Smart LED Lights Control Using Nano-Power Wake Up Radios

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Abstract. Wireless sensor networks (WSNs) are widely employed today in real world applications. Smart homes and smart cities are the most promising application currently exploiting WSN. Smart lighting with WSN in particular is promising to achieve a low cost, wireless, easily installed, adaptable system to automatically adjust the light intensity of LED panels, with the aim of saving energy and maintaining user satisfaction. However, lifetime and power consumption of wireless devices are still the most critical challenge that limits the success of this technology. This issue is especially critical when wireless sensor nodes are powered by limited energy storage devices (i.e. small batteries or supercaps). To overcome this issue, major research efforts focus on reducing power consumption, particularly communication, as the radio transceiver is one of the highest power consumers. In this work we present the design and development of a highly efficient wireless system targeting indoor control of lights using ultra low power wake up radio technology. Thanks to the wake up radio the energy efficiency of the communication is improved and this significantly increases the lifetime of the solution. We design the sensor and control devices for a smart light controlling system that can be retrofitted and maintain a long lifetime even when supplied by batteries. Measurements of current and power consumption of both the designed system confirm the ultra-low power of the nodes and the benefits to use the energy efficient power communication implemented with the wake up radio.

Keywords: Sensors network · Energy harvesting · Power management · Smart devices · Light control · LED system

1 Introduction

Today residential lighting systems represents one of the most energy consumption item in buildings even with modern lighting solutions. This is confirmed by a recent study that claims that 25% of energy consumption in residential and commercial buildings in United States of America is spent to supply lights [1]. In recent years, the trend for academic and industrial research is to try to reduce lights energy consumption and many results has been achieved (i.e. introducing LED lights instead of fluorescent light). However, there is still a lot of room to further improve the energy efficiency, especially reducing the energy waste. Thus, a lot of effort has been invested in autonomous system with distributed intelligence. This effort results in many solution

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that uses sensors and wireless communication to minimize the energy waste (i.e. switching off the light when nobody is around). In the previous solutions, the main aim was try to improve the system from an energy efficiency point of view, often without caring of the users' comfort (i.e. light switched off also if the user is inside). However, users' comfort has an enormous impact on human mood and it for example in working environment an reduce the employees' productivity, creating less than optimal working conditions, especially for focus intensive, problem-solving activities. Thus, new challenges in energy efficiency need to consider that lights do not just illuminate a building, but they affect also the mood and efficiency of users and eventually improve their sense of comfort [1].

New advance in technology, i.e. Wireless Sensors Networks (WSN), can bring improvements also to lighting solution. WSN is a popular technology that cover a wide range of applications from structural health monitoring to health care, from building and home automation to agriculture monitoring, and many other [6–11]. WSN are well-know to cover a large number of application as well as they are well known to suffer of limited lifetime when they are supplied by batteries. The most power hungry subsystem of a WSN device is typically the radio transceiver. For this reason, one of the most effective way to improve the lifetime is improve the energy efficiency of the communication. As well documented in literature, it is possible reduce the power consumption of the radio with adaptive duty cycling that limit the radio activity turning periodically the radio on ("idle listening or transmitting mode") and off ("power save mode") [1]. On one hand, duty-cycling is the most popular technique to reduce the overall power consumption of the communication; on the other hand, duty cycling has to stringent drawbacks: the radio still consumes power to listen the medium periodically also when there is no message for the receiver (called idle-listening). In the period where the radio is switched off, it is not possible receive messages, so it is important evaluated the latency of the communication and evaluate the trade-off between the reactiveness of the communication and energy saved. In fact, as it is obvious, more the radio stays in power save mode, more it is the power saved, however the communication latency will be increased. To overcome these two drawbacks, asynchronous communication has been investigated and it is recently raising a lot of interest. With the recent asynchronous techniques it is possible achieve energy efficient communication never achieved before [1] and this makes asynchronous an emerging technology in energy efficient communication. This is due to the fact, that with asynchronous mechanisms both the energy wasted for the idle-listening energy waste is eliminated and the latency of communication the communication is improved. Today, many protocols are exploiting wake-up radios (WUR) to achieve pure-asynchronous communication in WSN [2]. WUR are ultra-low power radios, in the order of microwatts or even nano-watts, which are always on listening the radio channels ready to receive short messages [3]. WUR are usually working in combination with main transceiver or more rarely are used alone or integrated into the transceiver self. The ultra-low power feature of the WUR allows the main radio and rest of the node to go into a sleep mode (consuming significantly less), however, the whole system can be woken up by the WUR using interrupts only when radio messages, called often wake up beacons, are received. Although only few years ago, wake up radio was a simple receiver to trigger when "something" was detected on the medium, today they are becoming more complex system with computational capability to process messages to implement part of the medium access protocols [4]. In this paper, we present the design and implementation of a micro-power wake up radio receiver that embeds an ultra-low System on Chip (SoC) with an integrated transmitter. Due to the presence of the SoC, the WUR can efficiently process the received data (i.e. enabling the addressing), implement part of the MAC directly on the WUR and eventually retransmit information without waking up the main radio. The designed wake up radio has been implemented and evaluated in-field in terms of power consumption, sensitivity and range.

In this work, we present a solution that exploits the ultra-low power nature of WUR and the transmission with On Off Keying modulation to achieve energy efficient communication. We designed and developed a smart light system where the two main devices have the WUR as a communication subsystem. The developed system has been implemented and developed in field to evaluate the solution's functionality and lifetime when the sensor node is supplied by batteries. In fact, the main goal of the proposed solution is to allow the designed devices to be supplied with long-lifetime Li-Ion batteries (i.e. several months or even years).

The remainder of this paper is organized as follows: Sect. 2 presents recent related work in the area. Section 3 presents the smart lighting proposed approach, describing the communication protocol and the developed nodes. Section 4 describes the experimental results including a comparative evaluation with the ZigBee network and Sect. 5 concludes the paper.

2 Related Works

Controlling lighting applications has been a widely explored topic in the last decade and many solutions have been presented in literature from academic and industrial researchers. Many commercial solutions are using wired systems that control the monitored area to increase the energy efficiency of the building [22]. The main drawback of the wired solutions is the high cost of the installation and the limited capability to retrofit existing lights in buildings. For this reason, wireless technology is increasingly used as a solution for demand-side energy management, monitoring and control in buildings. Wireless sensor network 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 wireless control systems and the energy efficiency of the LED lights, it is now possible to achieve a more energy efficient building [23]. WSN have recently been successfully applied to improving energy efficiency, especially controlling lights [1, 5]. Recently, WSNs were presented in many industrial and academic works that demonstrated how they can achieve better energy efficiency in light control applications for buildings [1, 2, 5, 13–20] or also for other application scenario [4, 6, 12]. The authors in [5] present an interesting study to evaluate the trade-off between the power consumption of building and the user satisfaction when a smart lighting system is used. In [5] the proposed solution the dimming and the switch on of the light is performed with the users' location to minimize the power consumption and to maximize the total utilities. However, the presented system has a fixed luminosity level for all the people and room, without take in count that the users need different light in different activities (i.e. cooking, reading, watching TV). In other previous work, the intelligent control for the light is done measuring the room-light intensity, using light-sensitive sensors [14]. This is a similar approach of our system and it demonstrate the benefits to use it in intelligent control. The authors in [15] present another interesting work where different users' requirements and cost functions are combined to maximize the overall energy efficient of the according to the cost of the energy. In [15] the results are demonstrated only for an entertainment and media production system rather than for lights in a building. A system baes on WSN to control the lights to improve the energy efficiency of the building is presented [16]. Unfortunately the authors did not give details of the control algorithm, especially it is not possible know if the system is base on centralized or distributed intelligence. It is interesting to notice that all these previous works demonstrate the benefits to use motion sensors and lights sensors to adjust the automatically the luminosity of the light in order to save energy in buildings. This is the approach that is to the base of our solution.

The previous literature showed several example of wireless sensors networks to lighting building control. One of main challenge when WSN are designed is to their energy consumption to achieve long-lifetime. In the recent years, many solutions have been proposed to improve the energy efficiency of the communication. Between others wake up radios shows impressive results in energy efficiency. Design of wake up radio that achieve high sensitivity (−55 dBm) with low power (nanoWatts) are presented in the following works [3, 21, 24, 25]. Other recent works [26, 27] show the benefits in terms of energy efficient when WUR are used in-field with optimized protocols.

In this paper, we focus on the development of an intelligent sensor network that achieves long-life time exploiting a novel wake up radio coupled with a SoC with a transceiver to improve the energy efficiency of the communication. The main features of the proposed design is the possibility to work years with a small battery, thus, to cut installation costs improving the flexibility. Our solution is also suitable for retrofitting existing light installations. In fact, the designed nodes have the capability to be supplied only with battery and then, they can be placed anywhere in the buildings to control the lights. The system includes also an automatic light control using an infrared sensor (PIR) and a light sensor, to improve both the building energy efficiency, dimming the lights in the optimal way, and increasing user satisfaction by allowing them to set users' preferences. In-field experimental results have been demonstrated that our wireless solution achieve low lower and long lifetime. We compared this novel solution with the results of a previous work [2]. The benefits of this solution in terms of building energy efficiency have been thoroughly demonstrated.

3 Smart Lighting Proposed Approach

The proposed wireless controlling system is shown in Fig. 1. The whole system is comprised of several groups of LED panels controlled by sensor nodes that embed both a pyroelectric infrared sensor and a light sensor. Both the *sensor nodes* and *driver nodes* have a wireless interface to exchange data and commands. In particular, each LED driver, which supplies the LED panel with DC current and controls the light

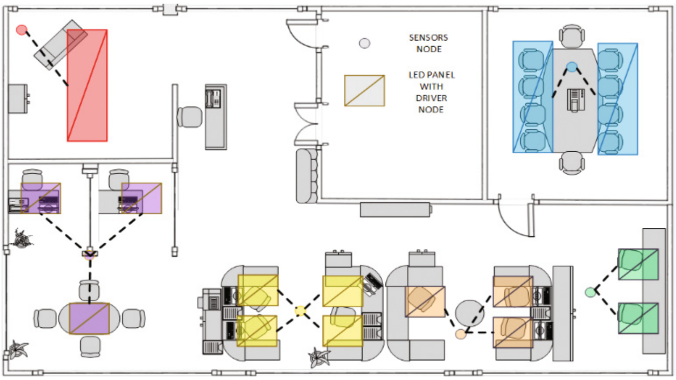

Fig. 1. Typical application scenario of smart lighting with the topologies of devices used: (i) coordinator of network connected to a host device; (ii) router to monitor the environment with light and motion sensors, (iii) end device connected to the panel to adapt the light intensity to save energy achieving the optimal level of brightness in the area.

intensity, is directly connected to a wireless *driver node*, designed in this work to provide the wireless interface. Figure 2 shows the power consumption measurement of a LED panel according to the dimming PWM signal to reduce the light intensity. As the figure shows, dimming the light can significantly reduce the power consumption of the LED panel and avoid energy waste if full light intensity is not needed. Thus, the *driver node* is directly connected to the LED driver through a pulse-width modulation (PWM) port. Using a PWM signal to encode the level of the LED brightness is the most common interface for commercial LED driver. In our solution, a microcontroller on the *driver node* sets the PWM value according to the command received by the *sensor node*; this is explained in more detail in next subsection. Due to the standard PWM, control port it is possible to retrofit many existing installations. On the other hand, each *sensor node* processes its sensor data on-board to evaluate the optimal intensity level according with the users' preferences. The main goal of the sensor node

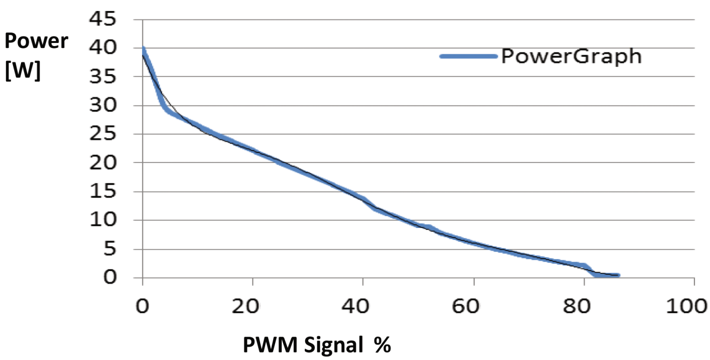

Fig. 2. Power consumption measurement of the PWM control signal to adapt the light intensity [2].

algorithm is to minimize the energy consumption of the LED panel by automatically adapting the light intensity to match the user preferences. The wireless interface allows the reduction of the installation costs and the deployment of the sensors node in the best position in the monitored area. This network configuration uses only two node topologies in various applications, which allows a scalable, extendable, and easy to deploy solution. In fact, each sub-group of LED panels is completely independent, and needs only a *sensor node* to control them. More precisely, each *sensor node* is able to control an adaptable number of associated *driver nodes* and LED panels. All the LED panels of the same subgroup can be controlled same conditions or with different luminosity according to the policy implemented on the *sensor node*. Due to this feature, it is possible to control different lights and areas with optimal intensity of lights according to the users' preferences. The entire systems can be managed by a higher-level super node that acts as a gateway connected to a PC or to another device (laptop, wall embedded devices, Wireless Lan/Bluetooth devices, and so on), to enable human interaction.

As in this work the primary goal is to build a system with devices that can achieve the best wireless communication efficiency to achieve long life time also when supplied by batteries, the two nodes topologies use an ultra-low power wake up radio technology. In next subsection, an overview of this technology and how the designed nodes exploit it to exchange data will be explained.

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

- The LED panel with a dimmable commercial driver that is able to be controlled trough a PWM signal.
- The wake up radio technology used as energy efficiency communication based on the PIR ultra low power microcontroller with transmission capability.
- Light and PIR sensors, used by the wireless sensor node to control the brightness and the movement in the area and decide the right dimming level.
- The wireless driver node that is connected with the commercial LED driver to set the dimming level of each LED panel.

In the following subsection the two nodes' architectures and the efficient communication are presented.

3.1 Wake Up Radio Technology for Energy Efficient Communication

The block diagram of the developed WUR is presented in Fig. 4. The node incorporate a wake up radio received and a transmission sub-system built around a system on chip (SoC) that has a radio transceiver integrated inside. The SoC is the main transmission block and it can also process the data received by the wake up radio. The whole node consists of three main sub-systems: (1) the receiving subsystem is basically a radio frequency (RF) front-end that demodulate the received data and generate an interrupt for the SoC when a data is received. (2) The processing subsystem (all around the SoC) that parses the received data. (3) The last sub-system is the transmitter that is also integrated into the SoC but it shares the antenna with the WUR trough a RF switch. The SoC is the core of the node allowing data processing directly on the WUR and makes

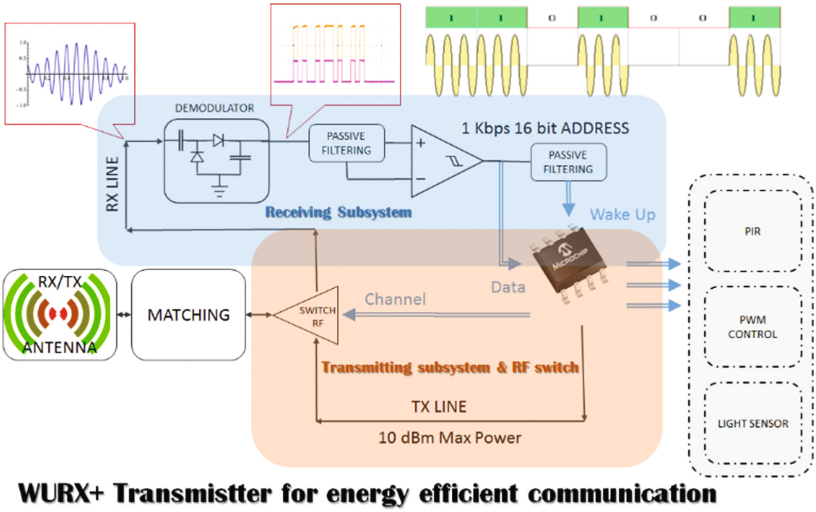

Fig. 3. Block diagram of the developed wake up radio with addressing and retransmission capability used as main block for both the wireless *sensor node* and the LED panel *driver node*

the decision and further actions. In fact, according to the protocol implemented it is possible to send: commands, wake up beacons, or addresses to only wake up the Main Node. With the computational capabilities of the microcontroller of the SoC is possible for a communication protocol to optimize the energy consumption (i.e. performing semantic addressing [21] to reduce the number of false positive wake ups (Fig. 3).

To achieve low power consumption the SoC has to consume very low power in sleep and active mode. For this reason, the Microchip PIC16LF1824T39 has been selected for the hardware implementation. This SoC has very low power consumption in low power mode of only 350 nW@1.8 V and in running mode achieve 80 μW at 1 MHz. The SoC integrates an 868 MHz transmitter so it is not needed to use other external chips and it is possible keep the power low. The power consumption in transmission (either using OOK or FSK modulation) is also very low compared with

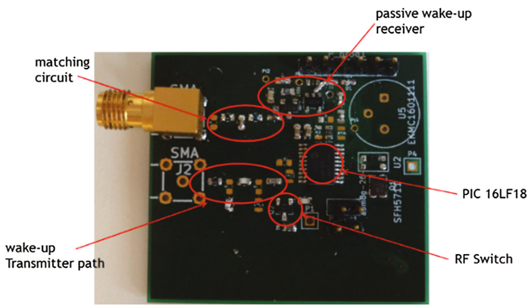

Fig. 4. Prototype of the wake up radio used for evaluations.

similar transmitter on the market. We measured a power consumption of only 20 mW@1.8 V when a message of 16 bit was transmitted with an output power of 0 dBm. Due to the presence of the transmitter, MAC protocols can leverage this novel WUR to acknowledge mechanism or support multi-hop communication.

The receiving subsystem works as a demodulator for on-off-keying (OOK) communication and it is based on a previous work [3, 21]. For this work, we tuned the implemented WUR at the 868 MHz of ISM band. One of most interesting feature of the WUR is its very low power consumption in always-mode. In fact, the power consumption measured was only 1.3 µW in our implementation, as the only active component is a low power comparator. As explained in [21] the comparator affects the sensitivity for our implementation we used a Texas Instruments LPV7215 that guarantees up to −55 dBm of sensitivity.

3.2 Wireless Sensor Node

The *wireless sensor node* has as its core the PIC microcontroller and the wake up radio presented in the previous subsystem. The main role of the sensor node is to take decisions on the light intensity using its sensor data, and to send the intensity level to each wireless driver under its control. The block diagram of the node architecture is presented in Fig. 5. The architecture includes an infrared sensor (PIR) and a light sensor which are directly interfaced with the PIC microcontroller. A Panasonic EW-AMN34111J has been selected to guarantee fast and accurate interrupt for any moving object in the range of 10 m. When a movement is detected the motion sensors generate an interrupt that is connected with a general purpose pin of the PIC microcontroller. On the other hand, the light sensor SSFH 5711 from Osram is connected to an Analog input of the PIC processor to detect the intensity of the light in the monitored area. The PIC evaluated both the

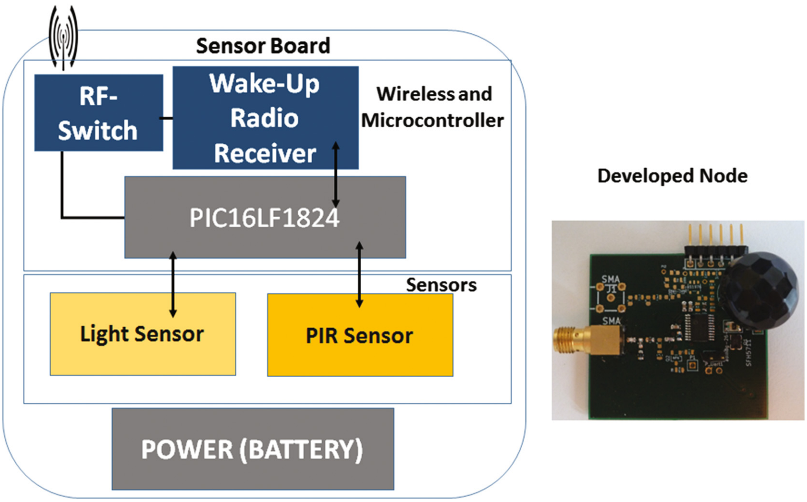

Fig. 5. Block diagram and developed wireless sensor node

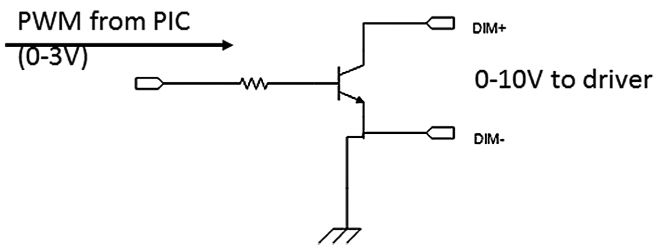

Fig. 6. Control circuits to convert PWM from PIC to 0–10 V for commercial drivers.

movement and the light intensity to decide the dimming level of its associated devices. If the dimming level is different from the previous one, the wireless node sends the new value via the integrated radio the OOK generated message to the *wireless driver nodes.*

3.3 Wireless Driver Node

The main goal of *wireless sensor node* is to provide an ultra-low power always-on wireless interface to receive the dimming level, and to control by PWM the driver LED when commands are received. The architecture of the wireless driver node is presented in Fig. 7. The *wireless sensor node* is designed to allow the power to be supplied by either commercial LED drivers or a battery. For this reason the power stage is able to cover a wide range of input voltage from 3 V to 42 V using an ultra-low power DC-DC converter which exploits the integrated circuit TLV70433 from Texas Instruments. Each designed *wireless node* can retrofit existing commercial LED drivers that are controlled by a PWM signal or be embedded inside the LED driver-self. Thus, each *wireless node* is associated with each LED panel and connected through the PWM port and eventually the power supply.

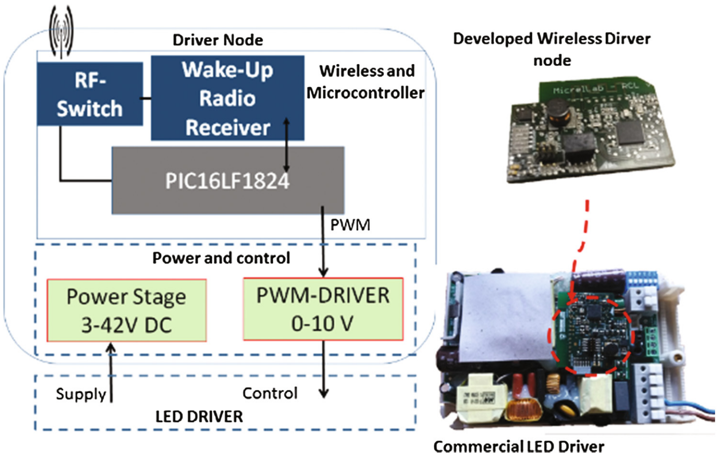

Fig. 7. Block diagram and developed control node.

The PWM-Driver block presented in figure is one of the most critical designed subsystems, as it converts the PWM signal from the microcontroller (1.8–3 V) to a 0–10 V signal needed to drive commercial LED panel drivers. In fact, the 0–10 V control is the standard control for such as driver and its support is mandatory for flexibility and retrofitting. In our solution, the design includes a P-MOS transistor that is connected in Common Collector configuration using the PWM signal from the microcontroller and 0–10 control input from the commercial driver (Fig. 6).

4 Experimental Results

The system has been designed, implemented and deployed in a real office testbed to evaluate the benefits in terms of energy saving. Both device topologies, *Wireless Sensor node and Wireless driver node,* were tested in terms of power consumption.

The current consumption of both designed and developed nodes in different states has been measured and are presented in Table 1. The supply voltage during the measurements was 3.7 V, typical for a Li-Ion battery, so the power consumption is taking into account the DC-DC conversion losses. In the experimental setup, we clocked the PIC microcontroller with 1 MHz, each node was in one of the three configurations presented in the following table. The table shows the very low quiescent current of only 4 µW and 0.5 mW of the sensor node and driver node respectively. The quiescent current also includes the power for the wake up radio, thus, both nodes can continuously listen the medium in this mode. As expected, the quiescent current of the sensor node is higher as this includes also the PIR sensor quiescent current and the circuits to generate an interrupt when movement is detected. Finally, the PIC in transmission has a much higher power consumption due to the activation of the radio to transmit the commands or other data.

Table 1. Nodes' current and power characteristics

Device/Mode	Consumption		
	State	Current	Power
Sensor node	PIC active and transmitting	19 mA	70 mW
	PIC active, Receiving by WUR	400 µA	1.4 mW
Driver node	PIC off, Waiting for interrupts from PIR or Wake-up radio	101 µA	375 µW
	PIC on, Radio TX, data processing	19 mA	70 mW
	PIC Active, Receiving in WUR	200 uA	1 mW
	PIC-off, Always active WUR	800 nA	4 uW

5 Conclusions

In this paper, we presented the design and implementation of ultra-low power sensors node to be employed in a smart lighting control system. The nodes are designed exploiting an ultra-low state-of-art power wake up radio technology that allow the nodes to receive messages consuming only few uW of power. Experimental results on the developed prototypes demonstrated the functionality of the nodes and the ultra-low power achieved. With this power consumption it is possible to achieve long lasting devices that can live continuously several years with small size batteries.

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