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Smart LED Light Control using wireless sensor network for green building

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Abstract:

In lights account for a great portion of total energy consumption ,and unfortunately a huge amount of this energy is The most waste of energy comes from the inefficient use of the electrical energy consumed by artificial light devices (lamps or light bulbs).Light emitting diode(LED) lights are being used to light offices, houses, industrial, or agricultural facilities more efficiently than old-fashioned lights. This paper presents a system with detailed design for saving electrical energy by directing the power of artificial light to a acceptable level and getting use of the day light when possible with the best effort for energy saving. However, due to high costs, installation issues, and difficulty of conservation existing light control systems are not effectively applied to home, office, and industrial buildings. This paper offers a low cost, wireless, easy to install, flexible, and smart LED lighting system to automatically adjust the light intensity to save energy and continuing user satisfaction.

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 withenergy consumption, these originated from the combustionof hydrocarbons (oil, natural gas and coal) either directlyseared (transportation and heating) or for generation of electricityin power plants [1]. Lighting systems are a main sourceof energy consumption in the world. In Europe, theamount of electrical drive used in informative buildings isconsiderable, about 40% and leads to approximately 35% of carbon dioxide emissions [2]. In recent years the EuropeanUnion EU has actively promoted political campaigns towardenergy efficiency. While earlier research and industrializedworks 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

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lighting control approaches have the potential to achieve even greater energy savings, better quality of service and offer many benefits over simpleon/off controls. However, until present, advanced control strategies, such as dimming light according to the day light or load cracking, which require a more systems-oriented approach, have been less successful. This is specially dueto the high cost of connection and maintenance and theimpossibility of retrofitting [3].On the technical side, Light Emitting Diode (LED) israpidly becoming a commonly used solid-state light sourceequipment in general lighting applications. This is due toits longer period, reduced power consumption, and havingno toxin mercury content compared with the conservative eluminous lamps [4], [5]. In addition, dimming control isoften needed to regulate clarification levels for individual humanneeds or preference as well as to achieve energy savings.New driver systems are improving the dimmable features to complete this goal and are gradually commercially available.

This new technology is growing interest in controlling thelight to reduce power utilization. The market for lightingcontrols in residential and commercial buildings has arriveda period of affectedconversion. The demand for bothwireless and local controls, such as use sensors, photosensors;and networked controls rises, and the acceptanceratio ofthe LED lighting systems begins to mount as well. Accordingto a new report from Navigant Research, worldwide incomefrom networked lighting controls will grow from $1.7 billionannually in 2013 to more than $5.3 billion by 2020 [6].With the advance of wireless sensor network (WSN) knowledge,it is now easier than ever to monitor and controlhouses, offices and industrial buildings. WSN is thesupportof a large diversity of cyber-physical systems (CPS)applications in environmental monitoring, healthcare, security, and industrial fields, among others, due to the flexibledelivery of WSN devices [7].The contributions of this paper are as follows:

• A procedure for deploying low power sensor networksto improve the power consumption of LED lights usingnovel, ultra-low power hardware architecture and smart distributed algorithm. The concept of using light sensorsand WSN in LED control is not new, however using it directly control a LED driver with distributed intellectand allowing retrofit is a new contribution.

• Experimental authentication of the proposed approach. Thepower consumption classification of panels accordingto the dimming and the average energy reduction in areal-life, long-term deployment is presented.

II. RELATED WORK

Research on monitoring, control and power efficiency inthe lighting domain has been productive in recent years; with avariety of solutions and techniqueplanned. The two mainapproaches are given by wired and wireless systems. Wiredconvenient lighting systems can determine the artificial anddaylight explanation through the use of sensors in a controllerarea network [12] or a set of data logger devices [13] to modifythe light intensity and hence its energy consumption. However,due to the incidence of bundles of cable to perform datacommunication the wired devices are much more costly, speciallydue to the installation and maintenance. Moreover

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thewired system is limited to retrofitting the existing light systemin buildings. To overcome this installation cost and issues,wireless technology has become a more popular alternative onthe demand-side energy management, monitoring and controlin buildings. WSN is the enable technology for
buildingenergy control as it is much easier and flexible to installand execute than wired networks. By using the combinationof complex WSN-based controls and DC grid poweredLED lighting systems, the advantages features generatedfrom this mutual technology should lead to greater

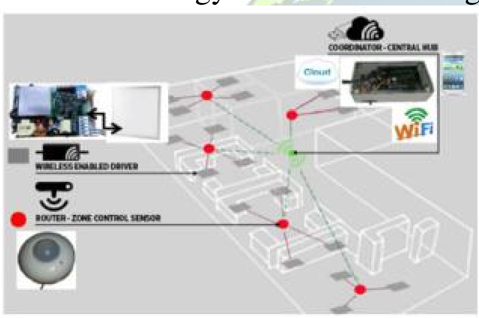

Fig. 1. Typical application scenario of Smart Lighting with the topologies of devices used: i) Coordinator of network connected to a host device; ii) Router to monitor the enviroment with light and motion sensors; and End Device connected to the pannel to adapt the light intensity to save energy achiving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

energysavings at the demand-side of the green smart building [14].Recently, wireless sensor networks have been appliedto energy protection applications such as lightcontrol [15], [16]. In [16], a trade-off between power consumption and users' satisfaction using light control was studied. The author applied utility functions whichconsidered users' location and lighting preferences so that clarification could be adjusted as to maximize the total utilities. In these previousworks, lighting devices are adjusted depending on ambient daylight strength and/or motion sensors. This approach is theoretically similar to the proposed system. However ourwork presents ainclusive, long term (over 6 months)in-field evaluation of power savings, during several seasonsand weather conditions. Moreover the control algorithm is notexplained in [19] and it is not possible know if the algorithmuses distributed or local decision making. Finally in [19] thereis no data about the power consumption of the wireless systemand its associated cost.

III. DEVICES AND METHODS

It consists of groups of LED panels managedby multiple sensors (motion and light) and distributedintelligence. The nodes PWM signal is used to encode the level of the LEDbrightness with the width of the pulse (duration) of microcontrollersignal as explained better in next subsection. Thevalue of the PWM is decided by a control unit, given byone of the distributed routers provided with sensors. Eachrouter uses the sensors' data to adapt the intensity accordingwith the user's preferences with the goal of maximizing theenergy saving and users' preferences. The Zigbee network ina mesh configuration permits building a scalable and modularsystem easily extendable, and allows each sub group of lights to be completely independent and flexible in terms of areamonitored/controlled. In fact, each router has a flexible andcontrollable number of associated ED's and LED panels,which it can control under the same conditions. This allowshaving different areas with different controls in order toincrease the power saving driven by users' preference.The whole network is managed by one supervision unit, theZigbee coordinator that both manages the network and ensuresthat all network devices are working properly. Furthermorethis unit

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works as a gateway with a remote host (laptop,wall embedded devices, Wireless Lan/Bluetooth devices, andso on), to enable human interaction. Thus, it is possibleboth to acquire users' preferences to adapt the dimming ofthe lights in desirable values and to enable a graphical userinterface for the management and for visualizing the energysaving data for each group of LEDs or single device. Thisis an important feature as the percentage of energy savingsdepends on several factors but the most important is the users'preference, and the user can evaluate this graphically. Otherimport factors affecting the power saving are the positionof each group of panels, i.e. a room with a big windowssouth facing saves more energy than a basement, the weatherconditions, season, geographical location, etc.The primary objective of the proposed approach is to reducethe power consumption of a generic (and also existing) LEDlight system using a flexible network deployed in the sametarget field reducing cost of installation and

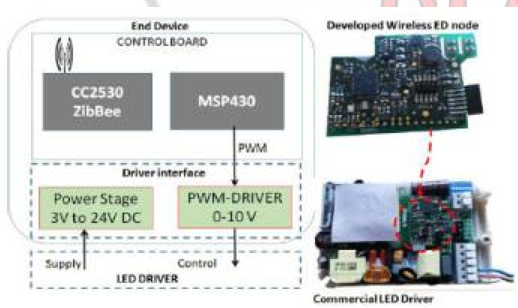

Fig. 2. End Device architecture and node developed to be plugged directly in a commercial driver to control and be supplied.

guaranteeing smart and green buildings with and high return of the investment savingenergy. In this work, all the devices needed for the network were designed, developed and deployed in the field around theCC2530 chip from Instruments (TI). This chip supports theZigbeePRO stack solution, with a small form factor andsufficient 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 CC2530which is in charge of the whole communication and theZigbee 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 portduring the deployment, to be interfaced with the remote hostand no more external hardware is required for networking. Therouter is equipped with sensors to monitor the controlled areawhile the end device is interfaced with the commercial lightdriver.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 ZigBeeand is present in each node of the network;
- The MSP430 for the control of the LED panels' smoothingand where the distributed intelligence is implemented.MSP430 is present in all the nodes;
- A dimmable commercial driver for the LED, whichprovides a highly dimmable range (up to 89%) and inaccurate control (constant current) for the smoothing.
- A light and PIR sensors, used by the router to monitorand control the brightness value.

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

A. Wireless Driver Device.

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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 This chip has a very low quiescent current with high conversion efficiency and it is optimized specifically forth MPS430.Fig. 3. Router Architecture.PWM to Driver Block in Figure 2 is the most important partof the end device and it is needed to convert the PWM signal generated from the microcontroller in a 0-10V signal neededto control the commercial LED driver. The 0-10V control isone of the earliest and simplest electronic lighting control signaling systems and it is included in the most commercialdrivers. Due to this interface the node can be adaptable to awide rangeof commercial drivers with the 0-10V port, andcan 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 signalof microcontroller and the 0-10V driver's input. For the enddevices, we do not have any sensors on board as the PWMvalue is decided from the router which controls more thanone device in the same group and it will be presented in nextsubsection. This has the benefit to bringing flexibility in thedeployment 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 workloadin the network with the following main duties: i) managethe routing protocol of the Zigbee stack, monitoring theenvironmental parameters throughout the sensors, ii) take thedecision on the light intensity, and iii) send the controlconfiguration to the panels that are assigned under its controlduring the network configuration. Figure 3 shows the hardwarearchitecture of the router node, which is very similar to theend device, where instead of the PWM driver control thereis the infrared sensor (PIR) block. This block includes thesensor and its coupling circuit which generates an interruptwhen an object moves in the filed of view. The PIR usedis the Panasonic EW - AMN34111J which guarantees a fastand accurate interrupt for any moving object in the range of 10m.

C. Wireless Sensor Network

One of primary goals in designing the proposed systemwas the scalability, the low power and a standardized networkfor commercial application. ZigBee is a wireless communicationtechnology based on the IEEE802.15.4 standard forcommunication among multiple devices in a wireless personalarea network (WPAN). The ZigBee alliance has developedlow-cost, low power consumption, wireless communicationstandard, and the CC2530 chipset was chosen. Therefore, thisstandard is designed to be more affordable than other WPANs(Wi-Fi or Bluetooth) for developing low power embedded systemsfor consumer electronics, home and building automation,industrial controls, PC peripherals, medical sensor application,toys and games. The ZigBee architecture is made up of aset of blocks called layers; each layer

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performs a specific setof services for the layer above.

IV. LIGHTING CONTROL ALGORITHM

As it was presented in the previous section there are threedifferent devices which need three different algorithms towork properly. The network software is a critical part of thesystem (Figure 7 and Figure 8). The Z-STACK from TI wasused 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. Themain task of the network management is to receive and set theright brightness for the LED panel (Figure 7). Thus, after thedevice joins the network, a router is associated to it. From thisinstant it waits for the PWM value decided from the router'sown algorithm and sets the LED light intensity of the panel.After the value is set, the radio goes into standby mode forenergy saving. The wake up time to get a new luminosity value can be selected by the user as this affects the responsetime, in the proposed approach 500ms was selected, since itis a good trade-off between power saving and reactivity. Thissimple procedure with the above mentioned hardware allows every commercial driver to be controlled through a standardZigbee network.

B. Router and Control Algorithm

The router algorithm is somewhat more complex than forthe end device. The core of smart lighting intelligence isdistributed to each router which then controls one or more end devices. To achieve this important goal, the router has asmain blocks, the communication and control algorithm on it.The communication block is in charge of receiving datafrom the network about the user's preferences and send dataabout the status of the controlled panels to the remote host.As the network is a mesh, the information can hop to other routers before reaching the coordinator which monitors thestatus of the panels and manages the errors.Figure 5 shows the control algorithm

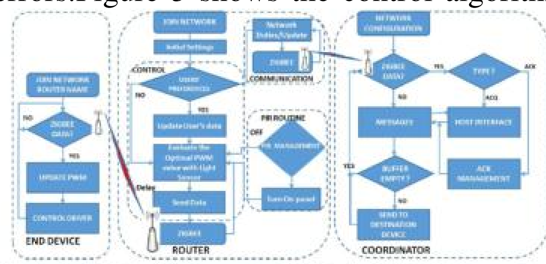

Fig. 5. Flow charts of the three devices. The Network management is not included in the flow chart and the Z-STACK from TI library were used to work with the ZigbeePRO protocol.

```
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.

running on the sensornode device. The control algorithm is the core of the smartlighting application setting the dimming value of the panel.To achieve this goal the microcontroller acquires the lightsensor data through the ADC port containing the brightnessof the room. The purpose of this measurement is to ensure an optimal level of illumination in the room according to the userpreferences and existing standards for lighting. For our deployment a conservative value of45minutes was chosen during the office time 8am-6pm, and 5minutes outside this time interval. As it will be presentedin the experimental results section, the deployment in a realoffice was active for a continuous 6

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months period with fulluser satisfaction who did not notice any difference with thetraditional system without the smart control.

C. Coordinator Algorithm

The main role of the coordinator, over setup and control ofthe Zigbee WSN, is to connect the wireless devices deployedin the building with a remote host which provides the userinterface. The coordinator also sends the user preferencesto the routers and collects the status information from therouters to store the monitored status in a remote database. The communication is done through the UART port of themicrocontroller and the UART to USB converter that allows

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

connecting the dongle to every host with an USB interface.Thus, the coordinator works as a gateway and it is required fora graphical display of the results and user input. Furthermore, data on wireless device operations are associated with theLEDs light address; consequently, all faults and the state areeasily identified.The graphical interface enables monitoring the state of thesystem with the state of the lights and the power consumptionof each controlled LED light (individual energy consumptionmeter) Figure 4. As the host interface also stores the dimmingvalue of all the panels the user or network manager can have an overlook of the power consumption and working time ofevery panel in a graphical vision. The program is also equippedwith a management system that acts in case of no acknowledgementsare sent from the panel to highlight the errors.

V. EXPERIMENTAL RESULTS

All prototypes have been developed, tested and deployed invariable real-life conditions to verify the overall functionality,the scalability and the robustness of the network and seek better performance. This section describes an experimentalevaluation of the. Evaluation of the power savingenergy of a commercial LED panel VER-P6060-43-840 fromVerdeLED with the dimmable driver LPF-40D-42 from MeanWell is presented. Secondly, the section presents power consumptionmeasurements done during 6 months of continuouswork in the company office where the smart lighting systemwas 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 whileFigure 1 shows the floor plan and where the sensor nodeswere placed. In this implementation, 25 wireless devices weredirectly connected to the power supply of LED panels, so ispossible to cover the whole office presented in

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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

Figure 1. TheZigbee network has been deployed in an office together with 2 Wi-Fi internet access points and several users' phones andPC connected to the access points. Under these conditions thesystem was working for 6 months without any interruptionshowing a high robustness to Wi-Fi interferences.The positioning of panels and sensors was done with apreliminary analysis on solar irradiation within the office as explained in interruption of services.

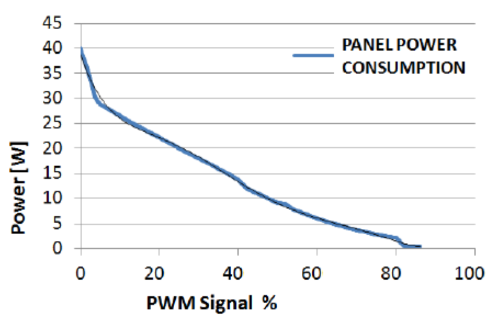

Fig. 10. LED panel + LED driver power consumption according to the the PWM signal of the microcontroller.

A. Power Measurements

The first step to evaluate the energy saving achievablewith our approach was to understand the power consumptionreduction dimming a panel, Figure 10 shows the characteristic of power consumption/dimming of each LED panel whichinclude the consumption of driver as well. As explained earlier, the microcontroller sets different PWM signals forthe brightness of the panel. The characteristic of the panelwas measured directly with an AC power meter changingsmoothly the PWM signal at step of 1%. This data showsthe importance of the dimming not to waste energy as it ispossible to save up to 99% of power by just dimming thelight. The characteristic shows also the limit of the driver tosmooth the light down to more than 87% of PWM. Below thisvalue 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 theone with the best performance in terms of range (0-87%) and accuracy of constant current in output (useful to guarantee longLED panel lifetime). In order to evaluate the ultra-low powerconsumption due to the extra hardware needed to add the smartlight wireless control of our approach, the end device androuters power consumption were measured in several states.Table I shows the wireless nodes' current consumption (EndDevice and router) with 5V power supply. Measurement of thewireless sensor's power consumption was performed, settingthe clock of the MCU at 1MHz, and assuming the node canbe in one of the three configurations shown in the table.The maximum power consumption due to the new hardwareis 100mW. This is a negligible consumption compared to thepower saving.

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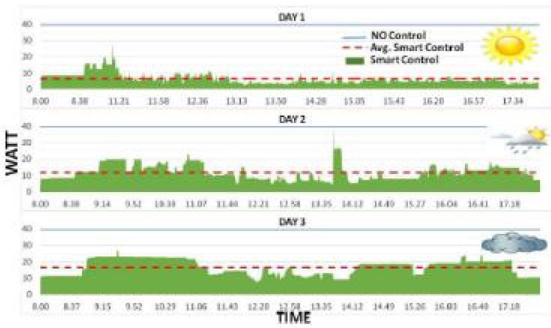
consume zero inthis case.



B. Power Saving Evaluation

To evaluate the proposed system in terms of power savinga real office was used as testbed. Four separated groups of5 LED panels each were controlled by four routers. Theuser preference was set to 600Lux, a common value to havegood quality of light. The network was run continuously for6 months and the coordinator saved all the states of the PWMsignal of each ED. Thanks to the characteristic of the panelin Figure 10 it is possible to know the instantaneous powerof each panel during the day and night. The data werecompared with an office scenario without the smart controland the Zigbee network. Without the smart control the averagepower consumption of each panel is 40W, as all the panelsare fully on to the max power during the time office. The power consumption of 40W is the power consumption withoutthe wireless control system and takes into count only the power of LED driver and the LED panel. As we presented inprevious sections when the smart control is active, the panelsare dimmed according to the user preference, the brightness in the room and

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 %

the motion detection sensor. The figure showsthe average power consumption of each panel during threedifferent days with 3 different weather conditions. This power was evaluated as total power measured to supply the entirepanels divided by the number of the panels. The three plots shows the influence of the weather conditions and the powersaving. In fact, the average power consumption is only 9Wagainst the 40W in a sunny condition, while it is 12W invariable conditions and 17.5W in cloudy conditions.TABLE II shows the power saving during six day for all thereas of the office. This table shows how the power saving isaffected by the external light and the presence of the people inthe room. For example, the day 5 was cloudy so the externallight brightness was not very high then the power saving ismuch lower. Moreover the showroom is the least used roomin the office as there is not a stable/regular presence of peopleinside so the power saving is always higher there. These resultshow how important it is to have

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different group of lightscontrolled by separate routers to have a more efficient control and power saving. Finally taking into account only the 6 daysfor space reason, the overall energy saved was around 43% dueto the proposed approach compared with the same deployment without it. This value does not take into account the nightperiod, supposing the user is always reminded to switch offthe office lights or lights being switched off due to inactivity. Another important parameter is the achieved power savingsaccording to different periods of the year.

.VI. CONCLUSION AND FUTURE WORK

A novel system to control LED lighting with a low cost andlow power wireless sensor network has been proposed. The method requires the deployment of complementary sensorswith Zigbee radio that generate a PWM signal to controlexisting commercial LED drivers, which can significantlyreduce the power consumption of the LED lighting. The use of a light sensor and a PIR sensor in combination with theuser preferences allows the distributed intelligence to saveenergy reducing the light intensity. Because many fixtures ofLED lights are already placed, this solution is also suitablefor retrofitting. Moreover the network is flexible and scalabledue to the Zigbee radio. Experimental results indicate thatthe proposed system outperforms the state-of-the-art witha significant reduction of power consumption and cost forthe single and groups of LED lights using the low power,scalable WSN. It has been shown that this approach decreasesthe power consumption in a real life office application bymore than 55% throughout 6 months (in an unpredictable Irishweather scenario). The prototypes are ready to be inserted in acommercial driver to enable wireless capability and distributedcontrol.

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