iLTC: Achieving Individual Comfort in Shared Spaces

Chayan Sarkar, Akshay Uttama Nambi S.N., R. Venkatesha Prasad
Delft University of Technology, The Netherlands
{c.sarkar,akshay.narashiman,r.r.venkateshaprasad}@tudelft.nl

Abstract

Automatic control of HVAC and artificial lights has been one of the popular methods for achieving energy-efficient buildings. The current systems operate using fixed set-point controls, which are usually based on a conservative approach. Additionally, the lighting systems require additional sensor deployment to cope up with continuous fluctuation of natural light intensity. In this work, we describe a smart system called **i**ndoor **L**ighting and **T**emperature **C**ontroller (**iLTC**), which eliminates the fixed set-points and requirement of additional light sensors. iLTC decides operating set-points more aggressively, which is energy optimal and it tries to provide maximal user comfort to all the co-occupants in a shared space. The flexibility in choosing energy optimal set-points stems from the knowledge of comprehensive temperature and lighting comfort functions of individuals. To track the fluctuations in natural light intensity, we employ a smart estimation technique that requires light measurements only once during the training phase. Using the proposed system, we show the energy consumption by HVAC can be reduced up to 39%. Similarly, compared to traditional on/off based and multilevel lighting systems with iLTC, energy consumption can be reduced up to 33% and 60%, respectively. We also provide qualitative user experience evaluation.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous; H.1.2 [**User/Machine Systems**]: Human Factors

General Terms

Energy-efficiency, Algorithms, Estimation

Keywords

comfort preference learning, shared space, individual comfort, shared lighting control, shared HVAC control

International Conference on Embedded Wireless Systems and Networks (EWSN) 2016
15–17 February, Graz, Austria

ISBN: 978-0-9949886-0-7

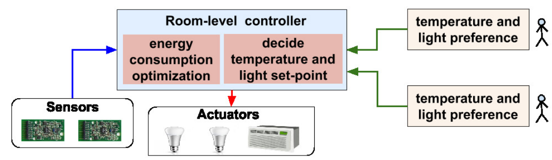


Figure 1: In iLTC a room-level controller sets an energy optimal operating point for the lighting and HVAC systems considering the comfort preferences of all the occupants.

1 Introduction

People spend more than 80% of their time in indoor environments [7]. Suitable lighting and thermal comfort plays a significant role in their physical and physiological well-being and productivity [21]. A significant amount of energy is spent on illuminating work places properly and also maintaining thermal comfort. According to the United States Energy Information Administration (EIA), HVAC (heating, ventilation, and air conditioning) and artificial lighting systems account for about 32% and 25% of electricity usage in residential and commercial buildings [4]. Thus efficient usage of the HVAC and lighting is one major step towards reducing the energy consumption in indoor spaces.

Typically, building energy management systems (BEMS) are installed to lower the energy cost by automatically controlling the actuators[1] based on the ambient conditions and occupancy [6, 8]. The trick to achieve higher energy-efficiency is to exploit natural conditions as much as possible and using the actuators to complement only the inadequacy, if any, in the natural conditions. However, most of these systems operate within a conservative range or set-point that is amenable to a large number of people providing only an average comfortable environment. For example, Monash set-point trials [3] suggested that ideally the temperature range of 21° C - 23° C, can provide thermal comfort to most of the occupants. However, HVAC operating set-point can also be chosen from a broader temperature range (19° C – 28° C) based on external conditions and thermal preferences of the users in the building. Similarly, the suggested 500 lux for an office environment may not be sufficient for some elderly people [23] and for young people lesser lumens may be suffi-

[1]In the rest of this article the term *actuators* is used for both HVAC and artificial lighting systems.

cient. Thus developing a user-centric automation method per room can reduce the energy consumption and, *pari passu* increase comfort level.

With many occupants in a shared space like office, there is a tradeoff in achieving the preferred comfort levels of users and yet achieving energy efficiency. In this work, we build and test **i**ndoor **L**ight and **T**emperature **C**ontroler (**iLTC**), which is a smart system that achieves a fine-balance while using this tradeoff. A brief overview of the system is shown in Fig. 1. Unlike traditional BEMS, iLTC employs a room-level controller[2] to decide on an energy optimal operating set-point for the actuators while trying to make all the co-occupants feel comfortable with respect to their comfort preferences. That is, the feeling of thermal and lighting comfort is not a single temperature or light intensity value for a person, but a range of values within which user can feel "equally" comfortable. Thus, iLTC needs to learn about the thermal and visual comfort preferences of each individual.

Implementing iLTC is highly challenging for the following reasons: *First*, operating set-point for the actuators is a mere number. It is not easy to correlate comfort levels of humans with a certain light intensity and temperature value. A tangible scale of comfort levels needs to be mapped onto the numbers that can decide the set-points. *Second*, thermal comfort level varies significantly from person to person. On the other hand, HVAC energy consumption is highly dependent on the temperature difference between indoor and outdoor environments. Complete information about the comfortable temperature range of each co-occupant is required to decide on a common temperature set-point while keeping HVAC consuming lowest possible energy. *Third*, lighting comfort level also varies significantly from person to person [10]. Further, unlike temperature, light intensity also varies significantly at various locations inside a room. Thus, we need a mechanism to identify natural light intensity at a desired location (e.g., work-desk of a user).

This article addresses the above challenges and provides a complete working solution. Specifically we make the following contributions and some of them are, hitherto, unexplored.

1. We develop a layered design for iLTC that can offer room-level control for the lighting and HVAC systems. The system supports distributed implementation and thus it is scalable in terms of number of rooms and occupants (Section 3).

2. Our system employs a non-intrusive mechanism to derive user comfort preferences with minimal user intervention and training. We provide comprehensive mapping functions for a person, which can indicate comfort levels of the person for any given light and temperature value. To the best of our knowledge, we are the first to provide such a comprehensive mapping functions (Section 4).

3. We estimate the natural light intensity at the work-desk of users by utilizing light sensor available in their smartphones. We derive a relationship between the light intensity measured by smartphone sensor and the outdoor light intensity with a single sensor. This eliminates the huge cost of deployment of additional sensors and their management (Section 4).

4. We propose an algorithm to determine the most energy optimal operating set-point for HVAC and lighting systems while making all the co-occupants comfortable. The option of choosing a set-point from a range of comfort values offers a wide scope for energy savings (Section 5).

The core of iLTC is implemented using Java, while an Android application was developed to collect preferences of users. Matlab scripts are used for various model developments. We collected user preference data from 21 participants housed in different rooms to create individual temperature and lighting comfort functions. A detailed evaluation of iLTC is performed based on these comfort functions to measure energy savings. Furthermore, the proposed iLTC system was tested and evaluated by many users.

2 Related Work

A significant amount of energy is wasted by the HVAC and artificial lighting systems in a building due to their inefficient usage. Thus, a large body of current works focuses on the efficient usage of these systems from various aspects. Simple solutions proposed to save energy elicit turning off the actuators automatically when there are no occupants [10, 13]. The occupancy is detected using some sensor-based mechanisms. ThermoCoach [19] provides a personalized thermostat recommendation exploiting occupancy pattern. However, the technique used cannot be applied for shared spaces where there are multiple occupants.

Another set of work focuses on the reduction in energy consumption and stable operation of the HVAC systems. While some of the research efforts have been to optimize operational efficiency of the HVAC for a given set-point temperature [12, 14], a significant number of work also emphasize on selecting a suitable set-point temperature for the HVAC in order to fulfill thermal comfort of the occupants. There are two main methods for determining thermal comfort, heat-balanced way and the adaptive approach. The predicted mean value (PMV) is the heat-balanced way and depends on six parameters: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity. Most of these parameters are difficult to obtain from typical sensors in BEMSs and hence the PMV proves to be impractical. The adaptive approach focuses on the adaptation of human psychological and physiological behavior [7]. Rather than using the traditional PMV model, which assigns a static comfort level to a user, recent studies have shown that participatory-based approaches can be used to optimize user thermal comfort and consequently reducing energy costs [11, 15, 17].

Participatory approaches allow occupants to give feedback based on their comfort level. From the feedback a consensus about common comfort value can be derived. One major challenge for such a system is that the set-point is resilient to outliers and thus a mechanism is required to cope up with the outliers. Zhang *et. al* [25] provided a strategy that overcomes outliers. Another challenge is to find the

[2]This could be a simple addendum to the main controller of the HVAC in the building.

balance between intrusiveness and user involvement in order for the occupants to maintain their incentive to participate. Most of these existing works require additional sensor deployment or detailed user information (preferences, demographics, etc.) and generate a fixed optimal set-point for each occupant given a room, which provides limited flexibility to decide set-point temperature. Erickson *et. al* [9] have used a participatory sensing approach to customize the HVAC conditioning. However, their approach does not consider shared spaces with multiple co-occupants. Moreover, it requires a significant amount of user participation to learn about one's comfort preferences.

With respect to reducing energy consumption by the lighting systems, the basic idea is to use artificial lights only when it is necessary. To do this light intensity inside the room need to be known. As the natural light level can change across days without any fixed pattern and also the light intensity varies at different locations within a room, measurements need to be done continuously at every location of interest. Thus many researchers have deployed a number of sensor nodes to monitor the fluctuation in natural light level [22, 5, 18]. However these approaches are intrusive and cumbersome.

In contrast to the above, we focus on: (a) selecting an energy optimal set-point as opposed to the fixed set-point; (b) employing only one reference sensor to provide the outdoor light intensity and using it to estimate the light intensity at desired locations across rooms; and c) use minimal data from occupants to learn their temperature and lighting comfort preferences.

3 iLTC: System Design

The system design for iLTC follows a layered design principal as described by Sarkar *et. al* for IoT applications [20] (Fig. 2). The system is divided into three layers - (i) virtual object (VO), (ii) composite virtual object (CVO), and (iii) service layers.

VOs are the digital world representation of the physical objects. A VO provides interface to access and control its associated physical object. Thus any entity (e.g., an application) can interact with any physical object without knowing the explicit interfacing mechanism. The CVO is a mash-up of one or more VOs. Based on the application requirements, multiple physical objects may need to collaborate and work harmoniously. A CVO facilitates this without hampering the independent operations of the physical objects. A CVO is a smaller unit to run any application logic. Specifically, it collects data from the desired VOs, processes the data and sends control signals. Not to mention, CVOs can also collaborate among themselves to cater to higher levels of application requirements. The service layer plays the role of an intelligent interface between the user and the execution engine (CVO). It creates appropriate services based on user request/input and coordinate among CVOs to provide the service. It can also create a service without explicit user request. All the three layers are wrapped within a placeholder called 'daemon'.

There are two major building blocks for iLTC – 'user daemon' and 'room daemon'. A user daemon is associated with each user and it is hosted on her smartphone. The proposed system employed a smart-phone based *App* to learn individual temperature and lighting comfort levels for various temperature and light intensity values. The data collected through the *App* is utilized to create comprehensive comfort function. On the other hand, any activity associated with a room is handled by the room daemon. For each room in a building, a separate instance of room daemon is created for their independent operations. These daemons can be hosted on a centralized server at the building or at a room-level embedded device. The virtual representations of the actuators (VO) are hosted by the associated room daemon. Additionally, a temperature and humidity sensor is required for every room to get thermal feedback. As the modern HVAC systems can maintain a near homogeneous temperature within a room, it eliminates various thermal zones within a room. Thus, a single temperature sensor for a room is sufficient. The corresponding VO is hosted by the room daemon.

The proposed system uses artificial lights only when the received natural light at the work-desk fall below the comfort level. The natural light intensity at various positions inside a room varies significantly, and it keeps on changing. Thus, a trivial solution is to deploy light sensor at every work-desks. In this work, we use a smart technique to avoid deployment of multiple light sensors inside a room. Rather we use a single light sensor for the whole building, and the effective natural light intensity at each user desk is estimated using this solitary sensor data. This reference light sensor is used by all users and room daemons, and is not part of either of the user and room daemons. Thus, the associated VO is hosted at a centralized location, which can be accessed by all stakeholders.

4 User Daemon

The user daemon obtains the preferences through the user interface and builds a comprehensive comfort function for thermal and visual preferences. In this section, we describe how individual user preferences are obtained and modeled. Furthermore, we also discuss how to estimate natural light intensity at a user's work-desk using only a single reference light sensor.

A user daemon hosts three CVOs – 'light profile', 'tem-

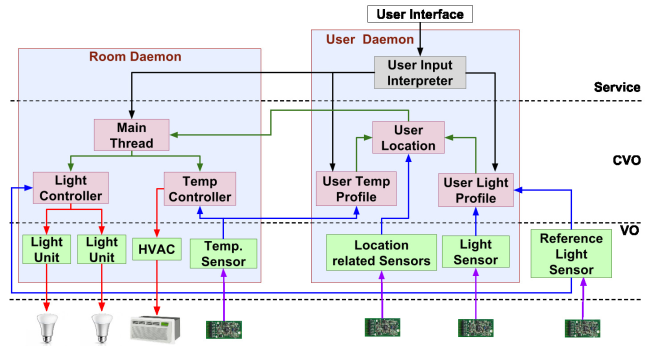


Figure 2: Layered design of iLTC and interactions amongst various components of its two main building blocks – the room daemon and the user daemon.

(a) Application screenshot

comfort indicator	ASHRAE values	comfort level
hot/very bright	+3	Hostile (<1)
warm/bright	+2	Uncomfortable (<2)
slightly warm/ slightly bright	+1	Amicable (<3)
neutral	0	Preferable (>=3)
slightly cool/ slightly dark	-1	Amicable (<3)
cool/dark	-2	Uncomfortable (<2)
cold/very dark	-3	Hostile (<1)

(b) Comfort levels

Figure 3: Screenshot of the App for collecting user preferences mapping them into a numeric scale.

perature profile', and 'location'. While the profile CVOs learn preferences of users during the training period, the location CVO identifies whether the user is inside a room or not. This binary classification of user presence is performed using WiFi based indoor localization. We utilized existing WiFi access points deployed in the building along with smartphones of occupants. When a movement is detected (i.e., change in accelerometer data or step detector), the data collection for localization is initiated. The localization has training and evaluation phases. During the training phase, WiFi scans are performed periodically at the user location (in her office room). This phase is also called the fingerprinting stage, where data from WiFi scanning is used to determine the list of visible WiFi Access Points (APs) and their Received Signal Strength (RSS) along with the timestamp. Since, only room-level occupancy is required the duration of training phase can be varied. The feature vectors for different periods at each location are used as training set for classification. A Bayesian classifier model is built on the feature vectors to determine the presence of users in the room [16]. In the evaluation phase upon detection of movement, new feature vector is evaluated with the classifier model to determine if the user has left the room or not.

4.1 Individual User Profiling

The core of iLTC is to build individual comfort profiles for temperature and lighting. For a person, maximum thermal comfort is not a single temperature value rather a range of temperature values. Similarly, visual comfort also spans over a range of light intensities. Most users cannot easily correlate their comfort levels with temperature or light intensity values. Even if they do, there is a chance of significant deviations. To this end, iLTC utilizes a smartphone *App* to learn the preferences, coupled with precise measurements from corresponding sensors. When new users enter the system, we consider a conservative approach with respect to her preferences. Initially, we assign preference values derived from survey/ASHRAE, which are then personalized based on the preferences data collected over time.

4.1.1 Collection of user preferences

Thermal comfort of a person for a particular temperature cannot be determined without the feedback from the person. We use both explicit and implicit way of learning the preferences (feedback on comfort levels) – explicitly by asking the users to indicate their comfort levels and implicitly (later while iLTC is in operation) when the user overrides the controller settings. This allows dynamic adaptation of comfort preferences. Furthermore, if the new setting is significantly different, then preferences are adapted again by collecting additional voting data from the user. Thus, by capturing the changes in user preferences overtime, iLTC eliminates any outliers.

A screenshot of the App, which is used to collect feedback, is shown in Fig. 3a. To indicate comfort a seven-point scale is used as suggested by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). However, we convert the traditional numeric scale of [-3,+3] to [1,4] (see Fig. 3b), because indicator level 'neutral' is given the highest preference, whereas indicator level 'cold' and 'hot' are given the lowest preference. To learn the visual comfort a similar scaling is also adapted as indicated in Fig. 3. The data collected from the App is used to model the comfort preferences for temperature and light. Note that the explicit data collection is done only in the beginning when a user becomes part of iLTC.

Our goal is to create comprehensive comfort functions that can indicate the comfort level of the person for any given temperature or light intensity. To build such a function, ideally, we should have comfort level indicator for each possible value, which is not a feasible option. Thus we collected a few comfort indicators and then we try to model them. The data collection was conducted from 21 users with 5 different ethnic background, age varying from 24 to 51 years. The data collection is done over several weeks with a dedicated sensor node deployed in each of the rooms of the occupants (participants). Next, we explain the mapping from these measurements to comfort levels.

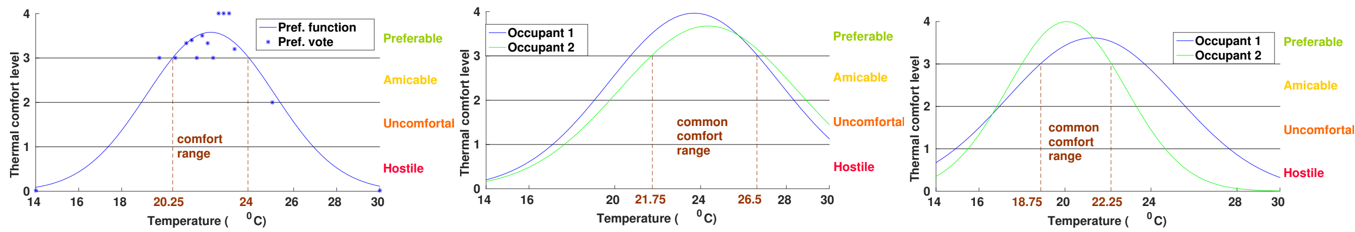
4.1.2 Modeling user profile: mapping from room temperature and luminance to comfort levels

Whenever a person indicates her comfort level, it is registered with its corresponding sensor values. During function creation, we cluster these comfort indicators in multiple equal sized bins. The bin size indicates a small range of sensor values for which user comfort remains unchanged. Different bin sizes were empirically evaluated across all the participants to determine the optimal bin size. More details on selecting appropriate bin size is discussed in Section 6. After analyzing user preference data collected from multiple users, we notice that thermal comfort function can be represented using a Gaussian function (eq. 1), whereas the light preference function can be represented using a Beta function (eq. 2).

$$F_T(\underline{\alpha}, t) = \alpha_1 \exp^{-(\frac{t-\alpha_2}{\alpha_3})^2} \quad (1)$$

$$F_L(\underline{\beta}, l) = \beta_1 l^{(\beta_2 - 1)} (1-l)^{\beta_3 - 1} \quad (2)$$

For every user, the parameters ($\underline{\alpha}$ and $\underline{\beta}$) of these functions differ. Based on the comfort indicators, we derive the individual function parameters using the least square curve fitting. To derive a reflective function from the limited samples, we assume that any temperature beyond 14° C and 30° C will be uncomfortable for any person. Thus, with the existing comfort indicator data set, we add two additional data points



(a) Comfort function of a person (b) Common comfort range: room 1 (c) Common comfort range: room 2

Figure 4: Comfort function of an individual based on preference voting, and common comfort range of a room based on individual comfort functions of all the co-occupants.

of these two extreme temperatures with comfort value 0 using the least square method. Similarly, for light these two extreme values are 0 and 1200 lux.

Fig. 4a shows the clustered preference data and the thermal comfort function derived for an individual. From this function, we can conclude that this particular user feels maximum comfort within the range of 20.25° C and 24° C . When multiple users occupy a room, a common comfort range needs to be determined. Fig. 4b and 4c, shows the common comfort range in two different rooms occupied by different set of people (each room with two occupants). It is clear that common comfort range of two different rooms can be quite different based on the individual comfort ranges of the occupants. Thus, a common temperature set-point for all the room can cause discomfort for some of the occupants or it will expend more energy by the HVAC or lighting systems or both. iLTC exploits the comfort ranges of all the occupants in a room to determine the most energy optimal HVAC set-point for the room. Moreover, the comfort range for a user is location independent and it can be carried over when user changes her location.

Similarly, the clustered lighting comfort indicators and the fitted comfort function for two users is shown in Fig. 5. From these figures, we can conclude that the minimum desirable luminescence varies significantly from person to person. Unlike temperature, a common comfort range for lighting need not be derived for following reasons. First, when the light intensity becomes uncomfortable due to superfluous light, the artificial lighting system cannot be used to reduce the intensity (like a HVAC through cooling). Rather, the lighting systems remain completely off and window blinds can be used to block additional sunlight. Second, the particular light intensity from the lighting systems can illuminate differently at various parts of the room. Thus, a work-desk close to window might get sufficient sunlight, while a work-desk far away from the window might experience light deficiency. As the received light intensity from a light source (natural or artificial) differs from desk-to-desk, only individual visual comfort threshold need to be considered.

4.2 Modeling of received light at work-desks

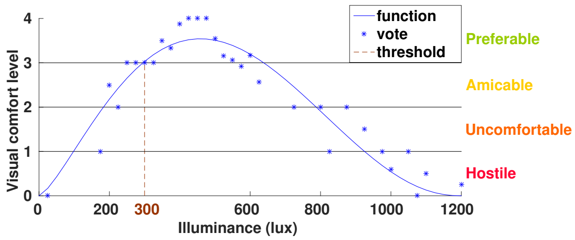
As the light intensity varies within a room, it is important to measure the amount of natural light reaching each work-desk for a particular outdoor light intensity. Thus a single light sensor is not sufficient to measure the amount of natural light at different locations (in case there are more occupants in a room). Moreover, setting a particular set-point (brightness level) for a light unit does not mean a uniform light intensity in all parts of the room. This necessitates measuring received amount of light at the work-desks of the users from different sources of lights – artificial and natural.

4.2.1 Modeling of received natural light

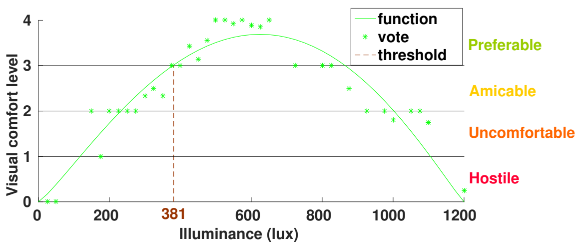
iLTC employs the smartphone light-sensor of a user to measure the received light intensity at his/her work-desk. However, for *natural light*, one time measurement using the smartphone is not sufficient as the natural light can vary over the days. To resolve this, we use one reference light sensor. Based on the measurement tuple of the reference light sensor and the smartphone light sensor, a relationship is established. This can be used to derive received natural light at the work-desk when there is a particular outdoor light intensity. Our goal is not to measure light intensity at every part of the room, but only at the work-desk of the occupant. Once this measurement is done, the relationship remains the same until the user changes his/her work-desk.

Though the gradient of light intensity can be expressed as, $l_r = \frac{l_s}{4\pi d^2}$, where l_s and l_r are the light intensity at the source and at a distance d from the source respectively, the gradient of light intensity inside a room cannot be described using the same relation. However, a similar form of relationship can be seen between outdoor and indoor light intensity as, $l_u = a_1 * l_o + a_2$, where l_u and l_o are the light intensity at the user work-desk and outdoor respectively. To determine the unknown parameters (a_1 and a_2) for a work-desk, we collected light values for a day after the user becomes part of the iLTC system (using her smartphone). Using the training data set, the parameters are estimated using least square method. Once these parameters are known for the work-desk, the received natural light can be estimated based on the reference light sensor values.

Intuitively, it is clear that once the parameters are found, the same parameters can be used to estimate light values for that location irrespective of the room and window dimension. However, the estimation accuracy suffers significantly if the same set of parameters is used irrespective of the time of the day and weather condition. To improve the estimation accuracy, our approach splits the data set collected into multiple segments based on the light intensity values of the reference



(a) User 1 preference function



(b) User 2 preference function

Figure 5: Comfort functions of individuals based on preference vote and lower bound of lighting comfort.

sensor. Then for each of these segments, we find the set of parameters.

Another important factor that influences the accuracy of natural light estimation is the visibility of the sun from the window (time of the day). Thus, we divide the data into various segments based on the location of the Sun and orientation of the window in the measurement room, and then determine the estimation parameters. Our detailed evaluation shows that dividing the data set into two parts – when the Sun is visible from the window, and when it is not visible from the window – improves estimation accuracy. By visibility of Sun, we mean the Sun's location is within the visible area of the sky through the window. Thus, to estimate the natural light at a work-desk, the right set of estimation parameters are chosen based on Sun's visibility from the window and light intensity segment of the reference light sensor. Though the visibility of Sun from a window changes drastically throughout the year, it can be easily determined. If the direction of the window and geographical location of the room (latitude and longitude) are known, visibility of Sun can easily be derived from the Sun's azimuth. To derive Sun's azimuth, we have used the algorithm provided by the measurement and instrumentation data center (MIDC) of the national renewable energy laboratory (NREL) [1]. This is a one-time data collection activity to determine the direction of the window and geographical location of the room.

4.2.2 *Modeling received artificial light*

Similar to the natural light, the amount of received artificial light also varies within a room. Thus, it is also necessary to measure the amount of received light from each of the light units at the work-desk of a user. During the training period, we turn on the light units in appropriate steps to measure the received light intensity from each of the light units at the work-desks. The light units were set to full brightness. Using the collected data, the gradient of brightness can be determined. For every light unit, there is a different gradient at different work-desks.

In building iLTC, we made the following two assumptions about modeling of preference: (a) since the temperature preferences is not location dependent, it can be utilized across various rooms, including a common meeting room and home environments; (b) the same is applicable for visual comfort. However, in a different room the gradient of light intensity from Sun and artificial sources varies differently. This necessitates a different set of parameters to model received light intensity for different work-desks. Since a user spends most of his/her time at a particular work-desk, one training campaign is sufficient.

5 Room Daemon

Most of the real-time activities are handled at the room daemon. Whenever a user enters or leaves the room the set-points for the actuators need to be adjusted. Moreover, if the natural conditions change, that also influences the set-point values of the actuators. Each room daemon hosts three CVOs – 'main thread', 'light controller', and 'temperature controller'.

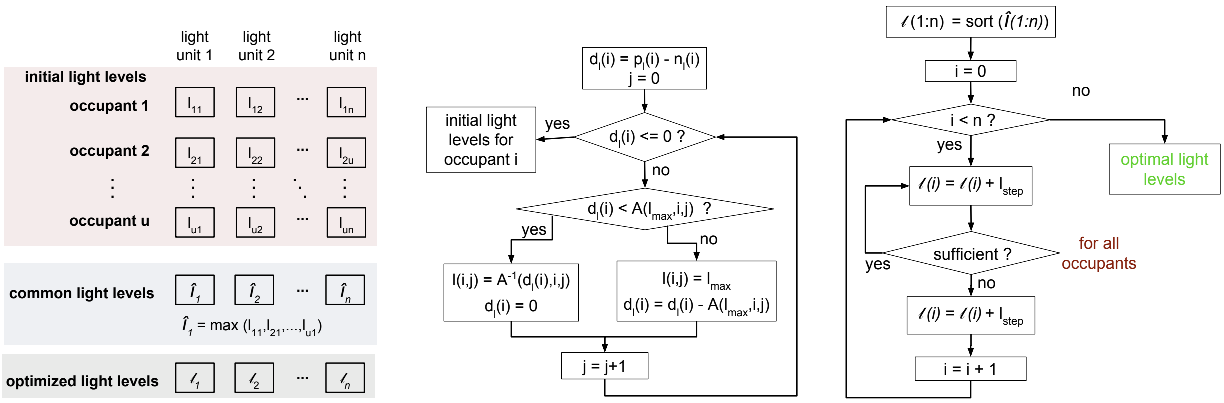
5.1 Main thread CVO

The main thread CVO manages overall execution of the room daemon. When a person enters a room, it sends an 'arrival message' to the room daemon. This message contains the identity of the users and their preferences. Upon detecting arrival of an occupant, the daemon communicates preference values to the controller CVOs. It also makes a temporary local copy of the user preferences along with marking the presence of the user. It periodically monitors presence of occupants inside the room, and instructs the controller CVOs to adjust set-points of the actuators if required. On the other hand, the user daemon sends periodic 'hello messages' to indicate the presence. If no hello message is received from a user for significant amount of time, CVO assumes that the user has left the room, and removes her comfort preferences. If the user daemon itself identifies that the user left the room, it explicitly sends a 'departure message' to the room daemon. Whenever a departure is detected, the controller CVOs are invoked to adjust the set-points if required.

5.2 Light controller CVO

The goal of the light controller CVO is to ensure usage of artificial light only when the natural light is insufficient for lighting comfort. Given that it knows the amount of received natural light at a work-desk (l_n) and the corresponding user preference regarding the lighting comfort (l_p) (see Section 4.2), the amount of light deficiency can easily be calculated ($l_d = l_p - l_n$). Using the artificial light modeling described earlier, received amount of light at the work-desk can also be calculated if a particular light unit illuminates at certain brightness. Based on these, the CVO can decide the minimum brightness for each light unit so that the light deficiency of the user can be supplemented. A minimum amount of energy consumption is ensured since lower brightness means lower energy consumption.

When there are multiple occupants inside a room, a certain brightness level for the light units may not satisfy every-



(a) overview of the algorithm (b) initial light level for user i (c) globally optimized light level

Figure 6: A three step algorithm to decide set-points of the light units inside a room when there is one or more occupant(s).

one's lighting preference. Thus, to fulfill light deficiency of all the occupants while maintaining lower energy consumption, a suitable combination of set-points (brightness level) for each light unit needs to be decided. We formulate this as an optimization problem and it is given below.

$$\min \sum_{i=1}^{n} l(i) \tag{3}$$

$$\texttt{subject to}: \quad \sum_{i=1}^{n} A(l(i), i, u) \geq d_l(u), \quad \forall u, \tag{4}$$

$$\texttt{where}, \quad A(l, i, j) = a_1(i, j) \times l + a_2(i, j). \tag{5}$$

The objective of the optimization problem is to select a combination of set-points for each light unit in a room such that the light deficiency is fulfilled while having minimum energy consumption. If a light unit i sets its brightness to $l(i)$, then the received light amount for user u can be calculated using 5. Eventually, the combined received light amount should be at least equal to the light deficiency $l_d(u)$. If there are 4 light units and each light unit have 16 brightness levels, there are a total of 65536 combinations to choose an optimal brightness level. Light intensity can change quickly within a short time period. Thus, the light controller needs to adjust the set-points every now and then. Selecting an optimal set-point out of all possible combinations can incur significant computational cost. Thus, we propose a heuristic algorithm to find the set-point that maximizes user comfort and minimize energy consumed.

A brief overview of the algorithm is shown in Fig. 6. First, a combination of optimal set-points for all the light units are derived for each of the occupants based on her light deficiency. The common set-point for a particular light unit is decided by taking the maximum among individual brightness levels required for all the occupants affected by that light unit. This ensures that everyone would receive sufficient amount of light. In the final step of the algorithm, the brightness levels are decreased one step at a time to see whether this new combination can fulfill the deficiency of all the occupants. This iterative process stops, when no further decrease in brightness level is possible. Here the algorithm assumes that the brightness level of the light units can be varied. However, for traditional lighting system with only two states (on/off), we use a similar but simpler technique to decide whether a light unit should be On or Off at any time instant. When there is a quick drop in natural light levels, the brightness levels are not increased immediately, rather a similar iterative approach is considered but with faster rate of change in brightness level. This ensures occupants do not notice any immediate fluctuation in the light units.

5.3 Temperature controller CVO

The temperature controller CVO decides temperature set-point for the HVAC, which maximizes the comfort of all occupants and minimizes HVAC energy consumption. Current HVAC systems are quite efficient in terms of maintaining a room temperature based on the given set point. Furthermore, with the introduction of zone heating, HVAC systems can now eliminate hot or cold spots in a room and maintain a set temperature value across the room. Moreover, several research efforts are conducted to determine the optimal pre-conditioned temperature of a room before an occupant arrives or after she leaves. In this regard, this paper focuses on how to obtain an optimal temperature set-point, which maximizes the comfort of all occupants and minimizes the energy consumed by the HVAC system. Determining a set-point is not trivial when there are multiple occupants present in a room. The temperature controller CVO finds the common comfort range of occupants based on the preferences collected previously.

A HVAC can be at three different operating states – default, heating or cooling. Default is a state when the HVAC consumes minimal amount of energy – without loss of generality, it can be the Off state. In heating state, the HVAC blows warm air inside the room such that the room temperature reaches a set-point value. The warmth of the air is decided based on difference between the desired set-point temperature and current temperature, whereas the energy consumption depends on the difference between the desired set-point temperature and outdoor temperature. In the cooling state, HVAC operation is similar.

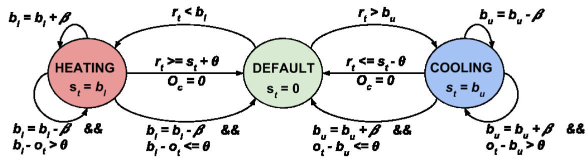


Figure 7: State diagram of the HVAC operation and associated temperature set-point (s_t) assignment. Transitions among the states depend on the room temperature (r_t), outside temperature (o_t), number of occupants (O_c), and the common thermal comfort range ($< b_l, b_u >$) of all the occupants.

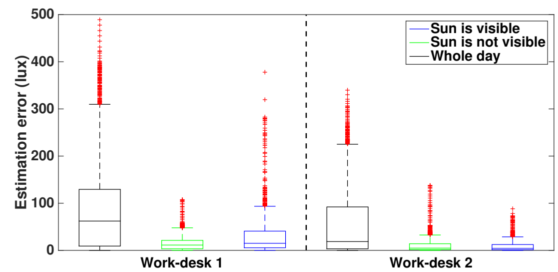


Figure 8: Estimation error of the received natural light at two work-desks.

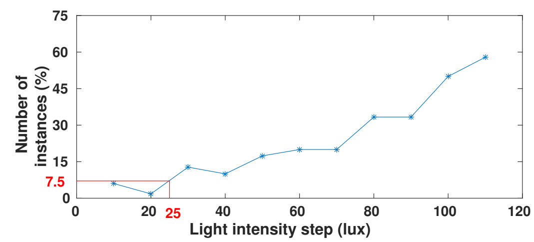


Figure 9: Various light intensity change in one step versus the number of instances when people felt annoyed with that sudden change.

We now describe how HVAC states are switched and how the set-point temperature is decided (Fig. 7) so that all the occupants feel comfortable. In the beginning, the HVAC is in the default state and its set-point is set to zero ($s_t = 0$). When an occupant enters the room, the room daemon receives her thermal comfort function. Then, the temperature controller CVO finds a comfort range for the person, which includes a lower (b_l) and upper (b_u) bound. The CVO also gets the current room temperature (r_t) from the temperature sensor VO. If the current room temperature is within this bound, then HVAC continues to remain in the default state. The CVO periodically checks if the room temperature falls out of this bound, and changes its operating state. This can happen for two reasons: (i) the room temperature changes due to occupants and/or the outdoor temperature; and (ii) the bounds of the comfort range are modified (narrowed) because of a new occupant entering the room. Hence our system periodically monitors the user presence in the room and the current temperature to maximize user comfort.

In case, the room temperature falls below the lower bound of the common comfort range ($r_t < b_l$), the HVAC enters the heating state, and the set-point is set to this lower bound ($s_t = b_l$). This ensures that all the occupants comfort preferences are met. At the heating state, if a new occupant leaves/arrives, the bounds for the common comfort range are modified. If the lower bound increases compared to the previous one ($b_l = b_l + \beta$), that means the heating need to be continued and the set-point is adjusted to the new lower bound. In case the lower bound gets reduced, there is a possibility of decreasing the heating intensity. If the new lower bound is significantly higher than the outside temperature ($b_l - o_t > \theta$), then the set-point is adjusted to the new lower bound and the HVAC continues in this state. Otherwise the HVAC is switched to the default state. At the heating state, if all the occupants leaves the room (O_c) or the room temperature reaches sufficiently higher than the set-point temperature ($r_t >= s_t + \theta$), the HVAC enters the default state with set-point being zero. The switching between heating to default state is guarded with a threshold θ to ensure that the state change does not happen frequently. A similar switching happens on the right side of the state diagram when room temperature goes beyond the upper bound of the common comfort range and the HVAC enters the cooling state. As mentioned earlier, this work focus on deciding the optimal set-point and assumes that the current HVAC system is capable of maintaining the set temperature value based on the physical conditions of the room. Thus by constantly monitoring the room condition and occupancy, iLTC adapts the set-points to maximize user comfort and minimize energy consumption of the HVAC system.

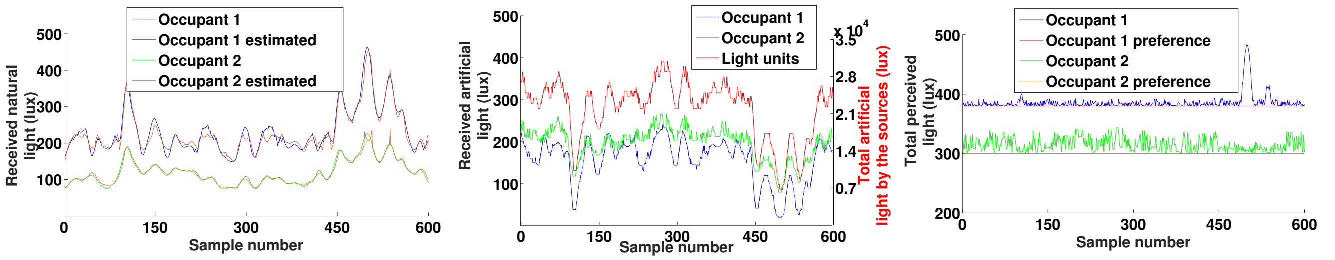
6 Evaluation

In this section, we describe our experimental setup and provide details of all the sensors used during the setup. Further, we present results regarding modeling of received light at the user work-desk and energy savings incurred with the deployment of iLTC system in shared environments.

6.1 Experimental Setup

Our iLTC system was deployed in an office environment with multiple rooms. The number of lights, window size and room size can vary depending upon the building considered. However, the functioning of the iLTC system is independent of these parameters. The set of devices used for our measurements, actuation and data collection includes: (i) Moteiv tmote-sky sensor nodes measuring temperature and light intensity in indoor and outdoor locations, (ii) Smartphones from different manufacturers for localization and user comfort indicator, (iii) Philips hue light bulbs for indoor lighting, and (iv) Plugwise circles were used to measure energy consumption of the hue bulbs.

Our experimentation considered 21 participants in an office environment from 5 different ethnic background with age varying from 25 to 51. The participant list includes both male and female users and all the users had their smartphone.



(a) Measured and estimated natural light

(b) Received artificial light

(c) Total perceived light

Figure 10: Based on the estimation of the received natural light at two work-desks, and their corresponding light preferences set-points are decided for the light units.

6.2 Results

The goal of iLTC is to decide set-points for the actuators such that (i) all the co-occupants in a room can be provided maximal comfort; and (ii) the energy consumption by the actuators is kept minimal. Deciding light unit set-point requires information about deficiency in natural light conditions. Thus, we first show the natural light estimation at the user work-desk using the estimation technique proposed in Section 4.2. Fig. 8 shows the estimation error of the received natural light at two work-desks. It can be seen that, when the whole day data is considered a high error is associated with the estimation. On the other hand, by splitting the data set based on visibility of sun significantly reduces the estimation error. This is mainly due to the consideration of rate of change of natural light with respect to sun visibility at the user work-desk.

Fig. 9 shows the light intensity steps (in lux) and the corresponding number of instances when the occupant noticed the change in light intensity. We experimented this across participants and the average results are shown in Fig. 9. It can be seen that, when the combined received light intensity at the work-desk changes in a bigger steps more number of users feel annoyed. From our experiments, we determined 25 lux to be the step change, applied when increasing or decreasing the light intensity to prevent user inconvenience. In Section 4.1, we discussed that a range of temperature and light values are clustered into bin before deriving the comfort functions. For the light values, a bin size of 25 lux is used for the range of 0 to 1200 lux (This is also clear from Fig. 9). For temperature, it starts from 14° C until 30° C with a bin size of 0.25° C , that means any comfort label indicator for the range 18° C to 18.25° C is mapped to 18° C .

The light intensity for the hue bulbs considered in our experimentation are within the range 600 to 16000 lux near the source, and the energy consumption ranges from 0.58 W/s to 5.4 W/s. Unlike the temperature set-point, setting a particular brightness of light units does not guarantee the required level of lighting comfort at the user's work-desk as the light intensity degrades significantly while moving away from the source. Consider two users inside a room with minimum light comfort preference of 300 and 381 lux (Fig. 5). Fig. 10a shows the amount of natural light received at the work-desks over a time period. The light samples are measured every 10 s. During the real deployment of the system, the measured value of received light intensity will not be available. Thus, we use an estimate of received amount of light using the reference sensor as described earlier. It can be seen that, the estimated light intensity closely follows the actual received light intensity. This estimated light is used as input for the light controller CVO.

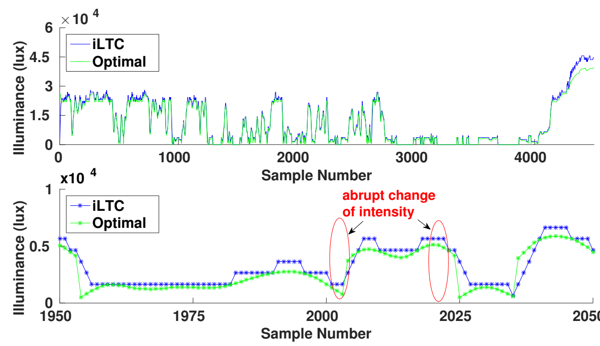


Figure 11: Combined luminance of all light units: a comparison between iLTC and the optimal light level selection.

As mentioned in Section 4.2, we measured the gradient of light intensity from each source at each work-desks. Fig. 10b shows the total amount of light seen at the source (with all six lights) and the received light intensity at the user work-desks. The decrease of received light at the work-desks is indeed due to distance from the artificial lights. Furthermore, Fig. 10c shows the total perceived light at the work-desk by considering both natural and artificial light. It can be seen that, lighting preferences of both the occupants are always met by adjusting the brightness level of the lighting system when necessary.

As mentioned in Section 5.2, the light controller CVO uses a computationally inexpensive algorithm to decide the set-points. From Fig. 10c, it is clear that the algorithm serves the purpose of providing lighting comfort to all the occupants. To evaluate efficiency of the algorithm, we derived the set-points using an optimal solution and compared it with iLTC solution. The optimal solution is found by testing all the possible combinations of brightness levels.

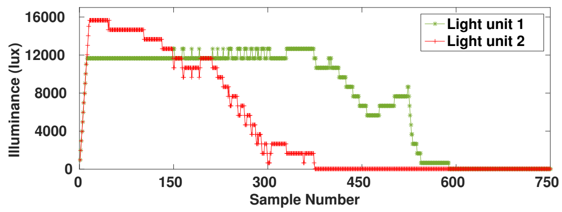


Figure 12: Brightness (set-point) decreases over time for two light units.

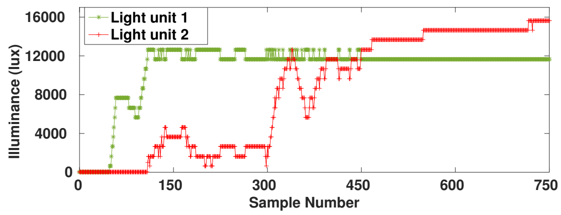


Figure 13: Brightness increases over time for two light units.

Fig. 11 shows the combined brightness of all the light units using the optimal and iLTC set-point solutions. As the energy consumption is directly proportional to the brightness level, this also reflects the level of energy consumption. From the figure, we can conclude that the iLTC solution is very close to the optimal solution. To be precise, iLTC uses only 6.92% higher light than the optimal solution. However, the number of iterations to find a suitable brightness levels using iLTC is mere 0.01% of the optimal solution. There is another significant drawback with the optimal solution. In order to find the least energy consuming brightness levels, the optimal solution can change the brightness levels of the light units too frequently with certain change in natural light level. This may cause annoying experience to the users. On the other hand, iLTC ensures that whenever the brightness level gets decreased, it decrease by only one level of brightness (a closer look at Fig. 11 for samples between 1950 and 2050). From our empirical evaluation, we found that a lux difference of 25 is unnoticeable by the users at their work-desk and we used that as the minimum brightness step (see Fig. 9). This ensures that the user will hardly notice any change in the brightness when decreasing the light intensity.

Fig. 12 shows the reduction in light intensity to maintain user comfort and minimize energy consumption across two lamp units. It can be seen that the light intensity is reduced iteratively such that not more than 25 lux difference is perceived at the user's work-desk. This approach ensures sudden fluctuations in natural light do not affect the user comfort. Moreover, when the natural light is not sufficient, artificial lights are turned ON to maintain the user comfort levels. For example, in evening the natural light perceived at the user work-desk might be lower than the comfort preference. During this stage, we follow an iterative approach to increase the lux value, but at a faster rate rather than abrupt change in lux causing inconvenience to the user. Fig. 13 shows the rise in lux value to maintain user comfort across two light units.

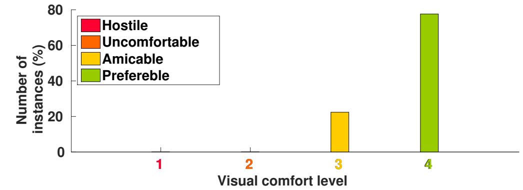


Figure 14: Visual comfort feeling of people when the artificial light units are controlled automatically using iLTC.

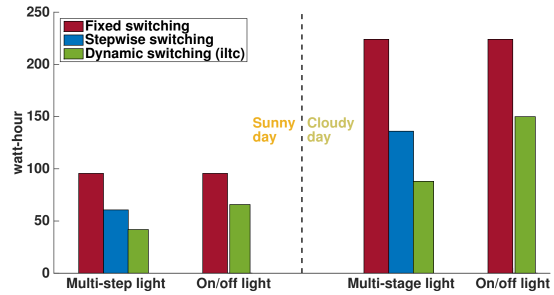


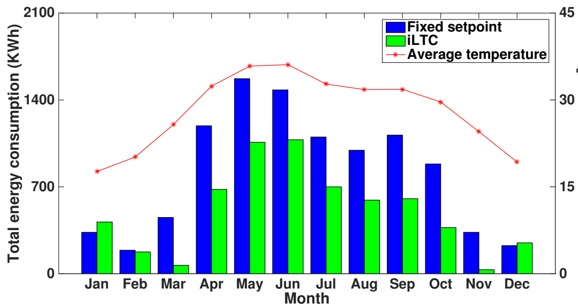
Figure 15: Combined energy consumption by all light units in a room for different switching strategies.

Thus iLTC avoids both abrupt increase and decrease in light intensity and follows a iterative approach to achieve the same without causing too much inconvenience to the users.

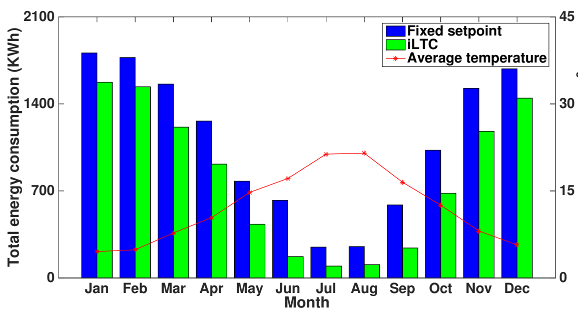
We also conducted a post-deployment user evaluation to determine the efficacy of the system (Fig. 14). Based on the user preferences collected, the set-points for the lighting system and the brightness level of the light units were constantly adapted. The feedback was collected using a questionnaire available on the smartphone App. The questionnaire comprised of questions related to visual comfort feeling. Each user selects one of the comfort levels *viz.,* (i) hostile, (ii) uncomfortable, (iii) amicable, and (iv) preferable based on the current set-points decided by the iLTC. The post-deployment evaluation was conducted on several days to generalize the outcome. On an average 78% of the feedback from 21 participants indicated preferable comfort feeling when the light intensity was adjusted due to either insufficient light intensity or excess light intensity. 22% feedback received indicated amicable feeling at certain time periods. A closer look revealed that these are due to the variation in comfort preference of the user and also due to sudden fluctuations in natural light perceived at the user work-desks. This change is pref-

Table 1: Reduction of energy consumption by iLTC as compared to fixed and stepwise switching of the light units.

	Sunny day		**Cloudy day**	
Switching Method	Multi-step light	On/off light	Multi-step light	On/off light
Fixed	56.25%	31.20%	60.71%	33.06%
Stepwise	31.03%	–	35.29%	–



(a) Delhi, India



(b) Delft, Netherlands

Figure 16: Comparison of energy consumption by the HVAC for fixed set-point technique and iLTC. Considering the total yearly consumption, iLTC is 39% and 27% less expensive based on the outdoor temperature in two cities.

erence was further considered to adapt the user preference models accordingly.

Finally, to evaluate the efficiency of the light controller, we compared iLTC with two switching mechanisms. (i) Fixed switching – where the light units are turned on to the maximum levels when the outdoor light intensity drops beyond a certain threshold. This threshold is decided when either of the users face light deficiency. (ii) Stepwise switching – where the light units are turned on with varying brightness with the variation of outdoor light intensity. We tested these strategies on the data sets for a sunny day and a cloudy day, where on the cloudy day indoor light intensity was insufficient for the occupants almost throughout the day. The total energy consumption by all the light units is shown in Fig. 15 when various switching strategies are used. All the strategies considered include occupancy detection before turning on the lights. iLTC based switching consumes the least energy as compared to other strategies. This is mainly due to the individual control of brightness level at each light unit. Table 1 shows the total reduction in energy consumption by iLTC as compared to fixed and stepwise switching mechanisms.

To compare the energy consumption of the HVAC, we adopted the energy-temperature correlation model $P = |\frac{\lambda}{M}(t_i - t_o)|$ as described in [24], where P is the amount of energy consumed by the HVAC system in one second, λ is the conductivity of a particular room, M is the efficiency of the HVAC system, and t_i and t_o are the indoor and outdoor temperatures respectively. For a particular room, λ and M are constant. So, the HVAC energy consumption is mainly dependent on the difference in set-point temperature and outdoor temperature. Additional details of the HVAC system such as duct type, radiation/convection, air re-circulation is not considered as it varies from one HVAC system to another and also dependent on the building characteristics. Our objective is to show the potential energy savings by finding the optimal set-point to maximize user comfort and minimize energy consumption. Thus we use a simpler energy model based on difference between indoor set-point and outdoor temperature as described in [24].

For our evaluation, we fixed the values of λ and M to be 70.5 J/s.K and 0.14, respectively (from [24]). We consider two rooms at two different parts of the world – (i) Delft, the Netherlands, and (ii) Delhi, India. We collected the yearly weather data for these two cities from public repositories [2]. Also there were two occupants in these rooms in both the places with comfort range spanning from 21.75° C to 26.5° C (Fig. 4b), and from 18.75° C to 22.25° C (Fig. 4c). iLTC sets the room temperature based on the common comfort range of the occupants and the outdoor temperature, whereas a fixed temperature set-point strategy selects a fixed temperature for rooms irrespective of the comfort preferences of the occupants. However, we assume that the fixed set-points also vary between 21° C to 23° C from winter to summer months. Both the strategies employed occupancy detection before selecting a set-point.

The total energy consumption of the HVAC on a monthly basis is shown in Fig. 16. In most of the cases, iLTC incurs significantly less energy consumption than the fixed set-point strategy. However during the winter season in India, iLTC induces more energy consumption. This is because the lower bound of the common comfort range is 21.75° C , where the fixed-point strategy sets the temperature to 21° C . But, when yearly basis energy consumption is calculated, iLTC outperforms fixed-point strategy in terms of lesser energy consumption. In India, the total yearly energy consumption is 6032 kWh and 9881 kWh for the two methods, respectively. On the other hand, in Netherlands, they are 13129 kWh and 9595 kWh, respectively. Thus, iLTC reduces energy consumption by 39% and 27% in the respective cities.

6.3 Discussion

As demonstrated in the previous sections, iLTC system can decide a set-point to reduce energy consumption to maximize the comfort level for all the co-occupants in a shared space. However, there are a few challenges that need to be addressed: (i) The light intensity values collected from smartphone of users may vary due to the heterogeneity of the sensors used by different manufacturers. Hence, the data collected needs to be calibrated to derive accurate user comfort preferences. Data calibration can be easily performed by comparing the sensed data with a baseline sensor data. (ii) In some scenarios, there may not be any common comfort range between the co-occupants in a shared space. It could even be discontinuous when more than two occupants share the space. iLTC then determines a set-point to save energy and also minimize the average discomfort for all the co-occupants. (iii) The efficiency of traditional BEMS can be very low, when there is frequent user movement. Our iterative approach in iLTC for controlling the actuators ensures that frequent movement of users does not affect the overall comfort drastically. (iv) The HVAC model utilized here shows the energy saving considering only the temperature difference between outdoor and indoors, however sophisticated simulation tools can be employed to derive detailed energy savings by considering other building parameters such as duct type, air re-circulation, zone thermal storage, etc. iLTC can take any given model and tries to set the operating point; (v) Since iLTC system measures the current light intensity and temperature at a specific space, it is agnostic with respect to building type and the surrounding spaces. It learns the comfort preferences and decides on energy optimal set-points. Hence iLTC can also be used in large shared spaces with multiple occupants; (vi) User involvement in iLTC is minimal where new users can join and leave the system freely.

7 Conclusions

We developed an indoor environment controlling system called **iLTC** that offers automated HVAC and lighting control at the room level trying to match individual user preferences. Instead of choosing a conservative set-point for the actuators that can provide nominal comfort to the occupants in a shared space, it decides a set-point that can be energy optimal while tuning the settings to cater to the comfort levels of all co-occupants. The system learns preferences of each individuals based on human perception of comfort through the developed smartphone *App*. We developed a comprehensive comfort representation function from a few comfort indicators using the collected data, and reduced explicit human intervention. We leveraged the light sensor in a smartphone to monitor the received light at users desk in addition to a single reference light sensor for all the users in the building. Thus iLTC reduces the deployment and management costs of multiple light sensors. Results show that iLTC set-point selection can reduce energy consumption up to 39% and 60% by the HVAC and lighting systems, respectively, compared to the fixed set-point mechanism. We evaluated iLTC with 21 participants housed in multiple rooms and qualitative user evaluation shows over 78% of the participants felt comfortable with the deployed iLTC system. We plan to extend this to multiple rooms and more occupants.

8 Acknowledgments

This work is supported by an EU FP7 project, called iCore (http://www.iot-icore.eu/), contract number: 287708. The authors cordially thank the early adopters of iLTC for providing valuable feedback.

9 References

[1] Measurement and Instrumentation Data Center. `http://www.nrel.gov/midc/`.

[2] Meteorologisk Institutt. `http://www.yr.no/`.

[3] Monash set-points trial. `http://fsd.monash.edu.au/environmental-sustainability/environmental-issues/set-points-faqs`.

[4] U.S. Energy Information Administration. `http://www.c2es.org/technology/overview/buildings`.

[5] C. Basu, J. J. Caubel, K. Kim, E. Cheng, A. Dhinakaran, A. M. Agogino, R. Martin, et al. Sensor-based predictive modeling for smart lighting in grid-integrated buildings. *Sensors Journal, IEEE*, 14(12):4216–4229, 2014.

[6] D. Caicedo, A. Pandharipande, and G. Leus. Occupancy-based illumination control of led lighting systems. *Lighting Research and Technology*, 43(2):217–234, 2011.

[7] R. De Dear and G. S. Brager. Developing an adaptive model of thermal comfort and preference. *Center for the Built Environment*, 1998.

[8] V. L. Erickson and A. E. Cerpa. Occupancy based demand response hvac control strategy. In *Proceedings of the 2nd ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Building*, pages 7–12. ACM, 2010.

[9] V. L. Erickson and A. E. Cerpa. Thermovote: participatory sensing for efficient building hvac conditioning. In *Proceedings of the 4th ACM Workshop on Embedded Systems for Energy-Efficient Buildings*, pages 9–16. ACM, 2012.

[10] A. D. Galasiu and J. A. Veitch. Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review. *Energy and Buildings*, 38(7):728–742, 2006.

[11] A. Ghahramani, F. Jazizadeh, and B. Becerik-Gerber. A knowledge based approach for selecting energy-aware and comfort-driven hvac temperature set points. *Energy and Buildings*, 85:536–548, 2014.

[12] A. Kelman, Y. Ma, and F. Borrelli. Analysis of local optima in predictive control for energy efficient buildings. *Journal of Building Performance Simulation*, 6(3):236–255, 2013.

[13] L. Klein, J.-y. Kwak, G. Kavulya, F. Jazizadeh, B. Becerik-Gerber, P. Varakantham, and M. Tambe. Coordinating occupant behavior for building energy and comfort management using multi-agent systems. *Automation in Construction*, 22:525–536, 2012.

[14] A. Kusiak, M. Li, and F. Tang. Modeling and optimization of hvac energy consumption. *Applied Energy*, 87(10):3092–3102, 2010.

[15] A. H.-y. Lam, Y. Yuan, and D. Wang. An occupant-participatory approach for thermal comfort enhancement and energy conservation in buildings. In *Proceedings of the 5th international conference on Future energy systems*, pages 133–143. ACM, 2014.

[16] D. Madigan, E. Einahrawy, R. Martin, W.-H. Ju, P. Krishnan, and A. Krishnakumar. Bayesian indoor positioning systems. In *INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE*, volume 2, pages 1217–1227 vol. 2, March 2005.

[17] D. Pan, A. H.-y. Lam, and D. Wang. Carrying my environment with me in iot-enhanced smart buildings. In *Proceeding of the 11th annual international conference on Mobile systems, applications, and services*, pages 521–522. ACM, 2013.

[18] R. Paulson, C. Basu, A. M. Agogino, and S. Poll. Inverse modeling using a wireless sensor network (wsn) for personalized daylight harvesting. In *SENSORNETS*, pages 213–221, 2013.

[19] D. Pisharoty, R. Yang, M. W. Newman, and K. Whitehouse. Thermocoach: Reducing home energy consumption with personalized thermostat recommendations. In *Proceedings of the 2nd ACM Conference on Embedded Systems for Energy-Efficient Buildings*, pages 201–210. ACM, 2015.

[20] C. Sarkar, A. Nambi, R. Prasad, A. Rahim, R. Neisse, and G. Baldini. Diat: A scalable distributed architecture for iot. *Internet of Things Journal, IEEE*, 2(3):230–239, June 2015.

[21] J. C. Vischer. The effects of the physical environment on job performance: towards a theoretical model of workspace stress. *Stress and Health*, 23(3):175–184, 2007.

[22] Y.-J. Wen and A. M. Agogino. Wireless networked lighting systems for optimizing energy savings and user satisfaction. In *Wireless Hive Networks Conference*, pages 1–7. IEEE, 2008.

[23] M. Wright. Philips lighting questions proper light-level standards for office workers. `http://www.ledsmagazine.com/`, 2015.

[24] Y. Yuan, D. Pan, D. Wang, X. Xu, Y. Peng, X. Peng, and P.-J. Wan. A study towards applying thermal inertia for energy conservation in rooms. *ACM Transactions on Sensor Networks (TOSN)*, 10(1), 2013.

[25] L. Zhang, A. H.-y. Lam, and D. Wang. Strategy-proof thermal comfort voting in buildings. In *Proceedings of the 1st ACM Conference on Embedded Systems for Energy-Efficient Buildings*, pages 160–163. ACM, 2014.