A Study on Saving Energy in Artificial Lighting by Making Smart Use of Wireless Sensor Networks and Actuators

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Abstract

This article is focused on adapting lighting conditions to user lighting preferences. A theoretical analysis of lighting conditions is carried out, and a case study is shown by means of the setup of an experimental environment and an empirical analysis of lighting conditions. Finally, a methodology for saving energy, which adjusts luminance to user preferences, is presented, and a study of the consump-tion results is given.

The Earth is at risk of irreversible damage. The greater the increase in world population, the higher the natural resource consumption. There is an abundance of clear evidence of significant changes in climate conditions, which affect ecosystems of flora, fauna, and, of course, humankind. These changes generate an incentive to find ways to better manage natural resources in order to preserve our current quality of life.

As in many developed economies, Spanish residential energy consumption continues to rise, accounting for about 20 percent of the nation's total energy usage. The Spanish authorities approved the new *Technical Building Code* in accordance with the European Parliament Directive 2002/91/CE, which requires the installation of solar panels and the use of solar, thermal, and photovoltaic energy in new buildings. However, these measures alone will not succeed in attaining real energy saving; they only curb the growing energy consumption in new constructions. The methodology proposed attends to obtain real energy savings by regulating the resources to reach optimal lighting conditions in buildings.

Saving energy in smart environment systems is one of the main goals of smart environment research. Wireless sensor networks (WSNs) — large networks of embedded devices, containing microcomputers, radios, and sensors — open new methods and approaches to saving energy. WSNs are used to retrieve data on lighting conditions. Several approaches have been proposed in [1, 2] to save energy in this scenario. Nevertheless, the first approach does not consider user preferences in illuminance; hence, a constant value of illuminance is considered suitable for every single inhabitant, and the last approach maintains no knowledge of inhabitants' preferences. Other approaches not based on WSNs, like [3] based on an embedded microcontroller, cannot store any knowledge about inhabitants, so it is not adaptable. Our approach considers inhabitant preferences about lighting and *learns* them in order to automatically adjust lighting to satisfy these preferences. The aforementioned Spanish Technical Building Code establishes 400 lumens as the optimal quantity of light for a standard office, but makes no mention of how it should be measured. A theoretical computation of how many lumens are provided by our artificial lighting setup can be made. To this end, a theoretical and empirical analysis about how natural lighting affects indoor lighting is carried out in the next sections.

Moreover, measurements may vary depending on where sensors are located, and on many other variables: type of lights, size of windows, number of windows, which direction the windows face, and so on. Our approach, as put forward later, avoids these difficulties, and makes an analysis of the lighting conditions in situ and in real time. The implementation of the experimental case study is based on the ideas exposed in [4, 5], which propose a multi-agent approach to control smart environments and a paradigm of design based on learning and prediction. The case study stores information according to [6], a model for smart environments divided in four categories: device related, inhabitant related, environment related, and background.

We then compute how much consumption can be saved by adjusting lighting to user preferences. This computation is based on the case study of a standard office at the Department of Computer Languages of the University of Seville. Conclusions are drawn in the final section.

Theoretical Analysis

In order to study how artificial lighting alters lighting conditions in an indoor environment, a mathematical analysis is carried out that relates the luminance of a room with the lights alternatively switched off and on. Let us suppose in this study that the artificial light has constant power (e.g., 100 W).

A function $y = f(x)$ is considered where x and y denote the quantity of light, measured by the same device, with artificial

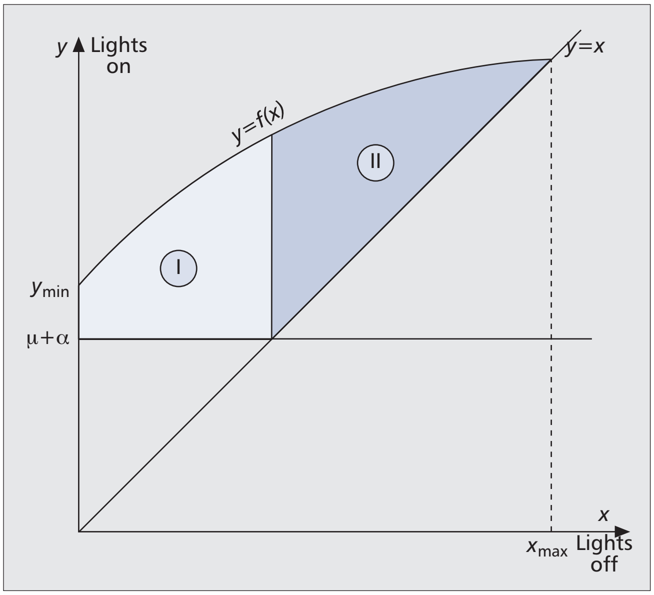

Figure 1. *The relationship between lights off and lights on.*

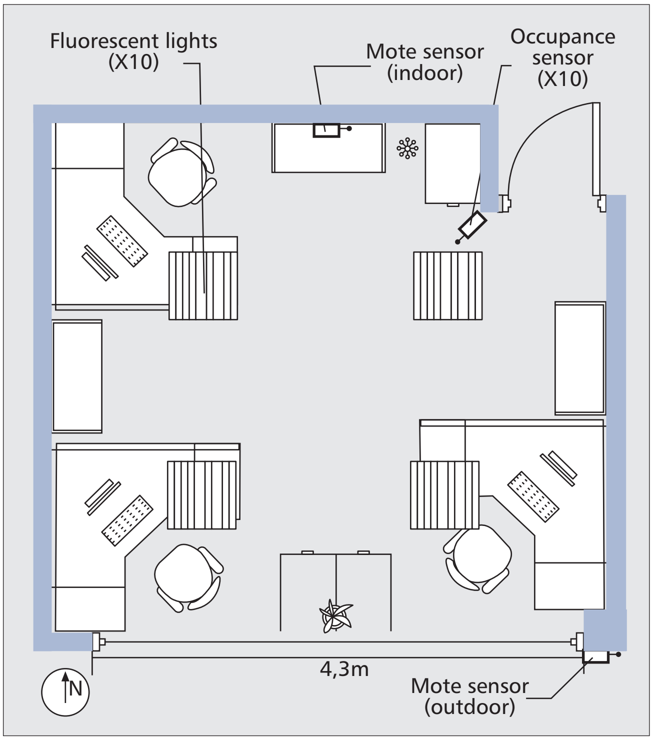

Figure 2. *Room setup.*

lights first switched off and then on (both in the same unit). Clearly, the illumination with the lights on is equal to or greater than that with the lights off; therefore, the inequality $0 \leq x \leq y$ holds.

Let x_{max} denote the maximum quantity of light the device can measure. This value is finite, and does not depend on whether lights are on or off; hence, $x_{max} = f(x_{max})$.

The function $f(x)$ is an increasing function, so its first derivative is non-negative. The reason for this result is due to theoretical properties of light, and the fact that artificial light has constant power such that for any $0 \leq x_1 < x_2 \leq x_{max}$, $f(0) \leq f(x_1) \leq f(x_2) \leq f(x_{max})$. Hence, $0 \leq x \leq x_{max}$ and $0 \leq y_{min} \leq y \leq x_{max}$, where $y_{min} = f(0)$. Note that y_{min} denotes the minimum quantity of light with the lights on and is reached when, in an indoor environment, only artificial light contributes to the lighting measurements.

With respect to the second derivative of $f(x)$, this must be non-positive since if it were positive, the first derivative of $f(x)$ would be an increasing function, which is impossible since artificial light has constant power.

On the other hand, let μ denote the lighting threshold of an inhabitant, which means that μ is the minimum quantity of light a user considers sufficient to render additional lighting unnecessary. This value depends on the preference of each user and can vary greatly depending on various factors, such as eye color, ocular difficulty, different habits, and different use of the space. Nevertheless, an interval $I = [\mu - \alpha, \mu + \alpha]$ is considered in this article due to the uncertainty of the human perception of lighting conditions. Therefore, the most important value is $\mu + \alpha$, which must be estimated for each user; this value permits us to ensure that the user has sufficient light.

The luminance of the artificial light must be such that $y_{min} \geq \mu + \alpha$ since it must guarantee that the lighting preferences of the user can always be satisfied. Clearly, the artificial light must attain at least the value $\mu + \alpha$, since otherwise, the artificial light would have to be changed. This characteristic should be borne in mind when carrying out maintenance of a lighting system. It should be noted that the value y_{min} depends solely on the power of artificial light.

In Fig. 1 an example of function $f(x)$ can be seen that verifies all theoretical conditions given. It is worth noting that the lighting preferences of the user are exceeded in the zones denoted I and II in Fig. 1. Thus, a regulator of light can be installed (zone I), and a motion sensor can then be configured to switch off the light when it is turned on while no people can be detected indoors (zone II). Therefore, electricity consumption can be reduced with these two devices. Nevertheless, some empirical problems must be solved in order to achieve these energy savings.

Case Study

In this section a particular case is studied that covers all the theoretical aspects mentioned above. Thus, an experimental environment has been designed in order to carry out an empirical study.

Experimental Environment

A standard office has been set up at the Department of Computer Languages and Systems of Seville University to obtain a real dataset. This office is intended to be used by three people, who could be visited by colleagues or students. The system of lighting consists of natural light from one large window, and four groups of four artificial fluorescent lights (16 in total) of model F18W/154 T8 manufactured by Sylvania [7], which can act as a complement to the natural light or as the sole source of light. In Fig. 2 the distribution and setup of the room can be studied. It can be observed that the geographical position of the city of Seville was taken into account in the design of the building since the window faces south, which maximizes the quantity of light received during the day. This fact alone implies great savings in consumption. It is worth noting that since any room can face any cardinal direction, the consumption saving and lighting threshold may vary, depending on user preferences (e.g., the position of the user's desk is in front of the windows, and the user prefers to close the blinds and have the light on since the user finds direct sunlight uncomfortable); hence, these factors must be considered when comparing results. For this reason, in order to study the dependence of lighting on these conditions, the need to retrieve data using several devices was placed in the proposed layout.

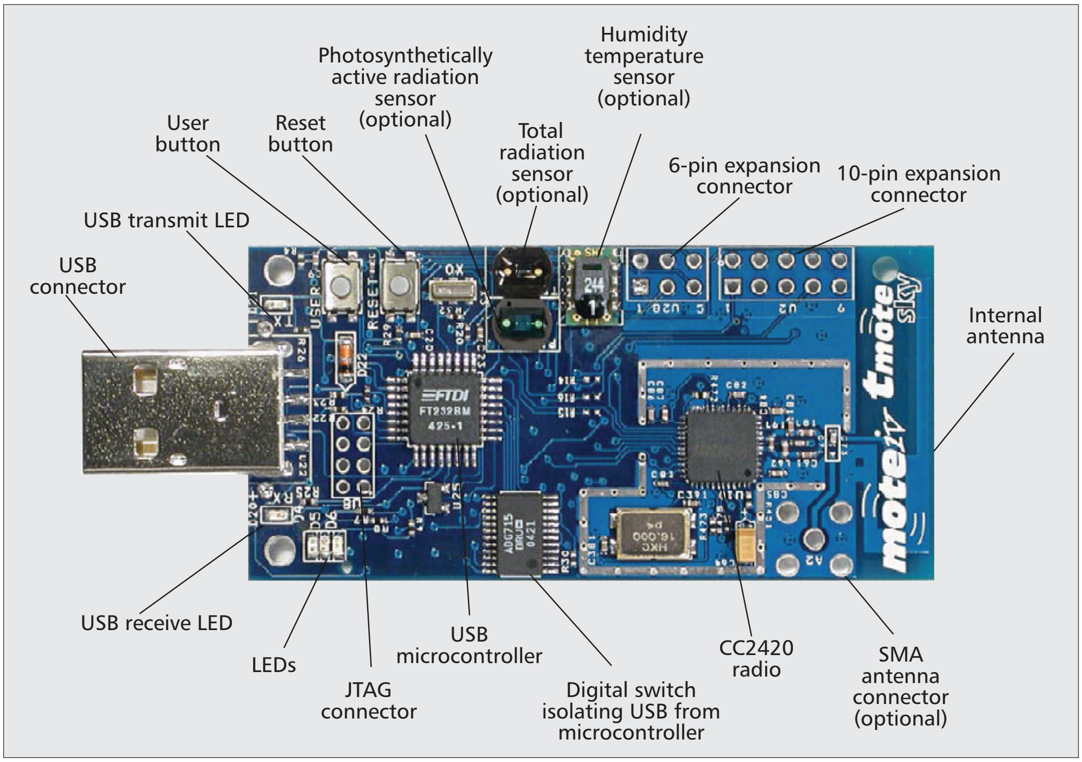

Figure 3. *Front of the Sentilla Tmote module.*

The devices used are the following: a motion sensor to detect whether someone is in the room, an actuator on the fluorescent lights to switch them on and off, and a couple of *Sentilla Tmotes* sensors.

Let us describe this last device. Sentilla Tmotes are devices that measure the quantity of light. The unit of illuminance is a *lux* and can be detected by either of two different photodiodes, as explained in *Hamamatsu* [8]:

- *S1087 photodiode*: For the visible range of the spectrum, from 320 to 730 nm. This range is often called *photosynthetically active radiation* (PAR). This region corresponds with the range of light visible to the human eye.
- *S1087-01 photodiode*: For the visible range up to infrared, from 320 to 1100 nm. This is called *total solar radiation* (TSR).

Only the PAR unit is considered in this article. The dimensions of the Sentilla Tmotes are 8 cm × 3.2 cm, so they are sufficiently small to suit ubiquitous applications and nonintrusive systems. These devices also include a humidity and temperature sensor, whose information is also retrieved for future improvement and expansions. In Fig. 3 the Sentilla Tmote module used in our experiment is shown.

The connectivity of the Sentilla Tmote with other motes and computers is executed through the IEEE 802.15.4 (ZigBee) protocol, which minimizes battery consumption. The mesh network protocol implemented by Tmotes software is chosen. In this way, a network to share information and forward it to reach a wider distribution can be designed for the motes.

Nowadays Sentilla Tmotes are packaged in a development kit, including an integrated development environment (IDE) based on Eclipse 3.2 for developing in Java. The hardware implements a Java Runtime Environment, which can run different applications for retrieving, processing, and sending data from sensors.

As can be seen in Fig. 2, two Sentilla Tmotes are installed, one indoor and another outdoor, although only those measurements given by the indoor Tmote are taken into account in this article.

User Preference Threshold

Furthermore, the threshold μ of an inhabitant needs defining. This threshold is the minimum quantity of light a user considers sufficient to stay in the room; hence, an experiment with four different inhabitants labeled *AFM*, *JAN*, *IN* (who share the office described in Fig. 2), and *JAA* (who works in a single office) is carried out. Each inhabitant independently completes a questionnaire about lighting conditions in the room every two hours for ten working days. The question is: "*Is this quantity of light enough for you*?"; each inhabitant answered either *Yes* or *No*. A complete threshold analysis can be found in [9]. According to the questionnaire, the preferences for each inhabitant are:

- **AFM**: The lowest satisfying value for PAR is 90 luxes, and the greatest non-satisfying value for PAR is 83 luxes, that is, $\mu + \alpha = 90$ and $\mu - \alpha = 83$ for this user.
- **JAN**: The lowest satisfying value for PAR is 95 luxes, and the greatest non-satisfying value for PAR is 88 luxes.
- **IN**: The lowest satisfying value for PAR is 89 luxes, and the greatest non-satisfying value for PAR is 75 luxes.
- **JAA**: The lowest satisfying value for PAR is 101 luxes, and the greatest non-satisfying value for PAR is 92 luxes.

Empirical Analysis

An analysis of the lighting data retrieved in the environment above is carried out. The main objective in this experiment is to study lighting conditions when lights are switched on and when lights are off. The data is obtained from an indoor mote via the S1087 photodiode (i.e., the PAR is used).

Tests, which include switching on and off lights at different moments of the day and night and pairing the luminance measures, are carried out 50 times. Let x and y be the retrieved data (the full dataset is available in [9]) of the luminance when lights are off and on, respectively.

In order to achieve a function that relates the x and y data, the linear correlation coefficient r is calculated. Since $r =$

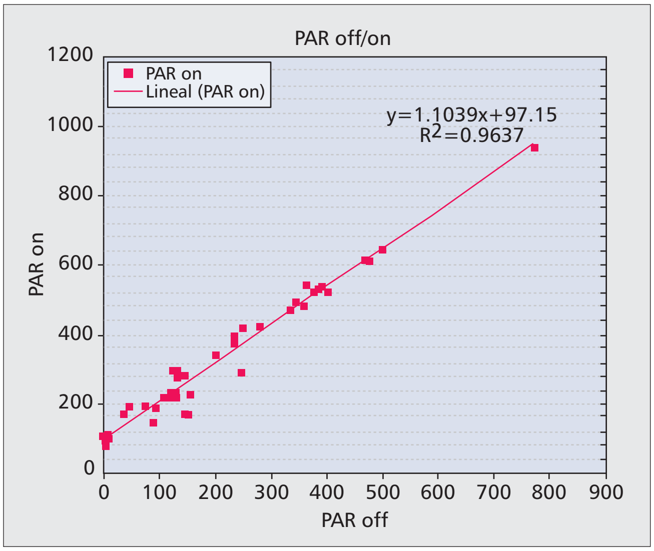

Figure 4. *PAR Off/PAR On relation.*

0.9827 is near 1, a linear model is obtained by using the least squares methods (Fig. 4): $y = f(x) = 1.1039x + 97.15$. It is worth noting that this function is increasing and that $y_{\min} = 97.15$.

The linear regression of x with respect to y is $x = f^{*}(y) = 0.873y - 77.15$. That is, if y is denoted PAR_{On} and is known, an estimated value of x, denoted $PAR_{\text{OffEstimated}}$, can be obtained.

Saving Energy

Under the conditions stated above, it can be guaranteed that $\mu + \alpha$ is the quantity of light an inhabitant considers. Therefore, in order to save energy, indoor artificial lights can be adjusted to this $\mu + \alpha$ value.

The main goal of the current work is to use the knowledge learned to save energy. Data from motes have been retrieved over several months in different periods of the year and data has been stored in a relational database as described in [10]. The methodology proposed used only one part of the dataset. This subset is shown in the list below:

- **Indoor lighting PAR**: This variable represents the quantity of light received from the indoor Sentilla Tmote S1087 photodiode. It is a continuous variable that ranges from 0 lux upward.
- **Indoor light state**: This variable represents the state of the lights of the room received from the X10 appliance module. It is a discrete variable, with value 0 for lights off and 1 for lights on.
- **Motion**: This variable represents the detection of motion sent by the MS13A X10 device. It is a discrete variable, with value 0 for no motion and 1 for motion detected.

From this dataset, several statistical analyses of lighting usage are made; for example, how long lights are left on and off, or when the quantity of light (PAR) is greater or less than user preference (μ_{PAR}). This analysis is shown in Table 1.

As can be observed in the table, the lights are on for 18.84 percent of the total time, that is, about 4.8 hours a day or 33.6 hours a week (non-working days are also included). The most important value to focus on is the number of instances that the lights are on while PAR values are greater than μ_{PAR}, since this means that the lighting conditions exceed those necessary to satisfy the preferences of an inhabitant, and hence energy is being wasted. Abnormal behavior of the illuminance sensor is present in the table since 0.15 percent of the instances have a value less than μ_{PAR} when the lights are on. These instances should be considered as error values, although the percentage is negligible. These values are computed for the μ_{PAR} of the AFM inhabitant (note that TSR analysis has been omitted but can be found in [9]).

The next task is to compute the quantity of luxes in all the instances of the database where the lights are on (PAR_{On}):

$$\sum_{lights=On} \left(PAR_{\text{On}} - PAR_{\text{OffEstimated}} \right),$$

where $PAR_{\text{OffEstimated}}$ is the estimated PAR value by regression $f^{*}(PAR_{\text{On}})$ with the lights off.

The wasted luxes can now be calculated (Fig. 1) as

$$\sum_{lights=On} \left[PAR_{\text{On}} - \max\left(\mu_{PAR}, PAR_{\text{OffEstimated}}\right) \right].$$

Notice that the maximum between μ_{PAR} and $PAR_{\text{OffEstimated}}$ is subtracted from the illuminance detected by sensors. This is the borderline between zones I and II shown in the theoretical analysis in Fig. 1.

The energy consumed by the lights is calculated as follows:

$$\text{totalTimeOn} * \#\text{tubes} * (\text{wattsPerTube}/1000) = \text{Total kWh},$$

and the undesired CO_2 generated is

$$\text{Total kWh} * 0.274 \text{ kg/kWh} = \text{total kg of } CO_2.$$

By supposing a linear relation between generated luxes and their consumption, the total *waste of lighting* can be computed as about *72 percent of consumption*. Making a smart adjustment of the lights could save about 340 kWh, 93 kg of CO_2, and €46 (€0.14/kWh) a year per standard office, based on the data retrieved for the case study and the methodology proposed.

It is worth noting that the adjustment of lights is not trivial; fluorescent lights are generally suitable for dimming, so a discretization of lights is carried out. A total of 16 fluorescent lights are employed so that some or all of them can be switched on at any time. Moreover, the regression line of the relation PAR On/Par Off can be used (instead of Par Off/Par On as shown in the previous section). In this way, the quantity of luxes ($PAR_{\text{OffEstimated}}$) when the lights are off can be estimated before any action is executed. See Table 2 for an analysis of the results.

	Total		PAR			
			PAR > µPAR		PAR < µPAR	
	#instances	%	#instances	%	#instances	%
Lights on	13,810	18.84	13,710	52.53	70	0.15
Lights off	59,490	81.16	12,390	47.47	47,100	99.85
Total	73,300	100	26,100	100	47,170	100

Table 1. *Study of lighting behavior.*

	Interval			Per year		
Days computed	101.8			365		
Days with lights on	19.2			68.77		
Total Luxes generated	167,010,000			598,775,280		
Total Luxes wasted	119,715,110			429,210,527		
	kWh	**CO_2 (kg)**	**Euros**	**kWh**	**CO_2 (kg)**	**Euros**
Total consumption	132.6	36.3	17.9	475.32	130.24	64.24
Total waste	95.0	26.0	12.8	340.72	93.36	46.05

Table 2. *Light consumption and wasting per interval and year.*

Conclusions

In this article it has been shown that electricity consumption can be reduced by incorporating two devices (a regulator of light and a motion sensor) in an indoor setup. Hence, any saving obtained in electricity consumption can be greater if the preferences of users and the environment are set up by following an optimal criterion. Thus, we have proved that in a experimental room, the waste of lighting is about 72 percent of consumption in spite of the optimality of the geographical orientation. Furthermore, the methodology proposed is adaptable to any environment and any user, due to the fact that lighting conditions are not predefined but learned by a smart environment system.

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