A Low Cost, Highly Scalable Wireless Sensor Network Solution to Achieve Smart LED Light Control for Green Buildings

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***Abstract*— Reducing energy demand in the residential and industrial sectors is an important challenge worldwide. In particular, lights account for a great portion of total energy consumption, and unfortunately a huge amount of this energy is wasted. Light-emitting diode (LED) lights are being used to light offices, houses, industrial, or agricultural facilities more efficiently than traditional lights. Moreover, the light control systems are introduced to current markets, because the installed lighting systems are outdated and energy inefficient. However, due to high costs, installation issues, and difficulty of maintenance; existing light control systems are not successfully applied to home, office, and industrial buildings. This paper proposes a low cost, wireless, easy to install, adaptable, and smart LED lighting system to automatically adjust the light intensity to save energy and maintaining user satisfaction. The system combines motion sensors and light sensors in a low-power wireless solution using Zigbee communication. This paper presents the design and implementation of the proposed system in a real-world deployment. Characterization of a commercial LED panel was performed to evaluate the benefit of dimming for this light technology. Measurements of total power consumption over a continuous six months period (winter to summer) of a busy office were acquired to verify the performance and the power savings across several weather conditions scenarios. The proposed smart lighting system reduces total power consumption in the application scenario by 55% during a six month period and up to 69% in spring months. These figures take also into account individual user preferences.**

***Index Terms*— Overlay networks, wireless sensor networks, power electronics, LED lighting control, power management, energy efficiency.**

I. Introduction

ENERGY saving and environmental friendliness/awareness is a hot topic in current research. In fact, Carbon dioxide (CO_2) emissions are strongly associated with energy consumption, these originated from the combustion of hydrocarbons (oil, natural gas and coal) either directly burned (transport and heating) or for generation of electricity in power plants [1]. Lighting systems are a major source of electricity consumption in the world. In Europe, the amount of electrical energy used in illuminating buildings is considerable, about 40% and leads to approximately 35% of carbon dioxide emissions [2]. In recent years the European Union EU has actively promoted political campaigns toward energy efficiency. While previous research and industrial works have shown that simple lighting controls using motion sensors, such as PyorelectricInfraRed (PIR) sensors, are effective at reducing the amount of electrical energy used for lighting buildings, advanced lighting control strategies have the potential to achieve even greater energy savings, better quality of service and offer many advantages over simple on/off controls. However, until present, advanced control strategies, such as dimming light according to the day lighting or load shedding, which require a more systems-oriented approach, have been less successful. This is especially due to the high cost of installation and maintenance and the impossibility of retrofitting [3].

On the technological side, Light Emitting Diode (LED) is rapidly becoming a commonly used solid-state light source technology in general lighting applications. This is due to its longer lifetime, reduced power consumption, and having no poison mercury content compared with the conventional fluorescent lamps [4], [5]. In addition, dimming control is often needed to regulate lighting levels for individual human needs or preferences as well as to achieve energy savings. Novel driver systems are improving the dimmable features to achieve this goal and are increasingly commercially available. This new technology is boosting interest in controlling the light to reduce power consumption. The market for lighting controls in residential and commercial buildings has entered a period of dramatic transformation. The demand for both wireless and local controls, such as occupancy sensors; photosensors; and networked controls rises, and the adoption rate of the LED lighting systems begins to climb as well. According to a new report from Navigant Research, worldwide revenue from networked lighting controls will grow from $1.7 billion annually in 2013 to more than $5.3 billion by 2020 [6].

With the advance of wireless sensor network (WSN) technology, it is now easier than ever to monitor and control houses, offices and industrial buildings. WSN is the backbone of a large variety of cyber-physical systems (CPS) applications in environmental monitoring, healthcare, security,

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and industrial domains, among others, due to the flexible distribution of WSN devices [7]–[9]. Each device embodies a networked node that integrates computing, wireless communication, power management and sensing capability in order to collect and process data from sensors, generally collaborating to coordinate activities [10]. WSN in combination with LED lights and novel drivers reduces the power consumption of the illumination in several application scenarios by several orders of magnitude [11]. WSN has the potential to achieve a low cost and ultra high power saving system. However, particular attention must be paid during the design process of hardware and software. For example, it is important to develop low power wireless sensor nodes, with small form factor and cost which can be easily fitted inside the driver casing. These features allow the future embedded devices to be attached to the driver, adding the wireless communication and "smart" capabilities to the driver, to achieve an automatically or remotely controlled system. The novel driver can be controlled using distributed sensors in the environmental area to increase the quality of the control reducing the power consumption and increasing the quality of the service. The control of lights becomes fast and rich-featured, going beyond on/off, dimming, to color (or color temperature) change and scene setting, with intelligence to react to human mood and activity, and adapt to environments and scenarios.

The contributions of this paper are as follows:

- A methodology for deploying low power sensor networks to enhance the power consumption of LED lights using novel, ultra-low power hardware architecture and smart distributed algorithm. The concept of using light sensors and WSN in LED control is not new, however using it to directly control a LED driver with distributed intelligence and allowing retrofit is a novel contribution.
- Experimental validation of the proposed approach. The power consumption characterization of panels according to the dimming and the average energy reduction in a real-life, long-term deployment is presented.

The remainder of this paper is organized as follows: Section II describes recent related work in the area. Section III describes the models and devices of the proposed approach, describing the nodes and the network architectures, respectively. Section IV presents the algorithms implemented in the whole system. Section V describes the implemented approach, along with measurements, comparative evaluation, and validation. Section VI concludes the paper.

II. Related Work

Research on monitoring, control and energy efficiency in the lighting domain has been prolific in recent years; with a variety of solutions and techniques proposed. The two main approaches are given by wired and wireless systems. Wired controllable lighting systems can measure the artificial and daylight illumination through the use of sensors in a controller area network [12] or a set of data logger devices [13] to modify the light intensity and hence its energy consumption. However, due to the presence of bundles of cable to perform data communication the wired devices are much more costly, especially due to the installation and maintenance. Moreover the wired system is limited to retrofitting the existing light system in buildings. To overcome this installation cost and issues, wireless technology has become a more popular alternative on the demand-side energy management, monitoring and control in buildings. WSN is the enabling technology for building energy control as it is much easier and flexible to install and implement than wired networks. By using the combination of advanced WSN-based controls and DC grid powered LED lighting systems, the advantageous features generated from this combined technology should lead to greater energy savings at the demand-side of the green smart building [14].

Recently, wireless sensor networks have been applied to energy conservation applications such as light control [15], [16]. In [16], a trade-off between energy consumption and users' satisfaction using light controls was studied. The authors applied utility functions which considered users' location and lighting preferences so that illumination could be adjusted as to maximize the total utilities. However, it did not consider the fact that people may require different illumination levels for different activities. The logic of lighting control systems may include factors such as daylight intensity, which can be measured by light-sensitive sensors [17]. In [18] the authors defined several user requirements and cost functions. Their goal was to adjust lights to minimize the total cost of energy supplied. However, the result was applied to entertainment and media production systems rather than to buildings. In [19], light control using wireless sensors to reduce energy consumption in commercial buildings is introduced. In these previous works, lighting devices are adjusted depending on ambient daylight intensity and/or motion sensors. This approach is conceptually similar to the proposed system. However our work presents a comprehensive, long term (over 6 months) in-field evaluation of power savings, during several seasons and weather conditions. Moreover the control algorithm is not explained in [19] and it is not possible know if the algorithm uses distributed or local decision making. Finally in [19] there is no data about the power consumption of the wireless system and its associated cost. In [21] and [22], a lighting control system is proposed that considers both users' preferences and energy conservation. This system assumes that the location of each user is known via a wireless sensor that is carried by each user that also detects local light intensity. An additional assumption is that there is no obstacle between whole lighting devices and fixed sensors. In [22] their model is designed for "point-link" light sources, such as LEDs. In [23] a smart lighting system where the ambient light at the user's location is controlled in real-time to give users the best indoor light experience but in energy efficient manner is proposed. This approach is very similar to the one proposed in this paper and the benefits are demonstrated. However, the network cannot control the LEDs' driver directly as it needs a digital addressable lighting interface (DALI) controller and this makes the system not ultra low power and very expensive. Also, the driver cannot be made wireless. Another standard for the lighting control is KNX [27], which is used to add intelligence to buildings. However, there is no native wireless communication and it has a very high cost with tens of

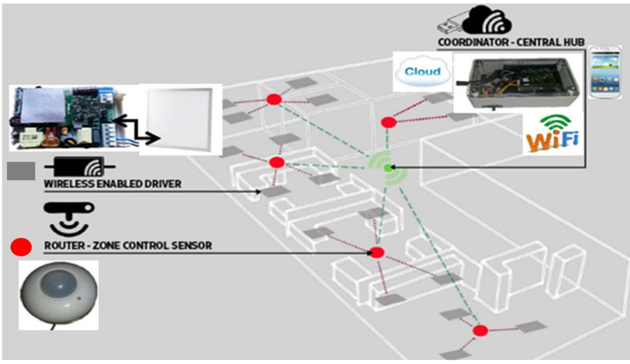

Fig. 1. Typical application scenario of Smart Lighting with the topologies of devices used: i) Coordinator of network connected to a host device; ii) Router to monitor the enviroment with light and motion sensors; and End Device connected to the pannel to adapt the light intensity to save energy achiving the optimal level of brightness in the area.

thousands of dollars for the basic installation. Our solution has been designed with low power, low cost, flexibility and scalability in mind. It is based on a low cost wireless sensors node, which uses the Zigbee standard to increase accessibility and scalability, the intelligence is distributed and it can directly control the LED driver to increase the accuracy and reactivity of the system. Finally the motion sensor and the light sensor monitor the surroundings to give the best user comfort using the lowest power consumption. An interesting approach for sensor-less lighting control using neural network algorithm has been proposed in [24]. However the network still needs a central intelligence unit and the DALI connection, moreover the power saving results are much lower than in the proposed approach. Several solutions for intelligent lighting applications using wireless modules have been proposed also in commercial products where NXP/Jennic [25] and Eshelon/LonWorks [26] are the most important examples. Even for commercial products the technology is still in its infancy since there are many options to be validated in practice by real applications. Surprisingly, there are no commercial low cost products on the market that offer the functionality features listed in this proposed smart lighting system such as flexibility, adaptability/ease of use (suitable for several commercial drivers), robustness, distributed intelligent, directly plug-in LED's drivers. A commercial wireless solution is Eyenut [30]. However, the sensor node is limited to movement sensors, meaning light sensors are excluded, and there is no real distributed intelligence. Moreover, the solution has a high cost of thousands of dollars for the base station and hundreds of dollars for the wireless devices.

This paper shows the design, development and accurate measurements of a whole low power and low cost wireless sensor network to achieve power saving through automatic control and demonstrates its benefits in terms of power saving and scalability using in-field experimental results.

III. Devices and Methods

Figure 1 illustrates a conceptual scheme of the proposed system. It consists of groups of LED panels managed by multiple sensors (motion and light) and distributed intelligence. The nodes communicate wirelessly through a Zigbee [31] (using IEEE 802.15.04 MAC protocol) mesh network with a coordinator, several routers and several End Devices (EDs). Each panel has a wireless controller (Zigbee ED) directly connected to its driver to be set the light intensity through a pulse-width modulation (PWM) signal. The PWM signal is used to encode the level of the LED brightness with the width of the pulse (duration) of micro-controller signal as explained better in next subsection. The value of the PWM is decided by a control unit, given by one of the distributed routers provided with sensors. Each router uses the sensors' data to adapt the intensity according with the user's preferences with the goal of maximizing the energy saving and users' preferences. The Zigbee network in a mesh configuration permits building a scalable and modular system easily extendable, and allows each sub group of lights to be completely independent and flexible in terms of area monitored/controlled. In fact, each router has a flexible and controllable number of associated ED's and LED panels, which it can control under the same conditions. This allows having different areas with different controls in order to increase the power saving driven by users' preference.

The whole network is managed by one supervision unit, the Zigbee coordinator that both manages the network and ensures that all network devices are working properly. Furthermore this unit works as a gateway with a remote host (laptop, wall embedded devices, Wireless Lan/Bluetooth devices, and so on), to enable human interaction. Thus, it is possible both to acquire users' preferences to adapt the dimming of the lights in desirable values and to enable a graphical user interface for the management and for visualizing the energy saving data for each group of LEDs or single device. This is an important feature as the percentage of energy savings depends on several factors but the most important is the users' preference, and the user can evaluate this graphically. Other import factors affecting the power saving are the position of each group of panels, i.e. a room with a big windows south facing saves more energy than a basement, the weather conditions, season, geographical location, etc.

The primary objective of the proposed approach is to reduce the power consumption of a generic (and also existing) LED light system using a flexible network deployed in the same target field reducing cost of installation and guaranteeing smart and green buildings with and high return of the investment saving energy.

In this work, all the devices needed for the network were designed, developed and deployed in the field around the CC2530 chip from Instruments (TI). This chip supports the ZigbeePRO stack solution, with a small form factor and sufficient computational resources to execute the proposed algorithms. The developed devices include two chips from Texas Instruments: an MSP430 microcontroller where the firmware can be developed and implemented, and a CC2530 which is in charge of the whole communication and the Zigbee stack. The device also includes an optional external board to be connected through an USB port for programming and testing. However only the coordinator uses the USB port during the deployment, to be interfaced with the remote host

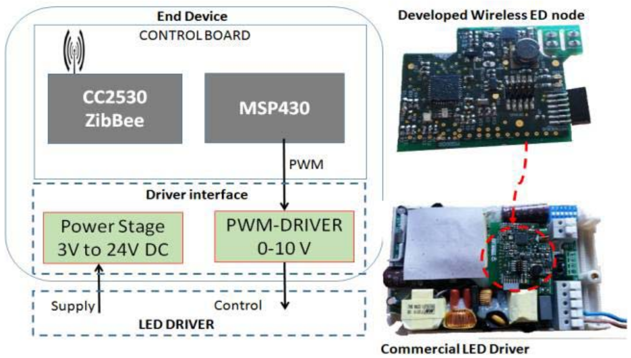

Fig. 2. End Device architecture and node developed to be plugged directly in a commercial driver to control and be supplied.

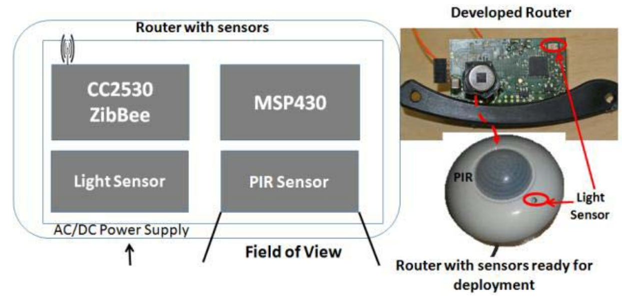

Fig. 3. Router Architecture.

and no more external hardware is required for networking. The router is equipped with sensors to monitor the controlled area while the end device is interfaced with the commercial light driver.

In the proposed smart lighting system the most important elements are:

- The LED panels, highly efficient white LED for illumination;
- The CC2530 that provides the management of ZigBee and is present in each node of the network;
- The MSP430 for the control of the LED panels' smoothing and where the distributed intelligence is implemented. MSP430 is present in all the nodes;
- A dimmable commercial driver for the LED, which provides a highly dimmable range (up to 89%) and an accrate control (constant current) for the smoothing.
- A light and PIR sensors, used by the router to monitor and control the brightness value.

In the following subsection the wireless network and the three architectures of the nodes are presented.

A. Wireless Driver Device.

In each LED panel a new device is needed to enable the wireless control. The sole purpose of this device is to control through PWM the driver LED providing an accurate smoothing of the light and to communicate with the wireless network. As mentioned earlier, the node is built around the CC2530 and MSP430 from TI, where the CC2530 chip is used for the network and the MSP430 on board is the core intelligence which manages the radio chip and where the firmware is running. Figure 2 shows the architecture of the device developed which includes the electronic circuits to control the industrial driver and to be supplied from an external power supply from 3V to 24V which can also come from the driver itself depending of the model. To allow the power stage to convert and give a stable 3V supply to the node, a step down low dropout (LDO) regulator with an ultralow quiescent current TLV70433 from Texas Instruments was used. This chip has a very low quiescent current with high conversion efficiency and it is optimized specifically for the MPS430.

PWM to Driver Block in Figure 2 is the most important part of the end device and it is needed to convert the PWM signal generated from the microcontroller in a 0-10V signal needed to control the commercial LED driver. The 0-10V control is one of the earliest and simplest electronic lighting control signaling systems and it is included in the most commercial drivers. Due to this interface the node can be adaptable to a wide range of commercial drivers with the 0-10V port, and can be incorporated directly into the driver as figure shows. To achieve this goal it is sufficient to insert a P-MOS transistor in a Common Collector configuration between the PWM signal of microcontroller and the 0-10V driver's input. For the end devices, we do not have any sensors on board as the PWM value is decided from the router which controls more than one device in the same group and it will be presented in next subsection. This has the benefit to bringing flexibility in the deployment and more reliable feedback on the light in the monitored area.

B. Router for Monitoring and Decisions Making.

This device is in charge of the most important workload in the network with the following main duties: i) manage the routing protocol of the Zigbee stack, monitoring the evniromental parameters throughout the sensors, ii) take the decision on the light intensity, and iii) send the control configuration to the panels that are assigned under its control during the network configuration. Figure 3 shows the hardware architecture of the router node, which is very similar to the end device, where instead of the PWM driver control there is the infrared sensor (PIR) block. This block includes the sensor and its coupling circuit which generates an interrupt when an object moves in the filed of view. The PIR used is the Panosonic EW - AMN34111J which garantees a fast and accurate interrupt for any moving object in the range of 10m. The interrupt generated by the PIR block is connected directly to a General Purpose Input Output (GPIO) pin of the MSP430 to recieve the interrupt. The light sensor on the board is enabled to monitor the luminosity in the area of interest and is an input to the algorithm. The light sensor is the SSFH 5711 a high accuracy ambient light sensor from Osram. The smart control of the light is managed by the low power microprocessor (MSP430) acquiring by ADC the light sensor data and computing the light intensity according to the implemented power policy and the user preferences. As for the

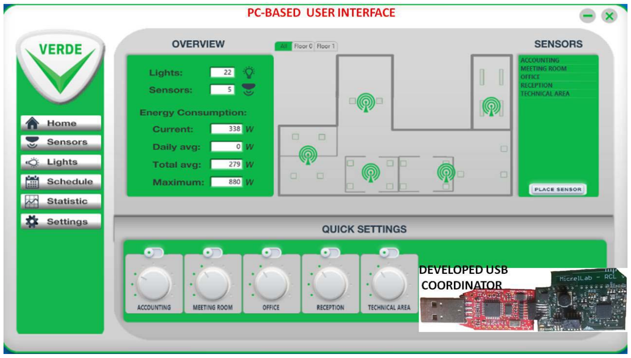

Fig. 4. Coordinator board connected to the remote host user interface and monitoring application.

end device, the routing protocol is managed using the CC2530 with the ZigbeePRO stack.

C. Base Control Station

The base control station is the hub of the proposed system as it allows the visualization of the lighting system and the setting of important parameters such as the users' preferences. The role of the coordinator is only to manage the network and allow the user interface through a remote host. The device is provided with interface to be connected with UART to USB ready to use as showed in Figure 4. Thanks to the interface and the remote host it is possible to set the users' preferences, and monitor the whole network and store all the data to evaluate the power saving.

D. Wireless Sensor Network

One of primary goals in designing the proposed system was the scalability, the low power and a standardized network for commercial application. ZigBee is a wireless communication technology based on the IEEE802.15.4 standard for communication among multiple devices in a wireless personal area network (WPAN). The ZigBee alliance has developed low-cost, low power consumption, wireless communication standard, and the CC2530 chipset was chosen. Therefore, this standard is designed to be more affordable than other WPANs (Wi-Fi or Bluetooth) for developing low power embedded systems for consumer electronics, home and building automation, industrial controls, PC peripherals, medical sensor application, toys and games. The ZigBee architecture is made up of a set of blocks called layers; each layer performs a specific set of services for the layer above. The IEEE802.15.4 standard defines the two lower layers: the physical (PHY) layer and the medium access control (MAC) sub-layer. The ZigBee Alliance builds on this foundation by providing the network (NWK) layer and the framework for the application layer, such as the ZigBee device objects (ZDO) and the manufacturer-defined application object.

TI provided the Z-Stack to use easily the Zigbee stack implemented on the CC2530. The network is built to transfer information from the router to the panels and from the user interface to the distributed routers who will perform the algorithm to select the dimming value of the lamps. The LEDs' light is associated to only one router that controls them as described by Figure 6. With the distributed approach, the routers can decide the brightness level without continuously sending and receiving messages to the central host. In this way, the system saves energy for the transmission increasing together the reactivity as the router is the closer parents of the controlled panels. This is especially true when the network is expanded and the number of nodes and messages exchanged increase [31].

A mesh network was chosen to maximize the scalability of the network to a dimension of more than 64000 wireless nodes. The ZigBee wireless communication network has been implemented using the CC2530 chip and the home automation PRO Stack already implemented on the chip. The developed devices have a PCB antenna and provide an operation range of tens of meters indoor and outdoor with selectable output power from −22 dBm to 4.5 dBm according with application scenario. The peak power during transmission, while covering more than 20 meters with an indoor application and +4.5dBm output power, is around 100mW at 3.3V. However, the firmware can adapt the transmission power runtime according to the received signal strength indicator. In this work we are not using an adaptive power transmission and we fixed the power output at +4.5dBm.

IV. Lighting Control Algorithm

As it was presented in the previous section there are three different devices which need three different algorithms to work properly. The network software is a critical part of the system (Figure 7 and Figure 8). The Z-STACK from TI was used to work with the ZigbeePRO protocol with the CC2530. In this section are presented only the algorithms needed for the smart light control residing on the three node topologies: End Device, Router, Coordinator (Figure 5).

A. End Device Algorithm

Figure 5 shows the main flowchart of the algorithm. The main task of the network management is to receive and set the right brightness for the LED panel (Figure 7). Thus, after the device joins the network, a router is associated to it. From this instant it waits for the PWM value decided from the router's own algorithm and sets the LED light intensity of the panel. After the value is set, the radio goes into standby mode for energy saving. The wake up time to get a new luminosity value can be selected by the user as this affects the response time, in the proposed approach 500ms was selected, since it is a good trade-off between power saving and reactivity. This simple procedure with the above mentioned hardware allows every commercial driver to be controlled through a standard Zigbee network.

B. Router and Control Algorithm

The router algorithm is somewhat more complex than for the end device. The core of smart lighting intelligence is distributed to each router which then controls one or more

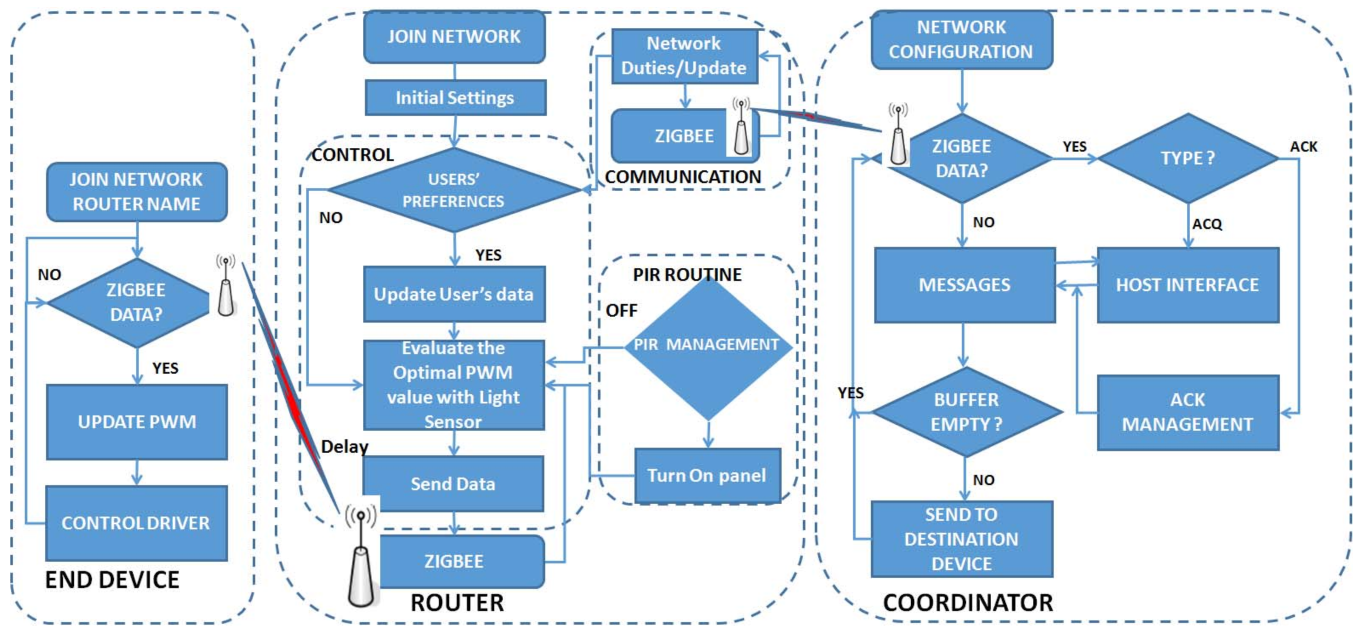

Fig. 5. Flow charts of the three devices. The Network management is not included in the flow chart and the Z-STACK from TI library were used to work with the ZigbeePRO protocol.

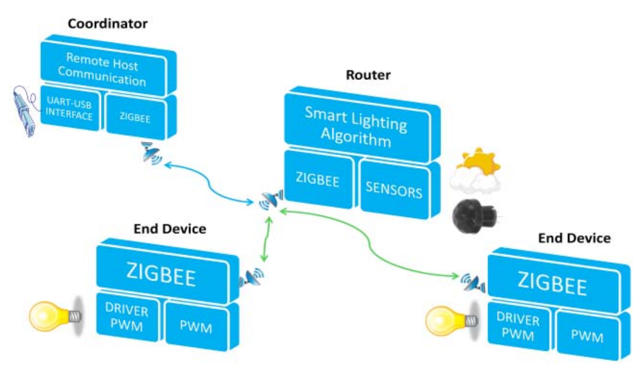

Fig. 6. Overview of the Zigbee network for the proposed system with one coordinator, one router who controls the panel according to the light and motion senosrs and the controlled end devices wich adapt the LED light intensity trough the PWM driver.

```
NETWORK_INIT() //JOIN THE NETWORK

SLEEP() //GO TO SLEEP MODE WAITING FOR MESSAGE

/*WAKE UP FROM INTERRUPT ROUTINE*/
READMSG() //READ THE PWM VALUE
PWM_DRIVER = PWM //SET THE DRIVER VALUE

SLEEP()
```

Fig. 7. Pseudocode of the End Device Algorithm to set the PWM value of the LED driver.

end devices. To achieve this important goal, the router has as main blocks, the communication and control algorithm on it. The communication block is in charge of receiving data from the network about the user's preferences and send data about the status of the controlled panels to the remote host.

```
#define DEFAULT_ROOM_LUX 600

ROOM_LUX = USER_PREFERENCE
LUX = LUX_FROM_ADC_LIGHSENSOR
PIR = PIR_FROM_TIMER

IF LUX>ROOM_LUX THEN
        PWM = PWM - SMOOTH_VALUE
ELSE IF LUX<ROOM_LUX THEN
        PWM = PWM + SMOOTH_VALUE
ENDIF
SEND PWM TO ASSOCIATE CHILD

INTERUPT ROUTINE PIR
        IF PIR=PEOPLE THEN
                SEND_PWM_TO_GROUP_LIGHTS_VIA_ZIGBEE
                RETURN PWM
ELSE IF PIR=NO_PEOPLE DURING A TIMEOUT_TIME
        SEND_OFF_TO_GROUP_LIGHT_VIA_ZIGBEE
        RETURN OFF
ENDIF
```

Fig. 8. Pseudocode of the Control Algorithm distributed in each wireless sensors' node.

As the network is a mesh, the information can hop to other routers before reaching the coordinator which monitors the status of the panels and manages the errors.

Figure 5 shows the control algorithm running on the sensor node device. The control algorithm is the core of the smart lighting application setting the dimming value of the panel. To achieve this goal the microcontroller acquires the light sensor data through the ADC port containing the brightness of the room. The purpose of this measurement is to ensure an optimal level of illumination in the room according to the user preferences and existing standards for lighting. The algorithm controls the brightness value of the panels setting the PWM to achieve the optimal value of luminosity in the area and save energy. As Figure 8 shows in case the brightness of the room is higher than the desirable user's value the PWM value is decreased. On the other hand, PWM value is increased when the monitored brightness is lower than the desirable user's value. Moreover with energy savings in mind, the algorithm includes a PIR management routine which identifies the presence of people from the motion sensor. The control algorithm turns off the group of LED panels to prevent waste if no movement is detected for a certain amount of time (which is set by the user). In the same way the PIR management interrupt routine turns the panels on quickly and wakes the control routine up if any movement is detected. This feature enables the capability to switch on the LED panels only when necessary, avoiding the waste of energy.

The main challenge with the sensors' node is its correct placement in the monitored area, because this can affect the performance of the whole system. For instance, if the light sensor is under direct sunlight or panel light it can give wrong feedback to the control algorithm. Moreover it is also important to avoid shadow places or places where the temporary shadows are generated from people's movements.

For these reasons the best positions were found on the ceiling in the middle of the light groups. Here the light sensor is not directly affected by the external environmental light or LED panels and from random shadows. In this position the Panasonic EW - AMN34111J PIR sensor also provided optimal performance covering 10 meters with a wide angle (around 120°) detecting all the movements in the field of view with a fast response of few milliseconds. Concerning the PIR sensors it is also important to avoid undesirable switching off if no movement is detected from a long of time. To avoid this condition the TIMEOUT_TIME of switching on has to be chosen carefully. For our deployment a conservative value of 45minutes was chosen during the office time 8am-6pm, and 5minutes outside this time interval. As it will be presented in the experimental results section, the deployment in a real office was active for a continuous 6 months period with full user satisfaction who did not notice any difference with the traditional system without the smart control.

C. Coordinator Algorithm

The main role of the coordinator, over setup and control of the Zigbee WSN, is to connect the wireless devices deployed in the building with a remote host which provides the user interface. The coordinator also sends the user preferences to the routers and collects the status information from the routers to store the monitored status in a remote database. The communication is done through the UART port of the microcontroller and the UART to USB converter that allows connecting the dongle to every host with an USB interface. Thus, the coordinator works as a gateway and it is required for a graphical display of the results and user input. Furthermore, data on wireless device operations are associated with the LEDs light address; consequently, all faults and the state are easily identified.

The graphical interface enables monitoring the state of the system with the state of the lights and the power consumption of each controlled LED light (individual energy consumption meter) Figure 4. As the host interface also stores the dimming value of all the panels the user or network manager can have an overlook of the power consumption and working time of every panel in a graphical vision. The program is also equipped with a management system that acts in case of no acknowledgements are sent from the panel to highlight the errors.

Fig. 9. Deployment of the system in the VerdeLED company offices.

V. Experimental Results

All prototypes have been developed, tested and deployed in variable real-life conditions to verify the overall functionality, the scalability and the robustness of the network and seek better performance. This section describes an experimental evaluation of the system as applied to indoor offices. Firstly, the measurements of power consumption of the devices in different states are presented. Evaluation of the power saving energy of a commercial LED panel VER-P6060-43-840 from VerdeLED with the dimmable driver LPF-40D-42 from Mean Well is presented. Secondly, the section presents power consumption measurements done during 6 months of continuous work in the company office where the smart lighting system was deployed as the primary and only light system.

Figure 9 shows the development system implemented in an office with the goal of testing it in real conditions while Figure 1 shows the floor plan and where the sensor nodes were placed. In this implementation, 25 wireless devices were directly connected to the power supply of LED panels, so is possible to cover the whole office presented in Figure 1. The Zigbee network has been deployed in an office together with 2 Wi-Fi internet access points and several users' phones and PC connected to the access points. Under these conditions the system was working for 6 months without any interruption showing a high robustness to Wi-Fi interferences.

The positioning of panels and sensors was done with a preliminary analysis on solar irradiation within the office as explained in section IV.B, and taking into consideration the work time difference of the employees in this office. This has permitted an accurate positioning of the sensors that, in combination with the configuration of the network (connections between LED panels and sensor) by user interface, have provided a stable and robust solution working at writing time for 6 months without any interruption of services.

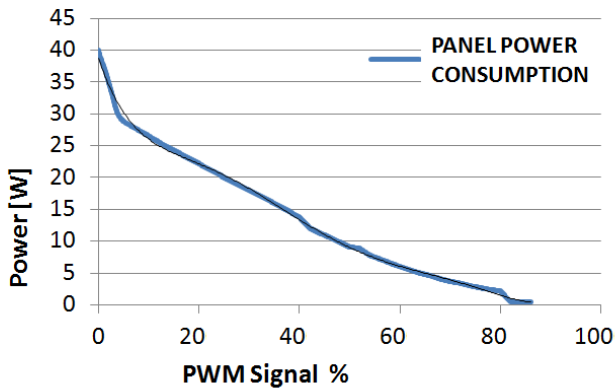

Fig. 10. LED panel + LED driver power consumption according to the the PWM signal of the microcontroller.

TABLE I
NODES' CURRENT AND POWER CHARACTERISTICS

Device/Mode	Consumption		
	State	*Current*	*Power*
Router	MCU on, Radio TX, data processing	19mA	95mW
	MCU On, No processing, Radio RX	18.5mA	92.5mW
End Device	MCU on, Radio TX, data processing	18mA	90mW
	MCU On, No processing, Radio RX	17.5mA	87.5mW
	MCU On, CC2530 Sleep for power saving	0.100mA	0.500mW
	Manully swithced off with the LED panel	0	0
LED PANEL+DRIVER	NO CONTROL	180mA@ 220V	40W

Current consumption of nodes in different configurations

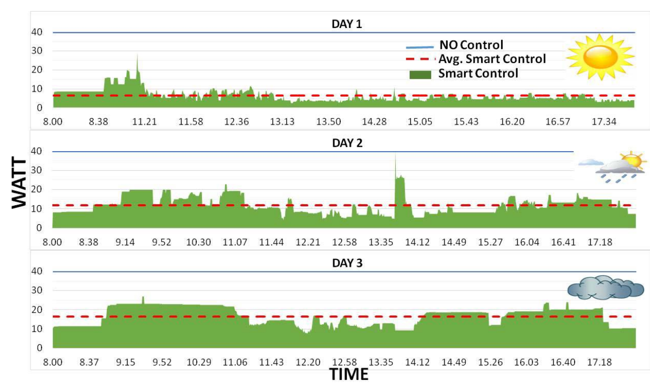

Fig. 11. Average power consumption measured in three different weather condition day on 20 panels of 40W each.

A. Power Measurements

The first step to evaluate the energy saving achievable with our approach was to understand the power consumption reduction dimming a panel, Figure 10 shows the characteristic of power consumption/dimming of each LED panel which include the consumption of driver as well. As explained earlier, the microcontroller sets different PWM signals for the brightness of the panel. The characteristic of the panel was measured directly with an AC power meter changing smoothly the PWM signal at step of 1%. This data shows the importance of the dimming not to waste energy as it is possible to save up to 99% of power by just dimming the light. The characteristic shows also the limit of the driver to smooth the light down to more than 87% of PWM. Below this value the panel is switched off so no light is provided. During the tests, several commercial drivers from different producers were evaluated and the selected driver LPF-40D-42 was the one with the best performance in terms of range (0-87%) and accuracy of constant current in output (useful to guarantee long LED panel lifetime). In order to evaluate the ultra-low power consumption due to the extra hardware needed to add the smart light wireless control of our approach, the end device and routers power consumption were measured in several states.

Table I shows the wireless nodes' current consumption (End Device and router) with 5V power supply. Measurement of the wireless sensor's power consumption was performed, setting the clock of the MCU at 1MHz, and assuming the node can be in one of the three configurations shown in the table. The maximum power consumption due to the new hardware is 100mW. This is a negligible consumption compared to the power saving. In fact, as Figure 10 shows with a dimming of only 20% the system is saving already around 20W. Moreover the ED has two power saving modes to save energy, one is switching the radio ON periodically according to the Zigbee stack to reach only 0.500mW; the second one is manually switched off by the user. The power supply of the ED is associated with the power supply of the LED panel so when the user switches off the Panel the node will consume zero in this case.

B. Power Saving Evaluation

To evaluate the proposed system in terms of power saving a real office was used as testbed. Four separated groups of 5 LED panels each were controlled by four routers. The user preference was set to 600Lux, a common value to have good quality of light. The network was run continuously for 6 months and the coordinator saved all the states of the PWM signal of each ED. Thanks to the characteristic of the panel in Figure 10 it is possible to know the instantaneous power of each panel during the day and night. Figure 11 shows the average power saving and consumption of three days from 8am to 18pm (during the open time of the office) for all the 20 panels to evaluate the benefits in terms of power saving and the influence of the weather conditions. The data were compared with an office scenario without the smart control and the Zigbee network. Without the smart control the average power consumption of each panel is 40W, as all the panels are fully on to the max power during the time office. The

TABLE II
POWER SAVING MEASURMENT COLLECTED DURING SIX DAYS

TESTS RESULT (average for each day)						
GROUP	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY 6
BOX OFFICE 1	44% power saving	33% power saving	59% power saving	85% power saving	15% power saving	25% power saving
BOX OFFICE 2	37% power saving	52% power saving	37% power saving	68% power saving	10% power saving	22% power saving
MEETINGROOM	12% power saving	33% power saving	33% power saving	65% power saving	12% power saving	33% power saving
SHOWROOM	72% power saving	90% power saving	52% power saving	72% power saving	44% power saving	52% power saving

TOTAL AVERAGE POWER SAVING	43 %

TABLE III
POWER SAVING IN TWO WEEKS IN MAY 2014 AND DECEMBER 2014

	May 2014			December 2013		
Day	Average Power [W]	Avg. Power [%]	Power Saved [%]	Average Power [W]	Avg Power [%]	Power Saved [%]
1	15,3	38%	62%	22,3	56%	44%
2	12,4	31%	69%	26,4	66%	34%
3	6,5	16%	84%	27,5	69%	31%
4	14,3	36%	64%	19,2	48%	52%
5	14,7	37%	63%	20,5	51%	49%
6	9,8	25%	75%	17,5	44%	75%
7	16,3	41%	59%	16,2	41%	60%
8	4,8	12%	88%	17,8	45%	56%
9	10,7	27%	73%	18,9	47%	53%
10	11,3	28%	72%	29,5	74%	26%
11	14,3	36%	64%	25,8	65%	36%
12	11,8	30%	70%	18,5	46%	70%
13	12,8	32%	68%	21,3	53%	47%
14	16,6	42%	58%	19,6	49%	58%
	12,3	31%	69%	21,5	54%	46%

Average power of each panel calculated on 20 panels, 40W each.

power consumption of 40W is the power consumption without the wireless control system and takes into count only the power of LED driver and the LED panel. As we presented in previous sections when the smart control is active, the panels are dimmed according to the user preference, the brightness in the room and the motion detection sensor. The figure shows the average power consumption of each panel during three different days with 3 different weather conditions. This power was evaluated as total power measured to supply the entire panels divided by the number of the panels. The three plots shows the influence of the weather conditions and the power saving. In fact, the average power consumption is only 9W against the 40W in a sunny condition, while it is 12W in variable conditions and 17.5W in cloudy conditions.

TABLE II shows the power saving during six day for all the areas of the office. This table shows how the power saving is affected by the external light and the presence of the people in the room. For example, the day 5 was cloudy so the external light brightness was not very high then the power saving is much lower. Moreover the showroom is the least used room in the office as there is not a stable/regular presence of people inside so the power saving is always higher there. These results show how important it is to have different group of lights controlled by separate routers to have a more efficient control and power saving. Finally taking into account only the 6 days for space reason, the overall energy saved was around 43% due to the proposed approach compared with the same deployment without it. This value does not take into account the night period, supposing the user is always reminded to switch off the office lights or lights being switched off due to inactivity. Another important parameter is the achieved power savings according to different periods of the year.

TABLE III presents the average power consumption of the each of the 20 panels. The data was acquired during 2 weeks in December 2013, when the deployment started and during 2 weeks of May 2014. The table shows how each day the power saving changes according to the weather condition and also that the average power consumption in December was much higher than in May. This is due mainly to the worse weather conditions and the lower sun light hours in winter with respect to the spring.

Finally, in order to evaluate better the benefit of the proposed approach, data of power consumption in-field for long period has been acquired. At the time the paper has been written the system has been running without any interruption in that office for 6 months from December 2013 to May 2014. The average energy saving in this period was around 55%. It is estimated that the power saving will be higher during a full year as in spring and summer the day light will decrease the average usage of the panel and the smart light system will be optimize the dimming level to minimize the waste of energy. Concering the low cost, in the proposed solution all the parts were evaluated in terms of production cost for a volume of 10000 units. For this not so high volume the system costs 200$ for the cordination and base station, 50$ for the sensors' node, and only 15$ for the end devices, which has to be connected to the LED Driver. TABLE IV shows a comparsion with the most popular light control system and highlights the significantly lower cost of the proposed solution.

VI. CONCLUSION AND FUTURE WORK

A novel system to control LED lighting with a low cost and low power wireless sensor network has been proposed. The

TABLE IV
COST COMPARISON OF DIFFERENT CONTROLLING SYSTEM

	DEVICES		
SYSTEM	**BASE SATION**	**SENSORS DEVICES**	**CONTROL DEVICES**
KNX [27]	3000-6000	200-500	100-200
REDWOOD[28]	1500-2000	150-300	70-100
LUTRON [29]	900-1000	150	100
EYENUT [30]	1000-3000	50-500	50-100
THIS SOLUTION	**200**	**50**	**20**

method requires the deployment of complementary sensors with Zigbee radio that generate a PWM signal to control existing commercial LED drivers, which can significantly reduce the power consumption of the LED lighting. The use of a light sensor and a PIR sensor in combination with the user preferences allows the distributed intelligence to save energy reducing the light intensity. Because many fixtures of LED lights are already placed, this solution is also suitable for retrofitting. Moreover the network is flexible and scalable due to the Zigbee radio. Experimental results indicate that the proposed system outperforms the state-of-the-art with a significant reduction of power consumption and cost for the single and groups of LED lights using the low power, scalable WSN. It has been shown that this approach decreases the power consumption in a real life office application by more than 55% throughout 6 months (in an unpredictable Irish weather scenario). The prototypes are ready to be inserted in a commercial driver to enable wireless capability and distributed control.

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