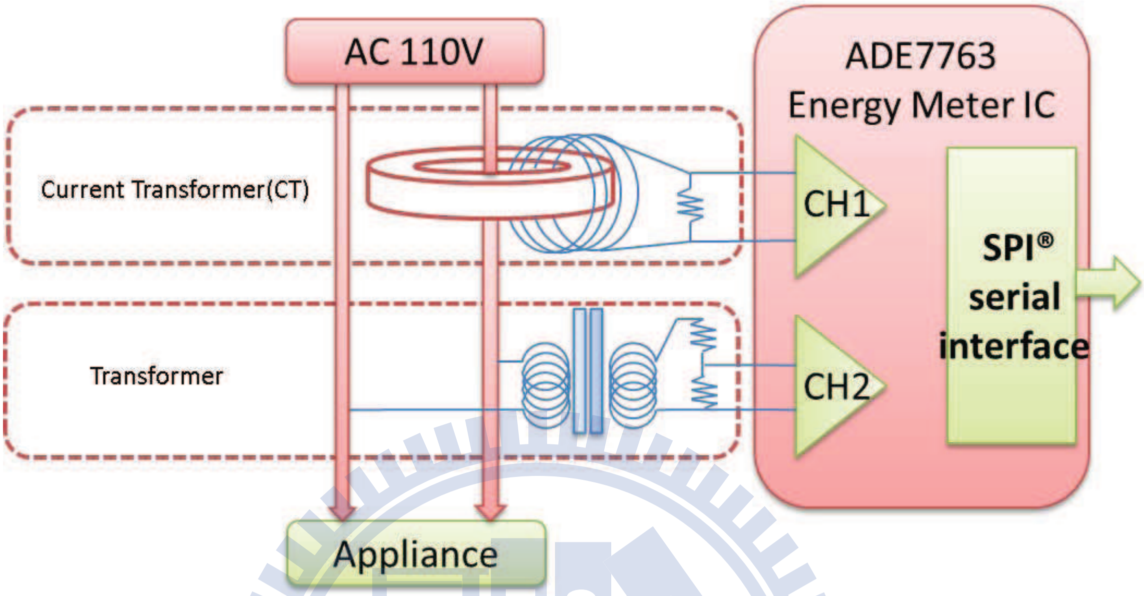
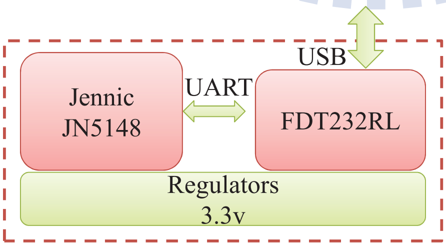
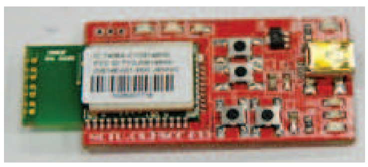


Figure 4.3: Hardware component of power sensing unit.



(a)



(b)

Figure 4.4: The hardware component of iPM system. (a) The hardware components of our sink receiver. (b) Our implemented sink receiver.

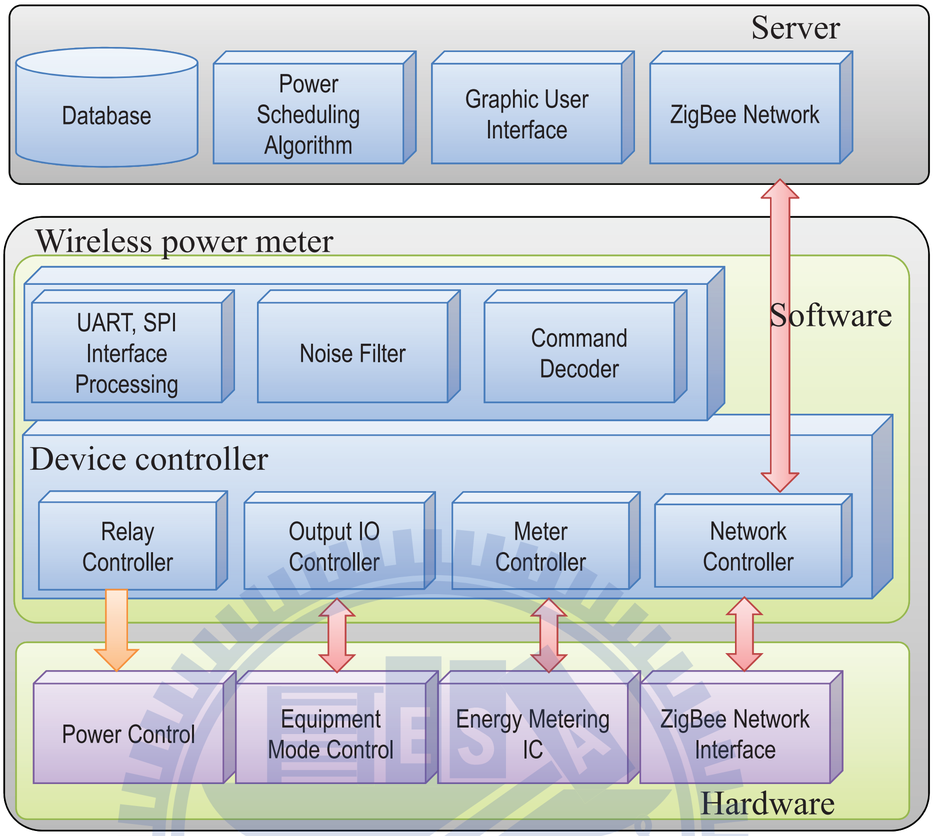


Figure 4.5: The functional block of implementation.

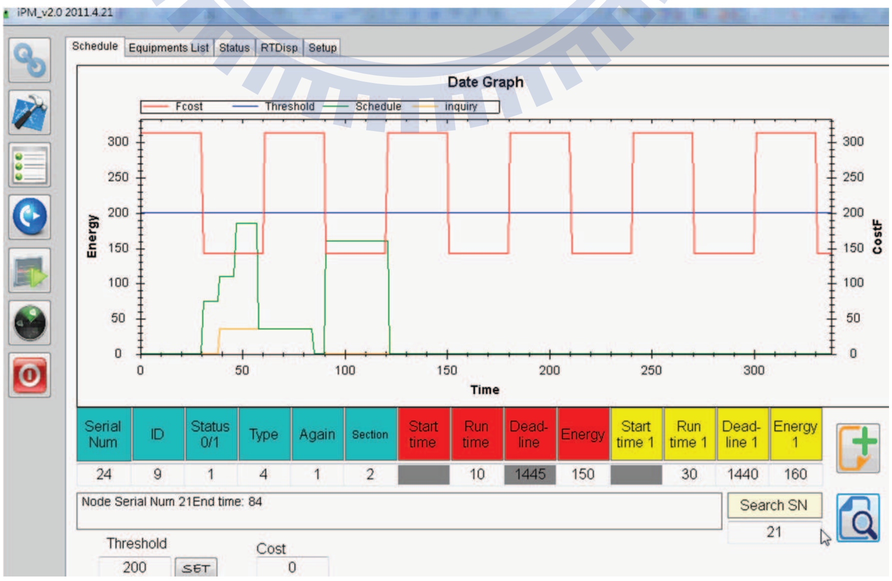


Figure 4.6: The graphic user interface of control server.

4.2 Software Components

Fig. 4.5 shows our functional block of implementation. In wireless power meter, four device controller modules send command and receive data from hardware components. The relay and output I/O controller can control the power and modes of electric appliances, receptively. The meter and network controller can get and send metering data to control server, respectively. Before sending the metering data to control server, we preprocess these data by noise filter to get more precision metering data. Beside, for ease of programming, we design some commands to communicate between wireless power meter and control server. The command decoder can decode command to do suitable actions. As shown in Fig. 4.6, in control server, we provide a graphic user interface to set and monitor whole system status. Also, we log all metering data from wireless power meter into a database system.

Chapter 5

Simulation Results

In this section, we present some simulation results to evaluate the system performance. We consider the power consumption of a house with a set of eleven electric appliances, where one is UC type, three are UM type, six are MN type, and the other is MD type. One hundred electric appliances are generated randomly from the set and inserted into different time slots during the simulation time. Table 5.1 lists the electric appliances set of our simulator. We set the instantaneous power threshold to 500 watt-second, and the simulation time is set to 168 hours (a week). In order to observe different scheduling results, we set the electric price is fluctuating every three hours as shown in Fig. 5.1.

We compare our iPM system with the non-schedule system in our iPM simulator to observe the power consumption and monetary cost. We define the power consumption as the accumulative power of the simulation time, and the monetary cost as the total cost of the power consumption.

The power consumption of our iPM system is similar to that of the non-schedule system as shown in Fig. 5.2. It is because all electric appliances are working well after scheduling. Fig. 5.3 shows the instantaneous power during the simulation time. However, we find that the instantaneous power of our iPM system, with the three heuristic methods, is more evenly stable than that of the non-schedule system. Even though some power loads can not be shifted from the peak time, the power load would never exceed the power threshold after scheduling.

With regard to monetary cost, iPM can save more. Customers can decide which heuristic method they want, or they may use the default setting, choosing the lowest cost from these three heuristic methods. From Fig. 5.4, we can find that iPM can save 24.5% cost less than the non-schedule system.

Table 5.1: The electric appliance set

Type	Execution time (minute)	Deadline after start (minute)	Power consumption per watt-second
UC	Uncontrollable	Uncontrollable	30
UM	30	Uncontrollable	80
UM	40	Uncontrollable	60
UM	50	Uncontrollable	70
MN	50	360	70
MN	60	360	90
MN	70	360	45
MN	35	720	120
MN	20	720	120
MN	120	720	50
MD	110 45	720 720	50 35

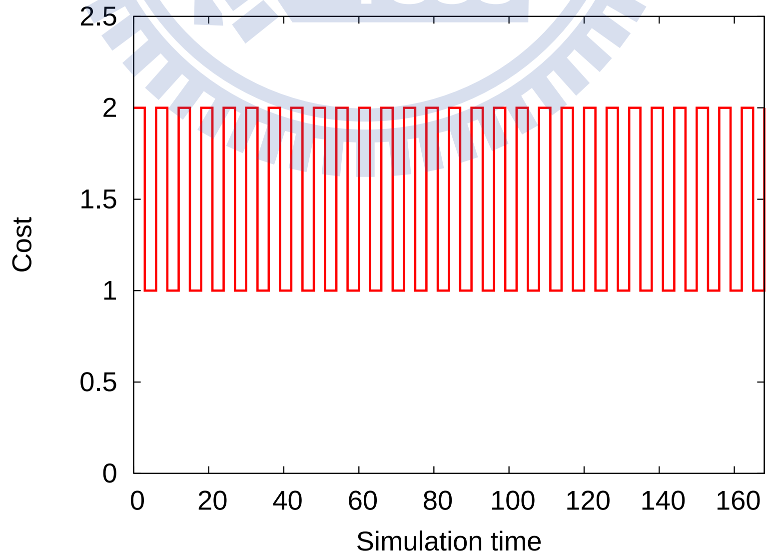


Figure 5.1: The fluactuating prices during the simulation time.

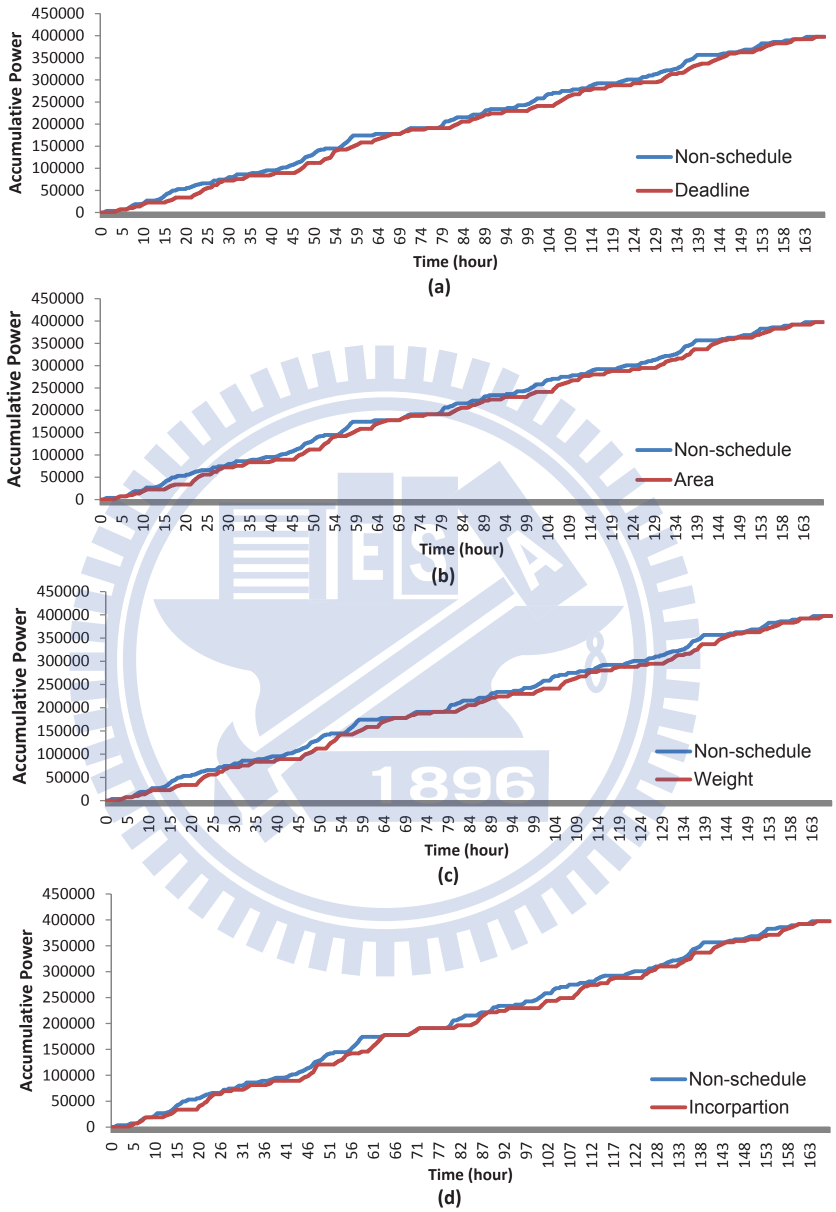


Figure 5.2: The accumulative power of (a) Deadline heuristic, (b) Area heuristic, (c) Weight heuristic, and (d) incorporation.

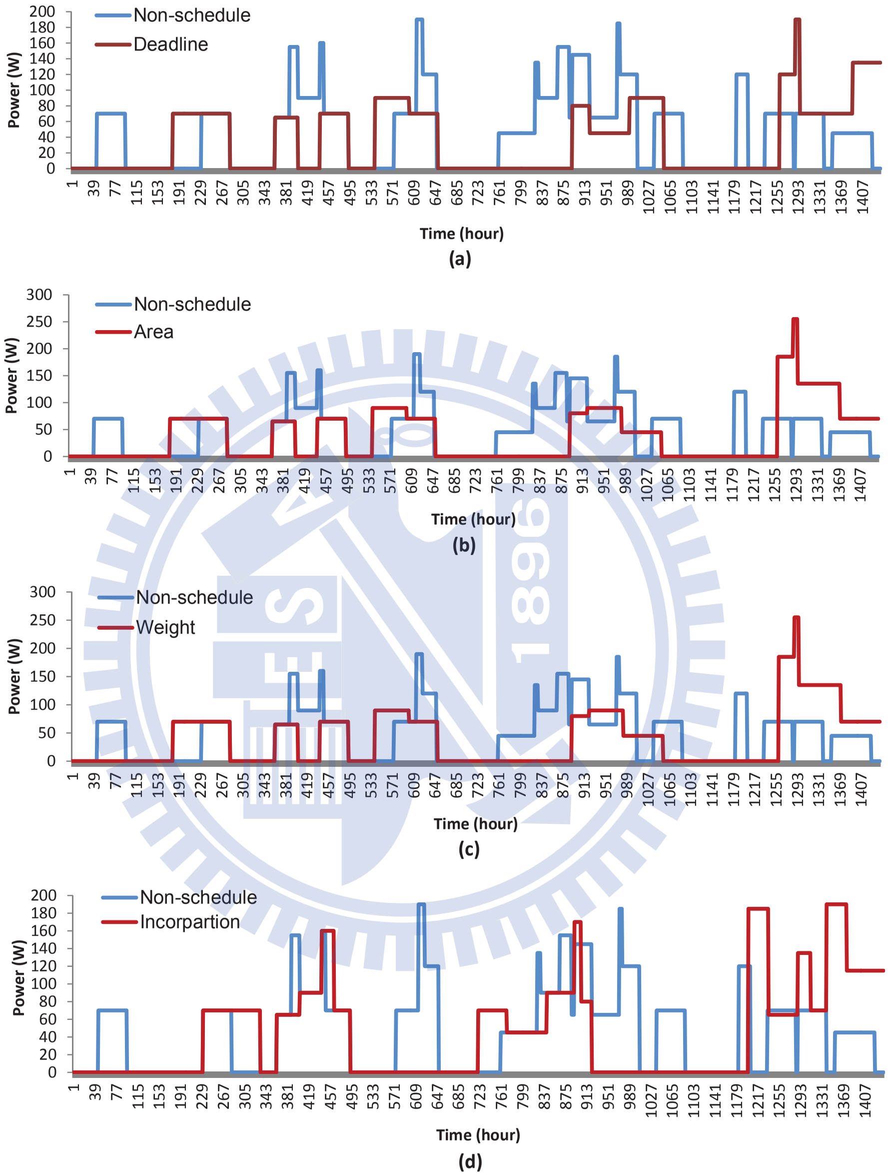


Figure 5.3: The power of (a) Deadline heuristic, (b) Area heuristic, (c) Weight heuristic, and (d) incorporation during the simulation time.

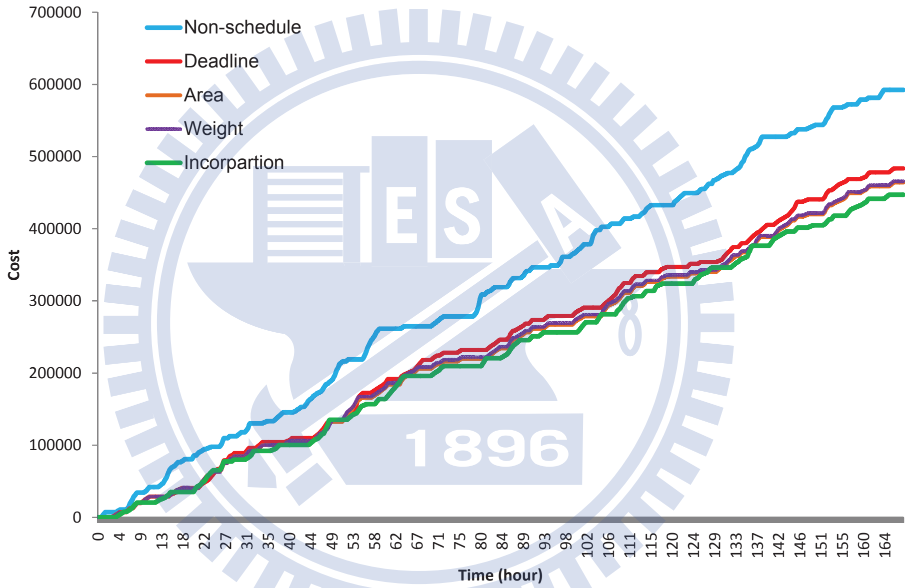


Figure 5.4: The cost of power.

Chapter 6

Conclusions

In this paper, we propose an intelligent power scheduling system (iPM) based on pervasive meters. Each electric appliance connects to a wireless power meter. Through these wireless meters, the current power consumption of electric appliances can be transmitted to the control server. Our goal is to dynamically schedule the execution time of each electric appliance in a home to minimize the total monetary cost. Still, it poses several challenges: 1) user demand response, 2) load management, and 3) minimizing the monetary cost of electricity consumption. Hence, we propose a power scheduling algorithm for smart usage of electric appliances in a home dynamically. We verify our results through simulations as well as a real prototype. Specifically, we develop a power scheduling system based on the ZigBee Smart Energy Profile to monitor and schedule the usage of electric appliances.

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