# 國立交通大學

## 網路工程研究所

## 碩士論文

# 藉由無線感測網路設計與實作智慧型燈光控制系統

# Design and Implementation of an Intelligent Light Control System Using Wireless Sensor Networks

研究生：陳彥安

指導教授：曾煜棋　教授

中華民國九十六年六月

# 藉由無線感測網路設計與實作智慧型燈光控制系統
# Design and Implementation of an Intelligent Light Control System Using Wireless Sensor Networks

研究生：陳彥安　　Student：Yan-Ann Chen

指導教授：曾煜棋　　Advisor：Yu-Chee Tseng

國立交通大學
網路工程研究所
碩士論文

A Thesis
Submitted to Institute of Network Engineering
College of Computer Science
National Chiao Tung University
in partial Fulfillment of the Requirements
for the Degree of
Master
in

Computer Science

June 2007

Hsinchu, Taiwan, Republic of China

中華民國九十六年六月

# 藉由無線感測網路設計與實作智慧型燈光控制系統

學生：陳彥安　　　　　　　　　　指導教授：曾煜棋 教授

國立交通大學網路工程研究所碩士班

## 摘　　要

近年來，無線感測網路已經在許多的應用上被廣泛的討論與應用。在此篇論文中，我們藉由無線感測網路，設計了一個應用於室內的智慧型燈光控制系統，其目標為提供適合的照度以滿足使用者的需求。在我們的系統中使用了兩種燈光照明裝置，分別為全區及局部的照明裝置，它們分別提供使用者背景及集中的照明。無線感測器主要的功能為測量目前環境的照度。我們提出的控制決策演算法，利用感測器的讀數用以決定提供給多位使用者的照明。另外，提出一個裝置控制演算法，使用閉環控制機制用以實際調整燈光裝置。

**關鍵字**：閉環控制，智慧型燈光控制，最佳化，普及運算，無線感測網路。

# Design and Implementation of an Intelligent Light Control System Using Wireless Sensor Networks

Student: Yan-Ann Chen Advisor: Prof. Yu-Chee Tseng

Institute of Network Engineering
National Chiao Tung University

## ABSTRACT

Recently, wireless sensor networks have been widely discussed in many applications. In this paper, we design a novel intelligent light control system for indoor environment, which aims to provide sufficient illuminations to satisfy users. In this system, there are two kinds of lighting devices, namely whole and local lighting devices, which can provide background and concentrated illuminations, respectively. Wireless sensors are responsible for measuring current light intensity of the environment. The proposed control decision algorithms utilize the sensory readings to decide proper illuminations for users. Then the proposed device control algorithms perform a closed-loop control mechanism to adjust lighting devices.

**Keywords:** closed-loop control, intelligent light control, optimization, pervasive computing, wireless sensor networks.

# 誌謝

首先，誠摯地感謝曾煜棋教授兩年來的指導與鼓勵，並且提供良好的研究環境及充足的實驗設備，讓我得以順利的完成此篇論文並取得碩士學位。

此外，也由衷地感謝指導我的潘孟鉉學長和葉倫武學長，在論文的研究及實作上，提供了許多寶貴的建議與指導。另外，感謝 HSCC 實驗室的全體成員，在我碩士班兩年中的幫助與鼓勵。

最後，感謝我的家人以及關心我的人對我的期許及關懷，使我能夠無虞地完成我的學業。

陳彥安 於
國立交通大學網路工程研究所碩士班
中華民國九十六年六月

# Contents

# List of Figures

# Chapter 1

# Introduction

The recent progress of wireless communication and embedded micro-sensing MEMS technologies has made *wireless sensor networks (WSNs)* more attractive. A lot of research works have been dedicated to this area, including energy-efficient MAC protocols [8][31], routing and transport protocols [4][12], self-organizing schemes [14][26], sensor deployment and coverage issues [13][18], and localization schemes [2][5][19]. In the application side, habitat monitoring is explored in [11], the FireBug project aims to monitor wildfires [9], mobile object tracking is addressed in [16][27], and navigation applications are explored in [15][28].

Recently, several works [20][21][24][30] investigate using wireless sensors to construct light control systems. References [20] and [30] introduce light control systems using wireless sensors to save energy for commercial buildings. Lighting devices are adaptively adjusted according to measured light intensity of daylight. Although [20] and [30] can save energy, they do not consider users' requirements about lights. References [21] and [24] design light control systems considering users' requirements. The system designed in [21] is specially for media production. The authors define several kinds of user requirements and the correspondence cost functions of requirements. The goal is to find a setting of lights which can minimize total cost. The work [24] models a light control problem as a trade-off between energy conservation and users' requirements. Each user's requirement is defined as a utility function. After light adjustment, users get utility values according to their utility functions. Since part of the goal is to maximize total user utility, in some cases, some users may obtain very low utility values. Both [21] and [24] need to know all possible combinations of dimmer settings and locations to light intensities at deployment stage. If there are $k$ interest points, $d$ dimmer levels, and $m$ lighting devices, we need $O(kdm)$ measurements to obtain all illumination combinations. We consider that the measurement procedures not only take time, but also need many efforts.

In this paper, we design an intelligent light control system using WSNs with considering user requirements. As shown in Fig. 1.1, we divide the network into grids. In a grid, there is a

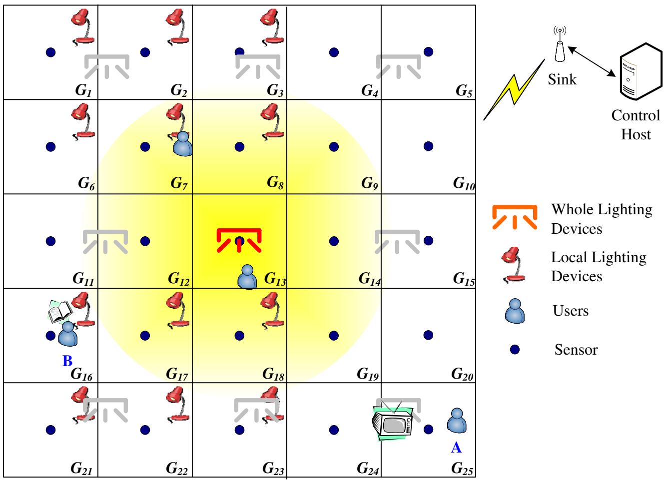


Figure 1.1: The network scenario of our system.

fixed sensor nodes deployed at the center. These sensors form a multi-hop ad hoc network. One node serves as the *sink* of the network, and it is connected to the *control host*. The control host can issue light control commands and config the network. In our system, lighting devices are divided into *whole lighting devices* and *local lighting devices*. A whole lighting device is the light such as fluorescent light, which can provide illuminations for several grids. For example, in Fig. 1.1, the light locates in the middle of the network can illuminate grids $G_7$, $G_8$, $G_9$, $G_{12}$, $G_{13}$, $G_{14}$, $G_{17}$, $G_{18}$, and $G_{19}$. On the other hand, a local lighting device is the one such as table lamp, which can only provide concentrated illumination. Each user brings a wireless sensor, which is used to locate user's location and sense the light intensity of the surface that user needs local illuminations.

We assume that users have different requirements based on their activities. For example, in Fig. 1.1, user A is watching television and user B is reading. User A may only specify whole lighting devices to provide sufficient illuminations. But, user B specifies both whole lighting devices and a local lighting device to provide sufficient illuminations at the same time. In this paper, the control host adaptively decides the illumination goals of lighting devices according to users' requirements. In this paper, we discuss two kinds of illumination requirements: one is *fixed user requirement* and the other is *personalized user requirement*. When using the fixed user requirements, two users are considered to have the same illumination requirement if their activities are the same. One the other hand, when using the personalized user requirement, users can specify their illumination requirements according to their activities. We will separately discuss the formulations and solutions for these two requirements. And then device control algorithms adjust the dimmers of lighting devices to achieve the illumination goals. Unlike [21] and [24], our system does not need to know all possible combinations of dimmer levels and locations to light intensities.

The rest of this paper is organized as follows. Section 2 presents the system architecture. Section 3 and Section 4 introduce the illumination decision algorithms for fixed user requirement and personalized user requirement, respectively. Section 5 presents the device control algorithm for lighting devices. Section 6 shows our prototyping results and Section 7 concludes this paper.

# Chapter 2

# System Architecture

## 2.1 System Model

In the following, we define the relationships between grids, users, and lighting devices. Assume that, in this system, there are $k$ grids, $n$ users, $m$ whole lighting devices, and $m'$ local lighting devices. We label those $k$ grids as $G_1$, $G_2$, ..., and $G_k$. In each grid, a fixed sensor is used to measure the light intensity of that grid. Fixed sensors periodically report the sensed light intensity to the sink. The control host saves those reported readings by a $k \times 1$ column vector

$$S^f = \begin{bmatrix} s^f(G_1) & s^f(G_2) & \cdots & s^f(G_k) \end{bmatrix}^T,$$

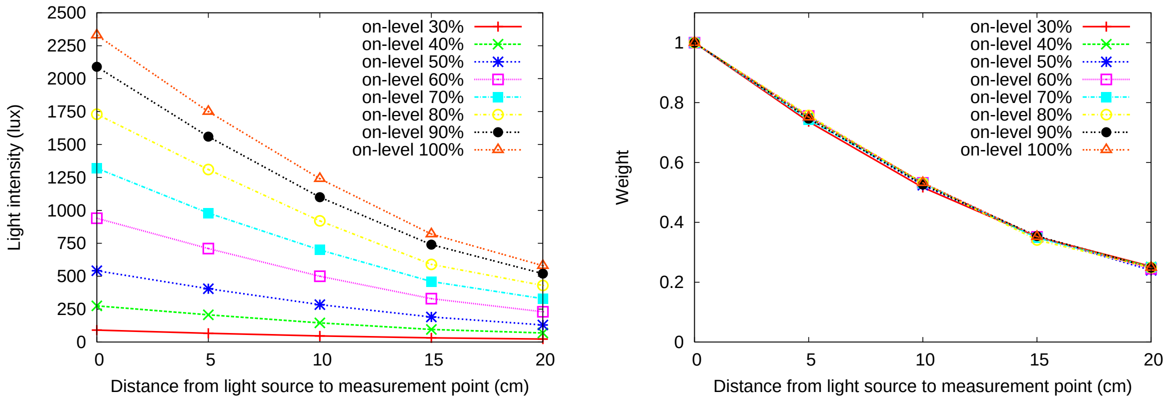
where $s^f(G_i)$, $\forall i \in [1, k]$, means the sensory reading of the fixed sensor $s_i^f$ in grid $G_i$. In this system, we consider that lighting devices have limited capability. For a whole lighting device $wd_j$, we define the maximum light intensity $wd_j$ can provide as $l^{max}(wd_j)$. The control host records this information by an $m \times 1$ column vector

$$L_{wd}^{max} = \begin{bmatrix} l^{max}(wd_1) & l^{max}(wd_2) & \cdots & l^{max}(wd_m) \end{bmatrix}^T.$$

For a local lighting device $ld_j$, we define the maximum light intensity $ld_j$ can provide as $l^{max}(ld_j)$. The control host records this information by an $m' \times 1$ column vector

$$L_{ld}^{max} = \begin{bmatrix} l^{max}(ld_1) & l^{max}(ld_2) & \cdots & l^{max}(ld_{m'}) \end{bmatrix}^T.$$

Then we define the relationship between the lighting devices and grids. Like radio signals, light signals degrade with distance. Here, we do a simple experiment to characterize this phenomenon by measuring the light intensity of a table lamp at different distances. Fig. 2.1(a) shows the measured intensity of the lamp turned on at different levels. The intensity at $0$ $cm$ is considered as the light intensity directly supplied by the lamp. We observe that the measured



(a) (b)

Figure 2.1: An experiment for characterizing the light degradation.

light intensity degraded following a trend, which can be obtained by normalizing the measured light intensity to the one at $0$ cm. Fig. 2.1(b) shows the result. From the above observation, we define a weight $w_i^j$ as the measured light intensity of a fixed sensor $s_i^f$ contributed by device $wd_j$ is the current light intensity supplied by device $wd_j$ multiplies by $w_i^j$. The control host maintains the weights by a $k \times m$ matrix

$$W = \begin{bmatrix} w_1^1 & w_1^2 & \cdots & w_1^m \\ w_2^1 & w_2^2 & \cdots & w_i^m \\ \vdots & \vdots & \ddots & \vdots \\ w_k^1 & w_k^2 & \cdots & w_k^m \end{bmatrix}.$$

We assume that weight values can be obtained at deployment stage. The complexity for measuring the weight will be $O(km)$. On the other hand, we assume that a local lighting device can only have effect on the illumination of a grid and the illumination provided by local light devices will not affect the measured light intensity of fixed sensors.

By the definition of $W$, we discuss how to obtain the current light intensity provided by $wd_j$, denoted as $l^c(wd_j)$. We first define an $m \times 1$ column vector $L_{wd}^c$ as

$$L_{wd}^c = \begin{bmatrix} l^c(wd_1) & l^c(wd_2) & \cdots & l^c(wd_m) \end{bmatrix}^T.$$

Physically, we can say that each whole lighting device $wd_j$ is belonged to one grid $loc(wd_j)$. Here, we construct an $m \times m$ matrix $\hat{W}$ by selecting the $loc(wd_j)$-th row, $\forall j \in [1, m]$, from $W$. From [24], we can know light intensities are additive. The light intensity provided by lighting devices is obtained by subtracting the light intensity provided by the sunlight from the measured light intensity. From $S^f$, we can construct a $\hat{S}^f$ by eliminating sunlight effect. The current light intensity provided by all whole lighting devices can be obtained by

$$\hat{S}^f = \hat{W} \cdot L^c_{wd} \Rightarrow L^c_{wd} = \hat{W}^{-1} \cdot \hat{S}^f \tag{2.1}$$

On the other hand, the light intensity provided by a local lighting device $ld_j$, denoted as $l^c(ld_j)$, can be simply obtained by subtracting the light intensity provided by the sunlight and whole lighting devices from the measured light intensity. The control host records the lighting intensity provided by local lighting devices by an $m' \times 1$ column vector

$$L^c_{ld} = \begin{bmatrix} l^c(ld_1) & l^c(ld_2) & \cdots & l^c(ld_{m'}) \end{bmatrix}^T .$$

In this system, each user brings a portable wireless sensor. The control host judges which grids that users locate by the signals emitted from portable wireless sensor. For example, in Fig. 1.1, user A and B are located in $G_{25}$ and $G_{16}$, respectively. A portable wireless sensor is used to sense the light intensity of the surrounding area (or working area) of a user. Portable sensors also report measured readings to the control host through wireless links. And the control host can record this information by an $n \times 1$ column vector

$$S^p = \begin{bmatrix} s^p(u_1) & s^p(u_2) & \cdots & s^p(u_n) \end{bmatrix}^T ,$$

where $s^p(u_i)$, $\forall i \in [1, n]$, means the sensory reading of the portable sensor $s^p_i$ of user $u_i$. We assume that a local lighting device can only serve one user at a time. We define an $m' \times n$ matrix $C$ to record the corresponding user of a local lighting device.

$$C = \begin{bmatrix} c^1_1 & c^1_2 & \cdots & c^1_n \\ c^2_1 & c^2_2 & \cdots & c^2_n \\ \vdots & \vdots & \cdots & \vdots \\ c^{m'}_1 & c^{m'}_2 & \cdots & c^{m'}_n \end{bmatrix},$$

where $c^j_i$, $\forall j \in [1, m']$ and $\forall i \in [1, n]$, is 1 if the user $i$ is the corresponding user of the device $j$. Otherwise, $c^j_i$ is 0.

This system controls the lights according to users' activities. Different activities will have different user requirements. At a time instance, each user can have a user requirement. Users can specify their current activities by wireless sensors. In this paper, we further consider two kinds of user requirements settings.

1. *Fixed user requirement*: In this setting, the system decides user requirements of different activities for users. A user requirement is divided into two parts. The first part is the *illumination demand* of whole and local lighting and the second part is the needed *illumination ranges* of whole lighting. The illumination demand of a user $u_i$ is defined as:

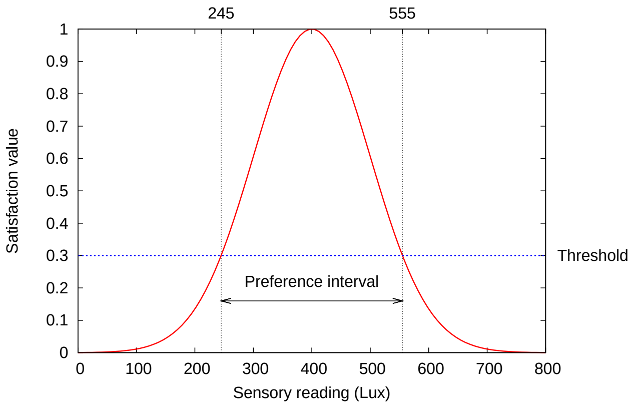


Figure 2.2: A preference function of a user with mean is 400 and variance is 100.

- Demand on whole lighting: $[D^l_{wd}(i), D^u_{wd}(i)]$, where $D^l_{wd}(i)$ and $D^u_{wd}(i)$ are the lower bound and upper bound of the demand on whole lighting, respectively.
- Demand on local lighting: $[D^l_{ld}(i), D^u_{ld}(i)]$, where $D^l_{ld}(i)$ and $D^u_{ld}(i)$ are the lower bound and upper bound of the demand on local lighting, respectively.

The system also decides illumination ranges for users. The control host records which grids are required to provide sufficient illuminations for a user $u_i$ by a $k \times 1$ column vector

$$R_i = \begin{bmatrix} r_i(G_1) & r_i(G_2) & \cdots & r_i(G_k) \end{bmatrix}^T,$$

, where, $\forall j \in [1, k]$, $r_i(G_j) = 1$ if $G_j$ is located in the illumination range of user $u_i$. Otherwise, $r_i(G_j) = 0$.

2. *Personalized user requirement*: In this setting, users decide their requirements. A user requirement is divided into two parts. The first part is the *illumination satisfaction* of whole and local lighting and the second part is the needed *illumination ranges* of whole lighting. The definition of illumination satisfaction is similar with the utility function in [24]. For each activity, a user $u_i$ specifies two mean values, $\mu^w_i$ and $\mu^l_i$, as whole and local lighting demands, respectively, and two variance values, $\sigma^w_i$ and $\sigma^l_i$, as whole and local lighting demands, respectively. We define the illumination satisfaction of a user $u_i$ by two functions

   - Satisfaction of whole lighting: $p^w_i(x) = exp(\frac{-(x-\mu^w_i)^2}{2(\sigma^w_i)^2})$, where $x$ is the measured light intensity.
   - Satisfaction of local lighting: $p^l_i(x) = exp(\frac{-(x-\mu^l_i)^2}{2(\sigma^l_i)^2})$, where $x$ is the measured light intensity.

The output values of these two functions will be between $0$ and $1$, where $0$ and $1$ mean that the user is the least and most satisfied, respectively. Fig. 2.2 illustrates an example. From Fig. 2.2, we can see that this user most likes the light intensity of $400$ lux. When the light intensity degrades or upgrades, the satisfaction of this user will decrease. For the second part, each user can specify which grids the whole lighting devices need to provide illumination. For each user $u_i$, $\forall i \in [1, n]$, the control host maintains a $R_i$ to capture the user $u_i$'s illumination range requirement.

## 2.2 System Flows

Fig. 2.3 shows the system flow of our light control system. System operations are triggered by a user's movement or by changes of the environment. Our system first adaptively decides the illumination of whole lighting devices.

- When using the fixed user requirement, our system tries to find the illumination which can minimize the power consumption under the constraint that users' requirements can be satisfied.
- When using the personalized user requirement, we aim to provide illumination to maximize the summation of all users' satisfaction values under the constraint that each user's satisfaction is larger than a threshold $\bar{t}$. For example, when setting $\bar{t} = 0.3$ and a user's preference as Fig. 2.2, we should provide illumination in the interval (denoted as *preference interval*) $[245, 555]$ for the user.

The outcomes of the whole lighting decision will be an $m \times 1$ column vector

$$A_{wd} = \begin{bmatrix} a(wd_1) & a(wd_2) & \cdots & a(wd_m) \end{bmatrix}^T,$$

where $a(wd_j)$, $\forall j \in [1, m]$, is the needed adjustment for whole lighting device $wd_j$. For example, if $l^c(wd_j) = 300$ lux and $a(wd_j) = 50$ lux, we need to level up $wd_j$ to provide a light intensity of 350 lux. After deciding the illumination, our system adjusts devices by a device control algorithm. The control algorithm utilizes fixed sensors' feedbacks to adaptively adjust light settings. The goal is to quick converge to the desired illumination.

After adjusting whole lighting devices, local lighting devices compensate illuminations to satisfy users' requirements on local lighting. Our system makes decisions of local illumination that can minimize the power consumption or maximize users satisfactions when using fixed or personalized user requirements, respectively. The control host decides the adjustments for each

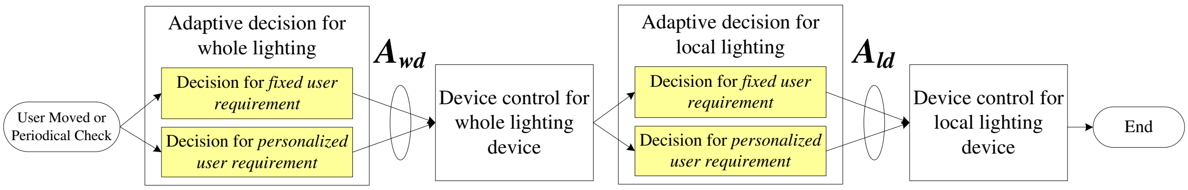


Figure 2.3: The system flow of our light control system.

local lighting device. The outcomes will be an $m' \times 1$ column vector

$$A_{ld} = \begin{bmatrix} a(ld_1) & a(ld_2) & \cdots & a(ld_{m'}) \end{bmatrix}^T,$$

where $a(ld_j)$, $\forall j \in [1, m']$, is the needed adjustment for local lighting device $ld_j$. Then the device control algorithm controls local lighting devices by utilizing the feedbacks from portable sensors.

# Chapter 3

# Adaptive Decisions for Fixed User Requirement

## 3.1 Decision for Whole Lighting Devices

We model the adaptive decision for fixed user requirement as a linear programming formula. Before presenting the formulation, we first introduce two needed notations. The first one is matrix $\bar{R}_i$, $\forall i \in [1, n]$ constructed from $R_i$, $\forall i \in [1, n]$. An $\bar{R}_i$ is constructed by the following rules. For the $l$-th element $r_i(G_l)$ in $R_i$, generate an element $\bar{r}_i(G_l)$ with the same value with $r_i(G_l)$ at position $(l, l)$. For all other elements in $\bar{R}_i$, assign to $0$.

$$\bar{R}_i = \begin{bmatrix} r_i(G_1) & 0 & \cdots & 0 \\ 0 & r_i(G_2) & \cdots & 0 \\ 0 & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & r_i(G_k) \end{bmatrix}.$$

We can notice that an $\bar{R}_i$ is a $k \times k$ matrix. The second one is a $1 \times m$ row vector, where each element in $X_m$ is $1$.

$$X_m = \begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}.$$

The $X_m$ matrix is used to sum all variables in our formulations.

In the proposed linear programming formula, the objective is to minimize the power consumption of whole lighting devices while satisfy users' requirements. The formula is defined as follows.

Objective:

$$\min \quad X_m(A_{wd} + L_{wd}^c) \tag{3.1}$$

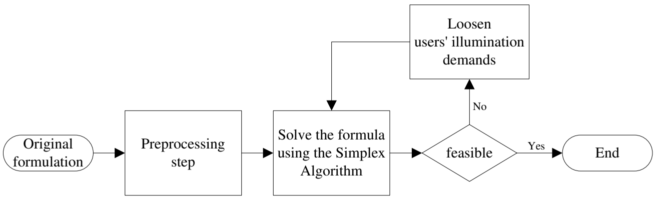


Figure 3.1: The flow of the adaptive decision for fixed user requirement.

Subject to:

$$D^l_{wd}(i)R_i \leq \bar{R}_i(S^f + WA_{wd}) \leq D^u_{wd}(i)R_i, \quad \forall i \in [1, n] \tag{3.2a}$$

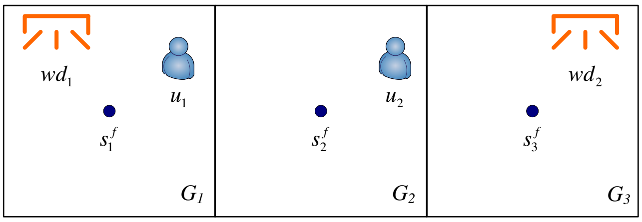
$$O \leq A_{wd} + L^c_{wd} \leq L^{max}_{wd} \tag{3.2b}$$

In Eq. (3.1), $A_{wd} + L^c_{wd}$ means the set of light intensities provided by all whole lighting devices. The object is to minimize the light intensities provided by whole lighting devices to conserve power. Eq. (3.2a) is the constraint for satisfying user requirements. $S^f + WA_{wd}$ represents light intensities of grids after light adjustment. The Eq. (3.2a) means that the light intensities of the grids located in the illumination range of a user $u_i$ should be bounded by $[D^l_{wd}(i), D^u_{wd}(i)]$. Eq. (3.2b) is to confine the adjusted light intensity of a device because that the maximum capability of a whole lighting device $wd_j$ is $l^{max}(wd_j)$.

In general, the above formulation can be solved using the Simplex algorithm [6]. But, in some cases, the above formulation may be infeasible, i.e. there is no solution. For example, assume that there are two users located in one grid. If one user is reading and the other is sleeping, their demands will be contradicted. If possible, our system should satisfy all users' demands. Otherwise, most users' demands should be satisfied. However, reference [22] shows that find a feasible subsystem of a linear system by eliminating the fewest constraints is NP-hard. In this paper, a preprocessing step is used to check if there exists constraints, which make the formula infeasible. If so, these constraints will be eliminated. Then the control host executes the Simplex algorithm to solve the formulation. If the Simplex algorithm can not find a solution, which means that the formulation is still infeasible after the preprocessing step. In this case, the control host carefully loosens users' illumination demands until the solution can be found. The decision flow is shown in Fig. 3.1.

The purpose of preprocessing step is to eliminate constraints which cause the formula infeasible. We propose two checking methods.

- Illumination demand interval check: For each grid $G_i$, find the users $\bar{U}$, whose illumination ranges contain $G_i$. Check if the illumination demands of $\bar{U}$ are intersected. If not, greedily eliminate $G_i$ from the illumination range of a user in $\bar{U}$ until the illumination demands of $\bar{U}$ are intersected.



$$S^f = [100 \quad 100 \quad 100]^T$$

$$R^1 = [1 \quad 0 \quad 0]^T \quad R^2 = [0 \quad 1 \quad 0]^T \qquad W = \begin{bmatrix} 1 & 0 \\ 0.6 & 0.6 \\ 0 & 1 \end{bmatrix}$$

$$L_{wd}^c = [0 \quad 0]^T \quad L_{wd}^{max} = [1000 \quad 1000]^T$$

Figure 3.2: An example of adaptive decision for whole lighting devices.

- Possible illumination check: By the definition of $S^f$, $L^c_{wd}$, and $L^{max}_{wd}$, we can compute the minimum and maximum possible illumination of grids as $S^f - WL^c_{wd}$ and $S^f + W(L^{max}_{wd} - L^c_{wd})$. For each grid $G_i$, find the users $\bar{U}$, whose illumination ranges covered $G_i$. For each user $u$ in $\bar{U}$, check if $u$'s illumination demand intersects with the minimum and maximum possible illumination of $G_i$. If not, eliminate $G_i$ from the illumination range of user $u$.

After the preprocessing step, the formulation may be still infeasible. When the Simplex algorithm can not find a solution, the constraints of users will be loosened. For each user $u_i$, $\forall i \in [1, n]$, $u_i$'s illumination demand will be changed to $[D^l_{wd}(i) - \alpha, D^u_{wd}(i) + \alpha]$, where $\alpha$ is a constant.

### 3.1.1 Example

We present an example to demonstrate the proposed formulation. In the Fig. 3.2, there are 3 grids, 2 users and 2 whole lighting devices. Assume that user $u_1$'s illumination demand of whole lighting is [200, 400] and the demand of user $u_2$ is [300, 500]. And other used parameters are listed in Fig. 3.2.

Objective:

$$\begin{aligned} & \min \quad \begin{bmatrix} 1 & 1 \end{bmatrix} \left( \begin{bmatrix} a(wd_1) \\ a(wd_2) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \right) \\ \Rightarrow & \min \quad (a(wd_1) + a(wd_2)) \end{aligned} \tag{3.3}$$

Constraint of $u_1$:

$$200 \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \leq \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \left( \begin{bmatrix} 100 \\ 100 \\ 100 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0.6 & 0.6 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} a(wd_1) \\ a(wd_2) \end{bmatrix} \right) \leq 400 \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$\Rightarrow \begin{bmatrix} 200 \\ 0 \\ 0 \end{bmatrix} \leq \begin{bmatrix} 100 + a(wd_1) \\ 0 \\ 0 \end{bmatrix} \leq \begin{bmatrix} 400 \\ 0 \\ 0 \end{bmatrix} \tag{3.4}$$

Constraint of $u_2$:

$$\begin{bmatrix} 0 \\ 300 \\ 0 \end{bmatrix} \leq \begin{bmatrix} 0 \\ 100 + 0.6a(wd_1) + 0.6a(wd_2) \\ 0 \end{bmatrix} \leq \begin{bmatrix} 0 \\ 500 \\ 0 \end{bmatrix} \tag{3.5}$$

Constraints of devices:

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} \leq \begin{bmatrix} a(wd_1) \\ a(wd_2) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} \leq \begin{bmatrix} 1000 \\ 1000 \end{bmatrix} \tag{3.6}$$

The above can be solved by the Simplex algorithm. The result of $a(wd_1)$ and $a(wd_2)$ will be 182 and 152, respectively.

## 3.2 Decision for Local Lighting Devices

In the following, we decide the $A_{ld}$. From $C$, we can know the relationships betweens users and local lighting devices. For each element $c_i^j = 1$ in $C$, we can obtain the following equation

$$D_{ld}^l(i) \leq a(ld_j) + s^p(u_i) \leq D_{ld}^u(i).$$

Since our goal is to minimize the power consumption, we can adjust local lighting devices to fit the lower bounds of user requirements. The $A_{ld}$ can be computed by the following procedures. For each local lighting device $ld_j$, if there is an element $c_i^j = 1$, where $1 \leq i \leq n$, set $a(ld_j) = D_{ld}^l(i) - s^p(u_i)$. Otherwise, set $a(ld_j) = -l^c(ld_j)$. Note that if $a(ld_j) < -l^c(ld_j)$, set $a(ld_j) = -l^c(ld_j)$, and, if $a(ld_j) + l^c(ld_j) > l^{max}(ld_j)$, set $a(ld_j) = l^{max}(ld_j) - l^c(ld_j)$.

Fig. 3.3 shows an example. Assume that user $u_1$'s illumination demand of local lighting is [800, 1000] and the device $ld_1$ needs to serve the user. The light intensity measured by sensor $s_1^p = 300$ lux and $l^c(ld_1) = 0$. Thus, the $a(ld_1)$ will be $800 - 300 = 500$ lux. Similarly, the $a(ld_2)$ will be $900 - 400 = 500$ lux.

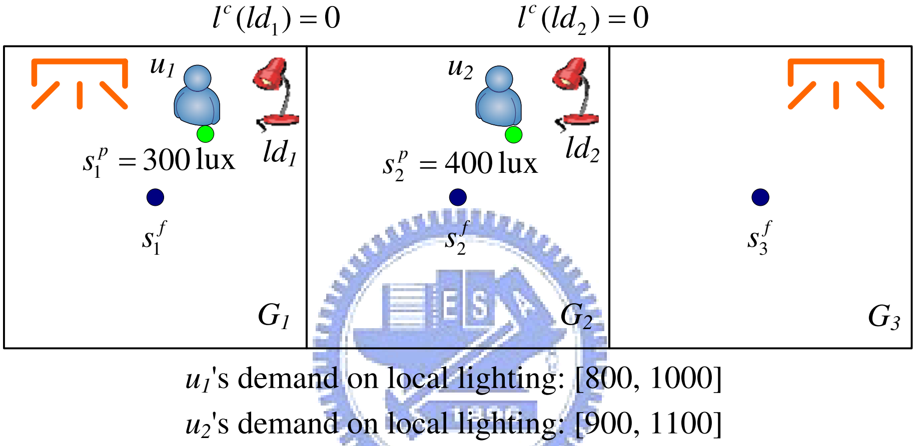


Figure 3.3: An example of adaptive decision for local lighting devices when using fixed user requirements.

# Chapter 4

# Adaptive Decisions for Personalized User Requirement

## 4.1 Decision for Whole Lighting Devices

We define a non-linear programming formula for personalized user requirement. The goal is to maximize satisfaction of users under the constraint that users' satisfaction values should be greater than or equal to a satisfaction threshold $\bar{t}$. For ease of presentation, in the objective, we further define a function $P'_i : \mathbb{R}_{(k\times1)} \rightarrow \mathbb{R}_{(k\times1)}$ for an user $u_i$ that $P'_i(A) = A'$, where $A = [a_{xy}] \in \mathbb{R}_{(k\times1)}$ and $A' = [a'_{xy}] \in \mathbb{R}_{(k\times1)}$ by $a'_{xy} = p_i^w(a_{xy})$. And, in the constraints, the preference interval of a user $u_i$ is $[pi^l(i), pi^u(i)]$, where $pi^l(i) = \mu_i - \sigma_i\sqrt{-2\ln(\bar{t})}$ and $pi^u(i) = \mu_i + \sigma_i\sqrt{-2\ln(\bar{t})}$. The formula is listed as below.

Objective:

$$\max \quad \sum_{i=1}^{n}(R_i)^T \cdot P'_i(S^f + WA_{wd}) \tag{4.1}$$

Subject to:

$$pi^l(i)R_i \leq \bar{R}_i(S^f + WA_{wd}) \leq pi^u(i)R_i, \quad \forall i \in [1, n] \tag{4.2a}$$

$$O \leq A_{wd} + L^c_{wd} \leq L^{max}_{wd} \tag{4.2b}$$

As shown in (4.1), a user $u_i$'s satisfaction is the summation of the satisfaction values in $u_i$'s illumination range. The objective is to maximize all users' satisfactions. Eq. (4.2a) is to restrict the satisfaction value in the illumination ranges of users should be larger than a threshold $\bar{t}$. Eq. (4.2b) is to confine the adjusted light intensity of whole lighting devices.

We solve the formulation by a sequential quadratic programming (SQP) [3] method. The basic idea of SQP is as follows. Given a non-linear formula, SQP first reformulates the original one by a quadratic programming subproblem using a give approximate solution $x^k$. Then, SQP uses the solution of the subproblem to construct a better approximation $x^{k+1}$. The process is iterated to create a sequence of approximations that will converge to an optimal solution $x^*$.

As in Section 3.1, in some cases, we cannot satisfy all users. Here, we can apply the preprocessing in Section 3.1 to check if the users' preference intervals are overlapped. If the formulation is still infeasible, we greedily decrease the threshold $\bar{t}$ to $\bar{t} - \gamma$, where $0 < \gamma \leq \bar{t}$, until there is a solution can be found.

### 4.1.1 Example

We present an example to demonstrate the proposed formula. The scenario is the same as Fig. 3.2. We assume that ($\mu_1^w$, $\sigma_1^w$) of user $u_1$ is (300, 100) and ($\mu_2^w$, $\sigma_2^w$) of user $u_2$ is (400, 100). Besides, we define $\bar{t} = 0.3$, which implies the preference intervals of user $u_1$ and $u_2$ are [145, 455] and [245, 555], respectively.

Objective:

$$
\begin{aligned}
& \max \quad \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} P_1^* \left( \begin{bmatrix} 100 \\ 100 \\ 100 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0.6 & 0.6 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} a(wd_1) \\ a(wd_2) \end{bmatrix} \right) \\
& \qquad + \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} P_2^* \left( \begin{bmatrix} 100 \\ 100 \\ 100 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0.6 & 0.6 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} a(wd_1) \\ a(wd_2) \end{bmatrix} \right) \\
\Rightarrow \quad & \max \quad \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} P_1^* \left( \begin{bmatrix} 100 + a(wd_1) \\ 100 + 0.6a(wd_1) + 0.6a(wd_2) \\ 100 + a(wd_2) \end{bmatrix} \right) \\
& \qquad + \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} P_2^* \left( \begin{bmatrix} 100 + a(wd_1) \\ 100 + 0.6a(wd_1) + 0.6a(wd_2) \\ 100 + a(wd_2) \end{bmatrix} \right) \\
\Rightarrow \quad & \max \quad p_1^w(100 + a(wd_1)) + p_2^w(100 + 0.6a(wd_1) + 0.6a(wd_2)) \qquad (4.3)
\end{aligned}
$$

Constraints of $u_1$:

$$(300-100\sqrt{-2\ln 0.3})\begin{bmatrix}1\\0\\0\end{bmatrix}\leq$$

$$\begin{bmatrix}1&0&0\\0&0&0\\0&0&0\end{bmatrix}\left(\begin{bmatrix}100\\100\\100\end{bmatrix}+\begin{bmatrix}1&0\\0.6&0.6\\0&1\end{bmatrix}\begin{bmatrix}a(wd_1)\\a(wd_2)\end{bmatrix}\right)$$

$$\leq(300+100\sqrt{-2\ln 0.3})\begin{bmatrix}1\\0\\0\end{bmatrix}$$

$$\Rightarrow\begin{bmatrix}145\\0\\0\end{bmatrix}\leq\begin{bmatrix}100+wa_1\\0\\0\end{bmatrix}\leq\begin{bmatrix}455\\0\\0\end{bmatrix}\tag{4.4}$$

Constraints of $u_2$:

$$\begin{bmatrix}0\\245\\0\end{bmatrix}\leq\begin{bmatrix}0\\100+0.6a(wd_1)+0.6a(wd_2)\\0\end{bmatrix}\leq\begin{bmatrix}0\\555\\0\end{bmatrix}\tag{4.5}$$

Constraints of devices:

$$\begin{bmatrix}0\\0\end{bmatrix}\leq\begin{bmatrix}a(wd_1)\\a(wd_2)\end{bmatrix}+\begin{bmatrix}0\\0\end{bmatrix}\leq\begin{bmatrix}1000\\1000\end{bmatrix}\tag{4.6}$$

After applying SQP, we obtain the result of $a(wd_1)$ and $a(wd_1)$ are 200 and 300, respectively.

## 4.2 Decision for Local Lighting Devices

In the following, we decide the $A_{ld}$ for personalized user requirements. Similar to Section 3.2, we first obtain the relationships betweens users and local lighting devices from $C$. The goal is to adjust local lighting devices that can maximize the satisfaction of users. The $A_{ld}$ is computed by the following procedures. For each local lighting device $ld_j$, if there is an element $c_i^j = 1$, where $1 \leq i \leq n$, find a setting of $a(ld_j)$ such that $p_i^l(a(ld_j)+s^p(u_i)) = 1$. Otherwise, set $a(ld_j) = -l^c(ld_j)$. Note that if $a(ld_j) < -l^c(ld_j)$, set $a(ld_j) = -l^c(ld_j)$, and, if $a(ld_j) + l^c(ld_j) > l^{max}(ld_j)$, set $a(ld_j) = l^{max}(ld_j) - l^c(ld_j)$.

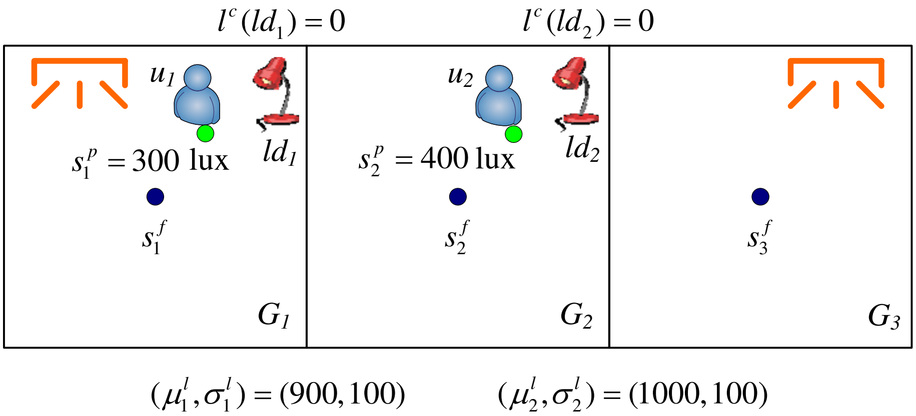


Figure 4.1: An example of adaptive decision for local lighting devices when using personalized user requirements.

Fig. 4.1 shows an example. User $u_1$ specifies $(\mu_1^l, \sigma_1^l)$ as $(900, 100)$ and the device $ld_1$ needs to serve the user. The illumination measured by the sensor $s_1^p = 300$ lux and $l^c(ld_1) = 0$. Thus, in order to let $p_1^l(a(ld_1) + 300) = 1$, we can set $a(ld_1) = 600$ lux. Similarly, the adjustment value for device $ld_2$ will be $600$ lux.

# Chapter 5

# Device Control Algorithm

The object of this algorithm is to adjust lighting devices to provide sufficient illuminations decided by the above decision algorithms. We use two column vectors $GD_{wd} = [gd(wd_1)\ gd(wd_2)\ \cdots\ gd(wd_m)]^T$ and $GD_{ld} = [gd(ld_1)\ gd(ld_2)\ \cdots\ gd(ld_{m'})]^T$ to record the adjustment goals of devices, where $GD_{wd} = A_{wd} + L^c_{wd}$ and $GD_{ld} = A_{ld} + L^c_{ld}$, respectively.

In this paper, we assume that the relationships between the on-levels and the provided light intensities of devices are unknown. After obtaining $GD_{wd}$ and $GD_{ld}$, this algorithm performs a closed-loop control mechanism to find on-level settings to achieve $GD_{wd}$ and $GD_{ld}$. The main idea of the closed-loop control is to perform a binary search on the on-levels of devices. The procedure is shown in Fig. 5.1. At beginning, the control host decides on-level settings for devices and then sends commands to control dimmers. After adjustment, sensors report light intensities to the control host. The control host can judge if the light intensities provided by devices achieve $GD_{wd}$ and $GD_{ld}$. If not, the control host decides new on-level settings with reduced search spaces. Fig. 5.2 shows the control flow. We use the example in Section 3.1.1 to explain the procedure of our device control algorithm. The $a(wd_1) = 184$ lux and $a(wd_2) = 150$ lux. Assume that $wd_1$ and $wd_2$ are not turned on. The $gd(wd_1)$ and $gd(wd_2)$ will be 184 lux and 150 lux, respectively.

- Round 1: We set on-levels of $wd_1$ and $wd_2$ as $50\%$ and $50\%$, respectively. Assume the current light intensities provided by $wd_1$ and $wd_2$ are both 500 lux. Since $500 \neq 184$ and $500 \neq 150$, the goals are not reached.

- Round 2: Since 500 lux is larger than 184 lux and 150 lux, the on-levels of $wd_1$ and $wd_2$ must be located in level $[0, 50\%]$. The control host will decide level $25\%$ and $25\%$ for $wd_1$ and $wd_2$, respectively. Assume the current light intensities provided by $wd_1$ and $wd_2$ are both 270 lux. Since $270 \neq 184$ and $270 \neq 150$, the goals are not reached.

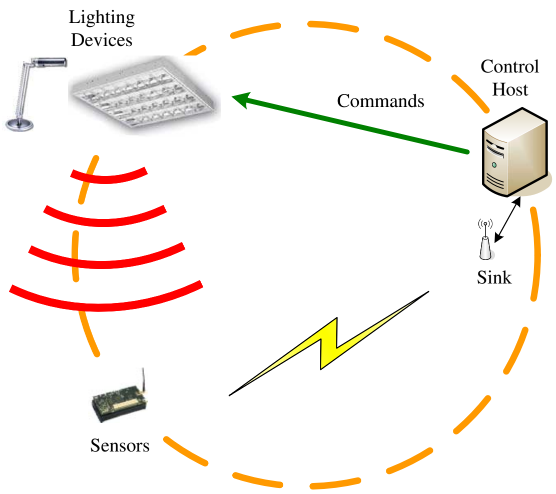


Figure 5.1: Mechanism of closed-loop device control.

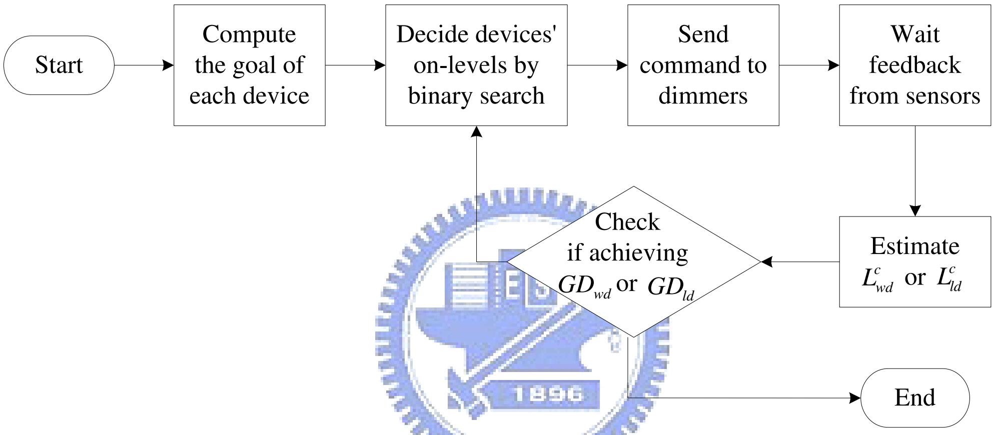


Figure 5.2: Flow of device control algorithm.

- Round 3: Since 270 lux is larger than 184 lux and 150 lux, the on-levels of $wd_1$ and $wd_2$ must be located in level $[0, 25\%]$. The control will decide level $12.5\%$ and $12.5\%$ for $wd_1$ and $wd_2$, respectively. Assume the current light intensities provided by $wd_1$ and $wd_2$ are both 150 lux. Device $wd_2$ achieves $gd(wd_2)$. The control process continues in the same way until $wd_1$ achieves $gd(wd_1)$.

Note that when controlling the whole lighting devices, the control host uses feedbacks from fixed sensors to estimate $L^c_{wd}$ by Eq. (2.1). On the other hand, when controlling the local lighting devices, the control host uses feedbacks from portable sensors to estimate $L^c_{ld}$. Also note that, in practice, the on-levels of dimmers are discrete and have finite levels. When control lighting devices, we can relieve the goals $GD_{wd}$ and $GD_{ld}$ to goal intervals. Moreover, during the device control procedure, the control host can record the relationship between the light intensities provided by devices and on-levels of devices. The control host can use this information to accelerate the device control procedure.

# Chapter 6

# Prototyping Results

## 6.1 Implementation

In this section, we present the implementation of our system in detail. Fig. 6.1 shows the architecture of our intelligent light control system. Wireless sensors collect illuminative values in the room and report to the sink. Then, the control host does a suitable decision by adaptive decision algorithm and triggers actions to adjust the whole and local lighting devices. Fig. 6.2 shows the prototyping result of our system. We built our system in a room with a size of $5 \times 5$ meters and divided into $3 \times 3$ grids. To implement the system, we design a protocol stack, as shown in Fig. 6.3. The protocol stack can be divided into three parts: wireless sensor network, actuators, and control host. We briefly describe each part separately in the following section.

### 6.1.1 Wireless Sensor Network

We use the MICAz mote [7] with light sensor board designed by ourselves as the sensor node, as shown in Fig. 6.4. The MICAz mote is an IEEE 802.15.4 compliant wireless module and operations in $2.4$ GHz. We use Si photodiode [23] to design a light sensor due to that the original light sensor with MICAz mote is not accurate enough to support our need.

In our system, two types of messages must be reported to the sink: *reporting message* and *updating message*. The reporting message contains sensory data and the updating message contains users' activities and location information. In order to support these two types of messages, we form a heterogeneous wireless sensor network which contains two kinds of sensor nodes with different functionalities. The first kind of sensor node is fixed sensor. The fixed sensors sense the illumination in each grid and transmit reporting message to the sink periodically. The second kind of sensor node is portable sensor. The portable sensors are carried by the users and used to identify each user and users' locations. Also, the portable sensors can measure the

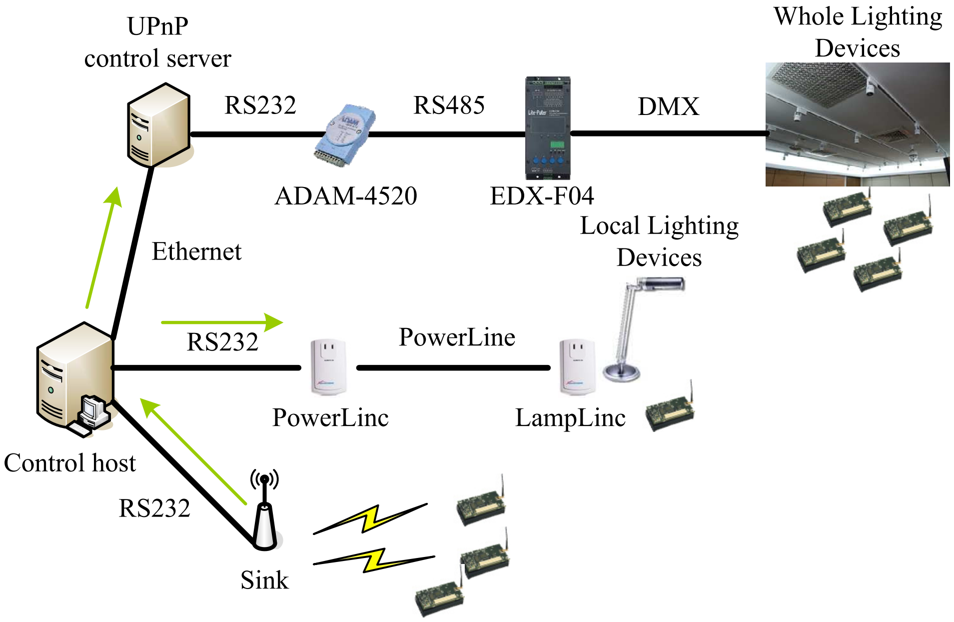


Figure 6.1: System architecture of the intelligent light control system.

Figure 6.2: Prototyping result of our intelligent light control system.

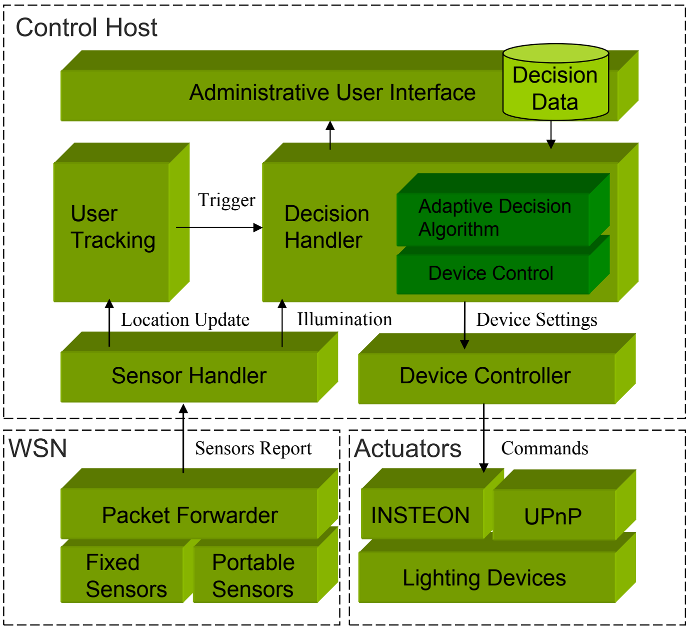


Figure 6.3: Protocol stack of the intelligent light control system.

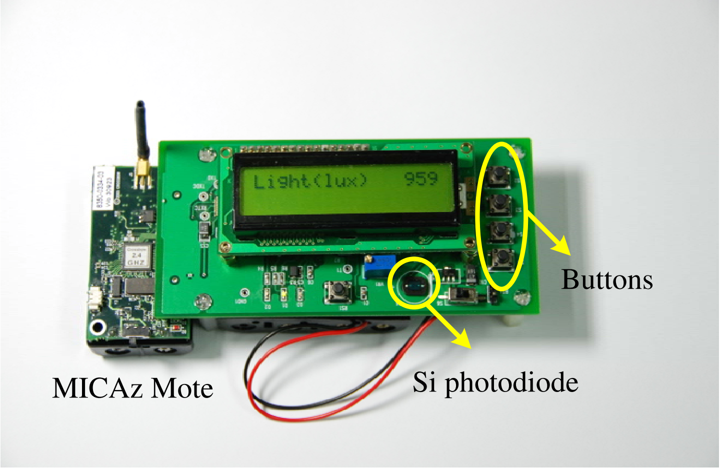


Figure 6.4: MICAz mote with light sensor board.

illumination of work surface for the users and report users' activities by pressing the button on light sensor board. The portable sensors report reporting message and updating message to the sink node periodically. In order to get users' location information, we adopt a simple localizing scheme for our system. The portable sensors carried by users overhear the reporting messages of fixed sensors around the users. If the strongest signal beyond a threshold is overheard by portable sensors in a period of time, the portable sensors send an updating message to the sink to announce user's location information.

The sink, which is connected to the control host via a RS232 interface, collects the reporting and updating messages from each sensor node in the system. The *Packet Forward* component receives the collected messages from the sink and forwards the messages to the *Sensor Handler* of the control host.

### 6.1.2 Actuators

For the actuators, we use two control protocols to control whole and local lighting devices in our current implementation. The whole lighting devices in Fig. 6.5 are controlled by UPnP [29] protocol. We adopt the dimmer and controller manufactured by SmartHome [25] to control the local lighting devices. These two kinds of lighting devices have 101 levels, ranging from $0\%$ to $100\%$ degree of luminance, for adjustment.

UPnP is a set of computer network protocols defined by the UPnP Forum. The UPnP control server sends the UPnP device control message to UPnP-enabled devices through Internet. The UPnP control server uses RS232 to connect ADAM-4250 [1], which is a converter that converts RS232 to RS485. The ADAM-4250 connects to an EDX-F04 [10], which is four channel DMX dimming pack and can adjust four lighting devices. We implement the UPnP Lighting Controls V1.0 standard [29] in our current implementation. When the UPnP control server receives commands from the *Device Controller* interface of control host, UPnP control server sends on-level commands to adjust the whole lighting devices.

We use the INSTEON LampLinc v2 and PowerLinc controller v2 produced by SmartHome [25] as the dimmer and controller to control local lighting devices, as shown in Fig. 6.6. The dimmer can be controlled by the controller device remotely through the power-line network. Dimmer and controller should be plugged in the outlet and use the protocol designed by the SmartHome to communicate with each other. Dimmer and controller have an unique INSTEON address assigned by the manufacturer to identify the devices. The controller is connected to the control host via an RS232 interface. When the controller receives the command from the *Device Controller* interface of control host, controller sends an on-level command to the dimmer to adjust the local lighting device.

Figure 6.5: UPnP-enabled whole lighting devices.

Figure 6.6: INSTEON controller and dimmer.

### 6.1.3 Control Host

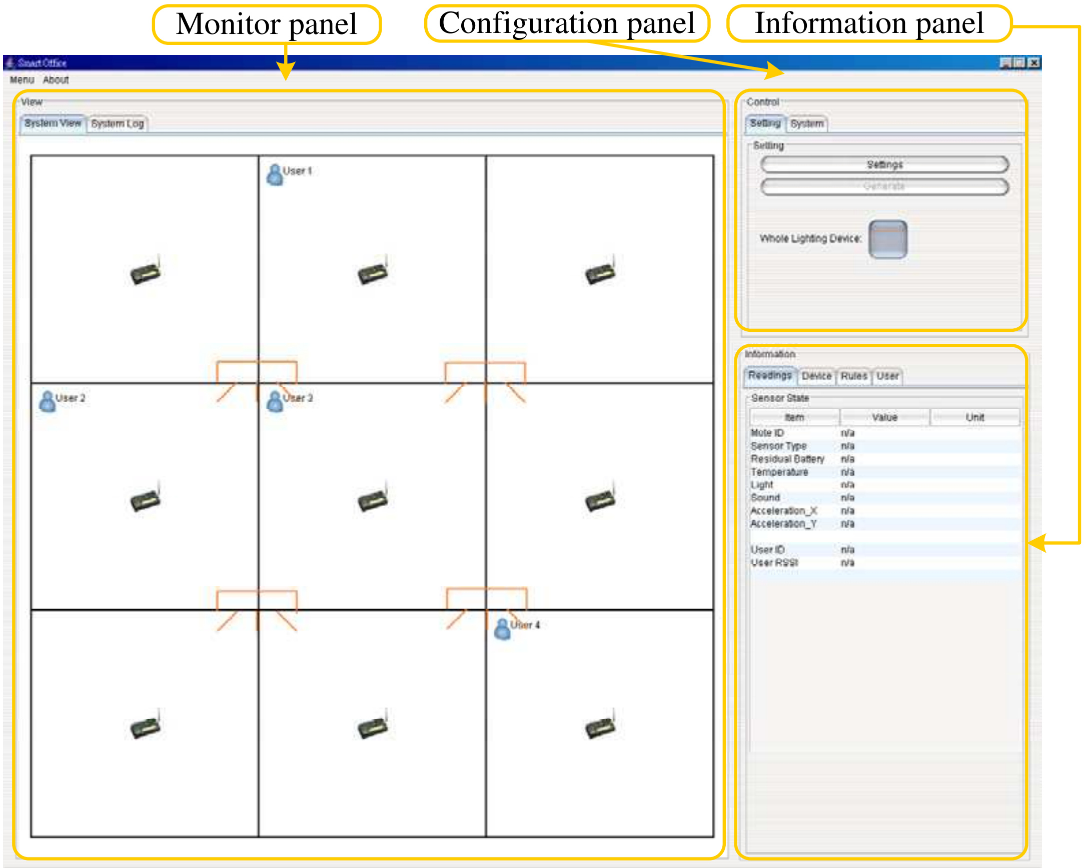
The control host is the core of our lighting system. We implement it in Java programming language. The control host is composed of five components: *Sensor Handler*, *User Tracking*, *Decision Handler*, *Device Controller*, and *Administrative User Interface*. Except the Device Controller, other components are implemented by Java thread and concurrently handle the tasks.

- *Sensor Handler*: The Sensor Handler receives the reporting and updating messages from the Packet Forward component of WSN. Based on the types of messages, Sensor Handler does following actions. If the message is a reporting message, the Sensor Handler has to translate the sensory data to the reading of standard unit. Take light for example, Sensor Handler translates the raw data of illuminative value to lux. Then, the Sensor Handler stores the sensory data into a table such that the data can be queried by other components. If Sensor Handler receives the updating message, it dispatches the message to the User Tracking component.

- *User Tracking*: The User Tracking component keeps and checks the newest users' locations and activities. If someone changes his/her location or activity, User Tracking sends triggers to the Decision Handler to adjust the lighting devices to satisfy the users' needs.

- *Decision Handler*: Decision Handler is the main component of the control host. It implements the adaptive decision algorithms in Section 3 and Section 4 and device control algorithms in Section 5. When the Decision Handler receives the triggers from the User Tracking component or a periodical checking timer expires, it starts to execute the adaptive decision algorithms. According the sensory data, users' locations, users' activities, and users' requirements, Decision Handler will execute the decision algorithm to compute a proper illuminative value for all lighting devices. We solve the linear or non-linear programming model in adaptive decision algorithms by MATLAB and translate the MATLAB program to Java program by MATLAB Builder for Java [17]. According to the results of decision algorithms, Decision Handler sends device settings to the Device Controller to adjust lighting devices.

- *Device Controller*: The Device Controller is an interface between the control host and the actuators. Device Controller sends UPnP commands to UPnP control server through Internet to adjust the whole lighting devices. Also, Device Controller sends INSTEON commands to INSTEION controller through RS232 interface to adjust the local lighting devices.

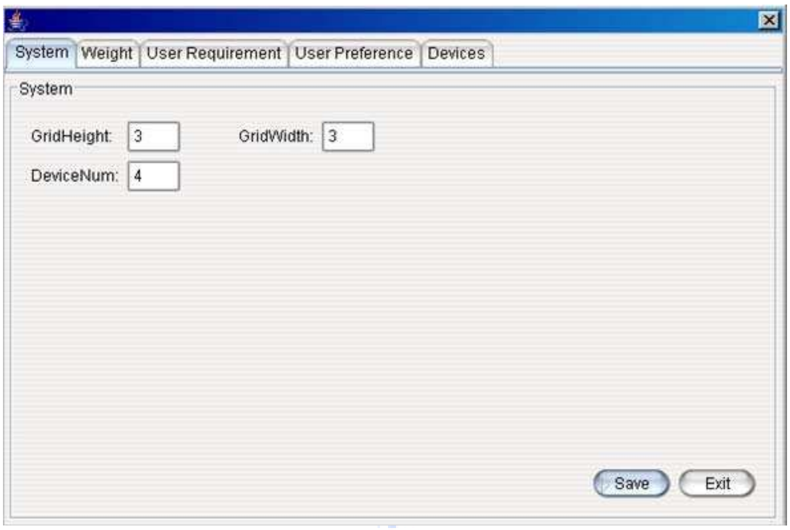


Sensor State

| Item | Value | Unit |
|---|---|---|
| Mote ID | n/a | |
| Sensor Type | n/a | |
| Residual Battery | n/a | |
| Temperature | n/a | |
| Light | n/a | |
| Sound | n/a | |
| Acceleration_X | n/a | |
| Acceleration_Y | n/a | |
| User ID | n/a | |
| User RSSI | n/a | |

Figure 6.7: *Administrative User Interface* at control host.

- *Administrative User Interface*: Fig. 6.7 is an Administrative User Interface, including *Monitor Panel*, *Configuration Panel*, and *Information Panel*. The Monitor Panel represents that users' locations and the positions of whole lighting devices. Through the Configuration Panel, administrators can manage the system. Information Panel shows the system information such as light reading, signal strength of sensor nodes, etc. Fig. 6.8 is the dialog for setting system information, such as grid size, the number of devices, and fixed users' requirement, etc.



System

GridHeight: 3

GridWidth: 3

DeviceNum: 4

Figure 6.8: Dialog window for setting system information.

# Chapter 7

# Conclusions and Future Works

In this work, we have presented an intelligent light control system that can automatically control lighting to satisfy each user's illuminative requirement. Besides, utilize WSNs to collect and report illumination of environment and user's information. The user requirement is decided by the current activity of the user. Fixed user requirement scheme can satisfy each user's illuminative demands which are set by our system according to users' current activities for background light and concentrated light. On the other hand, personalized user requirement scheme obtains users' requirements for different activities from users and attempts to maximize total satisfaction of each user to guarantee that satisfaction of each user should be above a predefined threshold. If the indoor environment has adequate sunlight, we can use the external light to reduce the energy consumption of lighting devices and still satisfy each user's requirement. The device control algorithm forms a closed-loop to control lighting to achieve the optimal illumination which is computed by decision algorithm for each device. We implement our the system in an indoor environment. While our system detects that users move or change activity in the space, our system adjusts the lighting to satisfy users' requirements.

We only discuss how to control lighting in an indoor environment. We can not directly apply our system to other environmental factors, such as sound, temperature, and humidity. In our future work, we can improve our system to adapt other environmental factors. Besides, the users' preference must be beforehand in our system. Hence, in the future, we can design a learning system to obtain the users' preference automatically such that our system would be more suitable to real life

# Bibliography

[1] Adam-4250. http://www.advantech.tw/products/Model_Detail.asp.

[2] J. Bachrach, R. Nagpal, M. Salib, and H. Shrobe. Experimental results and theoretical analysis of a self-organizing global coordinate system for ad hoc sensor networks. *Telecommunications Systems Journal*, 26(2-4):213–234, 2004.

[3] P. T. Boggs and J. W. Tolle. Sequential quadratic programming. *Acta Numerica*, 4:1–51, 1995.

[4] D. Braginsky and D. Estrin. Rumor routing algorithm for sensor networks. In *Proc. of ACM Int'l Workshop on Wireless Sensor Networks and Applications (WSNA)*, 2002.

[5] S. Capkun, M. Hamdi, and J.-P. Hubaux. GPS-free positioning in mobile ad-hoc networks. In *Proc. of Hawaii Int'l Conference on Systems Science (HICSS)*, 2001.

[6] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and C. Stein. *Introduction to Algorithms 2nd Edition*. The MIT Press and McGraw-Hill Book Company, 2001.

[7] Crossbow technology Inc. http://www.xbow.com/.

[8] T. Dam and K. Langendoen. An adaptive energy-efficient MAC protocol for wireless sensor networks. In *Proc. of ACM Int'l Conference on Embedded Networked Sensor Systems (SenSys)*, 2003.

[9] Design and construction of a wildfire instrumentation system using networked sensors. http://firebug.sourceforge.net/.

[10] Edx-f04. http://www.liteputer.com.cn/china/liteputer-tw/product.asp.

[11] Habitat monitoring on great duck island. http://www.greatduckisland.net/technology.php.

[12] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan. Energy-efficient communication protocols for wireless microsensor networks. In *Proc. of Hawaii Int'l Conference on Systems Science (HICSS)*, 2000.

[13] C.-F. Huang, Y.-C. Tseng, and L.-C. Lo. The coverage problem in three-dimensional wireless sensor networks. In *Proc. of IEEE Global Telecommunications Conference (Globecom)*, 2004.

[14] M. Kochhal, L. Schwiebert, and S. Gupta. Role-based hierarchical self organization for wireless ad hoc sensor networks. In *Proc. of ACM Int'l Workshop on Wireless Sensor Networks and Applications (WSNA)*, 2003.

[15] Q. Li, M. DeRosa, and D. Rus. Distributed algorithm for guiding navigation across a sensor network. In *Proc. of ACM Int'l Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, 2003.

[16] C.-Y. Lin and Y.-C. Tseng. Structures for in-network moving object tracking in wireless sensor networks. In *Proc. of Broadband Wireless Networking Symposium (BroadNet)*, 2004.

[17] Matlab Builder for Java. http://www.mathworks.com/products/javabuilder/.

[18] S. Meguerdichian, F. Koushanfar, M. Potkonjak, and M. B. Srivastava. Coverage problems in wireless ad-hoc sensor networks. In *Proc. of IEEE INFOCOM*, 2001.

[19] D. Niculescu and B. Nath. DV based positioning in ad hoc networks. *Telecommunications Systems Journal*, 22(1-4):267–280, 2003.

[20] F. O'Reilly and J. Buckley. Use of wireless sensor networks for fluorescent lighting control with daylight substitution. In *Proc. of Workshop on Real-World Wireless Sensor Networks (REANWSN)*, 2005.

[21] H. Park, M. B. Srivastava, and J. Burke. Design and implementation of a wireless sensor network for intelligent light control. In *Proc. of Int'l Symposium on Information Processing in Sensor Networks (IPSN)*, 2007.

[22] J. Sankaran. A note on resolving infeasibility in linear programs by constraint relaxation. *Operations Research Letters*, 13(1):19–20, 1993.

[23] Si photodiode s1133. http://jp.hamamatsu.com/en/index.html.

[24] V. Singhvi, A. Krause, C. Guestrin, J. H. Garrett, and H. S. Matthews. Intelligent light control using sensor networks. In *Proc. of ACM Int'l Conference on Embedded Networked Sensor Systems (SenSys)*, 2005.

[25] SmartHome Inc. http://www.smarthome.com.

[26] K. Sohrabi, J. Gao, V. Ailawadhi, and G. J. Pottie. Protocols for self-organization of a wireless sensor network. *IEEE Personal Communications*, 7(5):16–27, October 2000.

[27] Y.-C. Tseng, S.-P. Kuo, H.-W. Lee, and C.-F. Huang. Location tracking in a wireless sensor network by mobile agents and its data fusion strategies. In *Proc. of Int'l Symposium on Information Processing in Sensor Networks (IPSN)*, 2003.

[28] Y.-C. Tseng, M.-S. Pan, and Y.-Y. Tsai. Wireless sensor networks for emergency navigation. *IEEE Computer*, 39(7):55–62, 2006.

[29] Upnp forum. http://www.upnp.org.

[30] Y.-J. Wen, J. Granderson, and A. M. Agogino. Towards embedded wireless-networked intelligent daylighting systems for commercial buildings. In *Proc. of IEEE Int'l Conference on Sensor Networks, Ubiquitous, and Trustworthy Computing (SUTC)*, 2006.

[31] W. Ye, J. Heidemann, and D. Estrin. An energy-efficient MAC protocol for wireless sensor networks. In *Proc. of IEEE INFOCOM*, 2002.