The Scrovegni Chapel Moves Into the Future: An Innovative Internet of Things Solution Brings New Light to Giotto's Masterpiece

Paola Pierleoni, Alberto Belli, Lorenzo Palma, Simone Valenti, Sara Raggiunto, Lorenzo Incipini, and Piergiovanni Ceregioli

***Abstract*— This paper presents a complete architecture of an innovative wireless sensor network able to real-time monitor and control complex lighting systems such as the newly installation at the Scrovegni Chapel, Padua, Italy, representing the first world example in cultural heritage field. The realization effectively creates the Internet of Things paradigm, since all its components are directly connected to the Internet and each other thanks to global IPv6 addresses. The new IoT lighting system represents a "restoration of perception" project because the luminaries can be controlled in intensity and color temperature based on natural light and the desired rendering. In the initial phase, specifically designed sensors measure indoor lighting variations and this monitoring will be extended for a sufficient time to determine the proper control actions. Furthermore, besides adjusting the illuminance and color temperature for aesthetic and perceptual purposes, the system can also real-time monitor and control a variety of environmental parameters, fundamental for cultural heritage conservation, providing long-term studies of correlations between artificial light, natural light, and lighting performance, and also to evaluate over time the conservative aspects correlating them with any other critical environmental condition. The control of exposure to artificial light is also important in other contexts because light can interfere with biological processes controlled by endogenous circadian rhythms, with possible negative consequences for health results. Finally, this architectural solution can be extended to a complete Smart City system that integrates cultural heritage as one of the countless elements to be monitored and controlled in the city.**

***Index Terms*— Circadian rhythms, cultural heritage, Internet of Things, light of things, Smart Cities, wireless sensor network, LED lighting system.**

I. Introduction

THE presented paper exposes our contribution to the future Internet of Things (IoT) in the form of a proposal of an architectural reference model together with its applicability demonstration in a highly significative use case. The main challenge of IoT is that technological standardization in most areas is still remain fragmented. Today, only fragmented architectures and solutions for application silos exist and no coherent unifying concepts are disposable. Many island solutions do exist, i.e. for lighting, home automation, energy metering, environmental monitoring, etc., with little cross-sectoral reuse of technology and exchange of knowledge. In essence, only Intranets of Things exist [1]. Nonetheless, the IoT is glimpsing enormous potential and possibilities for new services, thus stimulating changes in industries and encouraging initiatives such as the IPSO Alliance (Internet Protocol for Smart Objects). The lighting industry is also moving in this direction by defining an Internet of Lights (IoL). There are many challenges to be met to fulfill the specific needs of each application sector. An interesting proposal in this direction, which suggests a reference architecture applicable to the lighting sector, is the Open Architecture for Intelligent Solid State Lighting Systems (OpenAIS) [2]. The authors of the proposal, through a comparison between the OpenAIS system and a popular commercial solution, have shown that IoL systems can overcome proprietary systems in several key performance indicators, such as security, interoperability, extensibility and openness.

Similarly, our IoT realization at the Scrovegni Chapel demonstrates the full feasibility of the IoT paradigm with its effective application to a particularly interesting sector such as cultural heritage (CH) and, specifically, cultural heritage lighting, also taking into account conservation and maintenance issues of the asset itself. The design problems of lighting systems of cultural heritage exhibited in historic buildings, museums or galleries are noteworthy, as are the implications for the impact that lighting can have on artifacts in such environments. The European technical specification CEN/TS 16163: 2014 "Conservation of Cultural Heritage - Guidelines and procedures for choosing appropriate lighting for indoor exhibitions" helps those involved in this difficult realization, bringing the necessary know-how to lightings, architects, conservators and all the other professional figures involved. This technical specification takes into account the aesthetic, exhibition and conservation aspects and discusses the implications of lighting design in order to safeguard cultural heritage. It gives recommendations on the minimum and maximum acceptable levels of illumination and its purpose is to provide the necessary elements to build a common policy and a guide

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to assist curators, conservators and project managers in achieving illuminations compatible with the conservation of objects exposed in confined environments. In fact, in the case of cultural heritage it is not enough to illuminate objects in the most effective or aesthetically best way, but it is necessary to do this fully respecting the problem of conservation, especially in the presence of photosensitive surfaces or in the event that lighting can produce heating, accelerate chemical reactions, or the deposition of suspended particulate matter, or favor the development of microorganisms. In fact, there are numerous objective aspects of cultural heritage lighting: the technical aspect (as light sources), the visual aspect (such as the impact of lighting on the visitor and the correct color perception, and the conservative aspect (related to the vulnerability of exposed objects) [3]. In any case, the matter is rather complex because such environment is very particular and there are many problems in lighting design of cultural objects displayed in historic buildings, museums or art galleries. Furthermore, it is also necessary to take into account the new scenario in terms of lighting sources and technical solutions. Beyond that, it is essential to have long-term studies that are able to correlate lighting systems with the plurality of other variables involved such as natural lighting, environmental parameters (e.g. ambient temperature, humidity, fine dust, pollution agents, etc.), the flow of visitors, and finally, provide further information such as, for example, the correlation between efficiency and color rendering. Even more important, it is the availability of real-time control tools of the environmental variables for undertake immediate corrective actions aimed at safeguarding both the purely aesthetic and conservative aspects of the cultural asset. Unfortunately, most of the proposals applied in world cultural heritage sites are limited only to monitoring function of subsets of these interest parameters, often without reaching a correlation between them and without control utilities. Moreover, they are implemented through the most diverse solutions both in terms of communication protocols and of the overall architecture proposed, often resorting to proprietary systems. For this reason, these systems are lacking in terms of replicability, expandability of the number of sensing units and their functions, complex realization of the related control functions, difficult implementation of an overall management system and, above all, the Internet communication typically achieved through multi-protocol gateways [4]. Furthermore, they often propose experimental test beds that are functional only to extemporaneous data collections as in [5] where data are off-line collected into SD cards and no real-time acquisition and communication infrastructure is provided. Even where the communication infrastructure is set up, proprietary solutions are typically used and corrective actions are generally not included in the proposed systems [6]–[8]. Therefore, most of the studies in this sector are limited to specific monitoring systems of certain particular quantities, aimed at a single application in the field of cultural heritage. Typically, control functions for the prevention of the asset's conservative nature problems and real-time resolution of critical conditions are not provided. Finally, the problem is rarely addressed in the correct IoT perspective, that is the proposition of a network of heterogeneous Smart Objects, as regards the fulfillment of different monitoring and control functions, each of which is directly connected to the global Internet through TCP/IP open protocols. The proposal presented in this paper moves in this direction and it mainly concerns the development of a complete IoT solution integrating sensors and actuators for lighting monitoring and control in the cultural heritage field. There are several research works on lighting control in various sectors ranging from Home Automation to Smart Energy with the main purposes of energy saving, lighting dimming, or intensity-based visual comfort [9]–[11] without taking care of the light quality in terms of light spectrum. Nevertheless, nothing has been proposed and has found concrete application in the field of cultural heritage in relation to real-time control of the light quality, intended as a joint contribution of illumination and color rendering, through widespread sensors and actuators aimed at perceptive restoration of artworks and their best conservation. Previous works on the application of IoT solutions in the cultural heritage field have been proposed [12]–[14], but no one is related to the monitoring and real time control of the illumination quality of cultural assets. This was made possible by the use of a specific IoT architecture that incorporates specially tested and calibrated lighting and color sensing units. These sensing units showed very high accuracy and sensitivity in relation to the proposed application. Furthermore, the IoT solution proposed in this work could be extended to a number of interest services in the Smart City context [15]. The IoT vision could become the building block to realize a unified Smart City platform as opposed to the plethora of noninteroperabily and heterogeneous technologies currently used in city and urban environments. Such a perspective could enable countless new services and enhance the ordinary services offered to the citizens with a series of advantages in terms of operational costs reduction and simplification of the management operations.

II. Case Study

A. Description of the Scrovegni Chapel of Padua

The Scrovegni Chapel is a catholic worship site located in the historic center of Padua, Italy, containing a fresco cycle by Giotto of the early 14th century (Fig. 1). The chapel is also known as the Arena Chapel because it was built on land purchased by Enrico Scrovegni that abutted the site of a Roman amphitheatre, known as the Arena. The Chapel, dedicated to Saint Mary of Charity and frescoed between 1303 and 1305 by Giotto, is considered one of the greatest masterpieces of western art. The nave is 20.88 m long, 8.41 m wide, and 12.65 m high. The apse area is composed of a first square area (4.49 m deep and 4.31 m wide) and a pentagonal area (2.57 m deep). Giotto and his assistants covered all the internal surfaces of chapel with frescos, therefore, when you are inside the Chapel, it seems taller than expected and give the feeling of being enclosed by images. There are lots of narrative scenes, but even in between those scenes are trompe l'oeil and faux marble panels, giving the sense that there is inlaid stone or three dimensional elements even where is all painted. The painting extends even onto the ceiling where we have a star-studded blue sky with images of Christ and Mary and other Saints and figures.

Fig. 1. Interior of the Scrovegni Chapel, towards entrance. The Last Judgment in the front wall.

Fig. 2. The exterior of the Scrovegni Chapel. The photo shows the six windows in the south side and the trifora in the west wall of the Last Judgment.

The largest element is extensive cycles focusing on the life of Christ and the Virgin Mary, celebrating her role in human salvation, that evolve along the northern and southern walls of the chapel. The paintings are organized in a very strict way according to three registers that begin at the top and move downward. It as kind of a spiral that tells a continuous story, beginning with Christ's grandparents, going into the birth of Mary, her marriage, and then when we get down to the second register, getting to Christ's life. Then, the bottom register is the Passion, these are the events at the end of Christ's life and immediately after his death. There are also panels in grisaille, that is in shades of grey imitating the effect of relief, along the lower side of the walls showing the Vices and Virtues. On the west side of the Chapel Giotto painted a large Last Judgment, with which ends the story of human salvation. In the Last Judgment we see Christ at the very top, and the damned are on Christ's left and the blessed are on Christ's right. The entire cycle ends at the apex of the triumphal arch on the opposite east side with God, who calls Gabriel for the Annunciation. The frescoes in the Scrovegni Chapel have always been considered as Giotto's first mature masterpiece, and at the same time as an important milestone in the development of western painting. For this reason, the Scrovegni Chapel has been nominated to become a site of Padua of the UNESCO World Heritage Site. Since 1880, the Chapel was acquired by the city of Padua, frescoes have been constantly given particular attention and, in the nineteenth and twentieth century, various conservative interventions have been carried out. The construction of the new body of access, together with the installation of an air treatment plant, allows to manage the strong flow of visitors so as not to affect the preservation of frescoes. The renovation of the Chapel lighting system, fits into this process of preservation and maintenance of this cultural heritage. Furthermore, the lighting design for the Scrovegni Chapel is part of a programme aimed at enhancing Padua's cultural and architectural heritage and improving the town's energy efficiency. This project involves the Municipality of Padua and is conducted under the supervision of the Interdisciplinary Commission for the Conservation and Restoration of the Scrovegni Chapel and in close collaboration with the Photometry section of the High Institute for Conservation and Restoration with the overall aim of creating a more emotional, true and immersive experience of the magical colors of Giotto's art. Actually, there are more than 300,000 visitors from all over the world who each year choose to visit the Scrovegni Chapel to appreciate Giotto's masterpiece.

B. Scrovegni Chapel Lighting Conditions

The asymmetrical arrangement of the six windows on the southern facade of the Chapel produces an uneven distribution of sunlight, as the windowed wall enjoys less natural light than the one opposite it (Fig. 2). This creates constant changes in the environment's visual balance and a counterlight effect that troubles visitors (Fig. 3). In addition, the backlight effect, produced by the natural light coming in from the south wall windows, prevents a correct view of the painted parts, especially during the middle and afternoon hours. Moreover, the natural light contributes to illuminate the north wall so the reduction of the artificial light flux is necessary to comply with the limits established for the conservation of the frescoes. The pre-existent lighting system, inaugurated in March 2002, consisted of a series of modules with asymmetric reflectors and fluorescent lamps, for lighting the walls, and projectors with metal halide lamps, for lighting the vault. These are technologies that have largely been superseded by both the latest traditional lamps and LEDs. These lighting modules consisted of pairs designed to illuminate the upper part and the lower part of the frescoed wall with a color temperature of approximately 4180 K. Obviously, no possibility of control over lighting or color temperature in the presence of contributions from natural light was contemplated in this system. To take into account of the rules concerning the upper limits of light exposure and contextually the specificity and

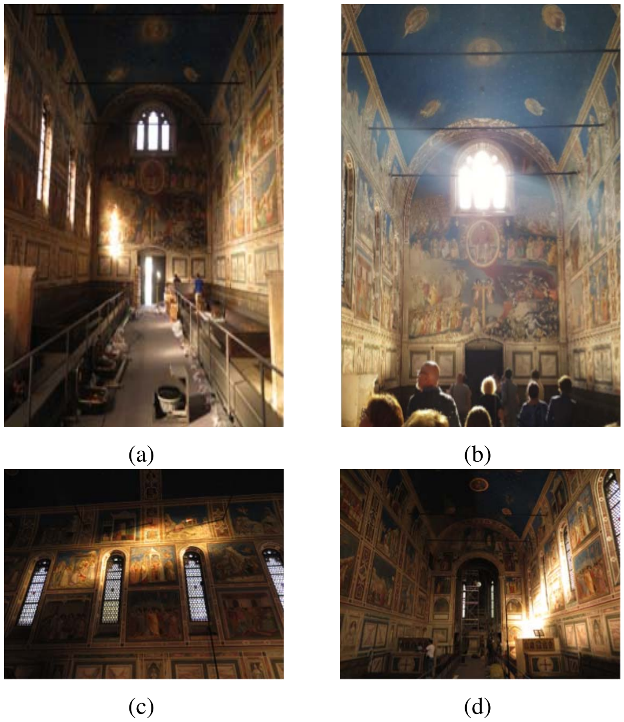


Fig. 3. The asymmetric distribution of windows inside the Chapel produces an uneven diffusion of sunlight. The south wall with windows is less illuminated by natural light than the opposite north wall (a). In some situations, the direct sunlight penetrate even through the trifora of the west wall (b). All this generates a constant change of visual balance in the environment and an annoying effect of backlighting on the observers (c), (d). All the photos are taken in the absence of artificial light.

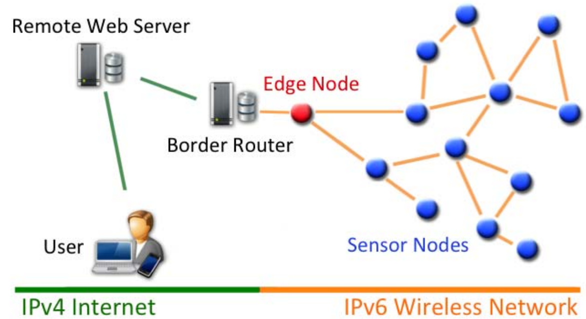


Fig. 4. The system architecture.

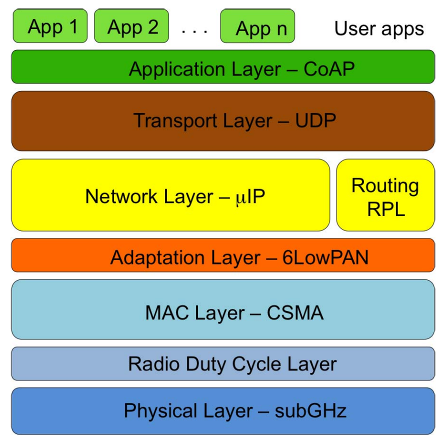


Fig. 5. The Sensor Node protocol stack.

conservation aspects of the Chapel, the most efficient solution is the widespread monitoring and control of the lighting system that takes into account the natural lighting. Thanks to the new system, the light variations will be detected and transmitted to the control system that will adjust the luminaires accordingly, in complete compliance with European standards regarding exposure limits for the conservation of artworks, and thereby improving the visitor's viewing experience.

III. System Architecture

The proposed architecture is mainly based on an innovative Wireless Sensor Network (WSN) whose components are entirely developed by the authors [16]. The overall architecture is illustrated in Fig. 4 and integrates sensor/actuator nodes directly connected to the Internet via a Border Router. Every node is part of the same self-configuring and self-installing μIPv6 (micro Internet Protocol version 6) mesh network and wireless communicates via the IEEE 802.15.4 protocol (868 MHz). The address mapping from IPv6 to IPv4, the fragmentation and reassembly mechanisms and the header compression are guaranteed by the 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks) protocol. The RPL (Routing Protocol for Low power and Lossy Networks), at the Network Layer, is used to attain a high degree of network life time and a very low network set-up time also in presence of nodes mobility or dead [17]. It has been recently designed to fulfill typical requirements of wireless sensor networks. The communication model is based on UDP (User Datagram Protocol). Finally, the CoAP (Constrained Application Protocol) is implemented at the Application Layer [18]. It is a constrained web transfer protocol oriented to embedded devices and designed for easy translation of the Hypertext Transfer Protocol (HTTP). CoAP allows WSN applications to be built on the top of the Representational State Transfer (REST) architectures and users to interact with the nodes by means a common Web browser [19]. Such communication model facilitates the development of IoT applications and the integration of constrained devices with the Web. The added value of this solution is its versatility and scalability with reference to a variety of constraints such as number and density of nodes, network typology and sensing or actuation functionalities embedded into the nodes.

A. Sensor Node

The Sensor Nodes represent the core of the implemented network architecture. Thanks to the embedded processing capabilities, they are able not only to host the entire protocol stack in Fig. 5, but also to carry out sensing and/or actuation actions such as acquisition of environmental quantities and, potentially, real-time analysis and command functions. Each Sensor Node becomes part of the Internet and is directly reachable remotely thanks to its unique IPv6 address. At power-up, each node calculates its IPv6 address through Stateless

Address Autoconfiguration (SLAAC) using the unique identifier owned by the microcontroller equipping the device, and the network self-configures thanks to the Neighbor Discovery (ND) protocol created for IPv6 and based on ICMPv6 (Internet Control Message Protocol version 6) [20]. ND and RPL work in synergy to create and maintain the network and the reachability of the nodes, even in presence of loss or motion of sensors. In each Sensor Node a CoAP server has been implemented and any specific resources can be accessed by CoAP/REST methods.

B. Edge Node

The Edge Node is the coordinator of the WSN and also routes data between an external IP network and the WSN. As shown in Fig. 4, the Edge Node is linked to the Border Router which furnishes the connection towards the global Internet. Through this Internet connection provided by the Border Router, the Edge Node acts as access point for the Sensor Nodes belonging to the WSN.

C. Border Router

The Border Router is the Internet access point via a plurality of wired/wireless network interfaces such as WiFi, Ethernet, GSM/3G/4G, etc. It establish the connection between the Edge Node and the global Internet. In order to embed a custom Local Web Server, the Border Router must be equipped with adequate computation and storage capabilities.

D. Remote Web Server

The Remote Web Server embeds functionalities ranging from simplest web browsing operations to more complex management ones and it uses content furnished from the WSN's nodes in creating services according to the desired application and specifications. It allows remote and bidirectional communication with the Sensor Nodes, is highly scalable and compatible with any type and data format. The platform provides for the creation of customized access profiles and the accessibility from any platform, thus ensuring interoperability with the plurality of systems on the market.

IV. Internet of Light Solution

On the described innovative approach is based the solution projected for the real-time monitoring and control of the Scrovegni Chapel's lighting system. It consists on a real Internet of Things solution allowing the communication between individual sensing or actuation elements, up to now not directly interoperable each other, and the connection of each of them to the global Internet. The network architecture presented in the previous section was properly customized in order to efficiently monitor and control lighting systems in complex scenarios, such as the Scrovegni Chapel one, but not limited to this. In fact, it can integrate different sensing and control functions and apply to differentiated application scenarios, and finally, to make cooperative, on a single network infrastructure, different applications and operational areas, according to a Smart City perspective [21]–[23]. The customized Internet of Light solution consists of four main interoperable components called Sensing System, Management System, Control System and Lighting System. Each component is immediately accessible, configurable and available through its global IP address. The complete network architecture, as well as each constituent element, are illustrated in Fig. 6 and detailed in the following subsections. In this figure, each main component of the network architecture is schematized and highlighted in different colors.

A. Lighting System

The newly Lighting System in the Scrovegni Chapel is a wired network of several LED luminaries, replacing the previous installation, and based on the two technologies Laser Blade Tunable White and Palco, developed by iGuzzini Illuminazione S.p.A.. These technologies have been used in a number of relevant CH lighting projects including The Last Supper of Leonardo Da Vinci in Milan, Italy.

Each wall of the Chapel's nave is lighted by 14 Laser Blade Tunable White projectors combined in pairs, each pair consists of luminaires of equal power with optics of 48° and 30° respectively to illuminate the lower and upper part of the walls up to the middle of the vault. Such solution ensure the optimal longitudinal and vertical uniformity of illumination along the nave. Each Laser Blade device contains 15 LED elements. The color temperature variation takes place by mixing the emission of 8 2700 K LEDs and 7 5700 K LEDs with a high color rendering index. In fact, the two series of LEDs are individually dimmable so giving a variable color temperature according to the adjustment of the two different light flows. Therefore, in principle, north and south walls can be illuminated by 14 divers light cones with variable flow and color temperature (Fig. 7). Thanks to Tunable White technology, the quality of light can now be adapted perfectly to meet the different requirements of the context in question. Because the color of light influences and alters our visual perception of objects, Laser Blade Tunable White allows the quality of light to be adapted to meet the chromatic characteristics of the objects and works on display. Varying light from a warmer to a colder temperature over time can now be achieved without changing the whole lighting unit, but simply by using this regulation method that allows the color temperature to be varied.

The west side wall of the Last Judgment is illuminated by 7 Palco devices whose optics allow an optimal coverage of the painted surface assuring a perfect visual uniformity. This is an adjustable projector with high efficiency of LED sources and Tunable White emission (i.e. tunable even in color temperature 2700-5700 K) [24]. The presbytery and the apse on the east side are also illuminated by 7 Palco projectors. Palco is a spotlight created specifically for museum lighting and contains a number of technical breakthroughs and the most up-to-date technology. Its main characteristics include a high Color Rendering Index (CRI) of over 96 and special sector optics for LEDs so enabling lighting scenarios and color ranges to be personalized to the highest degree. The Tunable White technology enables light to be adjusted dynamically,

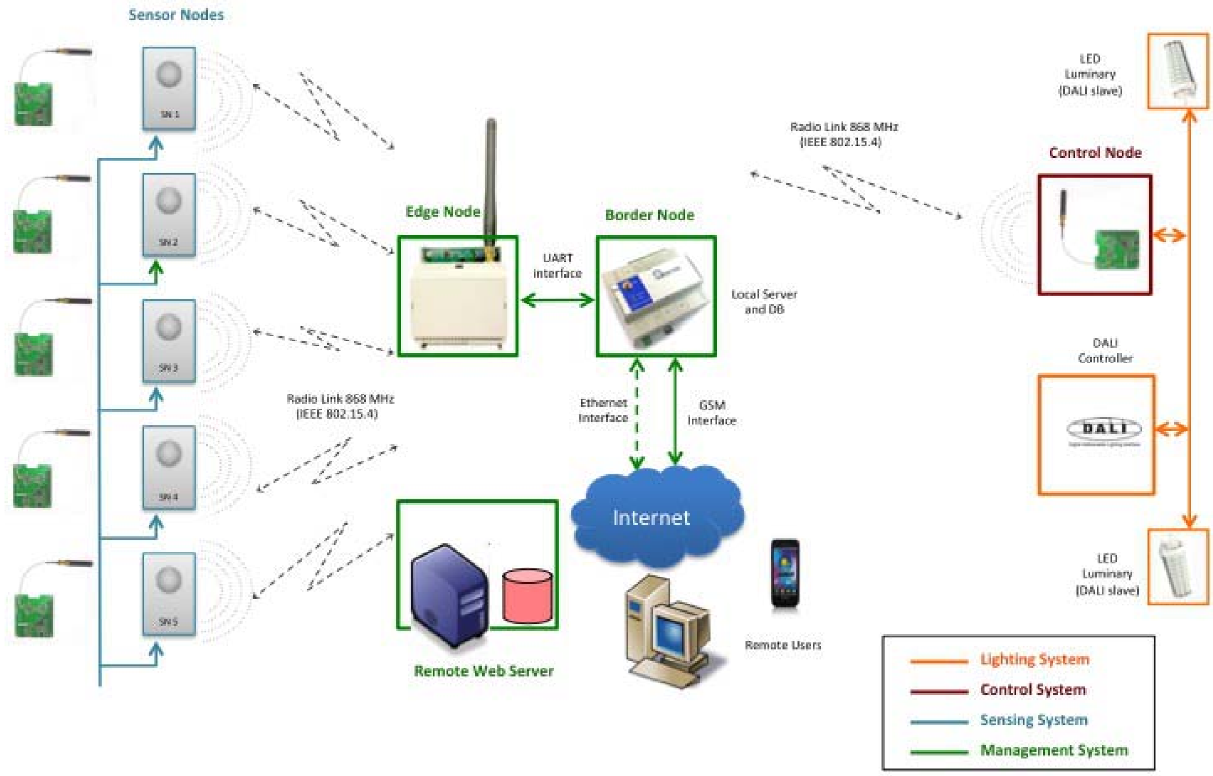


Fig. 6. The Internet of Light architecture realized for the Scrovegni Chapel.

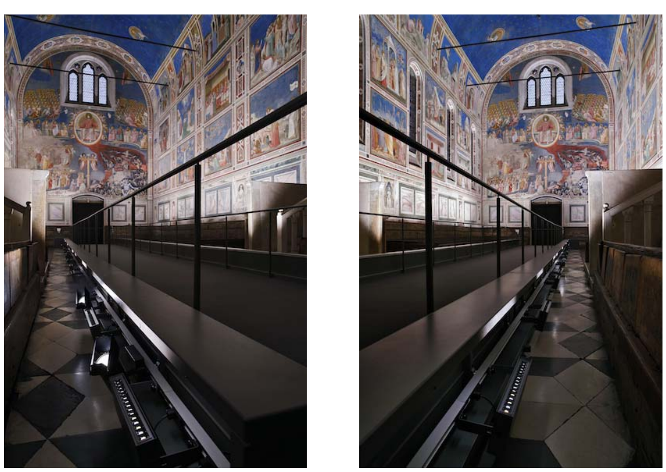


Fig. 7. New lighting system of the nave's walls by means of projectors combined in pairs to illuminate the lower and upper sides. The luminaires are installed on an electrified DALI track fixed to the ground: (a) south wall and (b) north wall.

both in illuminance and in color temperature, as the natural light varies. This can be achieved automatically thanks to the integration of lighting in the IoT architecture detailed in the subsequent sections, ensuring that, in a second phase, visitors will be able to see Giotto's frescoes more clearly no matter what time of day or season it is. Finally, to implement the connection of each lighting fixture to the Internet, the current interconnection standards in the lighting sector had to be taken into account. Specifically, lighting elements incorporate communication interfaces for digital addressable control compliant with the Digital Addressable Lighting Interface (DALI), which is a commonly adopted trademark for lighting control and an IEC international standard. According to DALI specifications, each luminaire embeds a DALI slave, for digital control of the light source, and is controlled by a DALI master with bus power supply functionalities. This protocol, as well as the great multitude of proprietary protocols that are currently on the market in the various application fields, lends itself little to interact with open IoT solutions. This problem has been effectively overcome through the design of a special device called Control Node, and described in the following paragraph, belonging to the WSN and able to interact with DALI devices.

B. Control System

The Control System is composed of wireless devices especially developed to interact with the DALI devices embedded in the each luminaire of the Lighting System. Each device, called Control Node, is based on the core platform of the Sensor Node that is generically described in Section III. This core component is called Core Unit and is more detail

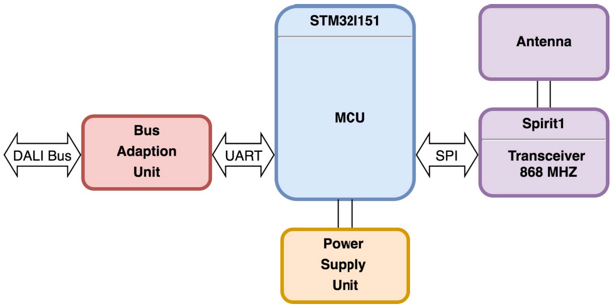


Fig. 8. Block diagram of the Control Node.

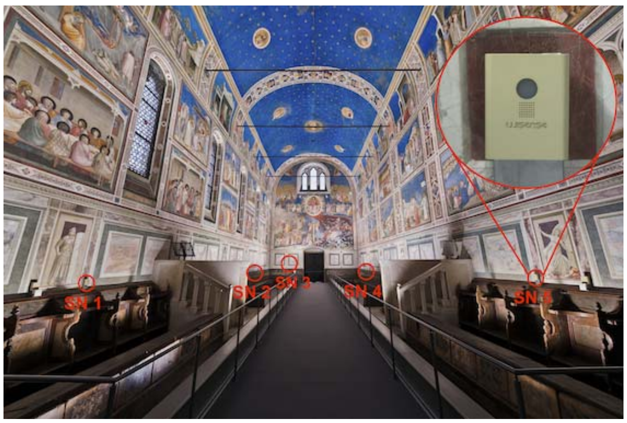


Fig. 9. Interior of the Scrovegni Chapel with the positions of the five Sensor Nodes installed. At the top right, the zoom of the installed device.

investigated in the following subsection. A block diagram of its hardware components is shown in Fig. 8. The Control Node consists in a Sensor Node integrating a bus adaption unit to send compliant DALI commands on the bus. The whole realized architecture integrates three Control Nodes to interact with the overall Lighting System. A CoAP server has been implemented in each Control Node and from which DALI commands can be send by CoAP's POST method. The Control Node can also power the DALI bus without the appropriate controller and therefore completely replace it in all the typical functions of a DALI master. In addition to these features, the Control Node performs diagnostic functions by acquiring and making available on the Internet the information and fault messages sent by each DALI slave (i.e. the lighting elements) on the bus.

C. Sensing System

The Sensing System consists of wireless Sensor Nodes distributed inside the Chapel in the positions shown in Fig. 9 and whose architecture is described in Section III.

The Sensor Nodes were customized in order to acquire values of illuminance, color temperature, ambient temperature and relative humidity (even if these last two features have been disabled by firmware because not required in the present application). Currently, their number is equal to five units, but it will have to grow during the monitoring phase that began with the installation of the overall system in September 2017 and will last for a year. In fact, during

Fig. 10. Photo of the hardware components of the developed Sensor Node: Core Unit (left) and Sensing Unit (right).

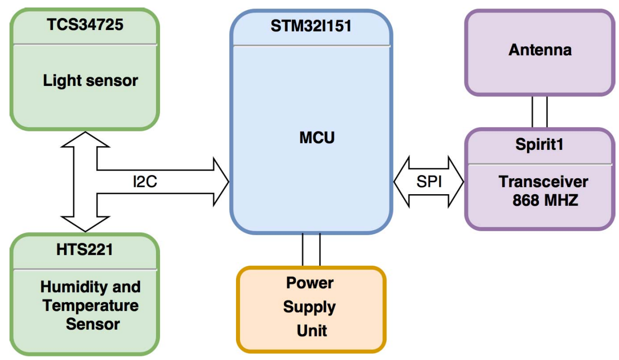


Fig. 11. Block diagram of the Sensor Node.

this phase, additional useful sensor positions will be identified and so their number increased after the analysis of the acquired data and the examination of the joint contributions of natural light and artificial light.

In each Sensor Node a CoAP server has been implemented, where two resources consisting of color temperature and illuminance measurements can be accessed by the CoAP's GET method. Therefore, the hardware of the Sensor Node is specially developed to measure the perceived light in a number of location over the Chapel's inner walls, complying with the power supply specification of nodes and of the lighting system, and, above all, the interoperability and expandability requirements of the whole system. The Sensor Node, as shown in Fig. 10, is composed of two main parts, the first called Core Unit and the second Sensing Unit. A block diagram of the Sensor Node with its hardware components is illustrated in Fig. 11.

1) Core Unit: The device called Core Unit is the fundamental component of the whole network architecture developed and it houses the processing unit (MCU) and the communication unit (transceiver). The transceiver of the Core Unit integrates an encryption co-processor for Advanced Encryption Standard (AES) secure data transfer. It is used to encrypt the RF communication and provide radio RF security in order to defense against unauthorized link access. The source code is installed in the MCU and allows the acquisition, processing and transmission of information about the measurements carried out by the Sensing Unit or the reception of commands from the Internet to vary the measurement settings. At the same time, the Core Unit allows the sending of opportune commands in the case in which the Sensor Node embeds Control Units, that is the implementation of control functions alternatively or in conjunction with sensing ones. In order to monitor the incident light on the frescoed walls of the Scrovegni Chapel, the firmware implemented into the Core Unit provides the color temperature and illuminance of the light affecting the Sensing Unit integrated into the Sensor Node. According to the previously described system architecture, information acquired from each Sensor Node is made available to the authenticated user via database login or direct access to the CoAP server implemented in the Core Unit. The sensor nodes capabilities to measure the color temperature of the light via a real time connection to CoAP servers is an unique feature that, in this use case, allows to monitor the presence of any shadow zones or visual dips in the frescoed walls. In order to ensure high system performance and interoperability between the application layer and the underlying protocol stack, the firmware implemented in the Core Node is developed using the Contiki operating system.

2) Sensing Unit: The developed Sensing Units embeds humidity, temperature, and light sensors. The first two sensors are not enabled in this use case even though their measurements might be particularly useful in cultural heritage applications. The latter sensor furnish us the digital return of red, green, blue (RGB), and clear light sensing values, once the estimation and calibration procedures are carried out as described in Section V. These measurements are effectively used to determine the illuminance and the Correlated Color Temperature (CCT) of the perceived light.

D. Management System

The Management System is a complete software and hardware solution that allows to control and monitoring the entire lighting system installed in the Scrovegni Chapel. In addition, it integrates monitoring and control functions that are not enabled for the specific installation at the Scrovegni Chapel, such as the measurement of environmental parameters and consequent automatic control of their regulation systems. The Management System developed for the Scrovegni Chapel is composed of Border Router, Edge Node, and Remote Web Server according to the architecture described in Section III. In the realized Internet of Light solution (Fig. 6), the installed Border Router is a rail-mounting PC based on Linux OS performing router functionality for the Edge Node. It is connected to the Internet through a standard 3G modem embedded into the Border Router itself. The Edge Node is wired connected to the Border Router through the RS232 interface. Both the Border Router and the Edge Node are able to transmit IP packets over the RS232 interface using the SLIP protocol. Therefore, the Border Router allows the interconnection of the Sensing System and the Control System to the global Internet. In this way, each element of these sub-systems as well as the DALI luminaires of the Lighting System have become part of the Internet and everyone is addressable and accessible by properly authorized users.

1) Local Web Server: The Border Router has enough computation and storage capability in order to host a Local Web Server. This means that the Local Web Server of the Management System may be completely controlled and monitored by local or remote users through the connection to the HTTPS server implemented into the Local Web Server of the Border Router. The Local Web Server is available through a Transport Layer Security (TLS) tunnel with the HTTPS server of the Border Router, where authorized users may access by a restricted profile. Moreover, only allowed requests can access the Border Router resources by specific firewall rules. A Border Router with Linux Raspbian operating system is used to implement the Local Web Server. The software architecture is mainly composed of an Apache server and a Python application communicating with each other through a Web Server Gateway Interface (WSGI) module. The Python application consists of four modules defined as CoAP client, DB manager, web application, and FOTA (Firmware Over The Air). The Border Router embeds a CoAP client module, which is a CoAP client making periodically GET requests to the servers of each Sensor Node. All the data collected by Sensor Nodes are locally stored into a NoSQL database of the Border Router, which uses a DB manager module and a MongoDB document-oriented database. Through the web application module, the stored data are taken from the database and provided to the web interface where authorized users have dedicated profiles. The Border Router also embeds a FOTA module allowing the wireless update of the firmware into each individual Sensor Node and also the reload of the user application inside the nodes or simply its modifications (e.g. the changing of the championship time in the sensing functions). Finally, the Block-Wise Transfers mode in the Constrained Application Protocol is implemented to transmit the large amount of information that can be required for firmware upgrades.

2) Remote Web Server: The aggregated information collect by the Local Web Server is transmitted to a Remote Web Server through the 3G modem embedded into the Border Router. The use of a TLS tunnel between the Local Web Server and the Remote Web Server ensures the secure transmission of the aggregated data acquired by the Sensing System.

The Remote Web Server allows authorized users to interact with the Control and Monitoring Systems. Therefore, through the connection to the HTTPS server implemented into the Remote Web Server, the availability of real-time and historical data of the Monitoring System, georeference of installed devices, alarms reception, remotely firmware update, settings change of the Control System are made possible. In Fig. 12 there is the user interface of the Management System through which all the previous activities can be carried out. Between them, it is possible to select the specific sensor to view the measurement history on a daily, weekly, or monthly basis or to force the acquisition / command of the same device in real time.

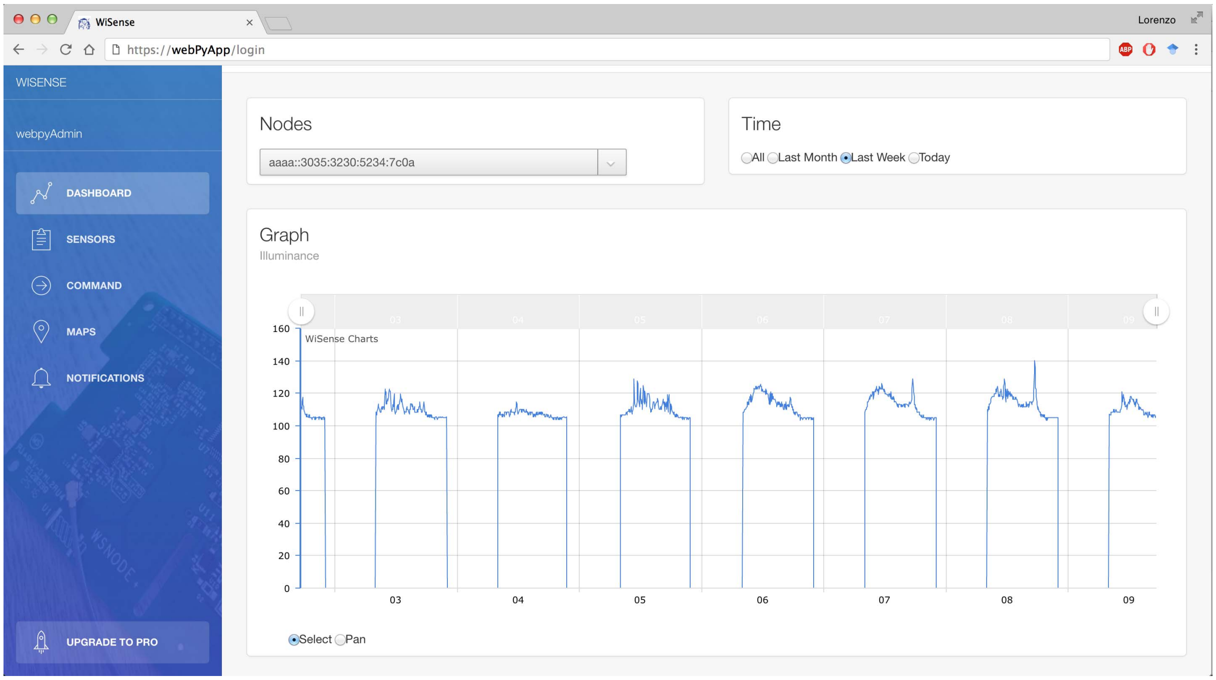


Fig. 12. The GUI of the management system.

V. Estimation and Calibration Procedure

In this paper we describe the IoT solution based on Sensor Nodes able to monitor the incident light on the frescoed walls of the Scrovegni Chapel in terms of illuminance and color temperature. The illuminance, measured in lux (lx), is the luminous flux incident on a surface per unit area, and can be characterized as the perceived brightness of the visible light. In such specific application, illuminance measurements can be used to detect and avoid the presence of shadow zones or dazzling glares in frescoes.

The color temperature of a light source is defined as the temperature of an ideal black-body radiator emitting light of a color comparable to that of the light source. The color temperature of a light sources that does not produce light from a heated element can be described by the Correlated Color Temperature [25]. The color temperature is conventionally expressed in kelvin, using the symbol K. Color temperatures above 5000 K are called "cold colors", while lower color temperatures in the range 2700-3000 K are called "warm colors" so "warm" lighting has a "colder" color temperature. The color temperature is a characteristic of visible light and has important applications in a lot of fields such as lighting for cultural heritage. In these applications, CCT measurements and controls can be used to improve the visual experience to the user in order to ensure a better colors perception and, in the actual case, the frescoes colors perception in terms of warm tones.

A. Estimation Procedure

The light sensor embedded in the Sensing Unit returns information on the light perceived by the integrated color photodiodes, providing digital data about Red (R), Green (G), Blue (B) and Clear (C) light channels. The response from the R, G, B, and C channels coming from the light sensor can be used to calculate the illuminance (E) and the Correlated Color Temperature (CCT) via the estimation process schematized in Fig. 13.

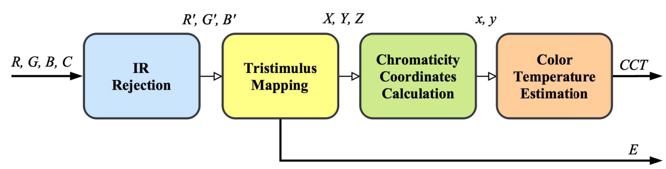


Fig. 13. Block diagram of the estimation process.

1) IR Rejection: The ambient light estimation can be influenced by the IR (infrared) content that could affect the measurement. In applications such as the presented one, which needs to estimate ambient light levels, the IR content cannot be neglected. To minimize the IR content and avoid adding a direct channel to measure the IR component, common RGB sensors integrate an IR-Blocking Filter as the sensor embedded in the Sensor Node. However, most of IR-Blocking Filters can be imperfect, allowing small amounts of IR content to pass through. To avoid that these inaccuracies of the IR-Blocking Filter compromise the measurement of ambient light carried out by the RGB sensor, the first step of the Estimation Procedure contemplates the IR rejection. In this step the IR content is indirectly approximated using the following equation [26]:

$$IR = \frac{(R + G + B - C)}{2} \tag{1}$$

where *R*, *G*, *B*, and *C* are respectively the red, green, blue and clear channels acquired by the light sensor. The removal of the IR components from the measurements made by the sensor produces the compensated *R'*, *G'*, and *B'* channels:

$$R' = R - IR$$
$$G' = G - IR$$
$$B' = B - IR \quad (2)$$

where *R'*, *G'*, and *B'* are the *R*, *G*, *B* channels from which the IR component has been removed.

2) Tristimulus Mapping: The second step of the Estimation Procedure is to map the compensated measures of the individual *R'*, *G'*, and *B'* channels in the *X*, *Y* and *Z* tristimulus values standardized by the Commission Internationale de l'Eclairage (CIE). This mapping is necessary to compensate the discrepancies between the sensor's spectral response and that relating to the tristimulus values defined by the CIE. The correct tristimulus values are then obtained starting from *R'*, *G'*, and *B'* by transformation through an appropriate 3×3 matrix indicated with **T**. The transformation matrix is typically provided by the device manufacturer in the relative application note. Nevertheless, for applications in which a high measurement precision is required, it can be derived from the analysis of empirical data obtained in experimental tests that characterize the sensor's response during its exposure to different light sources. The experimental tests that allowed us to derive the transformation matrix, starting from the data acquired during a campaign of measurements made by each Sensor Node, are described in the subsection Calibration Procedure. Once the transformation matrix **T** is available, it can be used to transform the sensor response into a series of equivalent tristimulus values using the following equation:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{T} \cdot \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \begin{bmatrix} t_{1,1} & t_{1,2} & t_{1,3} \\ t_{2,1} & t_{2,2} & t_{2,3} \\ t_{3,1} & t_{3,2} & t_{3,3} \end{bmatrix} \cdot \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} \quad (3)$$

Because the CIE *XYZ* color space was suitably designed so that the *Y* parameter is a measure of the luminance of a color, the tristimulus value *Y* supplies the estimation of the illuminance measured by the sensor.

3) Chromaticity Coordinates Calculation: The chromaticity of a color is then defined by the two derived parameters *x*, and *y*, two of the three normalized values being functions of all three tristimulus values *X*, *Y*, and *Z* according to the following equations:

$$x = \frac{X}{(X + Y + Z)}$$
$$y = \frac{Y}{(X + Y + Z)} \quad (4)$$

The derived color space specified by *x*, *y*, and *Y* is known as the CIE *xyY* color space and is widely used to specify colors in practice.

4) Color Temperature Estimation: Finally, the correlated color temperature can be calculated from the chromaticity coordinates through McCamy's formula [27]:

$$CCT = 449n^3 + 3525n^2 + 6823.3n + 5520.33 \quad (5)$$

where

$$n = \frac{(x - 0.3320)}{(0.1858 - y)}. \quad (6)$$

McCamy himself asserts that this formula can provide a maximum error of less than ±2 K for color temperatures ranging from 2856 to 6500 K given particular *x*, *y* chromaticity coordinates.

B. Calibration Procedure

The calibration procedure of the Sensor Node must necessarily be carried out if accurate measurements of illuminance and color temperature are required. Its purpose is to derive the transformation matrix necessary to associate the Light Sensor response with the tristimulus values *X*, *Y*, and *Z*. To carry out this procedure, it is necessary to characterize the sensor response with respect to a series of light sources to which the device could be exposed and to compare these measurements with those detected by an accurate instrument taken as reference. In the calibration procedure, to characterize the light sources, a spectrophotometer was used, which is a laboratory instrument used to acquire precise information on the light source and on its spectrum. In particular, the Konica Minolta CL-500 spectrophotometer was used that, in addition to acquiring the spectrum of a source, is also able to evaluate the *X*, *Y*, and *Z* components, the spectral irradiance, the illuminance, the color rendering index, and the correlated color temperature. This instrument was appropriately submitted to the control of its calibration in a specialized laboratory, before being used in the calibration procedure described here. This procedure should preferably be carried out in the environment in which the sensor will be installed and in the actual lighting conditions to which the device will have to be exposed. For this reason, we proceeded to the calibration only once installed the new LED sources and the Sensor Nodes inside the Scrovegni Chapel. During the calibration procedure, the Sensor Node to be calibrated and the spectrophotometer were placed next to each other so that, as the settings of the light sources vary, the simultaneous acquisitions took place both by the Sensor Node under calibration and by the spectrophotometer. Each Sensor Node and the CL-500 were exposed sequentially to four different light source settings that produced four different scenes (a, b, c, and d). For each scene, both the Sensor Nodes responses and the measurements made by the spectrophotometer were stored. In the scenes a, b, and c the measurements were made during the night so the Sensor Node and the CL-500 were exclusively exposed to the light produced by the new lighting system installed in the Scrovegni Chapel. In the scene a, the lighting devices have been set to emit a light with a color temperature of 2766 K (the minimum color temperature that this lighting can produce). In the scene c, the lighting devices have been set to emit a light with a color temperature of 5607 K (the maximum color temperature that this lighting can produce). In scene b, the lighting devices have been set to emit a light with a color temperature of 3966 K (the color temperature selected as the optimal configuration for the Chapel visual rendering). In all the previous scenes the lighting system has been set to give illumination values of approximately 120 lx on the walls of the Chapel. In the scene d, measurements were taken during daylight hours and with the lighting system switched off. In this scene, the light source was therefore only the natural light that entered from the windows of the Chapel and the acquisitions were made approximately at midday. Therefore, through the empirical data collected, it was possible to determine the transformation matrices **T** for each sensor to be calibrated. In fact, knowing the sensor response (*R'*, *G'*, and *B'* components) and the measurements made by the spectrophotometer (tristimulus values *X*, *Y*, and *Z*) for each scenes, a transformation matrix **T** was obtained for every Sensor Node. Taking into consideration only the scenes a, b, and c, the relative transformation matrix $\mathbf{T}_{a,b,c}$ can be obtained by multiplying the matrix of the tristimulus values **V** by the inverse of the matrix **S** of the sensor responses *R'*, *G'*, and *B'* [28]:

$$\mathbf{T}_{a,b,c} = \mathbf{V} \cdot \mathbf{S}^{-1} = \begin{bmatrix} X_a & X_b & X_c \\ Y_a & Y_b & Y_c \\ Z_a & Z_b & Z_c \end{bmatrix} \cdot \begin{bmatrix} R'_a & R'_b & R'_c \\ G'_a & G'_b & G'_c \\ B'_a & B'_b & B'_c \end{bmatrix}^{-1} \quad (7)$$

As the number of configurations of the light sources increases, or simply including the measurements relating to the scene d, an overdetermined system is derived from which a solution is to be obtained to get the transformation matrix **T**. Once the transformation matrix **T** has been determined, from this the accurate illumination and color temperature values can be obtained using the Estimation Procedure described above. Taking advantage of Moore-Penrose's pseudo-inverse to derive a solution of the overdetermined system minimizing the error in the described problem, it is possible to derive **T** using the following equation [29]:

$$\mathbf{T}_{a,b,c,d} = \left[X\ Y\ Z\right]_{3\times4} \cdot pinv\left(\left[R'\ G'\ B'\right]_{3\times4}\right) \quad (8)$$

where $[X\ Y\ Z]_{3\times4}$ represents the matrix built with the X, Y, and Z CIE values given by the spectrophotometer and $[R'\ G'\ B']_{3\times4}$ the matrix built with the *R*, *G*, and *B* values measured by the sensor, each of them obtained with reference to the four scenes a, b, c, and d.

1) Performance Evaluation: In order to validate the calibration procedure described above and to quantify the measurement accuracy of the realized Sensor Nodes, once the calibration procedure for each Sensor Node has been completed, experimental tests have been carried out in the same environment. Again, the CL-500 spectrophotometer was placed next to each Sensor Node and the acquisitions from the two instruments were compared in correspondence to several light scenes, created specifically within the Chapel to perform this test, and different from those created for the calibration. In such trial scenes, sources consisting only of artificial light (trial scenes 1, 2, and 3), natural light (trial scene 4) or a mix of the latter (trial scene 5) were used. For each test lighting scene, both the illuminance and the color temperature were measured by each Sensor Node and, at the same time, by the CL-500. Using this last device as a reference, the measurement errors in illuminance and color temperature of the Sensor Node were calculated. In Table I are reported the results of one of these experimental tests related to an already calibrated Sensor Node. In it, the first column lists the five trial scenes while in the subsequent coloumns we find the color temperature (CCT) and the illuminance (E) measured by the CL-500 and by the calibrated Sensor Node. The last two columns show the relative percentage errors, respectively of the color temperature and the illuminance, of the Sensor Node measurements referred to those of the CL-500 for each trial scene.

TABLE I

PERCENTAGE ERRORS OF A SENSOR NODE MEASUREMENTS AGAINST THE KONICA MINOLTA CL-500 SPECTROPHOTOMETER

Trial scenes	CL-500		Sensor Node		Measurements Error	
	CCT (K)	E (lx)	CCT (K)	E (lx)	CCT (%)	E (%)
1	2888	113	2890	113	0.07	0
2	4260	125	4291	125	0.73	0
3	5380	117	5388	117	0.15	0
4	5477	47	5508	47	0.57	0
5	4774	156	4812	155	0.80	0.64

The previous tests were conducted for each of the 8 Sensor Nodes realized, even if only 5 of these are actually installed at the Scrovegni Chapel. On the basis of all the data collected, average values of the relative percentage errors of the CCT equal to 0.38 % and illuminance equal to 0.14 % were obtained.

The conclusions that can be extrapolated from this test phase is that, in these environmental conditions, the post calibration percentage errors, both of the color temperature and of the illuminance, are at most in the order of a few tenth percent. From these results, it is evident that the measurement error of the Sensor Nodes is irrelevant, if referred to the absolute values of color temperature and illuminance and with regard to the specific application, since these are variations not perceptible to the human eye. Moreover, any measurement error of the Sensor Node results to be of the same order of magnitude of the nominal error and sensitivity of the CL-500 used as a reference, thereby attesting to a very high measurement accuracy of the realized Sensor Nodes, which exceeds the performance required by the specific application.

VI. EXPERIMENTAL RESULTS

The system described up to now, including the Sensor Nodes positioned inside the Scrovegni Chapel, has been designed to perform a continuous monitoring of light throughout the year, aimed at controlling the contribution of natural light. In fact, the deployment of sensors allows continuous detection for prolonged periods of time, so as to elaborate a complete model that includes the natural light contribution and takes into account its changes due to weather and seasonal conditions.

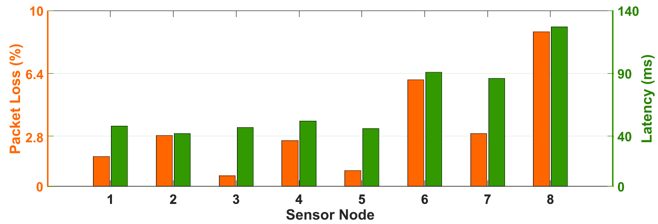


Fig. 14. Mean values of packet loss and latency evaluated for each Sensor Node.

The network architecture of the proposed IoT solution exploits the RPL routing protocol and implements the ETX (Estimated Transmission) metric. Anyway, to maximize the network performance, we have also optimized the routing protocol timers. In summary, the Neighbor Discovery mechanism was customized and reduced the inter-packet time between control and response messages defined by the RPL protocol. Consequently, the network was made more dynamic and with performance suitable for the developed application of lighting monitoring and control.

Before the inauguration of the new system, several field tests were conducted to verify the network performance in terms of packet loss, delay and scalability. Obviously, the performance are related to several application-dependent parameters such as data rate, packet rate, packet size, number of nodes, environmental conditions and so on.

Currently, the wireless sensor network installed inside the Scrovegni Chapel is constituted of eight Sensor Nodes and one Edge Node that is wired connected to the Border Router. Among these eight nodes, five are always directly connected to the Edge Node through a single hop, two are typically distant two hops, finally, the last one is typically distant three hops. Obviously, we are only referring to the most usual topology because the network is dynamic and automatically adjusts itself on the basis of the actual radio communication conditions.

Preliminary tests were conducted inside the Chapel during the week preceding the inauguration with a packet rate of 1 pkt/min for each node, because this is the typical condition suggested for the desired application. The tests were continuously carried out both during the day hours with public access and at night. Fig. 14 shows the mean values of packet loss and latency at the Network Layer as a function of the specific Sensor Node and consequently of its distance (number of hops) from the Edge Node. In the horizontal axis, the ordinal numbers from 1 to 5 indicate the typically single-hop nodes (from the Edge Node), 6 and 7 the two-hops nodes, while 8 the three-hops node. The average percentage of packet loss spans from 0.6% to 8.8% in the worst case, while the average latency is always less than 127 ms. The latter parameter shows extremely low values that do not affect the control features defined for this specific application. The results in Fig. 14 are referred, as previously specified, to values measured at the Network Layer. At the Application Layer, the CoAP protocol overcomes the packet loss event assuring the reception of 100% the transmitted packed. In fact,

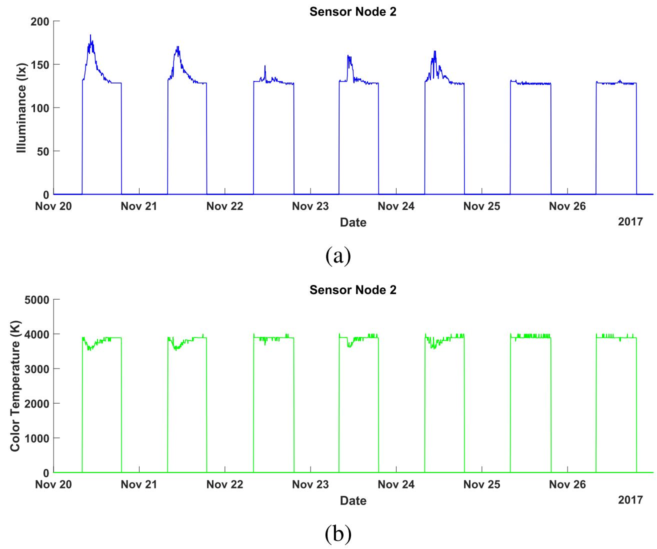


Fig. 15. Measurements of illuminance (a) and color temperature (b) acquired by the Sensor Node 2 on a window of one week in the presence of natural and artificial light with the control system disabled.

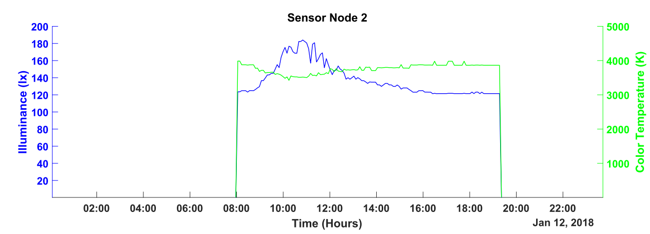
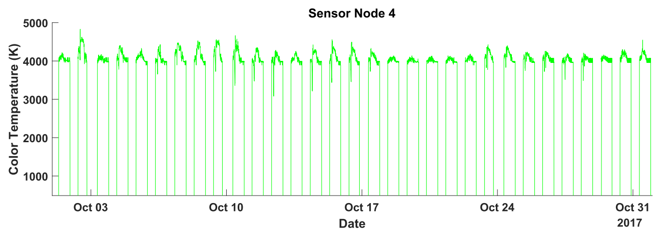


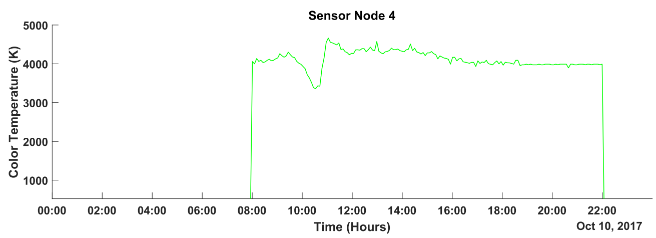
Fig. 16. Measurements of illuminance and color temperature acquired by the Sensor Node 2 on a window of one day in the presence of natural and artificial light with the control system disabled.

this protocol provides confirmable or non-confirmable request and response messages. We adopted the use of confirmable messages that must be acknowledged by the receiver through an ACK packet.

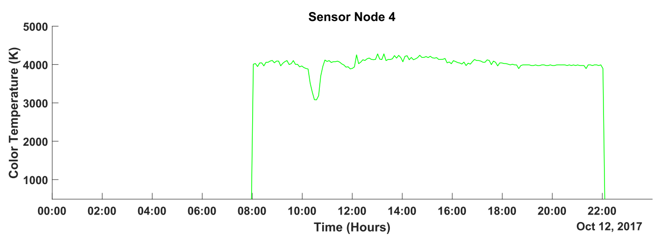
The Sensor Nodes measure both the illuminance (Fig. 15(a)) and the color temperature (Fig. 15(b)) of the light, taking into account the combined contribution of natural and artificial light. Fig. 15 shows the illumination and color temperature measurements acquired by the Sensor Node 2 over a window of one week in the presence of natural and artificial light and without enabling the control system. As "optimal" lighting, artificial lighting has been hypothesized to allow the best reading of the frescoes with homogeneously diffused light solutions, in the presence or absence of natural light, and in compliance with the restrictions set by the regulations for the conservation of cultural heritage. The tests with natural light excluded converged the assessments on a calibration of the color temperature around 3800 K. Regarding the illuminance levels, considering the indications of the conservation regulations, a limit value of 180 lx average daily was identified on the frescoes that led to set the illumination levels of the artificial light alone around 120 lx. The configuration of the artificial light system has therefore been set to reproduce these conditions in the absence of natural light and it will remain fixed in the monitoring phase. In Fig. 16 it is reported the monitoring through the Sensor Node 2 along a typical day



(a)

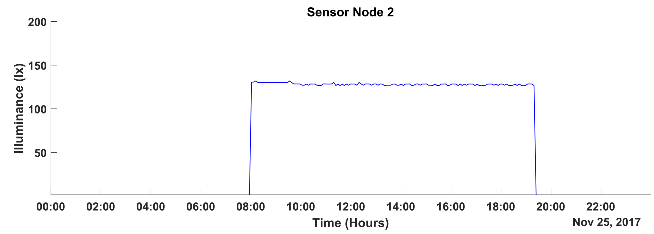


(b)

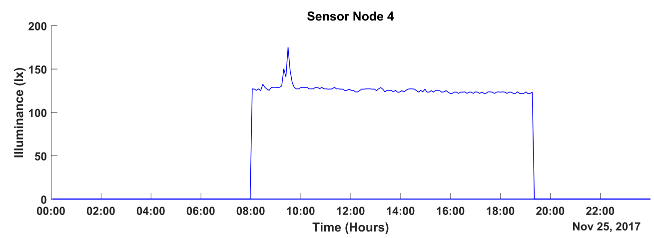


(c)

Fig. 17. Measurements of illuminance acquired by the Sensor Node 2 on a window of one month (a) in the presence of natural and artificial light with the control system disabled. In (b) and (c) the zoom of two days of the previous period.



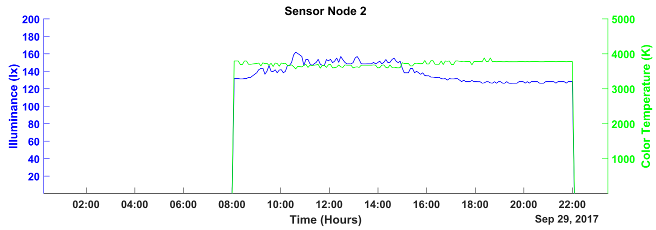
(a)



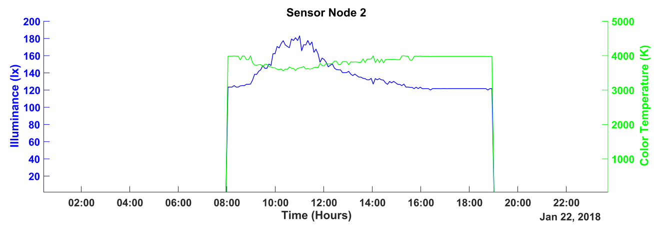
(b)

Fig. 18. Measurements of illuminance acquired by the Sensor Node 2 (a) and the Sensor Node 4 (b) on a window of one day in the presence of natural and artificial light with the control system disabled.

from the switching on of the artificial lighting, around 8.00 am, until its switching off, around 7.15 pm. On different days, the switch-off time may vary, as, in addition to the standard ten hours of opening to the public, evening visits on reservation that prolong the period of lighting up to about 10.00 pm can be added. In Fig. 16 we can see that the illuminance (blue curve) is on average around 120 lx, except in the hours between 9.00 am and 12.30 am where, as a consequence of the contribution of natural light, the illuminance increases and reaches a peak of 180 lx. At the same time, the color temperature (green curve) remains at about 3800 K except in the aforementioned time period in which, thanks to the contribution of natural light, it gradually drops to 3400 K at the illumination peak and then rises again. Consequently, with reference to the specific situation in Fig. 16, the system realized is able to perform an adequate regulation of the artificial light to lower the level of illuminance and, at the same time, raise the value of color temperature in the area of interest to a better light rendering in the central hours of the morning. Therefore, conservative aspects are even more safeguarded and further energy efficiency of the lighting system are pursued. On the contrary, with the progress of the day hours, a gradual replacement of natural light with artificial light is necessary, in order to constantly ensure the best perceptive quality of Giotto's masterpiece, both in color rendering and in illuminance level. The need for color temperature regulation is even more evident in Fig. 17(a) that refers to acquisitions of the Sensor Node 4 on a monthly window. High excursions of color temperature values can be seen, from a minimum of 3350 K to a maximum of 4663 K during the same day (Fig. 17(b)), or even situations in which a minimum value of 3079 K is reached (Fig. 17(c)). Therefore, to overcome this problem, algorithms to produce dynamic compensations of the measured light on the basis of the data acquired in real time are essential. It has already been pointed out that the Scrovegni Chapel has windows only on the south facade, it is therefore important that the uniformity of illumination is guaranteed not only between specific areas of the same wall, but also on the two opposite walls of the nave. Fig. 18 shows the lighting trends measured over the same day by the Sensor Node 2 and the Sensor Node 4 positioned in the two opposite south (Fig. 18(a)) and north (Fig. 18(b)) walls of the nave. As can be seen, the Sensor Node 4 reveals a lighting peak because reached by direct natural light coming from the windows on the south wall (Fig. 18(a)). Conversely, the Sensor Node 2, installed in the wall with the windows and therefore not directly exposed to natural light, has about constant lighting levels generated almost exclusively by the contribution of artificial light (Fig. 18(b)). In this situation, a strong illuminance contrast is created between the south wall and north wall, compromising the visitor's perception of the frescoes. An efficient regulation of the lighting system must allow the compensation of illumination levels avoiding, among other things, glare and overexposure phenomena inside the Chapel. Finally, in Fig. 19 are shown the acquisitions of the Sensor Node 2, placed under the windows of the south wall, in two different days of the year corresponding to two different seasons. During the day of early autumn with a clear sky (Fig. 19(a)), the illumination reaches a maximum level of about 162 lx during the central hours of the day then decreases from the early afternoon. The color temperature remains almost constant throughout the day and is substantially solely



(a)



(b)

Fig. 19. Measurements of illuminance and color temperature acquired by the Sensor Node 2 in two different days of the year in the presence of natural and artificial light with the control system disabled.

(a)

(b)

Fig. 20. Comparison between old (a) and new lighting (b) in night conditions (absence of natural light).

due to the contribution of artificial light. During the winter day (Fig. 19(b)) the contribution of natural light is concentrated in a much shorter period of time and reaches higher levels of approximately 180 lx. The information collected on the variations of natural light and its interaction with artificial light over the entire monitoring period, and of which the previously illustrated cases are only an exemplification, will be the basis for determining the configurations that will allow the lighting system to self-adjust according to the lighting conditions into the Chapel. This will guarantee an adequate integration between the two light sources and the best color rendering of the shades of color that characterize Giotto's frescoes. From Fig. 20 it is already widely evident how, under night conditions (absence of natural light), the new lighting system immediately guarantees a better perception of the frescoes colors, especially in terms of the warm tones (yellow-orange-red), which enhance the gold leaf used in the haloes and facilitates the vision of details. In conclusion, the dynamic control system must provide the regulation of the lighting on ideally set values (defined in night conditions) and such as to guarantee the visitor the best possible enjoyment of Giotto's masterpiece, allowing him to appreciate every detail without it being distorted or perceptively modified.

Moreover, the IoT architecture achieves the reduction of energy consumption and simplifies management operations.

VII. Conclusion

The design, implementation and operation of the new IoT system at the Scrovegni Chapel demonstrate the feasibility and advantages of the presented open architecture that does not require the use of complex and expensive gateways and is proposed as a reference both in the cultural heritage field and in the countless application sectors of the IoT. Thanks to the IoT solution, the tangible results in the current monitoring phase are the availability of a widespread and continuous monitoring system of lighting levels over time, aimed at preserving the frescoes, thereby enabling the storage of the acquired data and their long term analysis (e.g. for the creation of predictive models). Subsequently, the information collected on the variations of natural light, and the joint contribution of this and artificial light, will be the basis for determining the control actions allowing the artificial lighting system to automatically adjust itself to varying lighting conditions into the Chapel. Moreover, the WSN system installed for lighting monitoring can be easily extended in number and functionality, adding the most disparate sensing and actuation units such as those for monitoring of environmental parameters or inertial units for seismic and structural. It would be possible to monitor the state of cohesion and adhesion of the frescoes, identify the areas at risk, prevent the detachments, control the presence of pathogens, etc. and execute, where possible, automatic corrective actions. In fact, the system currently installed allows to implement real time controls to vary both lighting levels and overall environmental conditions, with the aim of preserving and maintaining the cultural asset and, at the same time, guaranteeing the visitor the best visual perception of the Giotto's masterpiece. In addition to the perceptive and conservative aspects, the IoT system could offer the creation of lighting scenarios oriented, for example, to the differentiated vision of frescoes details or the progressive reading of the pictorial story, which evolves along three registers on the walls of the Chapel, with a more suggestive and engaging narration of the pictorial masterpiece for the visitor. The new LED lighting system immediately guaranteed a 60% reduction in electricity consumption compared to the old system for lighting the Chapel with reference to the same lighting regime before and after the operation, i.e. with the lighting system always switched on at the maximum level, set in the absence of natural light. A further reduction in electricity consumption will be possible in the next phase, thanks to the automatic adjustment of the luminaires according to the contribution of natural light, made possible by the control system integrated into the IoT architecture. Finally, the possibility to equip LEDs with IP drivers, will fully realize the IoT paradigm, making each luminaire an Internet endpoint directly connected to the Network.

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References

[1] M. Zorzi, A. Gluhak, S. Lange, and A. Bassi, "From today's INTRAnet of things to a future INTERnet of things: A wireless- and mobility-related view," *IEEE Wireless Commun.*, vol. 17, no. 6, pp. 44–51, Dec. 2010.

[2] E. Mathews, S. S. Guclu, Q. Liu, T. Ozcelebi, and J. J. Lukkien, "The Internet of lights: An open reference architecture and implementation for intelligent solid state lighting systems," *Energies*, vol. 10, no. 8, p. 1187, 2017.

[3] A. Liu, A. Tuzikas, A. Žukauskas, R. Vaicekauskas, P. Vitta, and M. Shur, "Cultural preferences to color quality of illumination of different artwork objects revealed by a color rendition engine," *IEEE Photon. J.*, vol. 5, no. 4, Aug. 2013, Art. no. 6801010.

[4] M. C. Rodriguez-Sanchez, S. Borromeo, and J. A. Hernández-Tamames, "Wireless sensor networks for conservation and monitoring cultural assets," *IEEE Sensors J.*, vol. 11, no. 6, pp. 1382–1389, Jun. 2011.

[5] F. J. Mesas-Carrascosa, D. V. Santano, J. E. M. de Larriva, R. O. Cordero, R. E. H. Fernández, and A. García-Ferrer, "Monitoring heritage buildings with open source hardware sensors: A case study of the mosque-cathedral of córdoba," *Sensors*, vol. 16, no. 10, p. 1620, 2016.

[6] H. Agbota, J. E. Mitchell, M. Odlyha, and M. Strlič, "Remote assessment of cultural heritage environments with wireless sensor array networks," *Sensors*, vol. 14, no. 5, pp. 8779–8793, 2014.

[7] L. Lombardo, S. Corbellini, A. Elsayed, E. Angelini, M. Parvis, and S. Grassini, "Sensor network for museum environmental monitoring," in *Proc. IEEE Int. Workshop Meas. Netw. (M&N)*, Sep. 2017, pp. 1–6.

[8] A. Perles *et al.*, "An energy-efficient Internet of things (IoT) architecture for preventive conservation of cultural heritage," *Future Gener. Comput. Syst.*, vol. 81, pp. 566–581, Apr. 2018.

[9] M. Frascarolo, S. Martorelli, and V. Vitale, "An innovative lighting system for residential application that optimizes visual comfort and conserves energy for different user needs," *Energy Buildings*, vol. 83, pp. 217–224, Nov. 2014.

[10] Z. Nagy, F. Y. Yong, M. Frei, and A. Schlueter, "Occupant centered lighting control for comfort and energy efficient building operation," *Energy Buildings*, vol. 94, pp. 100–108, May 2015.

[11] M. Magno, T. Polonelli, L. Benini, and E. Popovici, "A low cost, highly scalable wireless sensor network solution to achieve smart LED light control for green buildings," *IEEE Sensors J.*, vol. 15, no. 5, pp. 2963–2973, May 2015.

[12] A. J. Jara, Y. Sun, H. Song, R. Bie, D. Genooud, and Y. Bocchi, "Internet of Things for cultural heritage of smart cities and smart regions," in *Proc. IEEE 29th Int. Conf. Adv. Inf. Netw. Appl. Workshops (WAINA)*, Mar. 2015, pp. 668–675.

[13] V. Mighali *et al.*, "Innovative IoT-aware services for a smart museum," in *Proc. 24th Int. Conf. World Wide Web*, 2015, pp. 547–550.

[14] P. Londero, T. Fairbanks-Harris, and P. M. Whitmore, "An open-source, Internet-of-Things approach for remote sensing in museums," *J. Amer. Inst. Conservation*, vol. 55, no. 3, pp. 166–175, 2016.

[15] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for smart cities," *IEEE Internet Things J.*, vol. 1, no. 1, pp. 22–32, Feb. 2014.

[16] L. Palma, L. Pernini, A. Belli, S. Valenti, L. Maurizi, and P. Pierleoni, "IPv6 WSN solution for integration and interoperation between smart home and AAL systems," in *Proc. IEEE Sens. Appl. Symp. (SAS)*, Apr. 2016, pp. 1–5.

[17] J. Vasseur, N. Agarwal, J. Hui, Z. Shelby, P. Bertrand, and C. Chauvenet, "RPL: The IP routing protocol designed for low power and lossy networks," in *Proc. Internet Protocol Smart Objects Alliance (IPSO)*, vol. 36, 2011, pp. 1–20.

[18] J. Mišić, M. Z. Ali, and V. B. Mišić, "Architecture for IoT domain with CoAP observe feature," *IEEE Internet Things J.*, vol. 5, no. 2, pp. 1196–1205, Apr. 2018.

[19] R. Piyare *et al.*, "Integrating wireless sensor network into cloud services for real-time data collection," in *Proc. Int. Conf. ICT Converg. (ICTC)*, Oct. 2013, pp. 752–756.

[20] F. Gont, "A method for generating semantically opaque interface identifier with IPv6 stateless address autoconfiguration (SLAAC)," Internet Eng. Task Force, Fremont, CA, USA, Tech. Rep. RFC 7217 (Proposed Standard), 2014.

[21] X. He, K. Wang, H. Huang, and B. Liu, "QoE-driven big data architecture for smart city," *IEEE Commun. Mag.*, vol. 56, no. 2, pp. 88–93, Feb. 2018.

[22] C. Kyriazopoulou, "Smart city technologies and architectures: A literature review," in *Proc. Int. Conf. Smart Cities Green ICT Syst. (SMARTGREENS)*, May 2015, pp. 1–12.

[23] P. T. Daely, H. T. Reda, G. B. Satrya, J. W. Kim, and S. Y. Shin, "Design of smart LED streetlight system for smart city with Web-based management system," *IEEE Sensors J.*, vol. 17, no. 18, pp. 6100–6110, Sep. 2017.

[24] M. Bálský, R. Bayer, J. Zálešák, and Z. Panská, "Use of tunable white luminaires for biodynamic lighting," in *Proc. 18th Int. Sci. Conf. Electr. Power Eng. (EPE)*, May 2017, pp. 1–4.

[25] L. E. Barbrow, "International lighting vocabulary," *J. Soc. Motion Picture Telev. Eng.*, vol. 73, no. 4, pp. 331–332, 1964.

[26] ams AG, "Lux and CCT calculations using AMS color sensors Rev 1.0," ams AG, Unterpremstätten, Austria, Appl. Note DN40, Aug. 2013.

[27] C. S. McCamy, "Correlated color temperature as an explicit function of chromaticity coordinates," *Color Res. Appl.*, vol. 17, no. 2, pp. 142–144, 1992.

[28] J. Smith, "Calculating color temperature and illuminance using the TAOS TCS3414CS digital color sensor," ams AG, Unterpremstätten, Austria, Tech. Rep. 25, 2009, pp. 1–7.

[29] J.-S. B. Valencia, F.-E. L. Giraldo, and J.-F. V. Bonilla, "Calibration method for correlated color temperature (CCT) measurement using RGB color sensors," in *Proc. Symp. Signals, Images Artif. Vis. (STSIVA)*, Sep. 2013, pp. 1–6.

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