IET Smart Cities

Review Article

eISSN 2631-7680
Received on 6th July 2020
Revised 1st September 2020
Accepted on 2nd September 2020
E-First on 23rd September 2020
doi: 10.1049/iet-smc.2020.0061
www.ietdl.org

LED lighting systems for smart buildings: a review

Héctor F. Chinchero[1] ✉, J. Marcos Alonso[1], Hugo Ortiz T[2]

[1]*Electrical Engineering Department, University of Oviedo, Campus de Viesques, Gijón, Asturias, Spain*

[2]*Electrical, Electronics and Telecommunications Department, Universidad de las Fuerzas Armadas ESPE, Sangolquí, Ecuador*

✉ *E-mail: UO248474@uniovi.es*

Abstract: This study presents a review of smart light-emitting diode (LED) lighting systems applied to smart buildings. The study is focused on drivers, protocols, technologies, communication networks and applications. An extended overview of the methodologies used for LED lighting control in smart buildings is addressed. The study also presents an integrated architecture able to achieve the necessary services and control methodologies for intelligent building energy management system for LED lightings systems in smart buildings.

1 Introduction

The energy consumption in the world faces increasingly complex challenges to solve, which are mainly linked to population growth, development of new infrastructure for transport in cities, growth and innovation of industrial production processes, as well as a dizzying increase in buildings, new environments, and those associated with the development of human activities, including those related to climate change. The high level of energy consumption is one of the largest contributors to climate change, accounting for about 60% of global greenhouse gas (GHG) emissions. On the other hand, studies show that improving energy efficiency standards could reduce the overall electricity consumption of buildings and industry by 14% [1, 2].

Buildings are one of the main players in global energy consumption, making up 30% of the global energy consumed on the planet and 60% of the electricity produced [2, 3]. In this sense, systems in a building, such as air conditioning, lighting, elevators, security, communications, among others, have an energy consumption that certainly depends on the type of technology, the control platforms and the functional behaviour of the system, its enclosure and the user's behaviour as internal factors, with external factors being those related mainly to those of the climate.

The lighting related to residential and working environments corresponds to 20% of the total consumption of the energy produced and 30% of the electricity consumed in the building [1, 3]. The energy consumption in buildings illumination is associated with the type of lamp, its efficiency, and mode of use etc. Optimising the energy consumption of lighting systems depends not only on how efficient the technologies with which the lamps and the electrical elements that makeup it are developed, but also on the techniques associated with the controllers of these lamps.

The new lighting systems based on light-emitting diode (LED) have become one of the best lighting sources currently used, owing to their high luminous efficiency [1, 4]. LED technology is increasingly replacing traditional lighting lamps in the industry such as incandescent light lamps and compact fluorescent lamps. LED lamps have also been found to require less power compared to incandescent or fluorescent lamps [4]. LED technology has also been used in various applications such as street lighting, signage screens and traffic lights, message signs panels, architectural lighting, greenhouse lamps, emergency lighting, vehicle lamps, personal accessories like watches, flashlights, home appliances etc. Compared to other type of traditional lighting sources, LEDs have a single physical structure, optical and electrical characteristics, as well as their own advantages such as: (i) energy saving, 40% of electricity is transformed into light; (ii) long lifespan, >100,000 h; (iii) quick response, the start time of LEDs is in the range of nanoseconds; (iv) solid-state encapsulation, belonging to the cold light source type; (v) they are environmentally friendly, do not include harmful elements such as lead (Pb) and mercury (Hg); and (vi) appropriate colour reproduction index, among others [1, 2, 4]. In addition, with the development of new methods and technologies of manufacturing LED for both encapsulation and coating, the cost of LED technology has been reduced dramatically, making it increasingly accessible in all types of applications. In the case of building lighting, LED technology is widely used for indoor and outdoor applications. There are lamps that replace traditional fluorescent tubes in working areas, point projection lamps such as those used in rooms, hallways etc. decorative indoors lamps, RGB type LED arrangements, higher power lamps used for outdoor lighting in the vicinity of the building, RGBW projection lamps for the exterior decoration of the building etc.

On the other hand, LED lighting technology has limitations that should be considered when implementing a lighting control system. For example, the high-gloss LEDs required for general lighting are more expensive, but every day the price is reduced. In many cases, the cost of drivers should be added. There may also be an incompatibility in control, due to the wide range of devices; not all LED lamps are dimmable and some of them can deliver poor performance when dimmed. This often makes it necessary to purchase complete systems that include the LED module, LED driver and LED dimmer to ensure compatibility. It limits the possibilities of integration and the development of broader energy efficiency strategies. In addition, it is important to indicate that outdoor architectural lighting spaces will still require the use of sodium lamps because of their specific colour temperature and spectral distribution. In any case, the same automation and control concepts presented in this paper can be applied to any kind of light source.

The remaining part of the paper is organised as follows. Section 2 presents lighting in smart buildings (SB). Section 3 presents LED lighting technologies for SB. Section 4 shows an overview of LED lighting methodologies. Finally, Section 5 presents the conclusions of this work.

2 Lighting in SB

Conventionally, lighting control has been manual, which requires physical, local control manipulation and is commonly used in the widest scope of applications. In the 1970s, automatic lighting control appeared, incorporating the use of autonomous motion sensors implemented in centralised systems [5]. On the other hand, smart lighting control includes micro-processed elements such as sensor input modules and relay outputs for turning lighting areas on and off. Fig. 1 shows the integral concept of smart lighting in intelligent environments.

Currently, smart lighting has evolved to integrated control systems that allow the designer to connect sensors, controllers and user interfaces for the development of applications such as intelligent RGB lighting environments, habitability scenes, advertising and promotion, light decoration, shows etc. Also, intelligent lighting control systems currently have the possibility to perform energy management, reporting of breakdowns, energy consumption reports, positioning, time programming and scheduling, voice control, local and remote control etc. [5].

2.1 Smart buildings

SB arise from a discipline coined in the 1990s known as ‘Inmotica’. Fig. 2 illustrates an SB scheme considering the principal components and systems. On the other hand, building automation system is the total integration of elements and services of the building into an automation system [5]. The goal of an automation system for an SB is to develop and implement services

Fig. 1 *Smart lighting in intelligent environments*

Fig. 2 *Smart building services*

that help the management of the building and improve the quality of service as well as the user comfort in the building [5, 6].

In SB there are two well-defined systems for environmental control. The room management system (RMS) controls individual zones and has connected some sensors and actuators to implement smart services in the room. The building management system (BMS) is an integrated platform that allows the building to achieve the following functions [5]: (i) control and supervision of technical installations; (ii) personnel control and supervision; (iii) optimisation of resources; and (iv) achieve large energy savings.

Services in an SB are related to the automation level of the control system. The services for SB must be developed according to the four systems that make up a truly intelligent building. These are the energy-saving system, security systems, wellness and comfort system, and finally the communications system [5, 7].

2.2 Energy saving in SB

The energy consumption of lighting in office buildings is ∼20%, while for hotels it is 15% [5, 8]. On the other hand, heating and air conditioning can reach up to 45% depending on the type of building. Energy consumption is one of the great expenses of a building; lighting and air conditioning systems together represent approximately 40–60% of energy consumption. However, they represent ∼80% of electricity consumption. The lighting system can occupy up to 40% of electricity consumption, so it is important to have strategies and energy management systems (EMSs) to optimise this consumption [5].

When it is not possible to know where and how much the building consumes, it is necessary to follow an energy efficiency guide to perform an energy audit, measure energy consumption, analyse the information to determine the exact consumption profile in real-time and determine energy efficiency strategies, as well as to choose the best automation system. In the case of the lighting system, energy is consumed in excess in areas and when it is not needed. Thus, traditional automation features include lamp on/off time programming, presence detection, motion detection, lighting level regulation, and power management from the BMS. These automation services achieve energy savings of up to 30% in the energy consumption of the building associated with the lighting system [5, 8].

The energy-saving services in an SB are developed in order to achieve great savings in electricity consumption, water consumption, reduce resource losses and optimise the investment made in implementing technology solutions in SB. For energy consumption management the ISO 50001:2011 energy efficiency normative [9–12] is applicable. This ISO normative consists of guidelines for energy-saving and intelligent use of energy without loss or waste, using the minimum energy and maintaining the quality of goods and services, to preserve comfort for the users [5, 9]. Currently the normative has been updated in ISO 50001:2018 [13]. In [10] the application of ISO 50001:2011 in the performance assessment of university buildings with thermal comfort is presented. On the other hand, in [11] the application of ISO 50001:2018 for energy audits is performed for academic buildings.

On the other hand, the GHG protocol establishes comprehensive global standardised frameworks to measure and manage GHG emissions from private and public sector operations, value chains and mitigation actions. A replacement policy of residential lighting optimised for cost, energy, and GHG emissions is presented in [14], where for each lamp technology, data of cost, primary energy, and GHG emissions is collected for the production, transportation, use, and end of life stages, where all GHG emissions are expressed in global warming potential (GWP) values, that includes the 100-year time horizon GWP relative to CO_2. The use of the fourth assessment report (AR4) values is recommended in AR4 GWP-100 [14, 15]. The latest AR5 values are presented in [15].

Another service that can be developed in the BMS is the management of the condition of the lamps considering the properties of heat dissipation, which will help increase the lifetime of LED lamps. The luminaires need to implement appropriate sensors and materials such as carbon nanotubes to improve heat

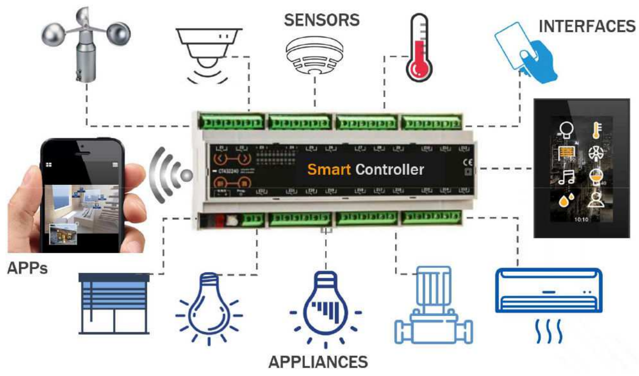

Fig. 3 *Smart lighting control*

evacuation. The BMS can implement services to configure set points to dissipate the heat easily and efficiently according to parameters such as ignition time, lifetime, temperature, movement, occupation etc.

3 Smart LED lighting technologies for SB

3.1 Sensors and controllers

The overall effectiveness of lighting control systems depends on the appropriate conjunction of intelligence in the control and sensitivity of the environment. In order to provide adequate sensitivity, a correct selection of the sensor and its appropriate location are required. Occupancy sensors (presence or movement) and illuminance level sensors are generally used. Conventional occupancy sensors are pyroelectric infrared (PIR) type, radar ultrasonic and radio frequency (RF) or microwave type, or combination of both technologies to increase their performance. The PIR sensors have been extensively used in indoor and outdoor applications as they are low cost, easy to use and widely available. PIR sensors respond to IR radiating objects moving in its viewing range. In this method, only moving objects can be detected and the rate of false alarm is high. These are ideal for hallways, entrances and general areas. In [16] problems and solutions with PIR in smart lighting systems have been described. Radar sensors are electronic devices capable of detecting motion by using electromagnetic radiation. These are able to detect motion by applying the Doppler effect and have greater coverage and sensitivity than PIR sensors. Illuminance level sensors are basically photoelectric devices used to provide trigger levels to lighting control systems, generally focused on the use of daylight. In [17] features and results of testing of several low-cost sensors of illuminance intensity are presented.

On the other hand, the provision of intelligent actions in lighting systems depends on the input/output (I/O) controllers. These electronic devices have specific functionality in handling the demands of talking to and controlling peripheral devices. These include the ability to drive the devices with the correct electric signal level and with the correct standard interface. It also includes the capacity to connect devices with the correct protocol. Controllers may be processing simple logic level inputs or outputs. They may also be required to measure the time between logic events, perform signal conditioning or to produce periodic waveforms that can be used to control specific output devices.

In addition, controllers also have the ability to interconnect different peripherals through standard interfaces such as serial, and are able to address and transfer data to and from devices. As interfaces can incorporate USB, UARTs and a variety of other standards. In [18] characterisation of typical I/O controllers, their operating parameters and specific applications is presented. Fig. 3 shows the components of a centralised smart lighting control application.

Another important component of LED lighting systems is user interfaces or human–machine interfaces (HMIs). Its acceptance by the user is key to ensure the success of the system. That is why in the last years a large number of new interfaces with enormous interaction capabilities have been presented [5, 7, 19–23]. This goes hand in hand with the great advancement of the internet, the development of mobile phone use and the development of wireless systems within facilities. In the list of devices are traditional interfaces such as push buttons (some with built-in sensors), displays, traditional touchscreens (resistive, capacitive, or infrared), smart touchscreens, plus user interfaces that include web servers or allow interaction through Apps (Android, IOS) or through smart TVs and desktop computers. In addition, voice control technologies must be easily integrated into a smart lighting system. Currently the automation systems as KNX, Lonworks and BUSing have interfaces with Alexa, Google Home and Amazon Eco integration. To do this, it is only necessary to have a web server or a touch screen with a Wi-Fi network connection, without the need for any additional equipment. This service in BUSing and KNX is completely free for customers [5, 22].

3.2 Drivers

Dimming is an important requirement in the lighting control systems, however, dimming means different things to different people. LED driver designers to refer to the drive current, fixture designers use the measured lumen output and end-users evaluation is based on the perceived light, i.e. the light that the eye sees. On the other hand, there is a common misconception that any LED light can be dimmed with an LED dimmer. LED lights need their own special electronic dimmer switch to have a fully functioning and dimming light. Dimmers use various techniques and resources to achieve the dimming, for example AC phase cut, 0–10 V, pulse width modulation (PWM), DALI, DMX, among others. For the dimming purpose, manufacturers generally offer universal (i.e. analogue) and electronic low voltage dimmers. There is currently a commercial offer of solid-state devices with different load capacities, a different number of channels, different types of mounting and specific devices for regulation (e.g. LED RGB or LED RGB + White) [1, 4].

3.3 Control network protocols for SB

Networking is important for LED lighting control and building automation systems. Networked systems in SB are based on a communication channel called BUS, through which information is transmitted in a control network. The control network allows the user to connect devices called smart nodes with their own processing capacity [5, 23]. These nodes are distributed through the different rooms of the building and are communicated through the bus to execute control orders such as the lighting on and off, comfort temperature setting, security event alerts, among others. Although there is no accepted common architecture for control networks, there are many communication protocols, open or proprietary, used in lighting control systems. The integration of incompatible systems and ensuring that they communicate, i.e. interoperability problem, it is one of the biggest obstacles that prevent taking advantage of all the technological potential. An open protocol allows interoperation without the need for a proprietary interface or gateway and its main advantage is their easy expansion of devices in the control network. In [24] the problems in different communication open protocols, their advantages and which protocols should be used are presented. Due to their wide diffusion and their performance, some protocols are more consolidated, such as Bacnet [19], Lonworks [21], Busing [22] and KNX [20], DALI [23], MODBUS [23] etc.

Bacnet and LonWorks are standards that are more focused on corporate buildings that require control and monitoring of variables in various zones, managing data centrally. Due to its conception, Bacnet could offer greater facilities for the automation of existing conventional systems in buildings. However, LonWorks, due to its greater flexibility allows it to more appropriately address systems that come out of the conventional services (e.g. smart grid) and lighting systems [25]. KNX is a widely used protocol. It was developed from EIB and EHSA European protocols and uses a distributed bus system that allows devices to exchange information directly, the reason why its main advantage is the easiness it offers for remote configurations. Meanwhile, BUSing stands out for its versatility, it is a distributed type communication system whose

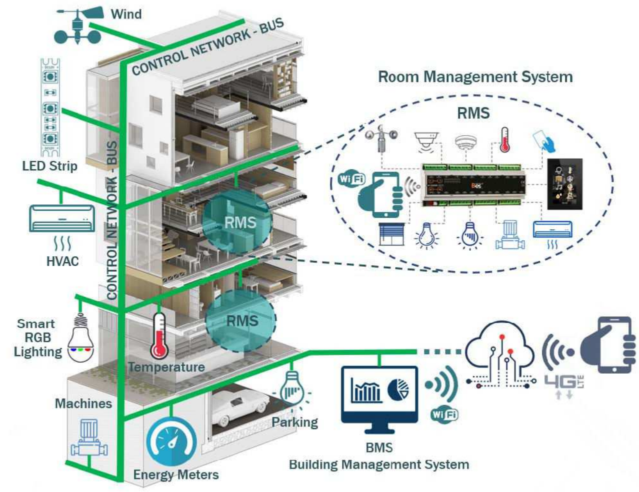

Fig. 4 *Smart building control network schema*

network uses a bus topology, thus allowing for an easy scalability in both the wired and wireless versions. In addition to the mentioned protocols, there are a large number of proprietary protocols developed by manufacturers for use in specific automation applications that are implemented exclusively with their own equipment and devices [18, 23]. Fig. 4 shows a common control network architecture used in SB applications.

There are many cases of smart building implementations using KNX, however, it is possible to highlight the cooperative headquarters building. co-operative group created one of the most sustainable commercial buildings in Europe and one of the first in the United Kingdom (UK) to be built to the building research establishment environmental assessment method (BREEAM) outstanding designation, which was awarded the BCSC award for sustainability. The BREEAM is now an international standard measure for sustainable design and building environmental performance [20, 26]. The project implements 3745 KNX devices. The smart building services include constant light control, fault safety and protection, leak detection, glass break detection and interaction with HVAC. For the SB operation, the manager can use a BMS PC, touch and display panels. Other services are energy management and smart metering, using renewable energy and distributed generation.

In Lonworks technology, a case study is the Endesa Corporate Building in Chile. This infrastructure has >5100 luminaries controlled by the BMS HoteLON [8, 21]. Among other functionalities of the lighting control system, it implements the following: (i) energy saving of >30%; (ii) increased life of the luminaire and user comfort; (iii) regulation on the work plane; (iv) energy saving and setting the room environment; (v) auto power off when no presence is detected, which is configurable from 1 s to 18 h; (vi) time scheduling performing scenes; (vii) predictive maintenance; and (viii) monitoring hours of operation.

With regard to BUSing technology, an example is the new Central University Hospital of Asturias (HUCA), located in the centre of Asturias, Spain, and completed in 2014 [22, 27]. In this smart building, 11,500 emergency luminaires are individually controlled. It is possible to know the status of the luminaires, obtain a daily, weekly, monthly or annual report of different parameters, hours of operation, or damage.

3.4 Network communication

Network communication technologies in SB have been evolving from the IEEE RS485 protocol used with the implementation of wired networks, so it is possible to find protocols for field networks such as ModBUS, ProfiBUS, BACNet, BUSing, KNX, LONWorks etc. [7, 23]. On the other hand, for information networks the basic protocol is internet protocol (IP) or transmission control protocol (TCP). TCP/IP is widely implemented through wired ethernet networks in the building infrastructure. In SB, TCP/IP is used to integrate field network communications with information networks. IP networks currently allow connecting all kinds of smart devices in the same network infrastructure of buildings for the deployment of all kinds of services, such as energy management, integration with service provider companies, cloud computing etc. This concept is currently known as building energy management system (BEMS) [6, 23].

Bluetooth arose with the idea of operating in a multi-user environment, by forming short-range networks, around 10 m or less, in what are called personal area networks or wireless personal area networking, without the need for a direct line of sight and with an initial bandwidth of about 730 kbps in version 1.0. One of its main advantages is its ability to simultaneously support voice and data transmissions. The special features of bluetooth, its bandwidth, the ability to integrate voice channels and the security and mating features of devices make this technology offer enormous potential for the home market [7, 23, 28–30].

Bluetooth allows the system to incorporate wireless devices into the personal area (mobile, agenda, headset) and communication elements such as routers-DSL or hands-free installers in vehicles. For lighting control, it is possible to find integrated systems that are controlled from smartphones, tablets, remote controls etc. The role that bluetooth technology plays in this case is to communicate user interfaces with the final controllers of lighting systems, both in residential infrastructures, buildings, street lighting etc. [7, 23].

In the late 1990s, ZigBee appears as an industrial initiative whose objective is to develop a radio technology that works in the industrial, medical and scientific bands ICM (866 MHz and 2.4 GHz). ZigBee is a very low cost and very low consumption technology (battery replacement time is several years). The goal is to provide service to all kinds of sensors and small electronic devices existing in the home that do not need the binary rates offered by Wi-Fi or bluetooth. This initiative initially responds to the names FireFly and HomeRF Lite to finally accept the ZigBee designation [7].

Open-space device coverage ranges from 10 to 75 m and is lower than wireless network technologies such as Wi-Fi. ZigBee is designed to be able to create networks with a moderate-high number of devices so that up to 254 active devices can coexist on each network and up to 100 networks simultaneously in the same area [7, 23]. Among the first applications of wireless sensor network (WSN) in smart lighting for SB are developments using ZigBee. However, the disadvantages in the short initial scope of communications, the complex of architectural distribution of buildings and the lack of integration developments with lighting drivers that use control network protocols, have made ZigBee mainly being used in residential smart lighting applications and outdoor lighting control [7, 28–30].

One of the latest network technologies developed is LoRa and LoRaWAN [23, 31–34]. This protocol is based on a mesh wireless communication network scheme in which sensor nodes, actuators, network interfaces etc. can be connected in small and long-range automation and control applications. The advantage of LoRa in long-range applications is that a single gateway or base station can cover the entire cities or hundreds of square kilometres. LoRaWAN defines the communication protocol and system architecture for the network while the LoRa physical layer enables the long-range communication link. On the other hand, low-power, wide-area networks (LPWANs) are projected to support a major portion of the billions of devices forecasted for the Internet of Things (IoT). LPWAN offers multi-year battery lifetime and is designed for sensors and applications that need to send small amounts of data over long distances a few times per hour from varying environments. LoRaWAN is designed from the bottom up to optimise LPWANs for battery lifetime, capacity, range, and cost. End-devices serve different applications and have different requirements. In order to optimise a variety of end application profiles, LoRaWAN utilises different device classes. These device classes trade off network downlink communication latency versus battery lifetime [31–34].

The ISM band for North America is from 902 to 928 MHz. LoRaWAN defines 64, 125 kHz uplink channels from 902.3 to 914.9 MHz in 200 kHz increments. The maximum output power 902–928 MHz band is 30 dBm but for most devices + 20 dBm is sufficient. Under Federal Communications Commission there are no duty cycle limitations but there is a 400 ms max dwell time per channel. LoRaWAN architecture is deployed in a star-of-stars topology in which gateways relay messages between end-devices and a central network server. The gateways are connected to the network server via standard IP connections and act as a transparent bridge, simply converting RF packets to IP packets and vice versa [31].

LoRa is currently used in automatic meter reading applications for water consumption in cities, EMSs for street lighting systems (SLSs), measurement of environmental parameters in cities to determine levels of CO_2 pollution, automation and control in the agricultural sector, among other IoT applications that have enabled the deployment of emerging services in smart city projects [28–34].

Other emerging technologies framed in IoT infrastructures that are being used for lighting control applications in buildings are SigFox [35, 36], *Z*-wave [29, 37], Wings [38], EnOcean [39], among others. These technologies are implemented in mesh topologies concept and use the 900 MHz RF communication band, allowing wireless sensors and controllers to communicate in smart lighting, heating and climate control, and ancillary building diagnosis and maintenance of smart environment applications [28–30, 35, 37, 38]. They also allow the integration of IoT sensor networks for the deployment of security, communications, energy-saving and comfort services for residential or LPWAN applications. For example, ZigFox is used in [40] to demonstrate the robustness of protocol communications by interconnecting sensor networks in scenarios for 200–3000 users in monitoring applications to allow the system to gather and visualise remote data from environmental sensors like temperature, air quality, home automation sensors, lighting control, management of parking lots etc. in an IoT infrastructure. *Z*-Wave on the other hand, enables IoT devices to be controlled via the internet and is very common among smart home (SH) systems. In [41], the *Z*-Wave integration between a Raspberri Pi Processor and a *Z*-Wave chip module for a security control system in an SH is presented. In the case of Wings, this technology allows the integration of sensor networks with a distance between devices of 15 m; communications are established at 868 MHz and it is free of interference in a mesh topology [38]. A Wings network allows an IoT network to interconnect up to 255 devices and allows the control of the installation using IOS and Android SC Apps. Wings are integrable with BUSing networks and are widely used for RMS applications in mixed infrastructures, that is, wired and wireless installations for the implementation of control networks in BMS applications for SB. In Lighting control applications, Wings is used for RGB dimmers to create comfort scenes in SH applications and smart office lighting systems [5, 42]. On the other hand, these described technologies have the ability to integrate with robust control network protocols such as BUSing, KNX, Lonworks, BACNet etc. using gateways to communicate intelligent devices deployed from the field network in RMS environments with mixed installations in BMS, HMS, SLS and EBMS, complying with the IoT infrastructure framework [30] to apply them in intelligent control systems for SB.

One of the latest applications of LED technology is light fidelity (Li-Fi), which integrates data transmission into LED lighting systems to provide information services. In June 2019, the light communications alliance was established with the aim of promoting new wireless technologies that enable the development of communication through light. In the case of SB, Li-Fi has been used to detect the indoor location of users [43].

Li-Fi technology offers a great opportunity to develop new research work, studies can focus on the components, materials and power control strategies of the lamps. The studies can also be developed in the convergence of services that can be deployed using Li-Fi, applications of this technology in SB for the optimisation of energy consumption etc.

The final aspect to consider when using technologies for smart lighting in SB is that all devices in the network infrastructure, both the field network nodes and the communication and control network nodes must be interoperable, that is, they must use open protocols with high integration capacity to share information, receive and send control orders, without the need for complex gateways and low integration costs, using open and friendly development platforms for designers, integrators and above all, easy installation.

3.5 Cybersecurity in SB

SB carry a number of cyber risks [5, 18], so unauthorised access can occur to perform false lighting activation actions and even damage the lighting system. To counteract these vulnerabilities, measures must be considered to protect their systems from cybercriminals. Security protocols must be verified and recorded of all users accessing the system and database. Cybersecurity not only affects the building's server or network connection; any connected device is a potential vulnerability to sensitive information. Cybersecurity measures such as virtual private network and secure server access should be enabled [5, 34]. Robust policies on file sharing via email and other collaboration tools need to be established. In addition, real-time monitoring and management services for security incidents with big data and artificial intelligence can be considered through the cloud.

Frequently a security operations center (SOC) is used in internet networks, which is a computer security centre that prevents, monitors and controls security on networks and the internet [5, 23]. SOC services must then be developed that identify and provide solutions to solve everything from the most strategic needs to the most operational ones in the lighting control system. This is a study area that requires more extensive analysis, so it is a research opportunity in the development of building security strategies and methodologies with a focus on lighting system, energy efficiency and user comfort.

4 Smart LED lighting control methodologies for SB

The following extended section presents the review of LED lighting control methodologies used in SB.

4.1 LED lighting drivers control

For a basic LED lighting control, a voltage supply for an LED is achieved using a DC source to apply a voltage between its terminals. It is important to limit the current circulating through the semiconductor because it exhibits a very low internal resistance. The current limiting resistance method consists of a resistor connected in series to the LED. Although it is a fairly simple, low-cost technique and does not produce electromagnetic interference (EMI), it is very inefficient due to the power losses that occur in serial connection. Due to its low efficiency it is also not used for high power. Regarding LED current regulation, it has a poor behaviour against input voltage changes and temperature variations [4].

On the other hand, the linear current source method allows the current regulation of the LED. It is one of the simplest methods, inexpensive and with few components. This method is used for LED current regulation and control. It is one of the most widely used techniques for LED lighting drivers. It has high efficiency and low power loss. The main disadvantage is that it presents EMI generation, however, it is very efficient in dimming LED applications [4].

Among the more traditional control methods is PWM dimming [4], which is a widely used process to control both the luminous flux as well as the LED brightness more efficiently and reducing power losses. This process regulates the amount of LED circulation current by generating a PWM signal, which switches in an open or closed state according to the duty cycle set in the switch's on/off times.

LED lighting systems are single-stage-based or two-stage-based. Single-stage control is a DC–DC converter with constant output current that may or may not obtain power factor correction (PFC), while a two-stage controller consists of a PFC circuit to a DC–DC converter. The DC–DC converters can be classified in: buck, boost, buck–boost, Cuk, flyback and zeta [2, 4]. In addition, there are control techniques extended to this type of converters, new methodologies are being developed that seek to optimise the transfer of input power to the output, as well as to make the systems more efficient for LED lighting applications.

All LED drivers must be designed to meet or exceed applicable standards for their use in lighting applications. Electromagnetic compatibility is specified as a series of different test criteria. These are radio interference suppression (EMI), immunity to interference and voltage fluctuations, flicker, and harmonic content. Harmonic content of the mains current lighting equipment is subjected to restrictions on harmonics [4].

The maximum permissible limits are defined in the standard EN 61000-3-2, classified as class C for lighting equipment. The performance standard EN 62384 defines the optimal operation of LEDs with LED drivers, ensuring that LEDs are only operated within their specified operating parameters. This guarantees the best performance and maximum lifetime of suitable LED modules. The safety requirements for LED drivers are defined in EN 61347-2-13. LED drivers have the following safety features: overload protection, short-circuit protection, partial-load/no-load-safe overtemperature operation, input overvoltage and surge protection. Immunity requirements are specified in EN 61547. This guarantees protection against interference from external high-frequency noise, discharge of static electricity, and transient over voltages on the mains supply [4, 44].

4.2 Position control

The development of intelligent lighting systems, adapted to the needs of those who occupy a specific space, are based on the use of sensory control methods combined with advanced sensor networks and communications implemented in control architectures [45]. For example, in a sensor network, when estimating the location and position of users it is possible to provide optimised lighting in a given environment. It is also possible to obtain information about the use of space, which can be essential to optimise the performance of management systems of building energy (HVAC, security, maintenance, and other construction services), improve human health and achieve high levels of productivity without affecting the comfort.

4.3 Context control

In [46] a method based on the context or scenario for the use of a lighting system is proposed. The context can be determined using physical, logical and virtual sensors. Physical sensors are used to measure environmental parameters like occupancy, noise, humidity etc. Logic sensors use information from the control system to perform a programmed logical function. On the other hand, virtual sensors are programmed based on information from the context of the application of the environment, learning databases, web services etc. For example, a basic context for lighting systems is based on calendar scheduler, where the system sets the operating time and LED lighting levels according to the environmental conditions. This way, context information can be integrated into a control network architecture to optimise the energy consumption of LED lighting systems.

4.4 Sensor network control

In [47] a technique is proposed to control LED lighting levels using PWM dimming regulation depending on the frequency of the primary stage of the power grid. The control system adapts to the frequency deviations produced by alternating renewable energy sources with the low voltage network to energise the building. For this case, a control network has been implemented using the DALI communications protocol, widely used in LED lighting systems in buildings.

4.5 IoT control

Currently, some applications of the use of WSNs can be found in intelligent LED lighting systems in buildings [48–50]. For example, in [48] wireless sensors are implemented for measuring parameters that define the context of the environment. The methodology of environmental intelligence focuses on performing the regulation of LED lighting systems, based on the luminance information and occupation of the environment for a given user profile. The WSN is implemented using the Texas Instruments SimpliciTI protocol. The control of LED lamps is based on a DALI control network controlled by a computer machine that sets the lighting conditions between 300 and 500 lux. In [49] a network of personal sensors is implemented to determine the context of the environment combined with time programming algorithms and intelligent control based on the environmental context for the regulation of a DC network of LED lighting.

Another technique reported recently uses a sensor network to know the indoor position of a user in the environment [51–53], determine the user's profile and measure environmental context parameters to implement intelligent LED lighting systems in buildings. The technologies to determine the internal positioning of a user in the environment are based on RFID technology, which allows the system to locate the precise area that needs to be illuminated. The context of the environment is determined based on the information provided by a WSN and the LED lighting control is performed between 300 and 500 lux [48–53]. In [53] the technique is implemented with microwave-based sensors for context determination, using continuous radar waves and continuous radar pulses, which allows for appropriately measuring the movement and position of objects.

Other methods implement communication networks taking advantage of the building's electrical network to transmit the context information to the LED lighting controllers, using protocols on power line carrier communication [2], which eliminates the need to implement additional wired systems and benefits from the existing infrastructure. In this case, the sensors and controllers are energised directly from the power grid, eliminating additional backup sources used in WSN wireless systems.

Another method of sensor network communication is power over ethernet [6], taking advantage of the development of technology that allows energising electronic devices using internet wiring in a building. The devices, in this case, have an RJ45 port that allows both to implement communications with TCP/IP protocol between the elements of the data network to have an intelligent network of information for sensors and controllers in an environment known as IoT.

4.6 Energy efficiency control

Another method developed for smart lighting in SB is the control with a focus on energy efficiency [6, 54–58]. These technique models implement control algorithms to perform efficient energy management in SB based on parameters such as space occupation, motion detection, natural light level, ambient temperature, price of energy, among others. In [54] the development of the technique using a sensor network in an IoT infrastructure is presented. The lighting energy requirement is calculated including the lighting power, the duration of their operation, lighting equipment including the effects of building users, and conditions that consider the contribution of daylight under different control conditions. The energy efficiency technique establishes that all the building systems that consume energy, such as the temperature system, HVAC, lighting, must be integrated into a building energy management platform. The goal is to develop control models to maximise energy efficiency for SB in order to achieve the established objectives for reducing CO_2 emissions and ISO 50001:2018 and Green Building standards compliance, without reducing comfort and security levels for the users in smart environments [6, 56–58].

Fig. 5 shows the general scheme that summarises the possibilities of implementing an intelligent building energy management system (IBEMS) for LED lighting systems in SB, based on sensor networks and control network methodologies. The proposed IBEMS for LED lighting systems in SB consists of a control network platform with BUSing, KNX or LoRa-based terminal nodes, network sensors and HMI devices.

The systems contain four well-defined environment systems, RMS, hall management system (HMS) for common zones as

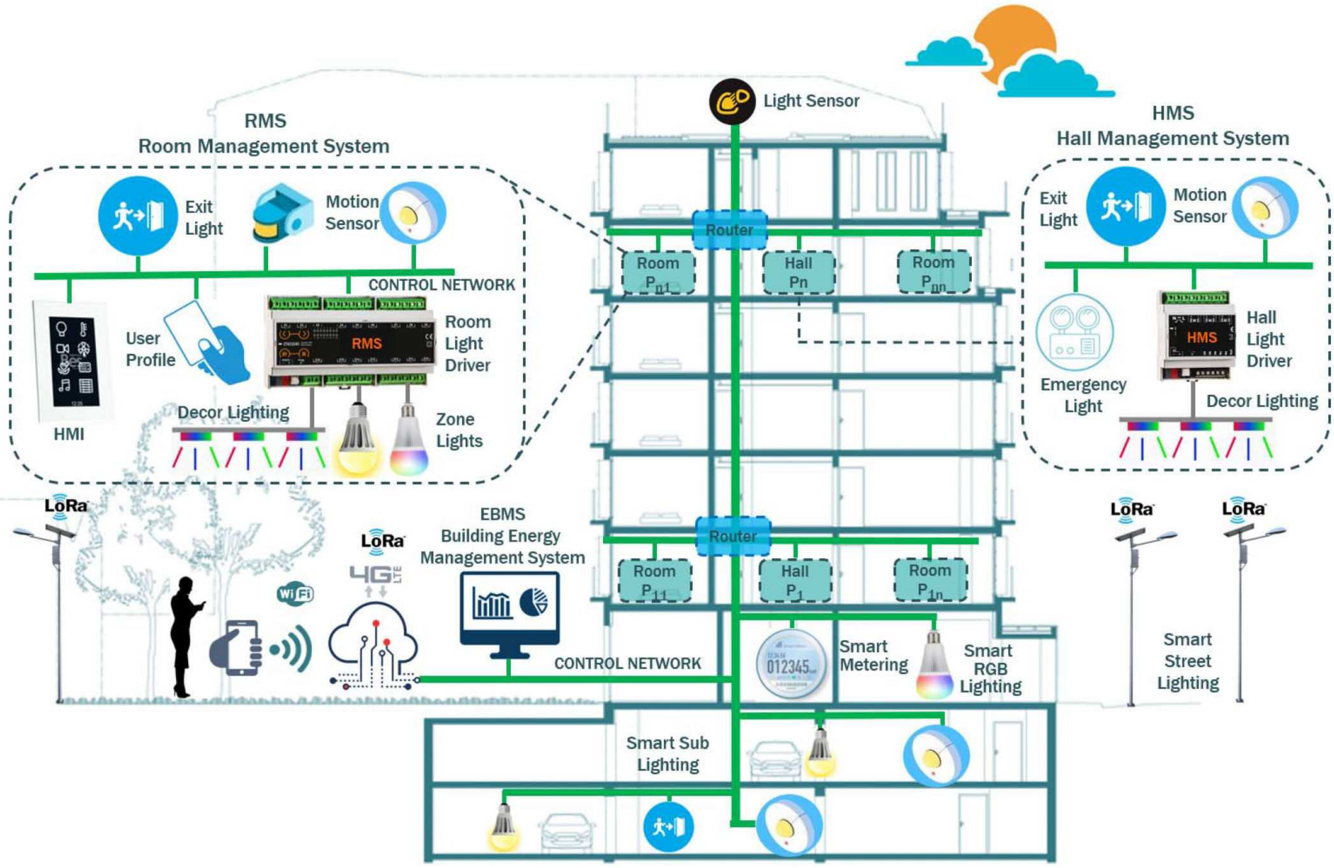

Fig. 5 *Intelligent building energy management system for LED lighting systems in SB*

Table 1 Smart LED lighting systems for SB

System devices	Technologies	Services
building energy management system (BEMS)		
BEMS PC	TCP/IP, 4G	smart lighting
BEMS Software	bluetooth, WiFi	energy
cloud access	BUSing, KNX	management
gateway	LoRa, ZigBee	local and remote
data base BDD	Bacnet, LON	periodic reports
smart terminals	OpenSource Soft	BDD and Apps
room management system (RMS)		
room light driver	BUSing, KNX	movement
motion sensor	Bacnet, LON	detection
LED strip	DALI, DMX	zone illumination
RFID access control	—	décor lighting
exit light	—	user recognition
smart touch panel	—	HMI control
control network	—	exit lighting
hall management system (HMS)		
hall light driver	BUSing, KNX	movement
motion sensor	Bacnet, LON	detection
LED strip	DALI, DMX	décor lighting
exit light	—	exit lighting
emergency light	—	emergency lighting
control network	—	—
street lighting system (SLS)		
street lighting	BUSing, KNX	movement
drivers	Bacnet, LON	detection
motion sensor	DALI, DMX	street lighting
control network	LoRa, ZigBee	—

corridors and hallways, SLS for exterior illumination applications and building EMS (BEMS). All the proposed systems are focused in smart lighting application. Table 1 shows the systems devices, as sensors, drivers etc. technologies and services involved in a smart LED lighting architecture for SB applications.

5 Conclusions

LED lighting in SB has become a hot topic of study. In this area, there are important opportunities of research in optimisation control techniques, materials, integration systems and services.

The methodologies and technologies for LED lighting systems use a full integration of sensors, controllers, interfaces, and network communication platforms to implement smart-lighting services.

BEMS for lighting systems in SB are implemented using control networks with the help of technologies like BUSing, Lonworks, DALI, KNX, BACnet, LoRa etc. These technologies have high integration capabilities both at the protocol level as well as at terminal nodes, so that increasing complexity of projects such as lighting control in SB, public lighting, among others, can be addressed.

To board an SB project design, the type of device, the communication and control network technology, and the services required for a given environment must be correctly specified.

Considering that LED technology is still being developed, there are many possibilities for innovation on control systems, their strategies and methodologies to improve the energy efficiency of the building. One of the problems detected on LED lighting systems is that the original fixed-manufacture colour of a lamp is not necessarily suitable for a certain use, so it is important to have the possibility to control the colour temperature, adjust the levels and colour of the lighting. These requirements in office buildings can be variable over the course of their lifetime. Strategies and methodologies for setting and reconfiguring LED lighting systems, the colour temperature of the luminaires, the colour of the spaces and functional uses can then be established, without incurring on major infrastructure changes.

6 References

[1] Wang, Y., Alonso, J.M., Ruan, X.: 'A review of LED drivers and related technologies', *IEEE Trans. Ind. Electron.*, 2017, **64**, (64), pp. 5754–5765

[2] Chinchero, H., Alonso, J.M.: 'Revisión de las técnicas de control de conversores dc-dc aplicadas a controladores de iluminación LED'. VIII Jornadas Internacionales de Doctorado, Universidad de Oviedo, Mieres, España, July 2019

[3] United Nations: '*The sustainable development goals report 2017*' (United Nations Publications, New York, USA, 2017), pp. 1–7

[4] Alonso, J. M.: '*LED lighting and drivers*' (Amazon KDP, Spain, 2019), Chapter 3

[5] Chinchero, H.F.: '*Control de iluminación en edificios inteligentes*' (Cintelam Campos Inteligentes de América Cia. Ltda., Course Material, Ecuador, 2020), pp. 1–12

[6] Chinchero, H., Alonso, J.M.: 'A review on energy management methodologies for LED lighting systems in smart buildings'. 20th EEEIC Int. Conf. on Environment and Electrical Engineering, Madrid, Spain, June 2020

[7] Lorente, S., Medina, J.: '*El hogar digital*' (Colegio Oficial y Asociación Española de Ingenieros Técnicos de Telecomunicación, Madrid, Spain, 2005), Chapter 3

[8] Martinez, C.: '*Los sistemas de automatización y control, aplicaciones para reducir el consumo energético en los edificios*' (ISDE S.L. Course Material, Spain, 2019), Chapter 1

[9] ISO 50001:2011: 'Energy management systems', 2011

[10] Yildirim, N., Sekerci, H.: 'Performance assessment of university buildings based on provided thermal comfort'. 2nd Asia Conf. on Energy and Environment Engineering (ACEEE), Hiroshima, Japan, 2019

[11] Rey, F., Velasco, E., Rey, J.: '*Eficiencia energética de los edificios*' (Ediciones Paraninfo, Madrid, España, 2018), Chapter 2

[12] Fiedler, T., Mircea, P.: 'Energy management systems according to the ISO 50001 standard – challenges and benefits'. Int. Conf. on Applied and Theoretical Electricity (ICATE), Craiova, 2012

[13] ISO 50001:2018: 'Energy management systems', 2018

[14] Liu, L., Keoleian, G.A., Saitou, K., *et al.*: 'Replacement policy of residential lighting optimized for cost, energy, and greenhouse gas emissions', *Environ. Res. Lett.*, 2017, **12**, pp. 1–10

[15] Green House Gas Protocol: 'Global Warming Potential Values', 2020

[16] Desai, P., Modi, N.: '*Problems with PIR sensors in smart lighting + security solution and solutions of problems*' (Smart Innovation, Systems and Technologies, Singapore, 2020)

[17] Hrbac, R., Kolar, V., Novak, T., *et al.*: 'Testing the properties of illuminance sensors designed for controllable lighting systems'. Proc. 12th IFAC Conf. on Programmable Devices and Embedded, Velke Karlovice, Czech Republic, 2013

[18] Brooks, B., Coole, M., Haskell, P., *et al.*: 'Building Automation & Control Systems', ASIS Foundation Project No.FDN-BMS-2017, 2017), pp. 22–32

[19] Bushby, S.: 'BACnetTM: a standard communication infrastructure for intelligent buildings', *Sci. J. Autom. Constr.*, 1997, **6**, (5), pp. 529–540

[20] KNX Association: '*KNX system arguments*' (KNX Basic Course, Belgium, 2019), Chapter 3

[21] Echelon: '*Introduction to the lonworks platform*' (Echelon Corp., San Jose. USA, 2009), Chapter 2

[22] Ingenium, S.L.: '*Manual de registros BUSing*' (BUSing Phartner Course, Spain, 2019), Chapter 1

[23] Sinopoli, J.: '*Advanced technology for smart buildings*' (Artech House Power Engineering Library, Boston, USA, 2016), Chapter 4

[24] Lohia, K., Jain, Y., Patel, CH, *et al.*: 'Open communication protocols for building automation systems'. 3rd Int. workshop on Recent Advances on Internet of Things: Technology and Application Approaches, Coimbra, Portugal, 2019

[25] Alonso, M., Ribas, J., Coz, J., *et al.*: 'Development of a distributive control scheme for fluorescent lighting based on LonWorks technology', *IEEE Trans. Ind. Electron.*, 2000, **47**, (6), pp. 1253–1262

[26] 'KNX Projects – KNX Org: https://www.knx.org/knx-en/for-professionals/projects/index.php, (accessed 31 August 2020)

[27] Perez, A.: 'Construcción y Rehabilitación de Edificios más Interconectados' Beyond Building Barcelona, 2019, pp. 1–27

[28] Al-Fuqaha, A., Guizani, M., Mohammadi, M., *et al.*: 'Internet of things: a survey on enabling technologies, protocols, and applications', *IEEE Commun. Surv. Tutor.*, 2015, **17**, (4), pp. 2347–2375

[29] Al-Masri, E., Kalyanam, K., Batts, J., *et al.*: 'Investigating messaging protocols for the internet of things (IoT)', *IEEE Open Access J.*, 2020, **8**, pp. 94880–94911

[30] IEEE Std 2413: 'IEEE Standard for an Architectural Framework for the Internet of Things (IoT)', 2019

[31] LoRa Alliance: '*A technical overview of LoRa and LoRaWAN*' (Technical Marketing Workgroup 1.0, San Ramon, California, USA, 2015)

[32] Verma, A., Prakash, Z., Srivastava, V., *et al.*: 'Sensing, controlling, and IoT infrastructure in smart building: a review', *IEEE Sens. J.*, 2019, **19**, (20), pp. 9036–9046

[33] Meneghello, F., Calore, M., Zucchetto, D., *et al.*: 'IoT: internet of threats? A survey of practical security vulnerabilities in real IoT devices', *IEEE Internet Things J.*, 2019, **6**, (5), pp. 8182–8201

[34] Mahoor, M., Hosseini, Z., Khodaei, A., *et al.*: 'State-of-the-art in smart streetlight systems: a review', *IET Smart Cities J.*, 2020, **2**, (1), pp. 24–33

[35] SigFox: '*SigFox technical overview*' (SigFox, USA, 2017), pp. 8–16

[36] Adame, T., Bel, A., Bellalta, B.: 'Increasing LPWAN scalability by means of concurrent multiband IoT technologies: an industry 4.0 use case', *IEEE Open Access J.*, 2019, **7**, pp. 46990–46992

[37] Hersent, O., Boswarthick, D., Elloumi, O.: '*The internet of things: key applications and protocols*' (Wiley, Chechester, UK, 2012), Chapter 8

[38] Ingenium, S.L.: '*Manual wings*' (Ingenium S.L, Spain, 2019), pp. 1–12

[39] Gratton, D.: '*Introducing the EnOcean ecosystem*' (EnOcean Alliance, USA, 2016), Chapter 1

[40] Lavric, A., Petrariu, A., Popa, V.: 'Long range SigFox communication protocol scalability analysis under large-scale, high-density conditions', *IEEE Open Access J.*, 2019, **7**, pp. 35816–35824

[41] Wei, C., Chen, Y., Chang, C., *et al.*: 'The implementation of smart electronic locking system based on Z-wave and internet'. IEEE Int. Conf. on Systems, Man, and Cybernetics, Kowloon, 2015, pp. 2015–2017

[42] Fermax.: '*Sistema Domótico Inalámbrico Wings*' (Fermax, Spain, 2020), pp. 4–15

[43] Huang, Q., Zhang, Y., Ge, Z., *et al.*: 'Refining Wi-Fi based indoor localization with Li-Fi assisted model calibration in smart buildings'. 16th Int. Conf. on Computing in Civil and Building Engineering, Osaka, Japan, 2016, pp. 1–8

[44] Osram Technical Application Guide: 'Standards for LED drivers, LED modules and LED luminaires', 2020

[45] Karlicek, R.: '*Illumination as a service: new paradigms for the future of lighting*' (Smart Lighting Engineering Research Center, N.Y., USA, 2015), p. 158

[46] Avotins, A., Bicans, J.: 'Context application to improve LED lighting control systems'. Int. Scientific Conf. on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, 2015

[47] Liu, J., Zhang, W., Liu, Y.: 'Primary frequency response from the control of LED lighting loads in commercial buildings', *IEEE Trans. Smart Grid*, 2017, **8**, (6), pp. 2880–2889

[48] Huynh, T., Tan, Y., Tseng, K.: 'Energy-aware wireless sensor network with ambient intelligence for smart LED lighting system control'. 37th Annual Conf. of the IEEE Industrial Electronics Society, Melbourne, Australia, 2011

[49] Tan, Y., Huynh, T., Wang, Z.: 'Smart personal sensor network control for energy saving in DC grid powered LED lighting system', *IEEE Trans. Smart Grid*, 2017, **4**, (2), pp. 669–675

[50] Magno, M., Polonelli, T., Benini, L., *et al.*: 'A low cost, highly scalable wireless sensor network solution to achieve smart LED light control for green buildings', *IEEE Sens. J.*, 2015, **15**, (5), pp. 2963–2972

[51] Moreno, V., Zamora, M., Skarmeta, A.: 'A low-cost indoor localization system for energy sustainability in smart buildings', *IEEE Sens. J.*, 2016, **16**, (9), pp. 3246–3261

[52] Floarea, D., Sgarciu, V.: 'LED smart illumination with DFID indoor positioning'. 21st Int. Conf. on Control Systems and Computer Science (CSCS), Bucharest, Romania, May 2017, pp. 515–520

[53] Tetervenoks, O., Suskis, P., Stegura, J.: 'Integration of microwave sensor into low cost indoor LED lamp – element of smart lighting system', 5th IEEE Workshop on Advances in Information, Electronic and Electrical Engineering (AIEEE), Riga, Latvia, 2017

[54] Metallidou, C., Psannis, K., Egyptiadou, E.: 'Energy efficiency in smart buildings: IoT approaches', *IEEE Open Access J.*, 2020, **8**, pp. 63679–63699

[55] Zhang, X., Pipattanasomporn, M., Chen, T., *et al.*: 'An IoT-based thermal model learning framework for smart buildings', *IEEE Internet Things J.*, 2020, **7**, (1), pp. 518–527

[56] Xu, W., Zhang, J., Kim, J.Y., *et al.*: 'The design, implementation, and deployment of a smart lighting system for smart building', *IEEE Internet Things J.*, 2019, **6**, (4), pp. 7266–7281
[57] Ha, Q., Phung, M.: 'IoT-enabled dependable control for solar energy harvesting in smart buildings', *IET Smart Cities J.*, 2019, **1**, (2), pp. 61–70
[58] Minoli, D., Sohraby, K., Occhiogrosso, B., 'IoT considerations, requirements, and architectures for smart buildings-energy optimization and next-generation building management systems', *IEEE Internet Things J.*, 2017, **4**, (1), pp. 269–282