

Article

Direct Illuminance-Contribution-Based Lighting Control for IoT-Based Lighting Systems in Smart Buildings

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Abstract: With the advent of low-voltage light-emitting diodes (LEDs) and advances in Internet of Things (IoT) technologies, smart buildings have recently become more energy efficient. Nevertheless, the lighting-control system is one of the major sources of electrical energy consumption in commercial buildings. This study proposes a direct illuminance-contribution-based lighting-control framework to reduce the energy of LED luminaires and ensure illuminance for user requirements in smart buildings. Specifically, we designed a direct illuminance-contribution-based lighting-control algorithm (DIC-LCA) using luminaires that are ideally axisymmetric with all light emitted below the horizontal plane and developed a WiFi lighting controller for the IoT-based lighting-control systems in smart buildings. The DIC-LCA can adjust the dimming level by calculating the illuminance based on the line of sight (LOS) distance for energy saving and user satisfaction. After simulation analysis, we prove that energy savings can be achieved by controlling the dimming levels of LED luminaires with high light contribution.

Keywords: lighting-control algorithm; lighting systems; WiFi lighting controller; energy saving; IoT lighting



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1. Introduction

Since the invention of low-voltage light-emitting diode (LED) light sources, high-efficiency LEDs have already surpassed the luminous efficacy of the once-efficient CFLs [1]. Lighting-control systems once accounted for about 20% of building energy consumption [2–5]. More recently, the widespread adoption of high-efficiency LED lighting has reduced lighting's share of energy use in commercial buildings to 17% in the United States, but it still consumes a large amount of electric energy in buildings after heating, ventilation, and air conditioning (HVAC) [6].

In the recent literature, various approaches to energy-efficient lighting-control systems have been studied to reduce energy consumption and improve user satisfaction [2,4,7]. Traditionally, authors have used a zoning approach to alleviate these problems [8], where multiple luminaires are grouped by a controller and associated sensors. However, due to the interaction between the zones, the energy saving effect is small. Other authors [7] have proposed intelligent home LED lighting-control systems with multiple sensors and wireless communication interfaces that can autonomously control the minimum light intensity value to solve both the energy saving and user satisfaction problems. However, residents with smartphones need to send signals to determine the luminous flux of the luminaire, which is inconvenient. In [4], the authors showed the energy saving effect of using a daylight-harvesting system based on an adaptive multi-input multi-output (MIMO) lighting control scheme. However, according to the changes in daylight, the authors considered light sensors at points of interest in the workspace plane, which may suffer from measurement errors due to user activity. In [2], the authors proposed a sensorless illuminance-control

algorithm using a feedforward neural network technique, which establishes relationships between the dimming levels of lights and the user's desired level of illumination. However, sensor feedback based on open-loop control slightly reduces the energy saving performance. Thus, there is still room to investigate novel lighting-control mechanisms to improve energy savings.

Typically, occupancy-based automatic control approaches using PIR sensors can lead to negative outcomes such as occupant discomfort and/or energy waste due to sensor issues such as the response speed, accuracy, and sensitivity of the PIR sensor, as well as issues not reflecting user preferences [9]. This is because the lighting environment, including the illuminance and color temperature, can affect users psychologically and physiologically, as well as their productivity [10,11]. Therefore, it is necessary to provide the right lighting environment for the purposes of the user space through lighting-control systems [12]. Indoors, daylight is also an important light source, so light sensors are used or skylights are redesigned to provide a lighting environment that reflects the influence of daylight [13,14]. Lighting-control systems save energy by controlling the luminous flux according to the ambient light in the room. Taking into account the effects of ambient light is an important factor in the energy savings of lighting-control systems. However, a drawback of these daylight-linked systems is that they typically have fixed thresholds for turning lights on or off without considering occupant preferences. In most workspaces, different surfaces, such as walls, desks, and partitions, have different colors and material properties, and these surfaces can reflect different amounts of light, changing the light distribution in the room. The amount of light intensity that creates visual perception is the luminance. Determining the luminance of a workspace requires the consideration of not only the direct luminance from luminaires, but also the reflective properties of that workspace. Since it is not always possible to account for reflected light in lighting environment design and analysis, there have been various efforts to use limited approximations and to obtain more accurate approximations [15,16]. More recently, with the advancement of artificial intelligence technology, lighting-control techniques that use artificial intelligence to self-adapt to occupant preferences and environmental conditions have been proposed [17]. The impact of lighting on a building's energy consumption is gradually decreasing as conventional luminaires are replaced by LED lighting. In addition, proper control of the color temperature of luminaires can change the user's perceived temperature, which in turn can reduce the energy consumption of the heating, ventilation, and air-conditioning (HVAC) system, which in turn can reduce the building's energy consumption [18].

The Internet of Things (IoT) is based on the concept of connecting all things to the Internet or other communication networks. An IoT device is a device that has communication modules, software, sensors, and more to do this and can connect to other devices or systems to provide its own data or receive control from services. A typical service that consists of IoT devices is a smart home service that connects various home appliances, including lights, to the Internet to provide user convenience and energy saving services. Also, smart buildings and smart cities are using intelligent lighting-control systems with low-power wireless communication modules, sensors, and controllers equipped with IoT technology to manage energy consumption more efficiently and reduce overall building energy consumption by connecting with Building Energy Management Systems (BEMSs) [4,7,19–21]. IoT devices such as light sensors, perception sensors, etc., are essential for the continuous maintenance and operation of an optimized lighting environment, and the application of wireless power transmission (WPT) technology is being considered to support the continuous operation of these IoT devices [22].

In this paper, we propose a lighting-control framework based on illuminance contribution for energy-efficient lighting-control systems. Specifically, we calculate the illuminance based on the distance between the target plane and the light source. Then, we design a direct illuminance-contribution-based lighting-control algorithm (DIC-LCA) that can automatically calculate the dimming level of the luminaire for energy saving. Next, for lighting control based on illumination contribution, we propose a lightweight WiFi light-

ing controller for intelligent lighting control that can use the location information of the target workspace plane and the luminaire to adjust the illumination level to meet user satisfaction. Finally, the experimental simulation testbed was used to verify that the proposed DIC-LCA shows high energy saving performance compared to conventional lighting control algorithms.

In addition, this paper aims to achieve both user satisfaction and energy savings by providing an optimal illuminance-selection algorithm that reflects user requirements. User satisfaction is achieved by reflecting user requirements. The optimal illuminance selection algorithm is an illuminance optimization algorithm that finds a trade-off between user satisfaction and energy savings. The initial illuminance is the theoretical target illuminance of the room, but the theoretical target illuminance may not be the illuminance that satisfies the user. Therefore, if the user requests an increase in illuminance, the target illuminance is increased to increase user satisfaction. Conversely, if there is no user request, the target illuminance is reduced to save energy until the user requests an increase in illuminance. If the user requests an increase in illuminance, the reduction in target illuminance is stopped or increased again to increase user satisfaction. However, the optimal illuminance-selection algorithm is not included in the simulations in this paper because it is based on user requests and can vary from user to user. If user satisfaction is taken into account, the energy savings in the simulation may vary from user to user.

The rest of the paper is organized as follows: In the next section, we discuss the line of sight (LOS) distance-based illuminance distribution and dimming level and then provide the details of a lightweight and energy-efficient lighting-control method for IoT devices with limited performance. In Section 3, we propose a direct illuminance-contribution-based lighting-control algorithm. In Section 4, we introduce the testbed environment used to prove the proposed algorithm and then show the simulation results. Conclusions and future research are included in Section 5.

2. Energy-Efficient Lighting-Control Systems

The rationale for incorporating IoT technology into lighting-control systems is to achieve energy savings goals while providing users with an adequate lighting environment through remote lighting control using IoT technology. The illuminance of the target workspace plane in which the user is located is the sum of the illuminance of light directly from each luminaire and the illuminance of light reflected from objects such as walls. The illuminance provided to a target workspace plane by light from a particular luminaire is determined by the luminous flux of that luminaire. Figure 1 proposes a lighting-control framework based on illuminance contributions that is used to determine the luminous flux of luminaires. Each luminaire calculates the illuminance of the target workspace plane itself using lighting preferences such as the photometric polar diagram function $f(\theta)$, the luminous intensity $I_v(\theta)$, the LOS distance r_i between the luminaire and the target, and the height h of the luminaire from the workspace plane. The luminaires in the proposed lighting-control system store the three-dimensional location information provided by the lighting control server where they are installed. Using the location information of the luminaire and the location information of the target point, the LOS distance between the luminaire and the target can be calculated. The luminaire location information of the proposed IoT-based lighting-control system can be assigned to the newly installed luminaire, even if the luminaire is replaced, so that the same service can be provided as before. The calculated illuminance information E_i is exchanged through a wireless communication module and used for the proposed lighting-control algorithm. At present, we are using a Constrained Application Protocol (CoAP) to exchange illuminance information. According to the illuminance contribution C of the luminaire and the luminous flux d_i of the selected luminaire, the luminaire whose luminous flux is to be controlled is selected and the dimming level is recalculated to meet the user's illuminance requirement of the target workspace plane.

of precise indoor positioning technology, we only consider the target work plane with a fixed position entered directly by the user in the IoT-based lighting-control system. This may be a better approach when considering lighting environments where the location of the work plane is more important than the location of the worker. Also, the luminaires in our proposed lighting-control system have their own location information, so we only need to know the location of the target work plane to calculate the LOS. In this paper, we use the previously measured distance provided by the simulation tool because we are going to simulate a fixed target and use the simulation testbed from [2].

According to the definition of illuminance [24], the illuminance distribution as a function of the LOS distance and dimming level, denoted by $E(r, d)$, can be written as

$$E(r, d) = \frac{I_v(\theta)\cos(\theta)}{r^2}d = \frac{f(\theta)\phi_v\cos(\theta)}{r^2}d, \quad (1)$$

where r is the LOS distance between the luminaire and the target and d is the dimming level, which varies from 0 (off, 0%) to 1 (full luminous flux, 100%) of the luminaire and is a uniquely controllable factor in a lighting-control system using a ceiling-mounted luminaire. The target angle $\theta = \sin^{-1}\frac{h}{r}$ is the polar angle ($0 \leq \theta \leq 90$) of the location with respect to the LED luminaire, and $\theta = 0$ denotes the vertical downward direction of the luminaire. $I_v(\theta)$ is the luminous intensity at the angle θ in units of cd; $f(\theta)$ is the photometric polar diagram function as a function of θ in units of cd/lm, and ϕ_v is the total luminous flux of the luminaire in units of lm. Table 1 shows the definitions and units of the photometric quantities and related parameters.

Table 1. The parameters of the proposed system model.

Symbol	Quantity	Units
E	Illuminance	lx
I_v	Luminous intensity	cd
ϕ_v	Luminous flux	lm
θ	Polar angle	degrees
r	LOS distance	m
d	Dimming level	decimal fraction

2.2. Calculating Illuminance

In this subsection, we introduce the basic concept of a lighting-control algorithm. The most important step in a lighting-control system is the design of a lighting-control algorithm with or without sensors. The important constraints for the design of lighting-control algorithms are the daylight variation and user occupancy. For a long time, various studies have been carried out to receive measured illuminance values from light sensors at a workspace plane and use them for intelligent lighting control [27–32]. In the recent industry practice, to reduce the measurement error, light sensors for illuminance measurement are placed on the ceiling with the luminaires; research is underway to apply an initial calibration step to match the values of the ceiling light sensors and the illuminance of the workspace plane [33,34]. The illumination reference point provided to the user is in the plane of the user's workspace, so placing sensors in the plane of the workspace is the best solution to achieve energy savings by controlling lighting in response to changes in daylight. However, this is difficult to apply in practice, so we used a lighting simulation program such as DIALux to simulate the lighting environment in advance. Therefore, we excluded external influences such as daylight, reflected light, etc., in our illuminance calculations and simulations for the suggested algorithm, except for direct influence by luminaires.

To design a lighting-control algorithm, we need to be able to calculate the illuminance produced by the luminaires. Assuming there are N luminaires, to calculate the illuminance by N luminaires, the set of luminaires is denoted by L , i.e., $L := \{1, \dots, N\}$, as shown in Figure 2. The total illuminance $\hat{E}(t)$ on the target plane at time t , given that the lighting-

control system with N luminaires is on a daylight dimming vector $\mathbf{d}$, can be written as

$$\hat{E}(t) = \sum_{i=1}^N E_i(r_i, d_i) + \hat{O}(t), \quad (2)$$

where r_i is the LOS distance between the i -th luminaire and the target, d_i is the dimming level of the i -th luminaire, and $\hat{O}(t)$ is the illuminance measured at the sensor at time t [35]. In this paper, the illuminance caused by daylight is difficult to apply in the real environment because it requires the installation of illuminance sensors on the target work plane, and it is also a factor that is difficult for luminaires to calculate in real time due to the direction of incidence of daylight and the changing amount of daylight. For this reason, the effect of daylight is excluded from the illuminance calculation.

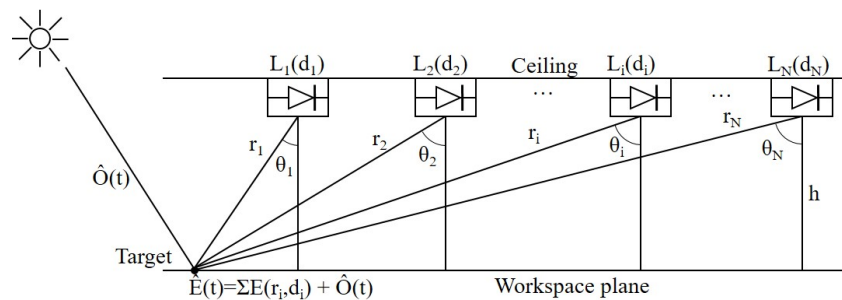


Figure 2. LOS geometry of multiple linearly placed luminaires.

2.3. Energy-Efficient Lighting Control

The final goal of recent intelligent lighting control, with or without light sensors, is to save energy by using the lighting-control system. This can be solved as a global optimization problem, as construed in [35,36]. We propose to solve this optimization problem with a luminaire-selection algorithm. The key to an energy-efficient lighting-control system is to provide the user with sufficient illumination with minimal energy consumption. This subsection presents the basic prerequisites to achieve effective energy savings while providing sufficient illumination. The theorem is based on the fact that illuminance is inversely proportional to the square of the distance from the luminaire.

Theorem 1. *To satisfy the illuminance of the target plane with multiple luminaires and to save energy, the luminaire should be selected according to the level of high illuminance provided to the target plane.*

Proof. Consider a lighting environment in which N luminaires, linearly installed as shown Figure 2, illuminate the target plane. The illuminance of the target plane $\hat{E}$ should satisfy the minimum illuminance required by user E_u , while minimizing energy usage. We denote the total power consumption P by N dimmable luminaires as

$$P = \arg \min_{d_i} \sum_{i=1}^N P_i d_i, \quad (3)$$

subject to

$$\hat{E}(t) \geq E_u, \quad (4)$$

where $E_i(r_i, d_i)$ is the illuminance of the target plane by the i -th single luminaire from the target by distance r at dimming level d_i . P_i is the power consumption of the i -th luminaire at full luminous flux.

When all the luminaires are identical, the power consumption of all luminaires is also identical. However, the illuminance of the target surface provided by each luminaire is different depending on the distance and radiation angle between the luminaire and the

target surface. That is, we assume that $r_i \leq r_{i+1}$ and $E_i(r_i, d_i)$ is greater than $E_{i+1}(r_{i+1}, d_{i+1})$ because the illuminance is inversely proportional to r^2 , as shown in (4). To minimize the total power consumption of the system P , when P_i and d_i of all luminaires are equal, the number of summations N must be minimized; to minimize the number of summations N and to satisfy the target illuminance $\hat{E}$, $E_i(r_i, d_i)$ must be summed from the largest value of (4). $\square$

3. Proposed Direct Illuminance-Contribution-Based Lighting-Control Algorithm

3.1. Illuminance Contribution of Luminaires

Energy saving in lighting-control systems is twofold: reducing the use of unnecessary luminaires based on the presence or absence of users and finding ways to minimize the energy usage of luminaires while still meeting the illumination requirements of the user's workspace. The former can be achieved in a variety of ways by controlling lighting based on the presence or absence of users using PIR sensors, microwave sensors, CCTV, etc. The latter, however, becomes a difficult problem of finding the optimal control conditions based on the trade-off between illumination requirements and energy savings. In particular, illuminance requirements are legal or theoretical requirements, which may differ from actual user satisfaction. However, the illuminance requirement can be a minimum requirement for user satisfaction. In this paper, we will find a solution to achieve energy savings while satisfying illuminance requirements, starting with the selection of luminaires that are optimal for energy savings. The basic idea of the proposed DIC-LCA is to solve this problem by first selecting luminaires with high a lighting contribution according to Theorem 1.

Therefore, the DIC-LCA is the process of calculating the illuminance contribution of each luminaire to the target workspace plane and, based on that, selecting luminaires and determining the dimming levels for those luminaires. The first step of the DIC-LCA is to calculate the luminaire's illuminance contribution to the target workspace plane. The total illuminance contribution of the i -th luminaire C_i is defined as the sum of the individual illuminance contribution C_j , for the j -th target workspace plane. The individual illuminance contribution is the illuminance of the target workspace plane per unit power consumption of the luminaire. Once the illuminance contribution of the i -th luminaire to each of the j target workspace planes is calculated, they are summed to calculate the total illuminance contribution of the i -th luminaire.

$$C_{i,j} = \frac{E_{i,j}}{P_i}, \quad (5)$$

$$C_i = \sum_{j=1}^M C_j, \quad (6)$$

where the unit C_i is in lx/W. $E_{i,j}$ is the illuminance of the j -th target by the i -th luminaire; P_i is the total power consumption of the i -th luminaire in W; M is the number of the target workspace planes. We can let the following be the vector of the illuminance contributions of N luminaires:

$$\mathbf{C} = [C_1, C_2, \dots, C_N]. \quad (7)$$

Consequently, a luminaire's high illuminance contribution means that it is located close to a specific workspace or is involved in the illumination of multiple workspaces. Conversely, a luminaire's low illuminance contribution means that there is a lack of workspace around the luminaire that needs to satisfy the illuminance requirements. These low-illuminance-contribution luminaires are the ones for which cognitive-based control is appropriate. The next step is to select luminaires based on their illuminance contribution and determine their dimming levels. Lower the dimming level for luminaires with low light contribution, and increase the dimming level for luminaires with high light contribution. This is repeated to satisfy the illuminance requirements for multiple workspaces.

3.2. Direct Illuminance-Contribution-Based LCA

In this subsection, we propose a direct illuminance-contribution-based lighting-control algorithm (DIC-LCA) for M target workspace planes using N luminaires (Algorithm 1). We assume that there are M target workspace planes, and the set of target workspace planes is denoted by T , i.e., $T := \{1, \dots, M\}$.

Algorithm 1 Direct illuminance-contribution-based lighting-control algorithm (DIC-LCA).

```

1: Initialization set  $d_i = 1$  for all  $i \in L$  and  $h, r_{i,j}$ , where  $r_{i,j} \geq h$ .
2: Initial Calculation for every  $i \in L$  and  $j \in T$ , compute  $\theta_{i,j}$ ,  $E_{i,j}$ ,  $E_j$ ,  $C_{i,j}$ , and  $C_i$ .
3: for  $i \in L$  do
4:   Select the luminaire and target by (13) and (14).
5:   Recalculate  $d_i$  of the selected luminaire by (15).
6:   Recalculate  $E_{i,j}$  by (8).
7:   Update  $E$ .
8: end for
9: for  $j \in T$  do
10:  Select the target and luminaire by (16) and (17).
11:  Recalculate the  $d_i$  of the selected luminaire by (15).
12:  Recalculate  $E_{i,j}$  by (8).
13:  Update  $E$ .
14:  if  $d_i' = 1$  then
15:    Remove the  $i$ -th luminaire.
16:  end if
17: end for

```

In the initialization process, the dimming level of all luminaires d_i is set to full luminous flux and the height of luminaire h is set to the vertical distance from the ceiling-mounted luminaire to the workspace plane. The distance $r_{i,j}$ between the i -th luminaire and the j -th target is measured and set. The $f(\theta)$ of each luminaire is a photometric polar diagram function that is calculated from the luminous intensity distribution data provided by the manufacturer.

In the initial calculation process, the total illuminance contribution of each luminaire is calculated. To calculate the total illuminance contribution, the individual illuminance $E_{i,j}$, the individual illuminance contribution $C_{i,j}$ of the j -th target by the i -th luminaire, the total illuminance contribution C_i of the i -th luminaire, and the total illuminance E_j of the j -th target can be calculated as

$$E_{i,j} = \frac{I_v(\theta_{i,j}) \cos(\theta_{i,j})}{r_{i,j}^2} d_i = \frac{f(\theta_{i,j}) \cdot \cos(\theta_{i,j}) \cdot lm_i \cdot e_i}{r_{i,j}^2} d_i, \quad (8)$$

$$E_j = \sum_{i=1}^N E_{i,j}, \quad (9)$$

$$C_{i,j} = \frac{E_{i,j}}{P_i}, \quad (10)$$

$$C_i = \sum_{j=1}^M C_{i,j}, \quad (11)$$

where $r_{i,j}$ is the LOS distance between the i -th luminaire and the j -th target; the target angle $\theta_{i,j}$ is the polar angle of the j -th target with respect to the i -th luminaire.

When the individual illuminance of the j -th target by the i -th luminaire at full luminous flux is defined as $E_{i,j}(full)$, the set of total illuminance of the target workspace planes E

can be expressed as an $N \times M$ matrix that is generated for the M target workspace plane using N luminaires; this can be written as

$$\mathbf{E} = \begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_M \end{bmatrix} = \begin{bmatrix} E_{11}(full) & \cdots & E_{N1}(full) \\ E_{12}(full) & \cdots & E_{N2}(full) \\ \vdots & \ddots & \vdots \\ E_{1M}(full) & \cdots & E_{NM}(full) \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_N \end{bmatrix}. \quad (12)$$

This matrix is updated each time the dimming level of a luminaire is adjusted. When the entire initialization process is completed, the process of selecting the luminaire and the target workspace plane and the process of calculating the dimming level according to the illuminance contribution are started.

The first dimming level adjustment step is a process of reducing the excess illuminance. The luminaire with the lowest C_i value is selected. The index of the selected luminaire and the selected target workspace plane are defined as follows:

$$i' = \arg \min_i [C_i], i \in L, \quad (13)$$

$$j' = \arg \max_{j, E_j > E_u} [C_{i',j}], j \in T. \quad (14)$$

After a luminaire is selected, respectively, the j -th target workspace plane with the highest contribution of the selected i -th luminaire is selected. The new dimming level $d_{i'}$ is calculated by

$$D(d_{i'}) = d_i + \frac{E_u - E_j}{E_{i,j}} = \begin{cases} 0, d_{i'} < 0 \text{ or } j = null \\ d_{i'}, 0 \leq d_{i'} \leq 1 \\ 1, d_{i'} > 1 \end{cases}, \quad (15)$$

according to the selected i -th luminaire and the j -th target workspace plane. In [2], the authors noted that LED-lighting-control systems exhibit nonlinearity because the Digital Addressable Lighting Interface (DALI) controller has a nonlinear power output for a linear input. This is due to the nature of the human eye's response to light. The human eye is much more sensitive to low light levels than to high light levels, so the lighting controller must adjust luminous flux more finely at low dimming levels than at high dimming levels. To account for this characteristic of the eye's response to light, the lighting controller uses a logarithmic dimming curve rather than a linear one. The DALI luminaire also uses a logarithmic dimming curve, which requires an inverse calculation for linear output. This process of decreasing illuminance is repeated for all luminaires in order of their total illuminance contribution.

The next step is a process of increasing insufficient illuminance. In this step, the target that has insufficient illuminance is selected. Using the difference between the target illuminance and the current illuminance, the target workspace plane is selected at a higher illumination order. The overlighted target workspace plane is selected as follows:

$$j' = \arg \max_{j, E_j < E_u} [E_u - E_j], j \in T. \quad (16)$$

After a target is selected, the luminaire that has the highest illuminance contribution for the selected target is selected as follows:

$$i' = \arg \max_i [C_{i,j'}], i \in L, j = j'. \quad (17)$$

The dimming level of the selected luminaire is recalculated, and the total illuminance is updated. This process is repeated for all targets in the order of the difference between the target illuminance and the current illuminance. The contributions calculated for the

illumination and target planes are based on point-to-point assumptions, which is a limitation that can lead to errors if the luminous intensity distribution of the luminaires is not axisymmetric.

3.3. Illuminance Control Based on User Request

In this subsection, we propose an optimal-illuminance-selection algorithm for target workspace planes (Algorithm 2). In the previous subsection, the target illuminance is the theoretical optimal illuminance of the room. Therefore, if the user requests an increase in illuminance, the target illuminance is increased to increase user satisfaction. Conversely, if there is no user request, the target illuminance is reduced to save energy until the user requests it. If the user requests an increase in illuminance, the reduction of the target illuminance is stopped or increased again to increase user satisfaction.

Algorithm 2 Optimal-illuminance-selection algorithm.

```

1: Initialization set an initial target illuminance at a theoretical optimal illuminance
2: Initial Calculation calculate dimming level of each luminaire by DIC-LCA
3: Initialization loop = true
4: while loop = true do
5:   Decrease the dimming level of all used luminaires by 1.
6:   Wait 1 min.
7:   if No user request then
8:     Update E.
9:   else if User requests dimming up then
10:    Increase the dimming level of all used luminaires by user request.
11:    Update E.
12:    Set E to the target illuminance.
13:    loop = false
14:   end if
15: end while

```

4. Experimental Results

4.1. Simulation Testbed

An illuminance simulation example of the proposed algorithms is presented in this section. We used the DIALux [37] lighting simulation software to calculate and display the illuminance distribution. To evaluate and verify the performance of the proposed algorithms, a testbed similar to the one used in [2] was constructed, as shown in Figure 3. The luminaires used were the 54 W and 19 W luminaires from the software, which were the most similar to the luminaires used in the reference paper to which this paper is being compared. The shape of the room and the arrangement of the tables were also designed as closely as possible to the room in the reference paper.

The testbed for the lighting-control system, with 12 working desks, is an 8.5 m × 8.2 m × 2.8 m office with two windows. The surface of the desk, which is the reference point for the illuminance calculation, is located at a height of 0.8 m. That means that the height h between the luminaire and the workspace plane is 2.0 m. A 54 W LED luminaire, which is a modular lamp with a normal beam angle, as shown in Figure 4, and a 19 W LED luminaire, which is a spot downlight with a narrow beam angle, as shown in Figure 5, were used. Figures 4 and 5 show the illuminance distributions of the 54 W and 19 W LED luminaires using the OpenGL 3D graphics of MATLAB. The luminous intensity distributions of the luminaires we used have the $f(\theta)$ axisymmetry features, as shown in Figures 4 and 5. When applying the proposed algorithms to real-world environments, it is important to consider that not all luminaires have the axisymmetric features, and even those with axisymmetric features may have errors. In the simulation environment, the effects of external influences and reflected light were removed to calculate only the illuminance from

direct light from the luminaire. Detailed information about the test environment can be found in Table 2.

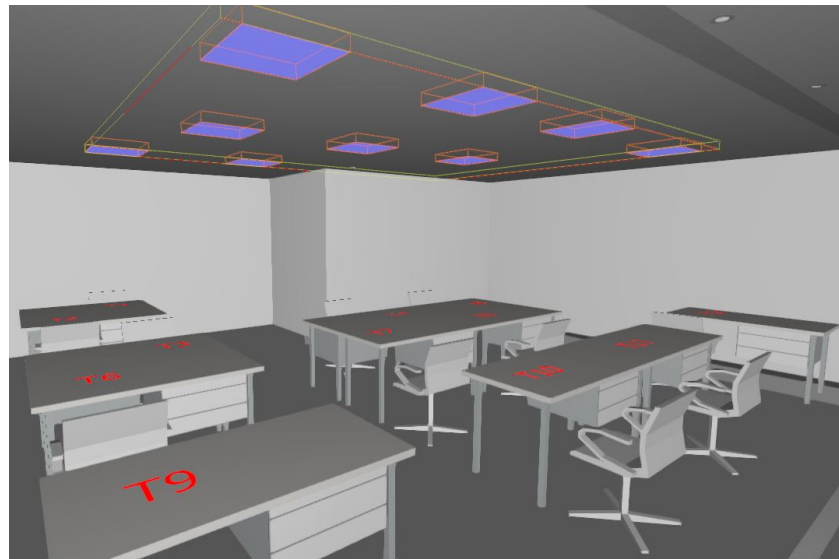


Figure 3. Simulation testbed in DIALux software [37]. Reflections from room surfaces are not considered in the proposed approach.

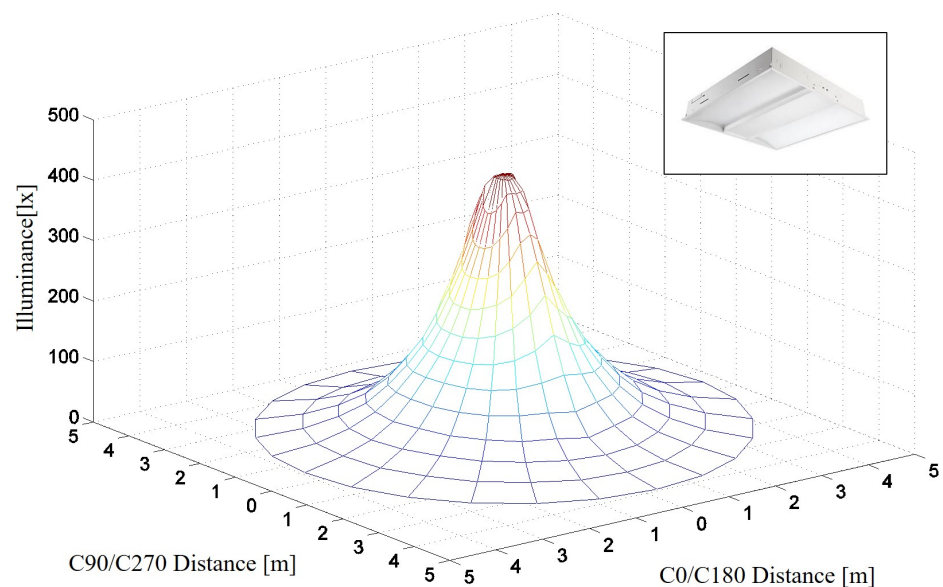


Figure 4. The 54 W luminaire 3D illuminance distribution diagram.

Similar to [2], we simulated two nighttime scenarios where Scenario I simulates the illuminance distribution for all 12 desks; this is the general environment. Scenario II simulates two desks, T2 and T11; this is the specific environment that requires user detection. In these simulation scenarios, we set the target illuminance E_u to 350 lx based on the center point of the selected desks.

Instead of calculating the distance using the three-dimensional position information assigned to the luminaires in the proposed lighting-control system, we measured the LOS distance r using the measurement tool in the DIALux simulation tool. Using the photometric data files provided by the manufacturer, the photometric polar diagram function $f(\theta)$ is recalculated as a function of θ .

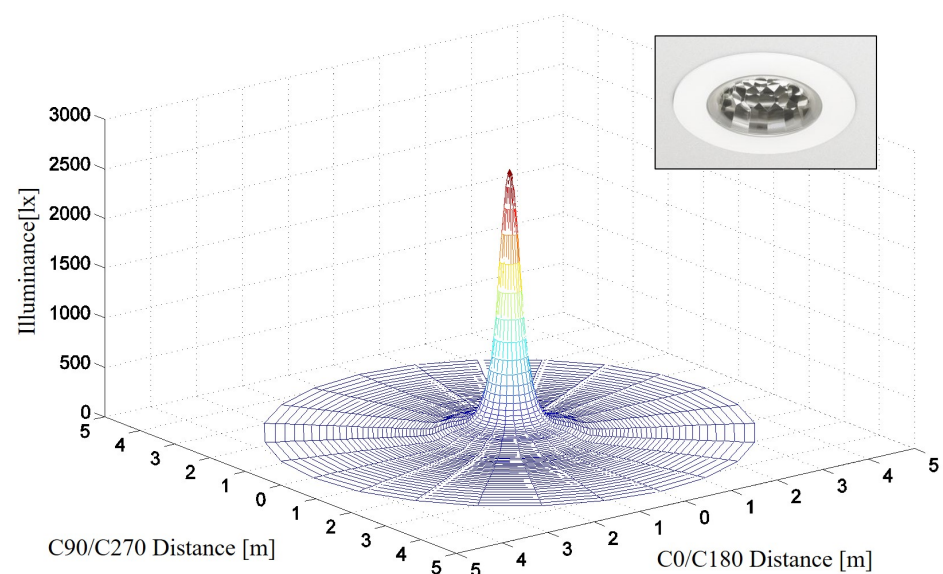


Figure 5. The 19 W luminaire 3D illuminance distribution diagram.

Table 2. Parameters for simulation testbed.

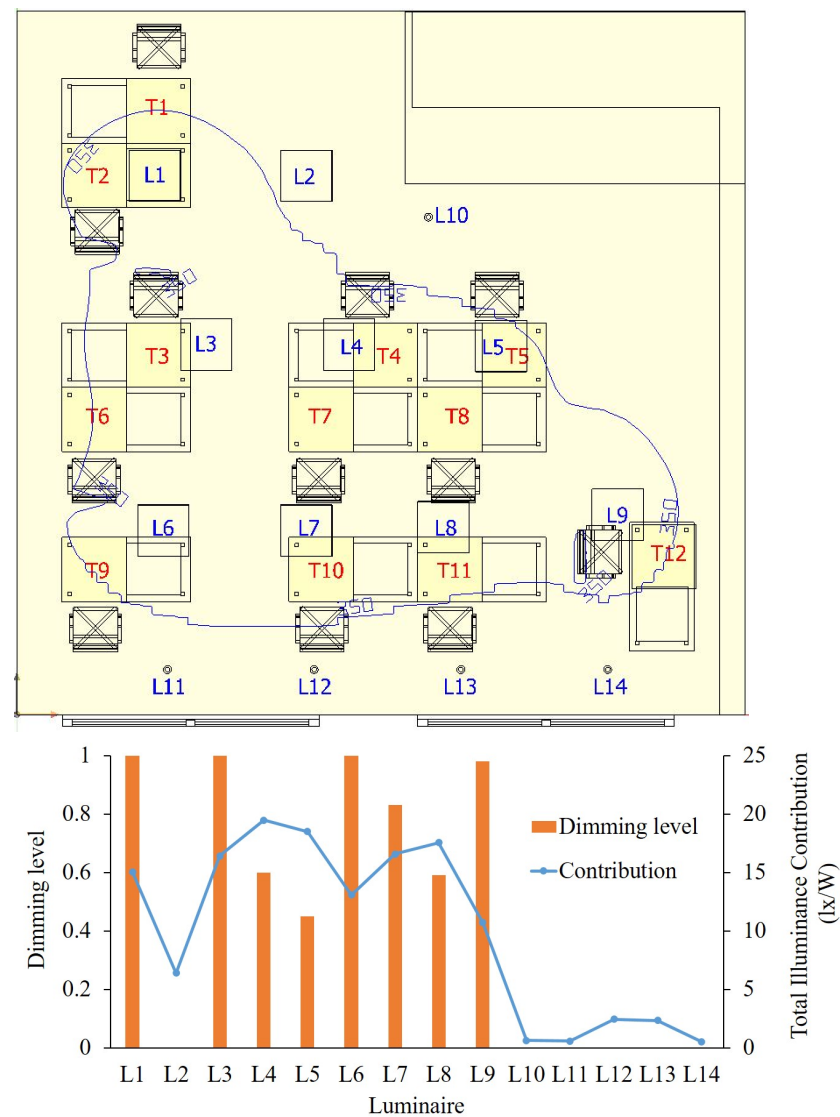
Symbol	Quantity	Value
h	Height from luminaire to workspace plane	2.0 m
N	Number of luminaires	14 ea
ϕ_v	Luminous flux of	
	54 W LED luminaire	4309 lm
	19 W LED luminaire	1200 lm

4.2. Simulation Results

When all the LED luminaires are at their full luminous flux, the total power consumption P_f is equal to that of [2] at 581 W. We used the simulation to achieve a value of 350 lx only on the working desks in the two simulation scenarios. Scenario I optimizes the simulation to achieve a value of 350 lx for all 12 desks, and Scenario II optimizes to achieve 350 lx for only 2 desks, which are T2 and T11, as illustrated in Figures 6 and 7. The total power consumption P_t is reduced to 350 W for all 12 desks and the power consumption reduction ratio P_r compared to the full luminous flux is 40%. For two desks, 115 W of power is consumed and the figure of savings is 80%. Table 3 provides a summary of the simulation results. Although the energy saving rate is better than that in [2], it is difficult to directly compare our results with those simple results because the arrangement of the luminaires and the working desks is not completely consistent with that in [2]. The main difference with the results of [2] is that our system does not use 19 W LED luminaires due to their low contribution, as shown in Figures 6 and 7. As observed in the results shown in Figure 6, the 19 W LED lights, especially when positioned behind or to the right of users using desks T4, T5, T9, and T12 may cause shadows on the user's work surface. Taking this into consideration, we should be careful with your lighting choices, and for this simulation, we recommend reducing the use of 19 W LED lights to save energy and avoid shadows.

Table 3. Simulation results.

Symbol	Quantity	Scenario I	Scenario II
T	Number of targets at full luminous flux	12 ea	2 ea
P_f	Total power consumption	581 W	581 W
P_t	Total power consumption at controlled	350 W	115 W
P_r	Energy saving rate	40	80

**Figure 6.** Scenario I: illuminance distribution of all 12 desks and calculated dimming levels of 14 luminaires.

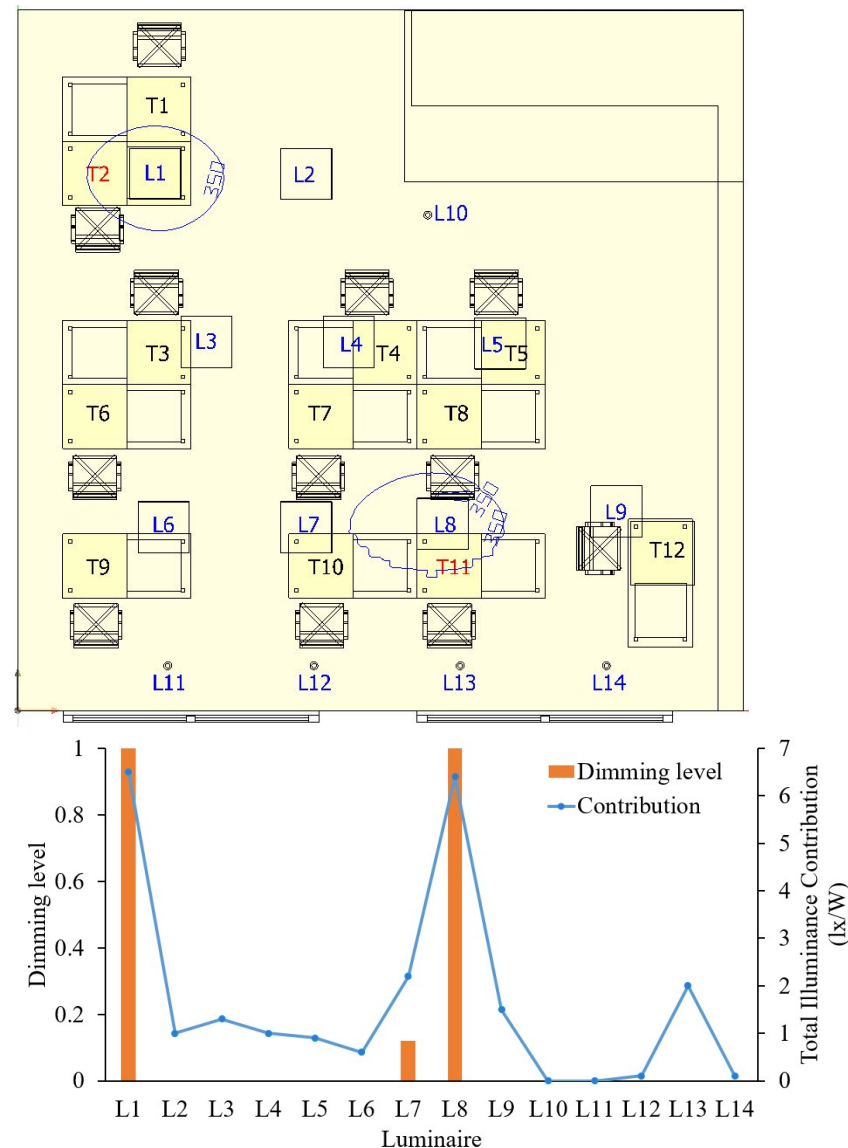


Figure 7. Scenario II: illuminance distribution of 2 desks and calculated dimming levels of 14 luminaires.

Unlike Scenario II, in Scenario I, the total illuminance contribution and dimming levels calculated by the DIC-LCA do not match, as shown in Figure 6. However, if we check the contribution of individual luminaires to each workspace plane, it can be seen that there is a correlation. In Figure 8, the first and second contribution percentages represent the illuminance contribution percentage of the highest and second-highest luminaires to each target workspace plane. The illuminance contribution percentage is a percentage that contributes to the total illuminance of the target workspace plane and indicates the importance of the luminaire selection for lighting control. As shown in Figure 8, the contribution of certain luminaires, such as L1, L6, and L9, to a particular target workspace plane, such as planes T1, T2, T9, and T12, located at the corner, is relatively high compared to that of other luminaires. In Figure 9, the illuminance contribution percentage of each luminaire to each target workspace plane is shown. In Figure 9, the illuminance contribution distribution of each luminaire to the target can be seen. The 54 W LED luminaire has a constant contribution to the workspace planes around the luminaire, while the 19 W LED luminaire has a higher contribution to the closest workspace plane. This reflects the characteristics of the illuminance distribution diagram of each luminaire, as shown in Figures 4 and 5. In particular, we can see that the 19 W LED luminaires are focused

exclusively on specific targets on the workspace plane. This means that, if we do not place a spotlight for a specific target well, we need to reduce its use to save energy. In other words, adjusting the position of the 19 W LED spotlight can save more energy.

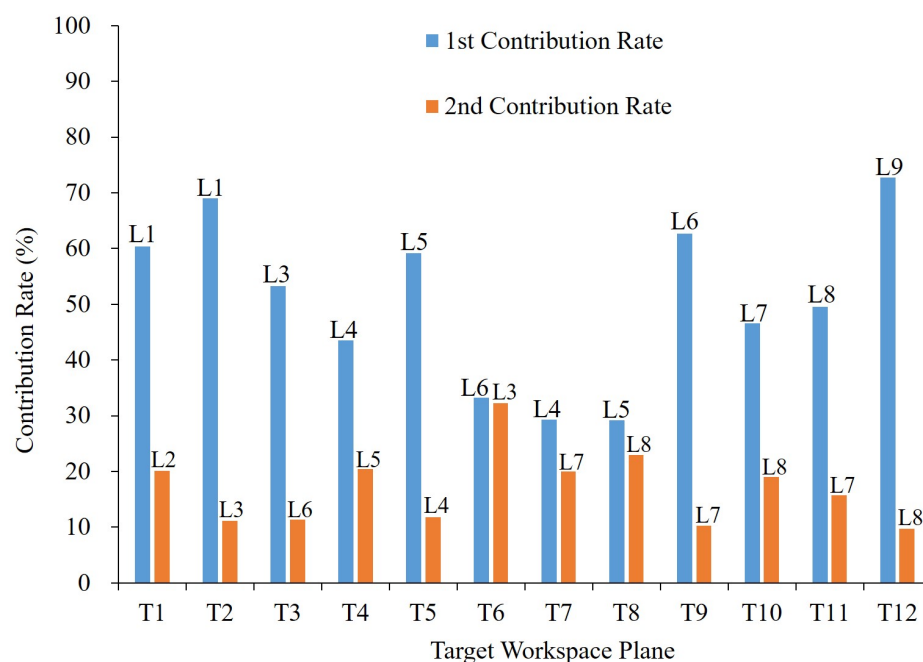


Figure 8. Comparison of the highest two direct illuminance-contribution percentage luminaires at each target workspace plane for Scenario I.

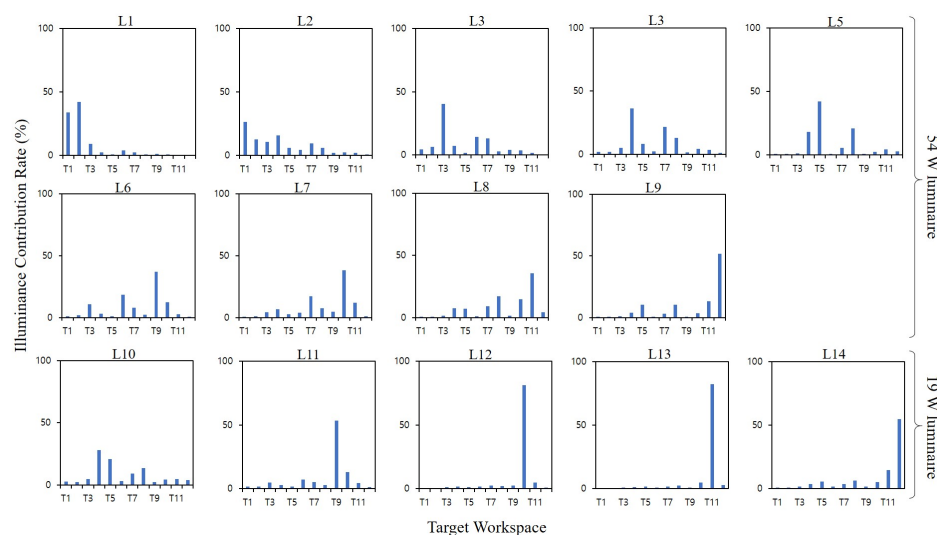


Figure 9. Direct illuminance-contribution percentage of each luminaire to each target workspace plane.

For real environment testing, as shown in Figure 10, we developed a lightweight lighting controller using the Texas Instruments (Dallas, TX, USA) CC3200 SimpleLink™ WiFi and IoT solution, which is a low-power WiFi microcontroller unit (MCU) for IoT devices. In our proposed lighting controller, the power consumption of CC3200 is at least 195 mW in receive mode and 756 mW in transmit mode [38]. The measured power consumption of the WiFi lighting controller, which includes switched-mode power supply (SMPS) and pulse-width modulation (PWM) module, was less than 1 W. Considering the power consumption of the 14 WiFi lighting controllers, the total power consumption was also reduced to 364 W for all 12 desks and to 127 W for the 2 desks, less than [2]. If we use

the low-power WiFi module developed for the IoT, the power consumption of the WiFi module will be a small part of the total power consumption of the lighting-control system.

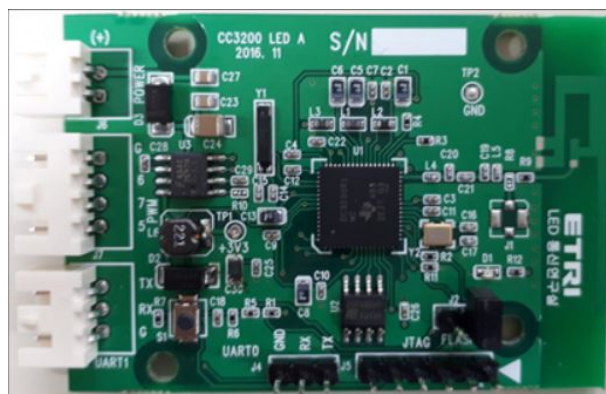


Figure 10. Proposed WiFi lighting controller based on TI CC3200.

5. Conclusions

In this paper, a direct illuminance-contribution-based lighting-control framework for IoT-based energy-efficient LED lighting-control systems using lightweight WiFi lighting controllers has been proposed. By using LOS distance-based high illuminance and adjusting the dimming levels, the proposed approach maximized the energy savings and ensured preferred task illuminance. Under the rigorous DIALux lighting simulation testbed, the proposed DIC-LCA shows an approximately 40% energy saving rate against the full luminous flux LED luminaire. While additional energy savings could be realized if external influences and reflected light were accounted for, it is difficult for lighting-control systems to measure or calculate external influences and reflected light, so only direct light from the luminaires was used to meet the illuminance requirements. The proposed algorithms also has the constraint that the luminaire must be ideally axisymmetric, with all light emitted below the horizontal plane. Thus, the proposed framework can provide a solution to achieve energy savings for smart buildings with low user density. Leveraging machine learning to learn user needs in conjunction with external environmental factors such as weather is expected to increase energy savings while providing an optimal lighting autonomy experience based on the user. Although the algorithms proposed in this paper can achieve energy savings, it does not take into account external influences and reflected light, has the limitation that the luminous intensity distribution of the luminaires must be ideally axisymmetric, and has not been verified in a real environment, which is left for further study.

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Abbreviations

The following abbreviations are used in this manuscript:

BEMS	Building Energy Management System
CCTV	Closed-Circuit TeleVision
CFL	Compact fluorescent lamp
CoAP	Constrained Application Protocol
DALI	Digital Addressable Lighting Interface
DIC-LCA	Direct Illuminance-Contribution-based Lighting-Control Algorithm
IoT	Internet of Things
IPS	Indoor Positioning System
LED	Light-Emitting Diode
LOS	Line Of Sight
MCU	MicroController Unit
MIMO	Multi-Input Multi-Output
PIR	Passive InfraRed
PWM	Pulse-Width Modulation
SMPS	Switched-Mode Power Supply
WPT	Wireless Power Transmission

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