Energy and Buildings 149 (2017) 180–191

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Engineering Advance

Smart lighting: The way forward? Reviewing the past to shape the future

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ARTICLE INFO

Article history:
Received 5 January 2017
Received in revised form 24 March 2017
Accepted 27 April 2017
Available online 24 May 2017

Keywords:
Smart lighting
Intelligent lighting
Energy-saving lighting
Lighting control
LED
Visible light communication
ZigBee
Internet of things

ABSTRACT

The push for ubiquitous networking and device inter-connectivity in buildings is fueling the development of a new wave of smart devices with embedded electronics, sensors and wireless connectivity that can collect, process and exchange data. Commonly known as the Internet of Things (IoT), it encompasses, but is not limited to wireless sensor networks, home automation, mobile devices and lighting control systems. Smart lighting systems are of particular interest as they evolve from traditional lighting control by introducing autonomous control of light through feedback from integrated sensors, user data, cloud services and user input, bringing with it a host of benefits including increased energy savings, enhanced functionality, and user-centric lighting. In this paper, we review the current state of the art in smart lighting technology, focusing on energy-saving, commercial, and advanced smart lighting systems. Furthermore, we also present a review of smart lighting connectivity options and discuss potential advancements through the integration of visible light communication technology.

Contents

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http://dx.doi.org/10.1016/j.enbuild.2017.04.083
0378-7788/

1. Introduction

Is smart lighting the way forward? Burgeoning interest in the Internet of Things (IoT) [1], which is a networked interconnection of everyday objects equipped with ubiquitous intelligence is fueling a growing demand to bridge the gap between lighting and smart grid systems through smart lighting. Smart lighting systems, which have been hailed as the next step in the evolution of lighting technology innovates traditional lighting control by utilizing feedback from user inputs and integrated sensors to manipulate the produced light output.

The potential benefits of smart lighting systems are manifold, the most immediate being increased energy savings. As a consequence, most works in this fledgling field of study are currently focused on extracting maximum energy savings in conjunction with efficiently driven LEDs [2,3]. In fact, systems with integrated energy-saving lighting control typically exhibit energy savings of 17–60% over traditional lighting control depending on occupant usage patterns [4]. These energy-saving smart lighting systems are generally installed in office buildings as they have the highest potential for power consumption reduction and are relatively straightforward to retrofit [5]. Beyond that, smart lighting can be used to increase light quality, regulate circadian rhythm [6], increase productivity [7], accelerate plant growth [8] and implement human-centric lighting, among other benefits. Hence, it can be argued that the advancement of smart lighting systems will have a positive impact on industrial applications and research on horticulture, architecture, building management, light quality control and human physiology.

Furthermore, recent advancements in sensing technologies open the door to a host of feedback information previously unavailable. Accurate occupancy information such as user location and activity, light spectral data from microspectrometers, and richer light information such as chromaticity and illuminance distribution can be exploited to develop smarter algorithms that enhance energy efficiency, user satisfaction, comfort, light quality, and functionality of smart lighting systems. Moreover, compatible technologies such as Visible Light Communication (VLC) [9] can also be designed for integration with novel smart lighting platforms.

The advent of high brightness light emitting diodes (LEDs) for general illumination are of particular interest to smart lighting research and applications. LEDs exhibit excellent dimming capabilities and narrow peak bandwidths, allowing a great degree of control over the produced light spectral power distribution (SPD). Furthermore, they also have low power consumption, instantaneous switching times and long lifespans, making them ideal primary emitters for a multi-channel lighting system. The LED lighting revolution is in full motion, and heralds a new age in lighting control technology.

The future of smart lighting development is a multi-disciplinary research area as it can potentially be used as a platform to bring advancements in key research areas pertaining to energy efficient buildings, building management, communication, human health, photobiology and human physiology to our living rooms, commercial buildings and offices. It is clear that the future of smart lighting is bright; however, barriers to its widespread adoption include average energy saving returns that do not justify the initial investment cost, inadequate functionality and a lack of robust light quality control. As a matter of fact, according to a recent article published by the Wall Street Journal, smart-home gadgets including smart lighting products are not faring as well as expected on the commercial market [10]. It is clear that there is still plenty of room for improvement before smart lighting products become an attractive option to the average user. The capabilities of smart lighting systems need to be drastically expanded to integrate useful functions such as increased energy efficiency, enhanced light quality, regulation of circadian rhythm, and user-centric lighting, all within a single framework. This can be achieved through the development of novel control algorithms and thoughtful design of robust multi-channel smart lighting frameworks (example in Fig. 1).

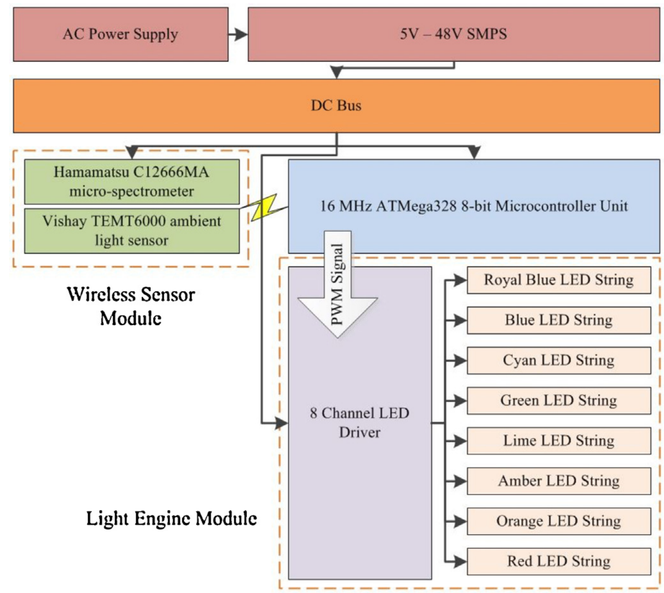


Fig. 1. Example of a wireless 8-channel smart lighting system framework.

This paper reviews existing smart lighting platforms for indoor use (residential and office), and discusses issues such as autonomous control algorithms, connectivity, applications, and their benefits and barriers, thus painting a comprehensive picture about the current state of the art. In addition to energy saving features, we have comprehensively surveyed commercial lighting systems, advanced control schemes and integration of VLC technology, compared to other surveys which focused mainly in the energy saving aspect [11,12].

The rest of this paper is organized as follows. Section 2 reviews various smart lighting platforms, including commercial smart lighting systems, energy-saving smart lighting systems and advanced smart lighting control systems; Section 3 takes a look at current smart lighting connectivity options, focusing on the prevalent wireless ZigBee standard; the integration of visible light communication into smart lighting systems is reviewed Section 4. In Section 5, we give an overview of upcoming smart lighting systems and briefly discuss their potential. Finally, Section 6 provides a concise summary and our concluding remarks.

2. Smart lighting platforms

Smart lighting systems can be broadly divided into three distinct categories:

(i) **Commercial smart lighting systems:** These are smart lighting systems that can be purchased off the shelf in stores today. They are generally focused on system aesthetics, mobile control, and the integration of user input, preferences, and data.
(ii) **Energy-saving smart lighting systems:** These are smart lighting systems with integrated energy-saving schemes designed to maximize energy efficiency through the implementation of an effective energy-saving control system.
(iii) **Advanced smart lighting control systems:** These are smart lighting systems that optimize critical lighting metrics beyond illuminance to gain a greater degree of control over the produced light output. These control systems are normally

developed on lighting systems with two or more tunable primary emitters.

2.1. Commercial smart lighting systems

The advent of high brightness LEDs opened the door to commercial smart lighting systems to make their mark on the global lighting market. The inherent controllability of LEDs, along with their well-known and easily marketable high energy efficiency are among the factors that drove major lighting companies to invest in the development of smart lighting systems. Early iterations of these smart lighting systems allowed users to control the color, Correlated Color Temperature (CCT) and brightness of their bulbs using a mobile device, typically personal smart phones; this affords the user greater control over their lights rather than the two-state (on/off) control system that has been the standard since electrical lighting was first introduced.

However, multiple factors including the high start-up cost of these early smart lighting systems contributed to their low adoption rate. In fact, smart lighting systems was, and still is seen as a luxury purchase, with little to no benefit over traditional lighting technology. One reason behind this is the limited functionality of these systems, especially when coupled with their high cost; simply put, the benefits do not outweigh the cost.

Perhaps the most well-known example of a commercially-available smart lighting systems is the Philips Hue series. The Hue system consists of wireless RGB LED bulbs and a ZigBee based wireless control bridge. The major selling point of the Hue light bulb was its novelty; it introduced the concept of lighting control beyond that of a simple on/off switch to consumers around the world. Feature wise, it allowed users to create scripts to change the light state. This brought about interesting uses for the lights such as programming the lights to flash red when you receive an email from your supervisor, setting the lights to turn on when you reach home via geofencing or making the lights vary in CCT throughout the day based on your schedule. Furthermore, the RGB channel intensities can also be individually controlled.

Based off the success of the Hue, other lighting companies such as OSRAM and GE also began to invest in smart lighting systems. Today, there are a plethora of smart lighting solutions on the market such as the GE Link, OSRAM Lightify, LIFX, Belkin WeMo, LightWave RF and Elgato Avea, among others. The functionality of all these smart lighting systems do not differ much from the original Philips Hue; only the method of implementation, number of LED channels and connectivity varies. Table 1 shows a summary of some popular commercial smart lighting products. One notable similarity of these products is the strong emphasis on aesthetics and mobile control. In fact, commercial smart lighting products almost always include a free cross platform mobile app that functions as a user interface to allow users to adjust the light output and control various parameters. In this respect, commercial smart lighting systems feel polished and are very much ahead of smart lighting systems used for research purposes.

Unfortunately, there are a number of issues that remains to be solved for these commercial smart lighting products. For one, these platforms do not have an option to integrate sensors to provide feedback about the immediate environment. As a result, these lights do not operate at their fullest potential as they rely mainly on user input and cloud data to implement their smart algorithms. The integration of sensors can increase the functionality and effectiveness of smart lighting by providing a new data source to act upon for the autonomous control of lights. Furthermore, the high cost of entry and limited functionality also remain significant barriers to adoption that need to be solved. Perhaps it can be argued that the inclusion of integrated sensors will negatively affect the cost of smart lighting products. However, it stands to reason that the extra added advantages such as higher quality lighting and increased energy savings can result in increased interest in smart lighting, therefore escalating adoption rate and consequently lowering production cost as defined by the economies of scale.

2.2. Energy-saving smart lighting systems

Traditional lighting control relies entirely on the occupants to switch off or dim lights when not in use. However, most users simply do not pay enough attention to the light switch, resulting in lights that are switched on when not in use and areas over-illuminated. In response to this, many novel lighting control systems have been developed with the goal of reducing lighting energy consumption while maintaining a high degree of occupant satisfaction and comfort through automatic lighting control. Common energy-saving techniques include manual dimming, occupancy sensing, and daylight harvesting as they usually result in a excellent energy savings and near-identical lighting performance compared to traditional lighting systems.

Unfortunately, the widespread implementation of energy-saving lighting systems has not yet been achieved, possibly due to the large variance in reported results that may or may not justify the high initial investment cost. In fact, most of the studies in this field are conducted via simulation or in controlled laboratory environments, which can raise doubts about their actual real-world performance. Furthermore, investigations into the commissioning of energy-saving lighting systems reveal significant problems with user acceptability and long term usability [13,14]. Interestingly, Eilers et al. postulated that people are likely to change their normal behavior when lighting control is present based on a study conducted in 63 private offices over a 11 month period [15]. According to the authors, the occupants were "half as likely to turn out the lights" when leaving spaces with occupancy sensors. In fact, switching the lights off manually would have resulted in additional energy savings of 30% due to the long timeout periods of the installed energy-saving lighting systems. This finding is backed by Jennings et al., who found that people normally select the maximum light output 95% of the time in offices with occupancy sensors and 89% of the time in the control group [16]. This leads to speculation by the authors of [16] that reliance on automatic lighting control results in a lower likelihood of choosing "a switch setting other than full illumination".

On the other hand, recent advancements in sensing and micro-controller technologies opened the door to improved

Table 1
Summary of notable commercial smart lighting products.

Product	Connectivity	Hub	Mobile control	Sensor integration
Philips Hue	WiFi + ZigBee	√	√	X
OSRAM Lightify	WiFi + ZigBee	√	√	X
Belkin WeMo	WiFi + ZigBee	√	√	X
LightWave RF	WiFi + LightWave RF	X	√	X
GE Link Smart LED	WiFi + ZigBee	√	√	X
LIFX	Mesh WiFi network	√	√	X
Elgato Avea	Bluetooth	X	√	X

Table 2
Performance summary of occupancy sensing based systems [18].

Research	Energy savings		Time delay (min)
	Regular usage	Irregular usage	
Richman et al. [19]	3–50%	46–86%	5–20
Floyd et al. [20]	10–19%	–	7–15
Maniccia et al. [21]	43%	–	30
Maniccia et al. [22]	28–38%	17–60%	5–20
Jennings et al. [16]	20–26%	–	15–20
Galasiu et al. [23]	35%	–	8–15
Chung et al. [24]	26.1–33.3%	–	5–20

energy-saving lighting systems, built upon novel smart lighting platforms [17]. It is necessary to tackle the energy efficiency problem holistically, from the system design to the integrated sensors and implemented smart algorithms. Combinations of energy-saving techniques can be deployed to address the fundamental flaws of individual techniques with the goal of increasing the energy efficiency, enhancing user satisfaction and lowering the setup cost. These energy saving techniques are reviewed individually and in tandem within this section.

2.2.1. Occupancy-sensing based systems

Occupancy sensing is a popular energy-saving technique due to its ease of implementation and effectiveness. In fact, occupancy sensing technologies have been heavily promoted in North American and European building codes, standards, and recommended practice documents [25,26]. The integration of simple occupancy sensors can potentially result in 3–60% energy savings, depending on occupant usage patterns [4]. Occupancy sensing systems rely on occupancy sensors to detect motion or human occupancy in an environment of interest. Feedback from the sensors is then used to control the state of the lights corresponding to that particular space. Occupancy data can be obtained from a plethora of occupancy sensors, light barriers and pressure sensors, or even from existing infrastructure that were installed for non-energy saving purposes. For example, Melfi et al. proposed a method for measuring building occupancy using existing network infrastructure by monitoring MAC and IP addresses in routers and wireless access points [27].

Current occupancy sensing technologies are normally based on single-point detection, where data collected by a single sensor is not shared with other building management systems or saved for further analysis [18]. This can potentially introduce significant uncertainty in the sensor feedback data, especially if the lighting system is not tuned or calibrated professionally. Preset time delays (typically 5–30 min) are often introduced to compensate for this uncertainty. However, this method normally results in increased energy wastage, more notably for spaces with sporadic usage patterns. The time delay is a tradeoff, as a longer time delay results in less disruption of occupant activity but a higher power consumption and vice versa. If the time delay is not properly calibrated, these energy-saving lighting systems may even be less energy efficient than a normal lighting system with manual control. Another challenge faced by occupancy sensing systems is the limited sensor field-of-view. Often, lights are switched off in occupied spaces because the user is located outside the sensor coverage area which sometimes provokes users to disable the installed sensors [18]. Table 2 summarizes the performance of some occupancy sensing based energy-saving systems.

From the data presented in Table 2, it can be seen that the amount of energy saved is highly dependent on the occupant usage pattern and the preset time delay introduced to combat the uncertainty in the sensor feedback data. For example, Richman et al. reported 3–50% energy savings for a regular usage pattern environment and higher energy savings of 46–86% for a irregular usage pattern environment with the same system setup and time delay [19]. This is a recurring trend that suggest an improved performance of these occupancy sensing based energy-saving systems when installed in environments with irregular usage patterns. When subjected to regular usage, occupancy sensing based energy-saving lighting systems simply do not perform as well, which is to be expected due to the inherent nature of occupancy sensing technologies. It is probably reasonable to assume that daylight-linked lighting control systems are a better fit for environments experiencing regular usage patterns.

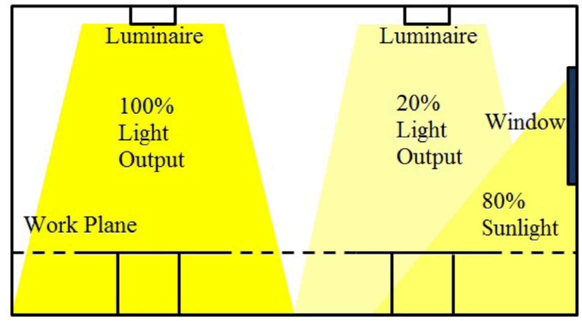


Fig. 2. Daylight harvesting – a daylight-linked lighting control technique. Ambient daylight is used to compliment existing lighting in a room.

2.2.2. Daylight-linked lighting control systems

Daylight-linked lighting control can be used to either switch lights on and off, or can be used with dimmable electronic circuits to provide artificial light when daylight is present. Daylight-linked control systems can be further divided based on its control algorithm: open-loop control and closed-loop control. An open-loop control system adjusts the light output solely based on the measured available daylight level. On the other hand, closed-loop control systems detect the light level within a specified control zone, which encompasses both ambient daylight and the instantaneous ambient light due to artificial lighting. An example of a closed-loop daylight-linked lighting control technique is daylight harvesting, which takes advantage of ambient light from building apertures to complement artificial lighting from installed lighting systems to achieve a target illumination level, illustrated in Fig. 2. This technique is of particular interest as most commercial and office spaces have sufficient daylight from windows to eliminate the need for electric lighting [28]. It can also be used to achieve a constant light output, therefore mitigating the effects of oversizing due to maintenance factor in illumination design.

A summary of the performance of some daylight-linked control systems is shown in Table 3. From the presented data, it can be seen that the energy savings reported by daylight-linked lighting control systems are typically above 40%. This shows an improvement over occupancy sensing based energy-saving systems, especially in buildings that experience a high amount of daylight. Furthermore, it is also probably reasonable to assume that daylight-linked lighting control systems are a better fit for environments experiencing regular usage patterns as the light control mechanism is not inherently tied to occupant usage patterns.

On the other hand, a major caveat of daylight harvesting is that its effectiveness is highly dependent on multiple factors, including: latitude and orientation, window characteristics, shading devices, reflectance of inner surfaces, ceiling height and partition height [12]. As a result, real-world studies have shown that most daylight-linked system do not come close to their anticipated energy savings once installed in real buildings [34]. From the summary presented in Table 3, it is notable that the reported real world performance of

Table 3
Performance summary of daylight-linked lighting control systems.

Research	Energy savings	Environment	Notes
Bodart et al. [29]	50–80%	Simulation	ADELINE and TRNSYS software on Belgian climate.
Athienitis et al. [30]	76–92%	Simulation	Location: Montreal with a Vision Control window with no obstructions.
Clarke et al. [31]	40–70%	Simulation	ESP-r and RADIANCE software.
Roisin et al. [32]	45–61%	Real-world	Occupancy between 27–44% leads to higher energy savings than an occupancy sensor.
Galasiu et al. [11]	50–60%	Real-world	Energy savings decrease by 5–25% with introduction of various static window blind configurations.
Yun et al. [33]	Up to 43%	Real-world	Location: office buildings in Korea with a double-glazed window including blinds.
Galasiu et al. [23]	20%	Real-world	Location: open-plan office building in Canada with a green-tinted glazed structure.

daylight harvesting systems are generally much lower compared to its simulated performance. Based on this, it is probably reasonable to suggest that the performance of these systems need to be validated experimentally to ensure an accurate reported energy-saving performance.

On the flip side, an argument can be made for the increased utilization of daylight in buildings as sunlight has been known to have a positive effect on the health and well-being of occupants. One such benefit is its effect on the regulation of human circadian rhythms, which can increase worker alertness during working hours [35]. Besides, research has shown that daylight is generally preferred to artificial lighting by building occupants [11]. Other than that, the presence of daylight tends to have a significantly positive contribution to lighting quality and can make a space look more attractive to users [12]. However, one disadvantage of daylight-linked lighting is that direct sunlight or reflection from building surfaces can results in glare, which may potentially cause discomfort or even eye strain [36]. This occurs when the luminance level of the visual field is higher than the level that human eyes are adapted to, causing annoyance, discomfort, or loss in visual performance and visibility [37]. Some daylight-linked lighting systems alleviate this problem by including automated window blinds to limit the incident daylight. Furthermore, excessive daylight may contribute to higher room temperatures, which increases the load on air conditioning systems in hotter climates. Similarly, larger windows also result in extra heat loss in during colder weather [38]. Based on these factors, Parise and Martirano have suggested that daylight and electric lighting need to be considered holistically to ensure maximum daylight utilization while maintaining visual comfort for building occupants [39,40].

2.2.3. Complementary energy saving systems

It is also noteworthy to discuss the integration of scheduling schemes, where lights are switched on and off based on a pre-fixed schedule. Suitable applications of time-scheduled systems include classrooms, offices, and auditoriums where the lights can be synced to a fixed timetable. Even though this is a rather crude method, this technique has actually been shown to be highly effective in areas where the occupancy pattern is accurately predictable [41]. Most implementations of time-based scheduling systems also include manual override switches to enable users to utilize the lights as the need arises.

Other than that, manual dimming is also a possible solution to improve the energy efficiency, where occupants are allowed to individually control the illuminance at their own workstations. Reported energy savings are typically low (around 10%) as this system relies solely on the occupants for feedback [23]. However, this system can result in satisfactory light levels for individual occupants as they are allowed to tune the lights to a preferred illuminance level. Recently, some energy-saving systems have begun to integrate manual feedback as an alternative form of control to improve occupant comfort and satisfaction [42–44]. These systems are typically implemented in office lighting scenarios, which are divided into a known number of workstations. Occupants are allowed to adjust the illuminance to a base preferred level as a reference set point for the control system.

In summary, these control schemes can be said to be highly ineffective on their own but are excellent in shoring up known weaknesses and/or improving the performance and functionality of other control systems. Therefore, they should be used as a complementary energy-saving technique rather than as a primary control system.

2.2.4. Combined energy-saving smart lighting systems

Recently, researchers have begun experimenting on combining multiple energy-saving techniques in a single lighting system to increase energy efficiency and improve lighting performance without compromising on user satisfaction. In fact, Tiller et al. postulated that multiple inexpensive detectors provide favorable performance over a single expensive sensor, with improved accuracy in detection allowing for greater energy savings [45]. Table 4 summarizes the energy-saving performance of notable energy-saving lighting systems with different combinations of energy-saving techniques.

Table 4
Summary of energy savings from different combined systems [46].

Research	Room type	Combination	Energy savings
Jennings et al. [16]	Office	Occupancy + daylight	46%
Nagy et al. [47]	Office	Occupancy + daylight	37.9–73.2%
Hughes et al. [48]	Office	Occupancy + daylight	68%
Roisin et al. [32]	Office	Occupancy + daylight	49–63%
Higuera et al. [49]	Office	Occupancy + daylight	13.4–43%
Chew et al. [50]	Classroom	Occupancy + daylight	55–62%
Byun et al. [43]	Office	Occupancy + daylight	21.9%
Rubinstein et al. [51]	Office	Scheduling + daylight	38–61%
Galasiu et al. [23]	Office	Occupancy + daylight + manual	42–47%
Tan et al. [44]	Office	Occupancy + daylight + scheduling	44%
Martirano [52]	Classroom	Occupancy + daylight + scheduling	35–42%

It can be seen that the integration of multiple control schemes results in a greater average energy efficiency over traditional, single control scheme energy-saving lighting systems. The bottom line is that different energy-saving techniques have distinct strengths and disadvantages. Multiple factors need to be considered when designing an energy-saving lighting system, not limited to, but including the room type, usage patterns and daylight availability. For example, a manual dimming scheme is suited as a complementary energy-saving technique for an office space with a fixed number of workstations. Besides improving the energy efficiency, an energy-saving lighting system also needs to be well designed to consider non energy related factors such as the occupant comfort to ensure optimal system performance, reliability and longevity. Furthermore, advanced energy-saving techniques can also be integrated to take advantage of existing smart lighting infrastructure with the goal of enhancing the system usability, performance and functionality.

2.2.5. Advanced control schemes related to energy saving

Advanced control algorithms serve to enhance the usability, performance and functionality of energy-saving systems. For example, Koroglu et al. proposed an illumination balancing algorithm that addresses the fundamental problem of cross-illumination and external light disturbances in daylight-linked control systems [53]. This control algorithm takes local light levels into account to achieve uniform lighting in a given space.

Location-based sensing is another field of study related to energy-saving lighting control systems [54]. This control scheme will be useful in environments that experience highly varying usage patterns as it has the potential to lower the time delay needed for occupancy sensing based systems through accurate sensing of occupant presence. Recently, Pandharipande et al. developed an enhanced ultrasonic sensor array to determine occupant location, which is used to determine the optimum dimming levels with the goal of minimizing the power consumption while maintaining a uniform illumination level and a minimum illumination level over unoccupied spaces [55]. The instantaneous location of occupants is known at any given time; this information can be appropriated for accurate dimming and occupancy based control.

Besides this, another lighting control approach is to derive the control system set points based on interaction with the user and statistical analysis of feedback data [47,56]. The objective of these control schemes is to improve system energy efficiency while maintaining user satisfaction. With precise analysis of a sufficiently large set of data, it is also possible to implement predictive illuminance modeling to accurately estimate the required illuminance for different spaces within a building. In fact, a model developed by Basu et al. was able to predict illuminance at seven monitored workstations with 80–95% accuracy while utilizing 60% fewer sensors compared with state-of-art systems using one photo-sensor per luminaire [57].

Feedback data from integrated sensors in energy-saving lighting systems can also be used for other purposes such as indoor positioning, building information services and building usage maps [58,59]. Indoor positioning can be achieved through the measurement of radio received signal strength via user mobile devices. Based on this, building usage maps can also be constructed with information from indoor occupancy sensors, especially if combined with advanced location sensing that can measure the occupant trajectory. Besides this, building-wide power consumption data of the smart luminaires can be collected centrally to enhance the effectiveness of building management services by exploiting existing wireless smart lighting infrastructure.

2.3. Advanced smart lighting systems: beyond illuminance control

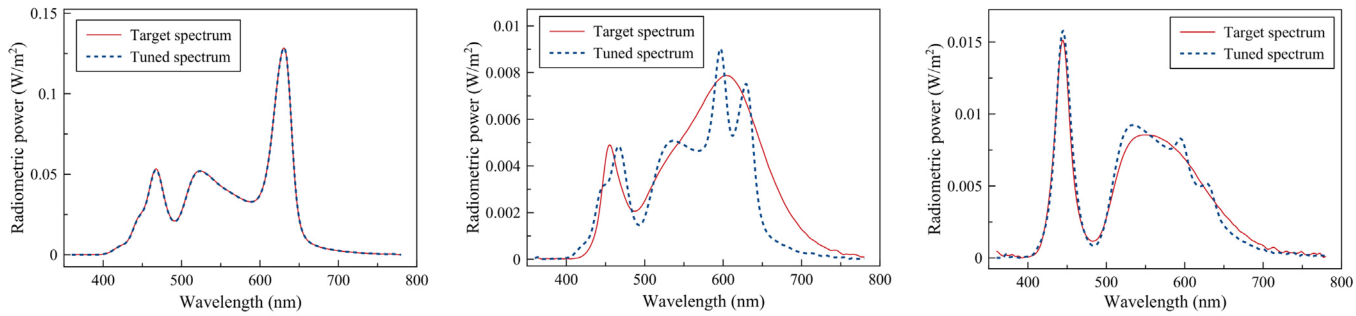
Energy-saving LED smart lighting systems generally optimize only the illuminance at a given work plane. This makes a lot of sense as a large majority of commercially available luminaires consist of a single LED type, typically a phosphor coated LED. These luminaires produce light with a fixed SPD, color temperature and color chromaticity, thereby exclusively allowing control over illuminance. With the recent advancement in LED lighting technology, mixed color systems are becoming more viable as the price, quality and luminous efficacy of LEDs are projected to increase yearly. These lighting systems with multiple primary emitters afford lighting engineers a greatly enhanced degree of control over many facets of the produced light. They open the door to novel control algorithms that calibrate the produced light autonomously with many different constrains such as the SPD, CCT, color coordinates, Color Rendering Index (CRI) and Gamut Area Index (GAI), among other things. This is particularly interesting as it bridges the disconnect between existing research on the visual and non-visual effects of visible light on humans and the actual real-world implementation of these systems. It stands to reason that the implementation of these novel smart lighting systems will allow new experiments to be designed to further research in these areas. Furthermore, it also allows the findings of this research area to be taken advantage of in real world systems, perhaps even in our homes and offices.

From existing literature, the benefits of moving beyond simple illuminance control are very obvious. Besides applications in specialized lighting such as stage and architectural lighting, it has been said that "recent discoveries in photobiology established a link between human physiology and light, and put in evidence the need to understand what the future of lighting practice will be if the non-visual effects of light will be considered in the future recommendations" [60]. Recent research has shown that the manipulation of the produced light SPD can be used to increase light quality, regulate circadian rhythm [6], increase productivity [7], accelerate plant growth [8], and implement human-centric lighting, among other things. Furthermore, the CCT has been shown to have an impact on human comfort and productivity [61–63]. As a matter of fact, suitable visual lighting and color has been demonstrated to drastically reduce stress levels and even affect the mood of the occupants [64]. By controlling the produced light SPD, and by extension the CCT, it is theoretically possible to ensure suitable, high quality lighting to suit the needs of the user.

2.3.1. Non-visual effects of light

Lighting quality metrics are useful for quantifying the photopic effect of light sources on humans. However, recent studies have also shown that there is a correlation between building lighting and human health and work performance. Therefore, good quality lighting should also account for its non-visual effects as it determines spatial appearance and regulates human well-being [65].

Perhaps the most obvious example of the effect of lighting on human psychology is the effect of different color temperatures on human perception of a space. Lighting is often used as a complement to building architecture and interior design. However, choosing suitable lighting has always been more of an art than a science. Recent research has confirmed that there are indeed have different preferences of color temperatures for different types of spaces [66]. In fact, it has been proven that the color temperature of lighting has an immense impact on the human physiological processes [67,68]. Generally, lower color temperatures are preferred for spaces such as bedrooms, hotels, and living rooms; higher color temperatures are normally required in work spaces such as offices, warehouses, and classrooms.



(a) Light engine (b) Warm white LED (c) Cool white LED

Fig. 3. Performance of a spectral replication control system. The figure shows the difference between the SPD of a target and tuned spectra [72].

Higher color temperatures are normally linked to greater alertness and increased work productivity [66,69]. This has been associated with the greater proportion of blue light (460–500 nm) in these light spectra. This spectrum has been shown to suppress melatonin secretion [35], which is vital to our day/night cycle; high levels of melatonin are secreted during the night and low levels are secreted during the day. This causes a shift in our natural circadian rhythm, which can be manipulated to make it harder for us to fall asleep or vice-versa. Properly implemented, short-wavelength-enriched light can be used to enhance alertness and performance and treat sleep disorders [70].

Unfortunately, human photopic response peaks at around 555 nm, which suggests that light optimized for our photopic response may not necessarily be effective for optimum non-visual effects. Furthermore, research has suggested that high levels of exposure to blue light can cause ocular damage [71]. A popular metric for measuring the effect of a light source on human circadian rhythm is the circadian action factor (CAF).

2.3.2. Novel control systems

Research focused on smart lighting systems that optimize light parameters other than the illuminance is currently very limited, likely due to the less obvious benefits and more complicated lighting systems required to implement these algorithms. The CCT seems to be the popular choice of focus for optimization, which is probably due to the fact that a varying CCT can be achieved in bi-color systems which are easier to implement that true color-mixed lighting systems. A bi-color lighting system is constructed with two LED phosphor-converted primary emitters, normally with a warm white source (∼2700 K) and a cool white source (∼5000 K). The intensity of each channel is controlled individually through PWM dimming, where the channel-wise duty cycle can be adjusted to achieve a mixing ratio as defined by the control algorithms.

Recent work done by Chen et al. is an example a of CCT control scheme implemented on a bi-color LED lighting system. A non-linear approach was taken to control the illuminance and CCT which resulted in a more accurate control system compared to the existing linear approach, which was also verified experimentally [73]. Even more recently, Lee et al., proposed a non-linear precise dimming and color control scheme for a bi-color LED lighting system. With this method, the maximum deviation in the CCT was reduced to 1.78% from 27.5% for a closed-loop linear approach. Furthermore, the maximum luminous flux error was also reduced to 3% from 20% [74].

Another type of system implementation is the use of RGB primary emitters. These primary emitters typically have very narrow bandwidths and a singular peak wavelength which allow tighter regulation of the produced light SPD. Buso et al. proposed a control system for regulating the illuminance and color temperature by adjusting the PWM duty cycle of each channel individually [75]. This control scheme managed to achieve color temperature variations of less than 2% from its target. However, it is bounded for a CCT range of 3000–6000 K due to the limited number of primary emitters.

The CCT can also be controlled based on a weighted linear combination of individual color coordinates [77]. These methods typically optimize only the CCT, disregarding other parameters such as the power consumption and luminous flux. Recently, Gao et al. proposed a constrained optimization technique for multi-color LED light sources to achieve accurate CCT control [76]. An optimization algorithm was implemented using linear programming to achieve optimal color rendering design while restraining the luminous flux, color temperature and blue light spectral components.

Closed-loop control systems have been shown to be effective in improving the performance of color-mixed lighting systems. In fact, the integration of sensor feedback is particularly effective for RGB lighting systems, as they suffer from a myriad of factors which can affect their color reproduction accuracy, such as thermal management, aging, and variance in individual LEDs [78]. An example of a closed-loop spectral control system is the spectrally tunable source (STS) developed by Fryc et al. [79,80]. The STS utilizes multiple LEDs as its light sources to mimic different SPDs over the spectral range from 380 to 780 nm as an improvement over an earlier system which uses a conventional lamp and monochromator with a multi-

Table 5
Comparison of notable lighting control systems for the optimization of various lighting parameters beyond illuminance control.

Research	Channels	Parameter	Control scheme	Purpose
Chen et al. [73]	2	CCT	Open-loop	General lighting
Lee et al. [74]	2	CCT	Open-loop	General lighting
Buso et al. [75]	3	CCT	Open-loop	General lighting
Gao et al. [76]	3	CCT	Open-loop	General lighting
Kim et al. [77]	4	CCT	Open-loop	General lighting
Muthu et al. [78]	3	Color	Closed-loop	General lighting
Chew et al. [72]	8	SPD	Closed-loop	General lighting
Fryc et al. [79]	Many	SPD	Closed-loop	Characterization
Fryc et al. [80]	Many	SPD	Closed-loop	Characterization

element liquid-crystal filter [81]. An optimization algorithm was implemented to facilitate matching of target source SPD. However, the STS was not constructed to be a general lighting source, but instead it is meant to replace the usage of many standard sources of optical radiation with a single spectrally tunable source in photometry calibration facilities. In fact, spectrally-tunable sources are normally used for calibration or characterization purposes rather than for general lighting [82–84]. An example of a STS used for general lighting was designed by Chew et al. [72], which features an integrated spectral replication control system (results shown in Fig. 3). The control system has been shown experimentally to achieve near perfect replication of target spectra, with an accuracy within 5% for the CCT and Euclidean distances which fall well within a five-step uv unit circle. Table 5 summarizes some notable lighting control systems in this area of research.

3. Smart lighting connectivity

Connectivity forms the backbone of a successful smart lighting system. Most commercial smart lighting systems rely on a bridge, which acts as the link between the user and the smart bulbs. The bridge connects local WiFi networks and the ZigBee networks that these smart lighting systems normally utilize to control the individual bulbs. In an effort to standardize wireless smart lighting connectivity, the ZigBee Alliance introduced the ZigBee Light Link (ZLL) in 2012 with the goal of providing a global standard for interoperable and easy-to-use consumer lighting [85]. The ZLL standard is endorsed by the Connected Lighting Alliance. ZLL is part of the IEEE 802.15.4 ZigBee standard, allowing interoperability with other products with ZigBee standards such as ZigBee Home Automation, ZigBee Remote Control and ZigBee Health Care. Commercial products such as the Philips Hue and GE Link Smart LED make use of the ZigBee Light Link as the base for their bulb connectivity.

Other wireless connectivity options for smart lighting include the IEEE 802.11a/b/g/n/ac WiFi standard, the IEEE 802.15.1 Bluetooth standard and Bluetooth Low Energy (LE) 4.0 standard. On the other hand, commonly used wired connectivity standards are the Digital Addressable Lighting Interface (DALI), Digital Multiplex (DMX512), Philips LightMaster KNX, Ethernet and Power Line Communications (PLC) interfaces. Wireless lighting networks are often easier to implement compared to wired solutions, which may require extensive cabling, and are often difficult to retrofit for existing buildings.

3.1. The ZLL standard

The ZigBee Light Link is a public application profile created by the ZigBee Alliance to support lighting applications based on the ZigBee PRO wireless network protocol. This last-hop connectivity standard offers operation at the 2.4 GHz ISM band with over-the-air data rates of up to 250 Kbps. Important networking parameters like routing, security and network management are also specified by the ZLL standard. Unlike a traditional ZigBee network, the ZLL does not require a coordinator; network formation is instead accomplished with a network commissioner called Touchlink. The purpose of this is to provide an easy and intuitive installation experience for the wide consumer market.

The ZLL protocol is described in Fig. 4. The ZLL standard includes provisions for two general categories of devices, which are:

1. **Light devices:** on/off lights, dimmable lights, color lights, extended color lights and color temperature lights.
2. **Controller devices:** light switches, occupancy sensors, remote control units, smart phones and computing devices. Can be classified as a color controller, non-color controller, color scene controller, control bridge and on/off sensor.

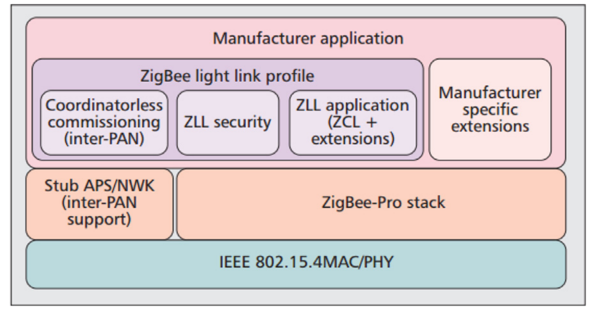


Fig. 4. The ZigBee Light Link protocol stack [86].

Light devices are often specified as routers while controller devices are usually end devices in a mesh network for maximum routing flexibility. As described earlier, the ZLL uses a coordinatorless commissioning method to form a network in addition to the conventional ZigBee commissioning method, called Touchlink. With Touchlink, a lighting device is added to the network by a controller device called an initiator. The lighting device needs to be close enough to the initiator so that its RSS exceeds the manufacturer specified threshold to join the network. Touchlink uses inter-PAN communication for commissioning messages, where three sets of commands between the initiator and the lighting devices are exchanged: discovery of target devices, transfer of device information and network settings and a request for network formation or to join. This is repeated for every new light device that wishes to join the network.

All ZLL networks employ 16-bit network addresses to identify devices, rather than the longer 64-bit addresses available for a conventional ZigBee network. The assignment of network addresses is handled by a ZLL controller device from a range of addresses. To broadcast a message to a set of devices on the network, group identifiers can be assigned in a similar manner. This mechanism is typically used by a controller application at a network endpoint. Security is handled at the network-level; a common network key is used by all network nodes to encrypt or decrypt messages with a 128 bit AES encryption. This key, which is unique for every network is randomly generated by the initiator device when the network is created. To further maximize network security, the distribution of this generated network key to new devices joining the network is secured with a ZLL master key defined during the manufacturing process for all ZLL-certified devices.

The ZLL standard allows control over various common lighting parameters including: on/off state, brightness, color temperature, color hue and saturation. These parameters can be defined for individual light devices or multiple groups of light devices. Furthermore, combinations of these lighting parameters can be configured into a “scene” and stored in memory to be recalled as needed. An individual lamp may belong to more than one group. The result is a highly flexible control system that allows lights to be controlled individually or collectively in a room to cater to different lighting needs at different times.

The ZLL standard also allows the home lighting network to be connected to and controlled from the World Wide Web. Therefore, the installed lights can be controlled by any device with an Internet connection (laptop, mobile device) anywhere in the world. The bridging of the ZLL network and the World Wide Web is handled by a control bridge which is one of the required network devices. This bridge acts as a transparent router to enable seamless connection between the end device and the network lighting devices by passing any commands as described above to the relevant recipients.

Table 6
Comparison between wireless connectivity options.

Parameter	Wireless technology		
	ZigBee	Bluetooth	WiFi
Cell nodes	>65000	Up to 8	<254
Range	Up to 100 m	Up to 10 m	Up to 50 m
Data transfer rates	Up to 250 kbps	Up to 1 Mbps	>1300 Mbps
Cost	Low	Low	High
Power consumption	Low	Low	High
Scalability	High	Short	Medium
Network formation	Flexible	Star	Flexible
Requires bridge	Yes	No	No

Another advantage of the ZLL standard is its interoperability with other ZigBee standards, most notably the ZigBee Home Automation (HA) standard if they are joined to the same ZigBee network. ZLL lighting devices can be controlled by HA devices in addition to the aforementioned ZLL controller devices, thus extending the compatibility of the ZLL standard. This is possible as both the ZLL and HA standards utilize the same clusters and the connections are formed with similar ZigBee mechanisms as established by the IEEE 802.15.4 ZigBee standard.

3.2. Comparison between wireless connectivity options

Besides ZLL, or IEEE 802.15.4 ZigBee, other wireless connectivity options include the IEEE 802.15.1 Bluetooth 4.0 low energy (BLE) and IEEE 802.11a/b/g/n/ac WiFi standards. Table 6 shows a brief comparison between these wireless connectivity options. It can be seen that ZLL has a combination of low cost, low power, high range and high scalability, which is suitable for home and office lighting scenarios. Furthermore, the ZLL standard is endorsed for use in residential lighting by the Connected Lighting Alliance, which is an industry consortium of leading lighting companies. As such, ZLL has a robust certification scheme and extensive application specific features for home lighting.

Bluetooth and WiFi networks have the advantage of higher data rates over ZigBee networks. However, the maximum ZigBee data rate of 250 kbps is more than enough for the purpose of transmitting and receiving lighting commands. Another advantage of these networks over ZigBee networks is the lack of need for a connecting bridge between user end devices and the lighting devices. With Bluetooth, it is possible to control the light bulbs directly from a mobile phone with a Bluetooth connection. However, it is unrealistic for a mobile device to actively serve as the lighting system coordinator due to the mobility and battery life constrains. Furthermore, a new network needs to be set up every time a new mobile device enters or leaves the room, which may degrade the user experience.

In summary, the IEEE 802.15.4 Zigbee standard remains the logical choice for the wireless network connectivity of smart lighting devices, as evidenced by its use in major commercial smart lighting products such as the Philips Hue and the OSRAM Lightify smart lights. Wireless ZigBee networks have also been applied to road lighting [87–89], office lighting [90], and home lighting systems under research [91–93].

4. VLC aided expansion

The previous sections in this paper discussed how improving energy efficiency and spectral control of lighting could be achieved through a myriad of techniques. In this section, we will explore how LEDs can be used to transmit information, also known as Visible Light Communication (VLC). VLC allows for ubiquitous lighting to be used as ‘LiFi’ modems [94], with the potential to substitute and supplement contemporary WiFi systems. VLC has gained focus

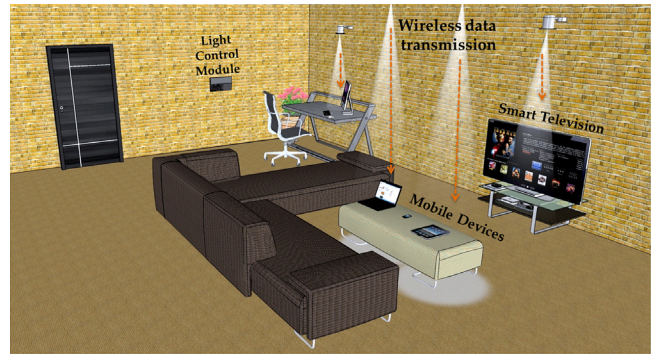


Fig. 5. Example of a VLC enabled smart lighting system.

with the rapid rise of LED technology as mainstream illuminators [9]. LEDs have been used in optical communication for decades due to its high switching capability – ranging in electrical bandwidths of several MHz to GHz. Information is modulated into the instantaneous luminous flux of the LED source, while photodetectors located at the receiver i.e. smart phones, tablets etc. convert the corresponding illuminance into a current used for demodulation. In the early years of VLC, it was seen as an extension to Infra Red communication, but recently LED adoption in indoor illumination, it is being viewed as a distinct technology exploiting the niche of simultaneous lighting and communication [9].

The basics of VLC have been surveyed and outlined in previous works [9,95], this section will focus on how it could potentially supplement smart lighting systems and smart homes.

4.1. Broadband information broadcasting

One of the primary attributes of VLC systems is that it is able to provide high data rates over confined spaces – which increases the information density. VLC could merge into spectrally tunable smart lighting systems through a technique known as Wavelength Division Multiplexing (WDM), where different colored light sources transmit independent information which is extracted using detectors with optical filters designed for the light wavelengths of interest [9]. Recently, high data rates have been demonstrated using laser diodes, micro LEDs or resonant cavity LEDs [96–98]. However, these techniques may not be suitable for indoor illumination purposes due to their lower narrow spectral width reducing the color rendering performance, as well as lower light output power. General purpose high brightness LEDs provide lower data rate potential – but at a much higher lighting quality. Nonetheless, such systems have generated data rates in excess of 1 Gb/s under experimental conditions [99–101]. An example of a VLC enabled home network is depicted in Fig. 5.

Most studies have focused on the use of ubiquitous lighting as modems to broadcast information. There remains open areas of study relating to VLC uplink. Proposed systems include WiFi, Infra Red and Ultra Violet bands [9]. The desired uplink system could well depend on the system requirements.

4.2. Indoor positioning

Recently, indoor positioning has been looked at as a potential offshoot of VLC technology. Visible Light Positioning (VLP) techniques serve to provide localization and location based services in indoor environments – where GPS systems are impenetrable [102]. VLP systems are much more accurate than WiFi based positioning schemes [103], and have already shown to be integrated into mobile phones [103]. Combining both communication and positioning yields the potential for localized transmissions [104], which can reduce the overall power consumption of the system, while complementing smart lighting systems of the future.

4.3. System integration and device connectivity

The expansion of a multi-channel LED system built for finer spectral control into a VLC enabled system has significant implementation challenges to overcome. A dynamic lighting system would result in changes in the VLC systems achievable data rate with varying illuminance and chromaticity [105]. As such, rate control is required at transmission depending on the illumination constraint.

Previous standards for VLC systems were modeled from IrDA standards [106]. IEEE proposed the first VLC networking standard, IEEE 802.15.7 in 2009. The IEEE 802.15.7 standard supports data rates of up to 96 Mbits/s using single carrier modulation schemes [107]. Recent VLC system demonstrations have yielded multi gigabit data rates using spectrally efficient multi carrier modulation schemes such as Orthogonal Frequency Division Multiplexing. Thus an improved IEEE standard for VLC networking which incorporate enhanced modulation formats with multi-channel sources could significantly increase the chances for eventual adoption with future smart lighting systems.

VLC leverages the existing lighting infrastructure for information transmission. The overarching wired infrastructure for VLC within the home network could utilize PLC to bring down the overall implementation cost. PLC is already being used within smart lighting system connectivity [108]. VLC could seamlessly integrate into a PLC system, and has been demonstrated in [109].

5. The way forward

In this section, we look to the future and identify up-coming smart lighting schemes. Energy saving schemes have been thoroughly researched, as shown in the previous sections, and a vast area of further development is the added-on enhancements such as the design of tunable luminaires that can be optimised for visual and non-visual qualities. As described in Section 2.3.1, the non-visual component of light in the wavelength range 460–500 nm (of the spectrum) affects functions of the human body, such as the circadian rhythm which affects the sleep-wake cycle and ultimately human alertness and productivity. Hence, there is a wide scope of work to be done on the investigation of various light spectra on hospital patients (in particular the Intensive Care Unit (ICU) which is illuminated at almost all times), shift workers, and travellers across multiple time-zones, just to name a few; these groups of people are subject to disruption in their sleep-wake cycles, and exposure to the right kind of light spectra that will help re-align the cycle will certainly be beneficial. Related research should be extended to the case of offices, work-places and homes, which can give knowledge on the types of spectra to improve productivity and general health and well-being. Following on from that, the next area of enhancement would be the development of lighting control systems that are able to produce lighting with spectrum that can achieve the aforementioned benefits (good non-visual qualities) as well as being pleasing to the eye (good visual qualities).

In addition to being able to deliver light more efficiently at a reduced cost compared to other types of light sources, LEDs are easily controlled, networked and embedded with sensors; these make them a key enabler of a quickly growing number of opportunities in the Internet-of-Things (IoT). For instance, in the retail industry, indoor location technology which uses sensor-embedded LEDs can enable retailers to understand foot traffic, manage sales-rep head count and collect data on customers in a similar manner that they can online. In the home environment, using sensors, a networked LED lighting system can follow the user and automatically light up whichever room they may be in, and for a hearing-impaired person the sensors can detect various activities and phenomenon (such as alarms, baby monitors, and smoke detectors) and cause the lights to flash up as a warning.

6. Conclusion

The fundamental nature of smart lighting platforms suggests that it is possible to integrate multiple smart algorithms in a single, well-designed framework via implementation on an integrated micro-controller. An energy-saving control system needs to be at the heart of every smart lighting platform as excellent energy efficiency is highly beneficial and is a highly marketable feature. Besides that, novel control algorithms should be continuously developed to improve the functionality and performance of smart lighting systems. Furthermore, the integration of VLC technology into lighting systems has huge potential in providing multi-gigabit wireless communications using light. It can be concluded that the future of smart lighting development is a multi-disciplinary research area; smart lighting has the potential to provide the platform to bring advancements in key research areas pertaining to energy efficient buildings, human health, photobiology, telecommunications and human physiology to our living rooms and offices. Consequently, current smart lighting systems need to be designed thoughtfully by drawing inspiration from the past to create a brighter future for lighting.

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