ENERGY-AUTONOMOUS WAKE-UP RECEIVER USING SOLAR PANEL AND VISIBLE LIGHT COMMUNICATION

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Resum

Els sistemes de comunicacions de wake-up representen una solució energèticament eficient i de baix cost per a la comunicació de dades de forma inal·làmbrica. En aquesta tesi, s'utilitza la comunicació amb llum visible (VLC) tant per a comunicacions de wake-up com per a recol·lecció d'energia. La primera part del document conté una introducció teòrica. A continuació, es presenta una avaluació dels diferents components, com ara panells solar i supercondensadors, que conformen el hardware del node receptor desenvolupat al llarg del document. Finalment, es presenten els resultats d'extenses proves de rendiment del sistema en diferents escenaris realistes. Aquests resultats inclouen la sensitivitat del sistema a diferents distàncies, angles i intensitats de llum, l'efecte de llums interferents i quantificacions de la capacitat de recol·lecció d'energia del receptor en diferents casos d'ús. En l'avaluació es demostra com el sistema de wake-up desenvolupat pot funcionar fins i tot autònomament, sense necessitat de cap bateria, gràcies al seu baix consum i capacitat de recol·lecció d'energia en la majoria dels escenaris d'oficina pel qual ha estat desenvolupat. Actualment, la principal aplicació del sistema de wake-up per llum visible són les xarxes de sensors sense fils.

Resumen

El uso de sistemas de comunicaciones de wake-ups es una solución potencial energéticamente eficiente y de bajo costo para la comunicación de datos. En esta tesis vamos un paso más allá, utilizando la luz visible tanto para comunicaciones de wake-ups como para propósitos de recolección de energía, con el objetivo final de desarrollar un módulo receptor de wake-ups energéticamente autónomo usando Visible Light Communication (VLC). En primer lugar, se presentan los detalles y los criterios de diseño de este novedoso sistema. A continuación se presentan los resultados de la evaluación de opciones de componentes tales como paneles solares y supercondensadores para incluir los dispositivos adecuados en el receptor. Por último, se presentan los resultados de pruebas del rendimiento del sistema en escenarios interiores realistas, analizando primeramente el efecto a diferentes distancias, ángulos e intensidades de luz, luego analizando el efecto de la presencia de luces interferentes y finalmente analizando las características de recolección de energía del receptor durante horarios laborales realistas de oficinas. Los resultados de la evaluación del desempeño demostraron que el sistema de wake-ups desarrollado con un receptor energéticamente autónomo puede funcionar correctamente en la mayoría de las condiciones típicas de escenarios interiores. El receptor de wake-ups autónomo de energía derivado puede incluirse en aplicaciones realistas; principalmente operando adjunto a sistemas de comunicaciones inalámbricas que requieren eficiencia energética como redes de sensores inalámbricos (Wireless Sensor Networks-WSN).

Abstract

The use of wake-up communication systems is a potential energy-efficient and low-cost solution for data communication. In this thesis, we go one step further and use visible light both for wake-up communication and energy harvesting purposes, with the final objective of developing an energy-autonomous wake-up receiver module using Visible Light Communication (VLC). First, we present the details and the design criteria of this novel system. We then present the results of evaluation of component options such as solar panels and super-capacitors to include the proper choices at the receiver side. Finally, we present the results of the system performance from realistic indoor scenario tests, analyzing the effect of varying distances, angles, and light intensities, analyzing the effect of presence of interfering lights and analyzing the energy-harvesting characteristics of the receiver during realistic office working hours. Performance evaluation results demonstrated that the developed wake-up system with energy-autonomous receiver system can operate properly in most of the typical conditions of indoor scenarios. The energy-autonomous wake-up receiver derived can be included in realistic applications; mainly working attached to wireless communication systems that require energy efficiency like Wireless Sensor Networks (WSN).

To my parents and godparents.

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1 INTRODUCTION

The advances in the technologic world help people to satisfy their necessities in an easier way, therefore people want to use the most advanced tools and services always. The information and telecommunication services play a crucial role into the technologic world and the demand of such services increases significantly. People constantly need more sophisticated applications, better quality of service and to transfer higher data volumes, and this requires higher speed and more bandwidth and forces the telecom industry to develop continuously. The constant advances of the telecom industry has a considerable impact on the environment. Currently, the information and telecommunication sector consumes around the 4% of the global electricity consumption, and a global goal is to reduce the current rate [1].

Projects about reducing power consumption and increasing energy efficiency in telecommunication systems have become a key topic of researching in current days. The trade-off between the growing demand and the energy efficiency requirements is a strong challenge for researchers. Most goals are focused to save energy by developing telecommunication systems using lower power consumption electronic devices, harvesting energy from the environment, optimizing protocols by implementing sleep modes and simplifying applications.

In wireless networks, the idle power consumption of the nodes has been noted to be around of the 66% of the total power consumption [2]. One of the most recent strategies evolved in wireless networks is the implementation of wake-up radio systems, a technique that has been demonstrated to decrease substantially the idle power of the devices [3]. Wake-up systems avoid the periodic node wake-ups to listen the channel for incoming data, as duty-cycling schemes define. A wake-up radio system sends the wake-up call to the target node, whenever the data communication is necessary. Hence its design is normally very simple, using small form-factor devices that consume very low power.

Light has been for decades a promising source to collect energy from the environment. Recently, visible light has also demonstrated the ability of carrying communication data allowing the creation of the IEEE 802.15.7 standard. The standard set the characteristics of the optical short range communication using the visible light spectrum (wavelengths between 380 and 780nm), also named visible light communication (VLC) [4]. Visible light communication enables a wide range of applications to ease and improve the human activity where artificial light is required (industries, offices and home), for instance: indoor localization, data networks, wireless sensor networks (WSN), or even wake-up systems. Taking advantages from these light properties, in a very recent researching work, a wake-up system was designed using VLC instead of typical radio signal, also able to use the light energy to power the receiver device [5]. A solar panel was established as light signal detector and converts it into electrical signal, and the receiver circuit designed is simple and very low power, able to be fed by the typical low current provided by the solar panel.

The main objective of this work, as a continuation of the previously presented work, is to achieve an energy-autonomous wake-up receiver using visible light communication. The completely energy-autonomous wake-up receiver will have the right properties to work in realistic indoor scenarios, becoming it in a helpful solution for battery-constrained communication systems such as sensor networks, as part of the emerging concept of Internet of Things (IoT). Also the energy-efficiency based receiver design will allow it to keep the configuration even in totally dark places for long time periods.

This document present the analysis and evaluation of several design proposals of this novel energy-autonomous system. A deep study of features, based in performing individual experiments of electronic devices, allows to choose the correct options to make the system to work properly in realistic indoor scenarios, maintaining a small size. The receiver design is changed to find better energy efficiency, where a commercial solar panel is used for two purposes: energy harvesting and VLC communication reception. A high capacity super-capacitor has been included for energy storing instead of using batteries. Feasibility tests in realistic indoor environments and lighting conditions are also presented, through which we show that the proposed system covers reasonable operational distances and is resilient to different light interference conditions. Also experiments performed with the new receiver configuration show that certain challenges from previous projects, such as low wake-up probabilities or losing the receiver chip configuration due to a significant decrease of the voltage, are resolved. Experiments results verify that the new receiver solution is able to keep the chip configuration and the operational voltage level, by consuming very low power of the retained energy, for reasonably long periods of darkness.

The rest of the document is structured as follows. In chapter 2, the fundamentals of visible light communication, wireless sensor networks, Internet of Things and wake-up systems are described, where an overview of the state of the art on related work is also included. The study of different component options and design criteria is presented in chapter 3, which details the physical experiments performed to take the design decisions. In chapter 4 performance evaluation tests under realistic environments are presented along with the analysis of the findings. Finally, in chapter 5 the conclusions as well as potential future works are presented.

2 CONCEPTS, FUNDAMENTALS AND STATE OF ART IN RELATED WORK

2.1 Visible Light Communication (VLC)

Optical Wireless Communication (OWC) is a generalized term that envelops some communication techniques related with optical technology, being Visible Light Communication (VLC) one of them. Visible Light Communication is a recent technique which has been studied by numerous companies and research institutes around the world, and its implementation is standardized by the IEEE 802.15.7 standard. Visible Light Communication means the use of signals between 380 and 780nm of wavelength, corresponding to the visible light spectrum, for short-range communication purposes in mediums optically transparent, and the IEEE standard defines the PHY and MAC layers for such communication technique [4].

VLC uses a source of visible light to transmit the signal, the air is the medium of transmission and a photodetector device is the signal receiver. Flashing the light source is the way to encode information, and therefore the light source should be able to support fast switching, faster than the human eye can perceive, while the light detector should have good response to visible light region and sensible to fast switching [6]. The fast switching regime of artificial light and the light intensity modulation is possible thanks to the development of laser diodes (LD) and light emitting diodes (LED). The possibility of modulating LED light with data signal allows the application of LEDs to be extended, not just for illumination but also for communication purposes. In addition, the development of photodiodes and indoor solar panels has made a proper detection of light intensity modulation schemes possible, the use of indoor solar panels for this purpose being pioneered by Universitat Politecnica de Catalunya.

2.1.1 Modulation schemes for VLC

To transmit data through the visible light, several modulation options are possible. Most of the methods have been previously used for Radio Frequency (RF) and wired communications. The main modulation methods are described below.

2.1.1.1 On-Off Keying (OOK)

Aligned with the name OOK, this method is literally related with the presence and absence of a carrier signal. This method is the simplest case of Amplitude Shift Keying (ASK) modulation. In this scheme, the presence of a carrier represents a digital one ('1') while the carrier absence represents a digital zero ('0'). OOK is the simplest method to modulate and demodulate, but is not feasible for high data throughput and light dimming. When long strings of ones or zeroes are sent, light flickering is perceived by human eye at certain frequencies, due to long time periods of presence and absence of light. Figure 1 illustrates the OOK modulation method.

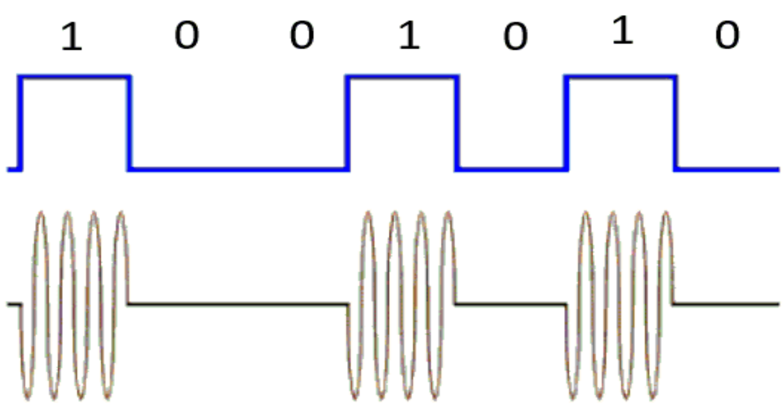


Figure 1. On-off Keying Modulation (OOK).

Manchester coding is commonly used in OOK modulation to reduce the flickering effect. Manchester code sets that a digital '1' is represented by a '01' OOK symbol and a digital '0' represented by a '10' OOK symbol. This coding avoids the low signal level of more than two consecutive zeroes, resulting in a DC balanced code [7]. Figure 2 provides an example of Manchester coding.

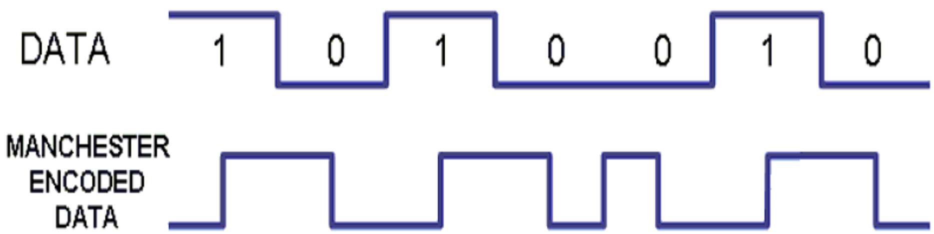


Figure 2. Manchester coding.

2.1.1.2 Pulse Width Modulation (PWM)

This modulation technique is based on the duration of pulses. This method controls the width of the pulses (duty cycle) into the PWM period according to the dimming level and keeping the amplitude of the pulses constant. PWM method allows to send more than one bit of data within each pulse, making it more advantageous than OOK, and is also relatively simple to implement. Nevertheless, PWM is relatively more expensive than OOK and the light flickering is also perceptible when using this technique at low frequencies, i.e. setting the driver below 100Hz. In **Error! Reference source not found.** the Pulse Width Modulation method is presented.

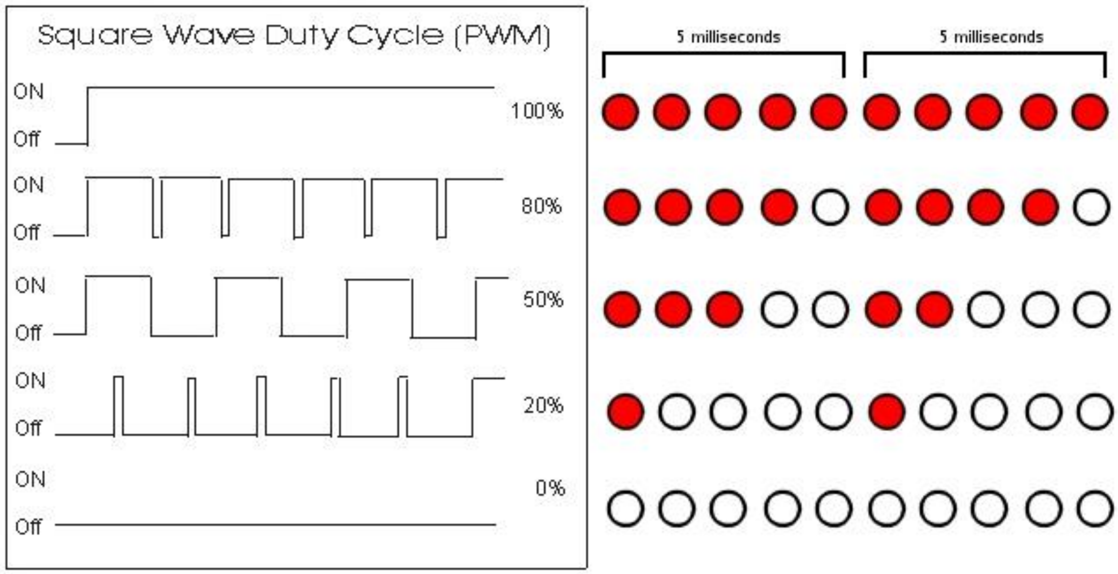


Figure 3. Pulse Width Modulation (PWM).

2.1.1.3 Pulse Position Modulation (PPM)

In PPM the coding is done according to the position of the pulse into a specified time frame. This method keeps constant the amplitude of the pulses, but the delay between them changes, and therefore a synchronization clock is required in this technique. As in the previous PWM method, PPM allows to convey more than one bit in each pulse, and in addition with this method the optical energy is maintained constant in each time frame [8]. **Error! Reference source not found.** shows an example of the PPM modulation method.

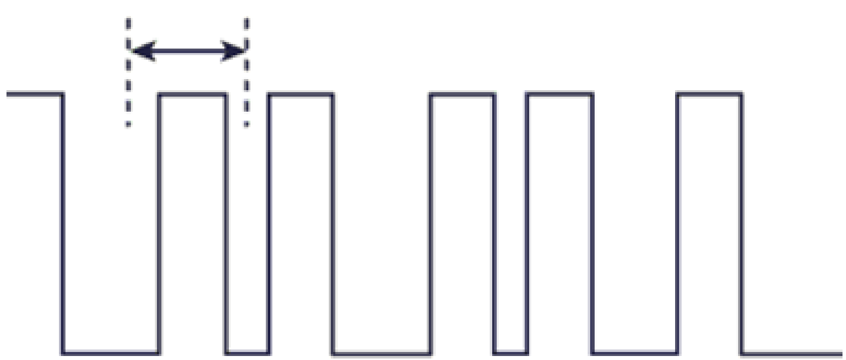


Figure 4. In Pulse Position Modulation pulses are unevenly spaced in time.

An advanced method based in PPM is Variable PPM (VPPM), it is a combination of PWM and PPM modulation schemes. In VPPM optical symbols are determined by the pulse position, like in PPM scheme, but also the duty cycle of the optical symbols is changed for encoding bits, similar to PWM. The variation of the duty cycle is performed in correspondence to the required dimming level. In this method, the pulse width of the digital '0' and '1' symbols modulated in PPM can be adjusted to the required duty cycle for supporting the dimming level.

2.1.1.4 Color Shift Keying (CSK)

This modulation method is possible if the system uses multicolor LEDs. In CSK, bits are encoded with color combinations, so data frames can be carried by any color of light, determined by the combination of red-green-blue (RGB) LEDs. This technique is similar to Frequency Shift Keying (FSK) modulation, but using frequencies corresponding to the spectrum range of colors. The IEEE 802.15.7 standard has divided the spectrum into seven colors bands available to use in CSK method. With this technique the output intensity can be constant, but the complexity of the system increases due to the requirement of multiple color LEDs at the transmitter, and a color sensitive device at receiver side.

2.1.1.5 Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is an advantageous modulation technique commonly used in wireless communication systems, due to the robustness against the inter-subcarrier interference and its high spectral efficiency. In this technique, data frames are modulated in a determined number of subcarriers that can use the same frequency but separated in orthogonally different phases. Figure 5 illustrates the OFDM modulation, in which four subcarriers are shown in time and frequency domains.

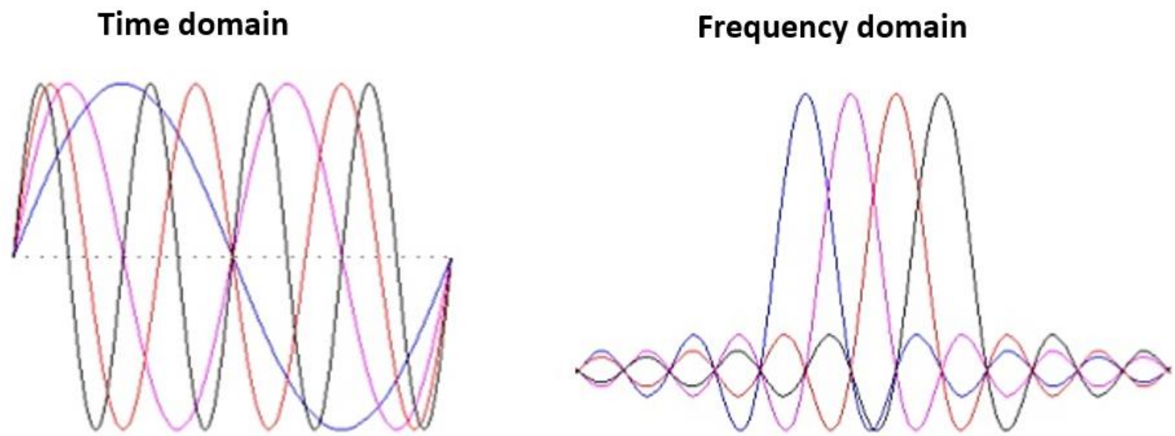


Figure 5. Orthogonal Frequency Division Multiplexing (OFDM).

At the transmitter side, the output signal is the result of performing an Inverse Fast Fourier Transform (IFFT) to the data stream, and such data are recovered at the receiver side by applying the Fast Fourier Transform (FFT) [9]. Some adaptations have been done in OFDM modulation method to be used in optical communications providing better average-power efficiency than other modulation methods. The system complexity is a challenge for this technique along with light dimming levels support.

2.1.2 Line of Sight (LOS)

Line of sight is a key concept in VLC systems and it is a classification of links configurations. For better understanding of some aspects in next chapters of this work it is important to define the four basic classifications [10]:

- Directed line-of-sight: Transmitter and receiver are focused face to face and there is no obstacle in the light path.
- Non-directed line-of-sight: Absence of obstacles in the light path, but transmitter and receiver are not focused face to face.
- Directed non-line-of-sight: Transmitter and receiver are focused face to face, but obstacle(s) are present in the light path.
- Non-directed non-line-of-sight: Transmitter and receiver are not focused face to face and obstacle(s) are present in the light path.

In realistic scenarios the most common situation is the non-directed line-of-sight. In indoor places, lights are normally fixed, which can be used as VLC transmitter, and the receiver can be a mobile device or can be fixed in any place with LOS, but not often directly faced to the transmitter.

2.1.3 Comparing VLC with other wireless media

VLC has demonstrated to be an advantageous telecommunication technology. The adaptation of modern modulation methods brings considerable high data rates to this technology. VLC systems are thought to be installed in LED lighting systems, making wider the field of application of this technology and becoming this technology in an attractive solution for consumer communications.

- VLC and radiofrequency (RF) communications: Visible light spectrum is unlicensed to use, while RF spectrum is crowded and partially licensed. Moreover, VLC, unlike RF, does not provide Electromagnetic Interference (EMI), an undesirable feature in places as hospitals, power nuclear generation, airplanes. Since VLC goes together with LED illumination the energy consumption is much lower than RF communications, and also the implementation cost is cheaper than RF. The top level of transmission power in any RF transmitter is standardized to avoid risks in human health, while light, up to now has no negative influence in human health.

- VLC and infrared (IR) communications: Since infrared signals are not seen by the human eye, this media is used mostly just for communication purposes, while VLC is used for both illumination and communication. Laboratory tests have shown that data transmitted in a VLC system can achieve longer distance (> 10m) than the one achieved by an infrared LED (approximately 3m). Also data rate sent by an infrared transmitter has been measured of around of 20 megabits per second

(Mbps), and the data rate measured to a VLC transmitter shows results up to five times higher.

2.2 Internet of Things (IoT) and Wireless Sensor Networks (WSN)

The concepts and technologies of Internet of Things (IoT) and Wireless Sensor Networks (WSN) have been developed in a parallel way. IoT, in particular, is referred to any device as part of a telecommunication network, while WSN is specified to sensors wirelessly interconnected, and in general are referred to integrate communication capabilities in any possible device to share information between them and to Internet. Advances in Wireless Sensor Networks has allowed to include simple sensors into the IoT field, being the most important evolution of the WSNs. The evolution of wake-up systems technology constitutes a significant contribution to advances in IoT and particularly in WSN. As the application of the wake-up systems and VLC in IoT and WSN is very wide, it is important to include in this project a background of the state of the art of these modern technologies.

Internet of Things means a system composed of any physical object capable to connect to Internet. This concept has been known since 1999 by Kevin Ashton while he was working in networked Radio Frequency Identification (RFID) and emerging sensing technologies [11]. The evolution of this concept has led that properties of some devices, sensors or any everyday object are extended to computing and Internet connectivity capabilities. This means that after years of evolution of computing and communication trends, IoT represents a convergence point of such trends. The evident advantages of IoT technology have made that every day more companies of sectors like healthcare, home and consumer electronics, automotive, are motivated to include this technology in their services and products [12].

People, in the actual society, needs to measure and control thousands of parameters from the environment, industrial processes, machineries and even at home, so, since some years, developed sensing tools are performing such kind of tasks. Features like size, precision, energy efficiency, automation have been developed constantly using sensors. Advances in material science technologies, semiconductors and telecommunication networks have driven to increase the complexity level of sensors [13]. Therefore, the addition of wireless communication properties to sensors nodes has allowed the creation of wireless sensor networks (WSN) in current times.

A wireless sensor network is a type of network in which autonomous sensor nodes are interconnected to share the gathered and processed information from a determined environment using wireless media. The number of sensor nodes is determined by the size of the place to be installed, so WSNs can be composed even by thousands of devices monitoring parameters and sharing information. For that reason, WSNs should include some key features such as: to be able to tolerate faults, and should include self-organizing and self-optimizing skills [14].

Devices like gateways, clients, actuators and sensor nodes are the components of a current typical wireless sensor network, in which actuators and sensor nodes are randomly distributed inside the area to monitor. In **Error! Reference source not found.** a diagram with the main components and the typical architecture of a WSN is shown. In WSN data is gathered and transmitted by sensor nodes hopping along others sensor nodes. Therefore routing protocols are a key point in WSN, because data are handled by several nodes before reaching the gateway to be sent to Internet [15].

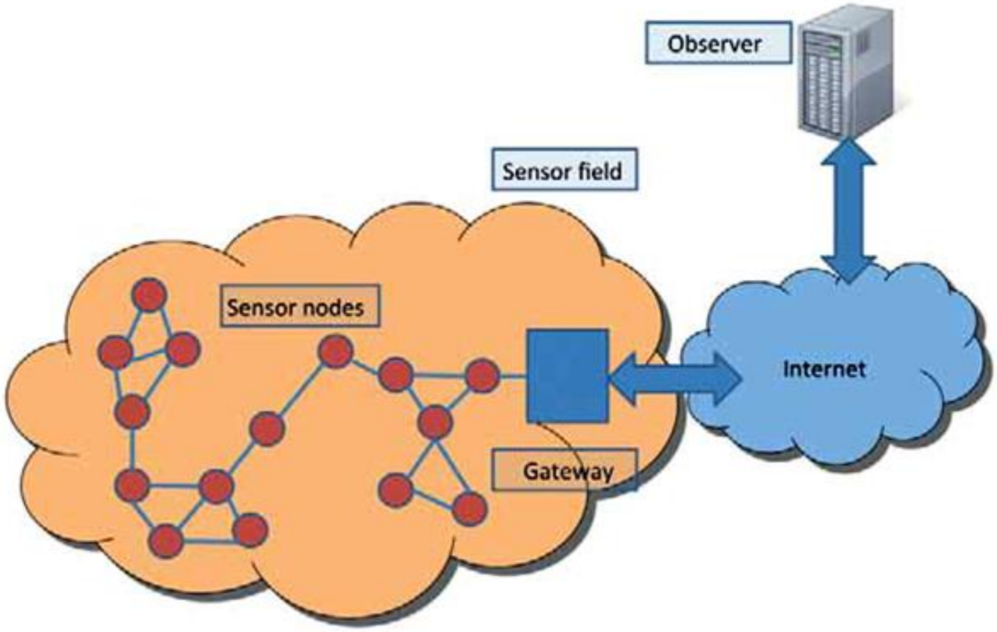


Figure 6. Wireless Sensor Network components and architecture

The wake-up system proposed in this work is focused for saving energy, so it can be widely used in wireless sensor networks. The implementation of this proposal improves the optimization features and the performance of such type of networks, mainly in sensor networks installed in indoor environments like buildings, houses, offices, storages. Also, specific networking methods and protocols developed for WSN can be readjusted to provide more control and get more profit of the network devices when including this wake-up technique into sensor networks.

2.2.1.1 WSN nodes

Sensor nodes are the main components of any wireless sensor network. Thanks to advances in semiconductors, microelectronic and materials science, wireless sensor nodes are every time cheaper and smaller. In addition, these advances have increased the capabilities of sensor nodes to perform data processing, storage, and data transmission and reception. Also a current sensor node is able to collect different type of data from thermal, optical, biological and chemical attached sensors. Multiples devices based in microelectronic manufacturing and very low power consumption are included into a wireless sensor node, as shown in **Error! Reference source not found.**: a central processing unit (CPU), memory, radio transceiver, power supply, as well as one or more sensors, a signal conditioner and analog-to-digital converter.

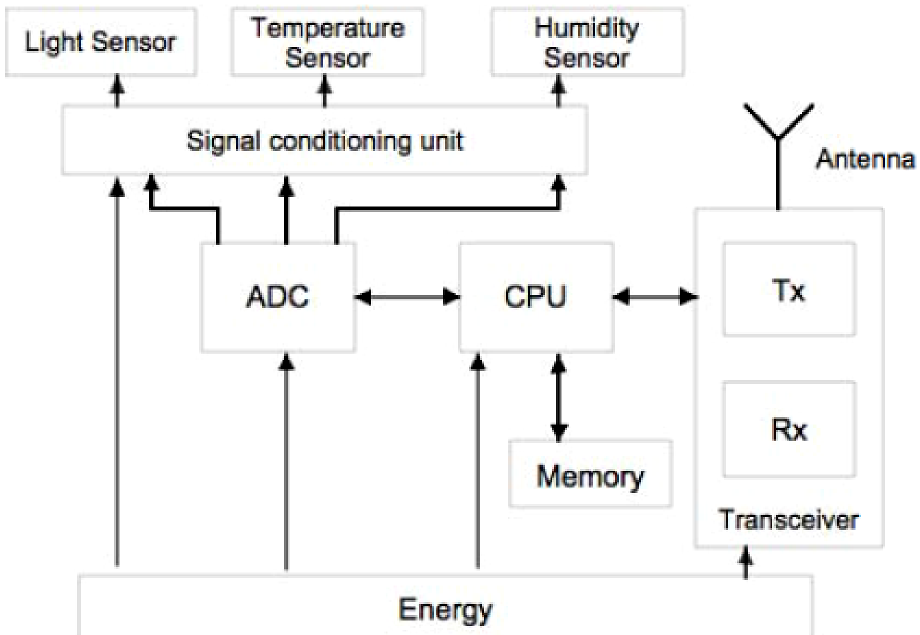


Figure 7. WSN node hardware architecture.

Including the previously described components inside the sensor nodes increase considerably the complexity, but also the functionalities and the automation of the nodes. Therefore current sensor nodes have a functionalities list longer than earlier times sensors. The set of procedure stages of current sensor nodes are described below [14]:

<u>Related to sensing and data treatment:</u>

- data acquisition from attached sensors
- signal conditioning
- data temporary storage
- data processing
- processed data is analyzed for diagnosis or alerting
- performing data packets

- transmission, reception and forwarding of data packets

Related to the node itself:

- self-monitoring (e.g. storage capacity, supply voltage)
- management of the sensor node configuration
- scheduling and performing monitoring tasks

Related to networking:

- coordination and management of communication and networking

2.2.1.2 Challenges for WSN

The constant outstanding contributions in wireless sensor networks technologies have led this term to be every day more known and widely applied by the human society. Nevertheless, as it is a recently evolved concept, there still some features, tasks, techniques to accomplish, to develop and improve. In fact, there still a list of challenges to address in order to create successful commercial solutions, so most significant challenges are described below [11, 14].

- Energy sources and powering solutions. This is one of the main challenges to be addressed in WSN and IoT in general. As any WSN can be composed by thousands of nodes deployed in areas of some kilometers squared, does not result convenient to change the nodes batteries every certain time. Therefore, the idea is that nodes could get energy from environmental sources such as light, wind, vibrations, and temperature changes. For that reason, today's research is focused on creating energy-autonomous sensor devices. The goal of this work is mainly to contribute to this challenge, because the powering and lifetime of the wireless sensor networks can be improved by including wake-up systems using VLC.

- IP addresses solutions. Modern sensors include connectivity properties, that means that every node requires an IP address. It becomes a problem when a huge amount of new devices, placed worldwide, will be included to the telecommunication network, even knowing that IPv4 addresses are over. The idea is to create new sensor nodes supporting IPv6, because this protocol can provide addresses for any amount of new devices, also security features are improved and network management is easier due to auto-configuration properties.

- Small size devices. This is also an essential point in WSN, IoT and in electronic devices in general. The trend of reducing devices size is always in mind, because at smaller sizes becomes more appropriate for more applications. Also, the energy consumption of electronic devices is normally proportional to size.

- Creating standards. The IEEE standards related to WSN are an advantageous aspect to regulate this technology. Nevertheless, aspects like architecture, privacy and security need more specific norms. For that reason, more standards are required in this field to set rules for compatibility between different manufacturers products, increasing in this way, the available choices.

- More easy systems for people. The WSNs are thought to be used and deployed by users with no deep knowledge in telecommunication, electronics and informatics. It is a requirement for WSNs to be understandable and easy to install, to manage and maintain. New approaches are proposed, such as easier-to-use software interfaces and dedicated operative systems, more effective software modules and plug-and-play mechanisms.

The implementation of the wake-up system using VLC improves the performance of WSNs mainly in term of powering by extending the network lifetime. Energy efficiency and, in particular, the development of an energy-autonomous device that harvests energy from light are the main objective of the present work. Also, device size is another aspect taken into account during the development of this project. In fact, this work could be a potential contribution for addressing some challenges presented by the wireless sensor networks, mainly those related with powering and energy efficiency.

2.2.1.3 Energy-efficiency solutions in WSN

As seen in previous subsection, energy management is one of the key challenges for WSN researchers. Advances in many technologic fields have made considerable improvements in energy systems' efficiency. For instance, advances in chemistry keep the battery systems as the preferred technology for low-cost energy storage, so batteries are still widely used in WSN nodes. Today, batteries can be developed for different application conditions: lithium manganese dioxide ($LiMnO2$) batteries are recommended for short-range temperature variation and short lifetime, while lithium thionyl choride ($LiSOCl2$) batteries are designed for larger temperature ranges and long lifetime [13]. With respect to batteries, WSN scenarios can be classified as fixed size battery storage and replaceable fixed size battery:

- Fixed size battery storage. Refers to WSN scenario, with harsh environmental conditions, where nodes are powered just until these attached batteries drain out, being impossible to replace them, and node is then discarded from the network operation.
- Replaceable fixed size battery. Refers to accessible WSN scenarios in which batteries can be replaced when drain out. Today most of the available WSN nodes work on this principle.

Ambient energy harvesting technologies have also become an interesting solution for microelectromechanical systems (MEMS) [15] that require little power like modern sensing systems, remote control and domotic systems. Today there are different methods to get energy from the ambient environment, and every time, new researching approaches are focused in becoming more efficient such methods. Harvesting methods can be classified according to the way of getting energy from the environment, so beside the known power generation from photoelectric cells, other harvesting methods, such as using thermoelectric and pyroelectric effects, kinetic motion of piezoelectric materials and micro-oscillators and conversion of electromagnetic waves energy have been currently evolved and used.

In addition, other approaches are focused toward the energy consumption, as another way to manage the energy in WSN systems. These approaches try to develop more energy-efficient mechanisms and systems, in general, based in reducing the power consumption. Most relevant trends on this working field are described below [16], and in the following subsection.

- Duty cycling. This topic enclose different algorithms intended for adjusting the duty cycle of the nodes, and is considered to be one of the most effective ways to improve the lifetime of sensors networks. Algorithms try to save energy by setting the sleep and wake-up modes periods optimally: reducing the active mode time and extending the sleep (low power) mode time as much as possible. In this way, nodes wakes up just in case of data transmission or reception, saving energy considerably.

- Data driven. These approaches are based in the idea of minimizing the number of sampled data, but keeping an acceptable accuracy when sensing. Data reduction is one of the schemes related to this approach and the trend is to avoid unneeded samples. Also, data prediction is used in data reduction schemes, which performs an abstraction of the sensed data as a model for future data prediction.

- Mobility. This approach is thought for networks with a reduced number of mobile nodes, and such nodes are classified according to their mobility behavior: fully controllable mobility and unpredictable mobility. Also, algorithms based in mobility approach are classified in mobile sink based approach and mobile relay based approach. Algorithms based in mobile sink try to increase the network lifetime using a mobile sink to collect data from source nodes deployed in the field. Mobile relay algorithms use message ferries, that move around the field collecting data from source nodes, and then the carried data is forwarded to the destination node.

2.3 Wake-up systems technology

In wireless systems, devices consume energy not only when communicating with other devices, but also when listening the medium. Wake-up receivers represent a recent technique and one of the most effective methods for saving energy in wireless sensor networks, avoiding the listening mode of wireless nodes. Wake-up receiver technique is a sleep/wake-up scheme, in which an external receiver device is attached to the core receiver to act as an alarm clock just in case of requiring data communication. **Error! Reference source not found.** shows a block diagram of a basic wake-up system. In wake-up systems, when data is ready to be sent, the transmitter sends previously a wake-up call that is detected by the wake-up receiver, which sends a pulse to interrupt the sleep mode of the target receiver, which switches to the reception mode [17].

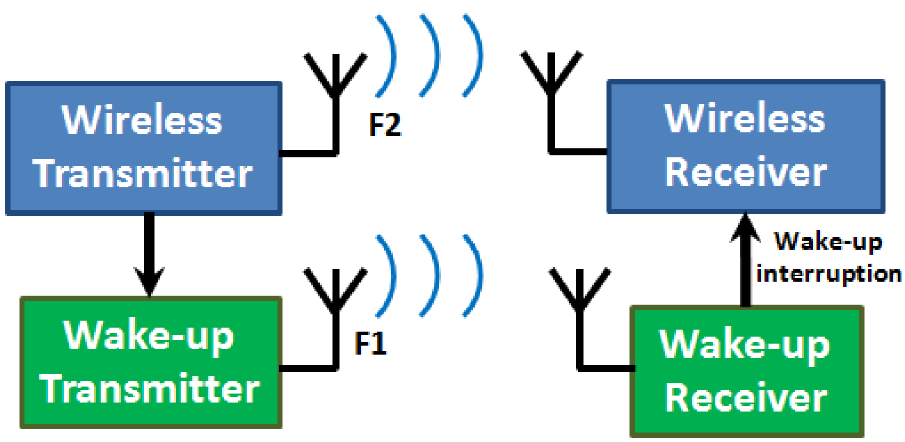


Figure 8. Basic wake-up system

Wake-up receivers are normally composed by ultra low power consumption devices to be able to keep sensing the medium constantly. Wake-up receivers sense the medium according to the type of signal used to send the wake-up call, for instance: use of antennas for radiofrequency (RF) detection, photodetectors devices for light signals. Devices like signal demodulator and pattern correlator are also included in the wake-up receiver, being the main processing signal stages. Such stages require powering, therefore it is important to use the most energy-efficient options. In wake-up systems, power can be obtained from the core system, but normally wake-up receivers use their own power source, like batteries, supercapacitors or energy harvesting methods. Today wake-up receivers, like presented in [18], are energy-efficient enough to operate continuously for years.

2.3.1 Works on wake-up systems

There have been numerous studies on the wake-up systems, covering different methods of implementation and media options. These systems are usually built on radio triggered approaches, typically using a different channel than the main radio to send wake-up signals. Wake-up systems can also be classified as active or passive, according to how they are powered [19]. In active systems, the receiver is powered by a battery or by sharing the battery of the attached node. In passive systems, the receiver is fed by harvesting energy from the environment, for instance using the transmitted RF signal.

Research studies on wake-up systems are more commonly focused on active powering methods. An example of active infrared wake-up system is presented in [20], which operates in listening mode until an incoming signal is detected and the microcontroller is woken up. A very low power amplifier along with an ultra low power microcontroller at the receiver side allows it to operate in waiting mode for long time, where it requires just around 4μA during such waiting mode. However, the system can detect wake-up signals from up to 30m depending on the transmitter signal intensity. This approach is destined to work in indoor environments, for identification and positioning tasks, so can be implemented in wireless sensor networks. On the other hand, our system is able to work using visible light, allowing to extend the utility of lighting systems to energy harvesting and communication purposes.

In [21], another approach of active wake-up system is presented, in which the transmitted signal uses free space optical communication. The transmitted signal is detected by two photodiodes located at the receiver side, requiring line of sight and directional communication. The receiver uses a MCU and a CC2420 radio both manufactured by Texas Instruments. The system can reach 15m of communication range, working with very low power consumption, requiring around of 16.5mW by the transmitter to send the signal and just 317µW by the receiver when operates in receive mode. System characteristics make it an interesting solution for indoor environments. However, our wake up receiver proposal uses an indoor solar panel, which demonstrated in previous tests, better performance than photodiodes. Moreover, our wake up receiver harvests energy from light for feeding purposes, providing greater efficiency to our system.

An example of passive wake-up system, using a harvesting method, is presented in [22], where a radio wake-up receiver is implemented and the energy is obtained by using a piezoelectric device. The light, the energy source used in our wake-up system is more common in human life than radio waves, so our wake-up system will have a wider field of application.

Also a wake-up receiver presented in [18] has the ability to be energized via harvesting methods. System features, presented by developers, make the system suitable for several applications in the field of Internet of Things, like building automation, intelligent lighting, wireless sensor networks, remote control, etc. The system uses a radio triggered method operating in the 868 MHz and 2.4 GHz radiofrequency bands. The energy consumption is around of 3µA when operates in standard configuration at 1 kbps of data rate and provides a response time of 32ms. In comparison, our proposal harvests energy from light signal used for lighting and carrying the data. The use of light improves the energy efficiency of our proposal of wake-up system and increases its field of application.

3 SYSTEM DESIGN, FUNCTIONALITY TESTS AND ANALYSIS

The wake-up communication system developed in this work keeps the operating principle of the system designed in [5]. In this work, visible light is also used as the media to transmit data from the wake-up transmitter towards the wake-up receiver. A diagram of the VLC wake-up communication system proposed is shown in **Error! Reference source not found.**.

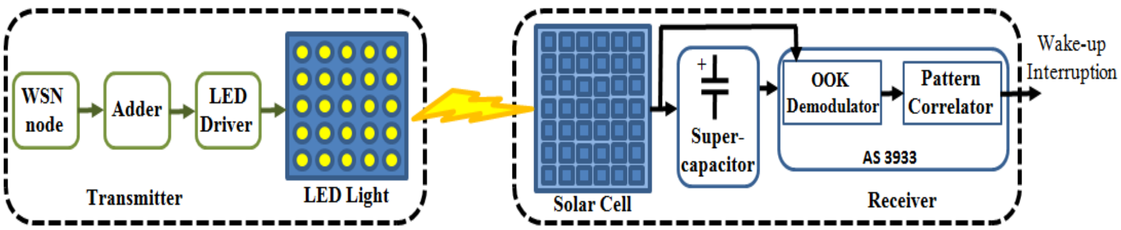


Figure 9. Block diagram of the wake-up system

The transmitter is composed of a programmable WSN node that assembles and modulates the wake-up signal, an adder stage, a module for driving the LED and the LED. The wake-up signal, assembled by WSN node, carries the address of the target wake-up receiver, which enables an addressable wake-up. The amplitude changes of the wake-up signal varies the output current of the LED driver module, varying also the LED brightness according to the wake-up signal.

The receiver is composed of an indoor solar panel that receives the light signal and converts it into electric current. At this phase, the electric signal has two functions: charge a capacitor and carry the sent information to the demodulator. The capacitor feeds the demodulator, the MCU or any signal processing stage when the light sources are off. The solar panel and the capacitor relieves the need of any other power source for wake-up purposes, providing totally energy-autonomous wake-up receiver component. In this way, any attached wireless receiver can be put to deep-sleep for very long times, eliminating the energy waste of the listen/idle modes set by protocols.

At the receiver side, the electric signal, from solar panel, is delivered to an AS3933, a 3D low-power low-frequency radio wake-up receiver developed by Austriamicrosystems [25], through pin 9 (LF1P) and pin 10 (LFN). The pinout of the AS3933 is shown in the Figure 10. This device powered through pins 5 (VCC) and 6 (GND), and it is configured using pins 1 to 4.

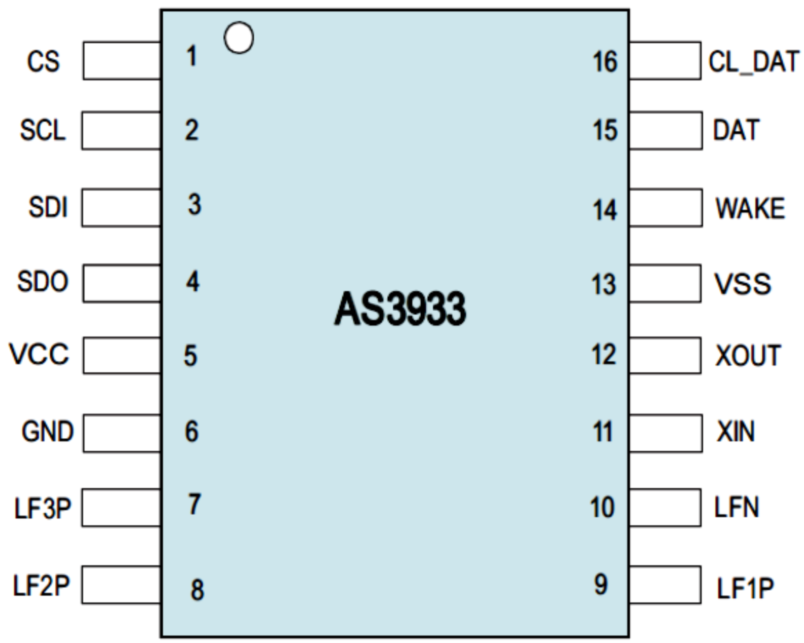


Figure 10. AS3933 pinout.

Inside the AS3933 as illustrates the Figure 11, the signal is demodulated as OOK (On-Off Keying) signal by an internal OOK demodulator, which extracts the original information and delivers it to the pattern correlator. The pattern correlator compares the demodulated signal with the address of the receiver, and in case of a match, a wake-up interrupt is generated for the attached device. Subsequently, this attached device can start its operation, for example, receiving an incoming data transmission, performing sensor measurements, etc.

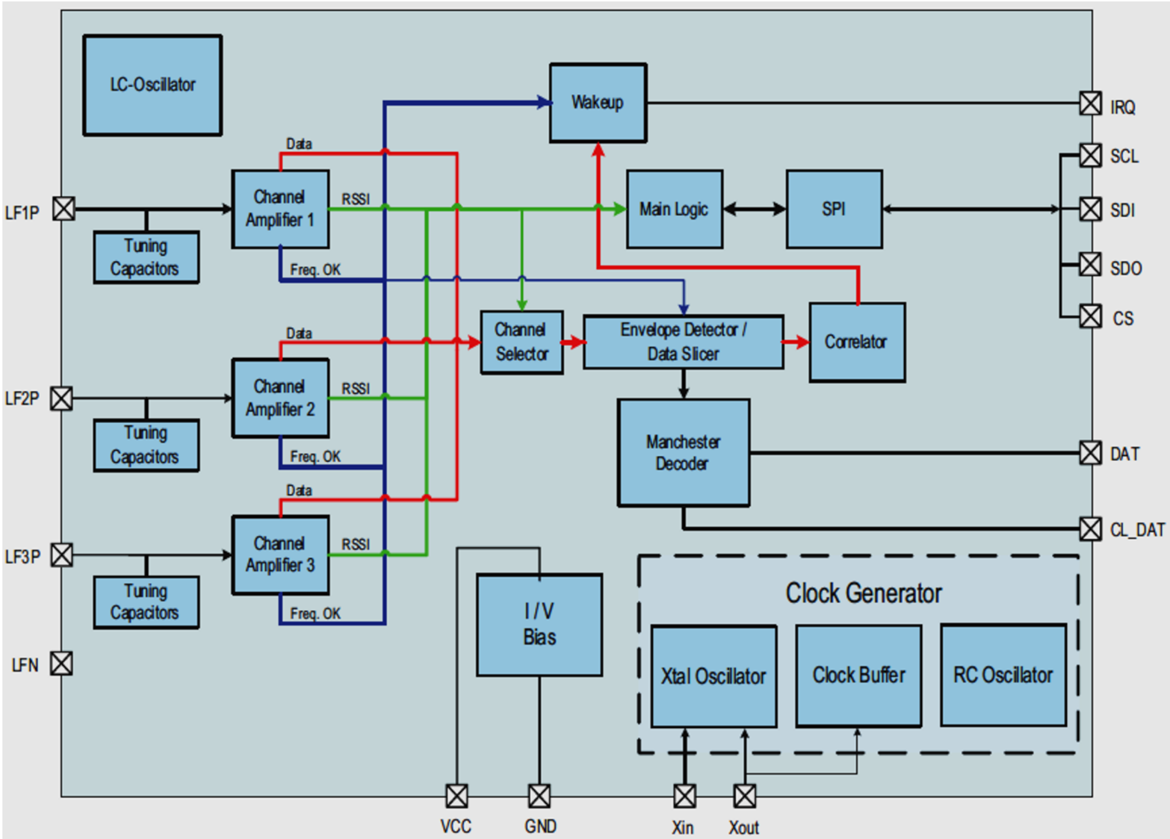


Figure 11. Block diagram of AS3933.

In indoor environments there are some requirements and conditions to be taken into account when developing a VLC system. In indoor environments, the light intensity received in different parts of the area varies due to distance from the light source, the presence of obstacles blocking the direct line of sight, etc. Moreover, some key features must be present when designing indoor wake-up systems, such as small footprint, feasible wake-up distances to achieve, very low power consumption or develop energy-autonomous systems. In such way, we tested and analyzed different system component choices to devise a system satisfying all these criteria.

3.1 Components of the energy-autonomous wake-up receiver

In this work we focused on the receiver design and its components, to adapt it to work in an energy-autonomous manner. Figure 12 shows the circuit diagram of the receiver, in which the solar panel and the capacitor are the main components to be tested and analyzed.

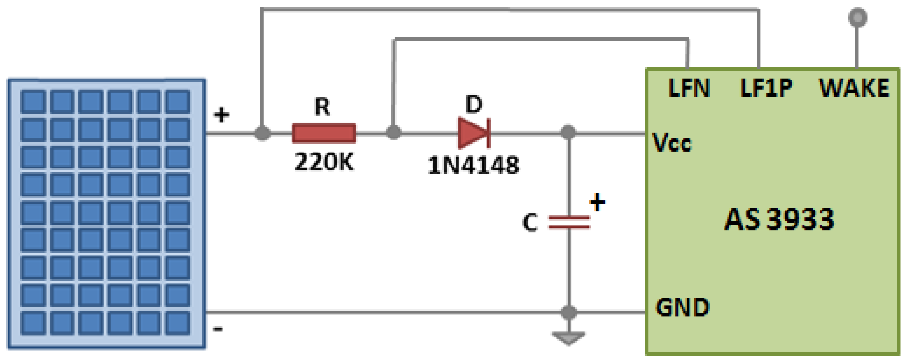


Figure 12. Circuit diagram of the wake-up receiver.

3.1.1 Indoor solar panel

To make an effective choice, it is important to take into account some key solar panel parameters. Cell efficiency parameter depends on manufacturing technology, and involves aspects such as spectral sensitivity, light source and power density. In addition, the voltage range a solar panel provides is also important for its compatibility with the rest of the system components. In our receiver system, the active components require at least 3.6V. Finally, the frequency response characteristic, in terms of peak-to-peak voltage (Vpp), is crucial for the choice of modulation frequency of the OOK signal.

To choose a proper option we evaluated the key parameters of three indoor solar panels and compared the results. First one is a solar module consisting of 10 crystalline silicon solar cells, especially optimized for indoor lighting conditions provided by IMTEK Research Institute[1]. It provides a maximum open circuit voltage of around 5.4V, with cell size of 6cm x 3cm and less than 0.1cm of thickness. The other two solar panels are off-the-shelf panels manufactured by Blue Solar, and are built with amorphous silicon solar cells. The differences between the last two are the size and the open circuit voltage, the SC3726I-8-1 (Small Off-the-shelf) has a rectangular shape of 3.6cm x 2.6cm and 0.1cm of thickness and around

[1] https://www.imtek.de/

6.24V of maximum open circuit voltage; while the SC5375I (Large Off-the-shelf) has also a rectangular shape, but with the dimensions of 7.5cm x 5.3cm x 0.1cm providing around 5.96V of maximum open circuit voltage.

3.1.1.1 Frequency response tests

In order to analyze the frequency response characteristics of these alternative indoor solar panel options, we performed a set of tests varying the transmitter frequency within the range of 100Hz to 48.35 kHz. For the tests, a 10W LED was used, and was powered by a Direct Current (DC) source supply, setting the voltage at 31V to avoid to exceed the maximum voltage level allowed by the laboratory source supply. The solar panels were located at a distance of 1m from the LED in straight line and, disabling other light sources. The resulting light intensity measured by a lux meter in that position was approximately 158 lux. The test setup is shown in Figure 13.

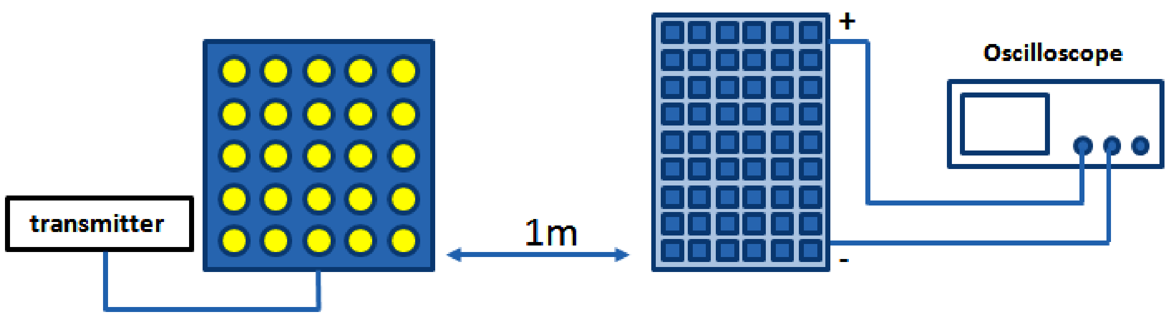
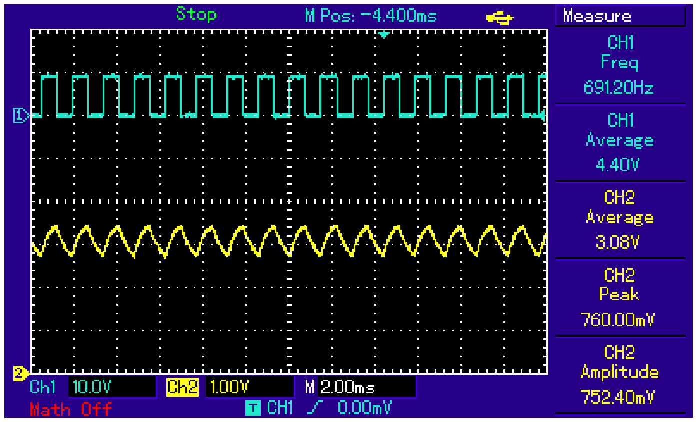
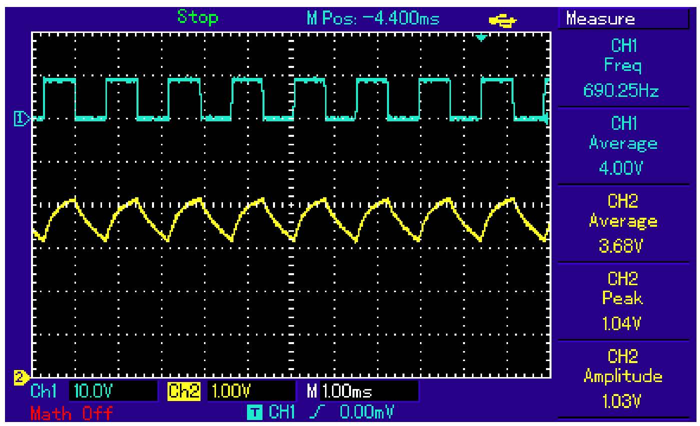


Figure 13. Frequency response test setup.

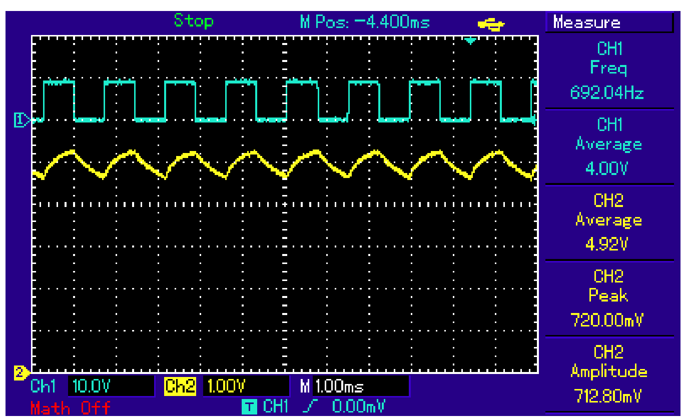
In Figure 14 illustrative oscilloscope screenshots are shown. From these screenshots it is possible to compare some parameters of the signals received by each of three solar panels, with a square signal at 690Hz transmitted by the LED. A difference between peak-to-peak voltage values can be seen in the set of screenshots, such values are measured by the oscilloscope channel 2 and shown in the screenshots as “CH2 Peak”. In current test, it is the main parameter to be analyzed.



(a) IMTEK solar panel frequency response at 690Hz.



(b) Small Off-the-Shelf solar panel frequency response at 690Hz.



(c) Large Off-the-Shelf solar panel frequency response at 690Hz.

Figure 14. Oscilloscope screenshots of the three solar panels frequency response at 690Hz.

The results of the frequency response measurements are shown in Figure 15, in which the graph shows the relation between the light OOK frequencies with the relative voltage ($V_{relative}$). The relative voltage corresponds to the ratio between the absolute peak-to-peak voltage of the solar panel output signal at each frequency and the DC voltage of the respective solar panel. The DC voltage is measured using an oscilloscope connected to the solar panel and programming the transmitter to generate continuous light. A table with all test values is presented in Appendix A.

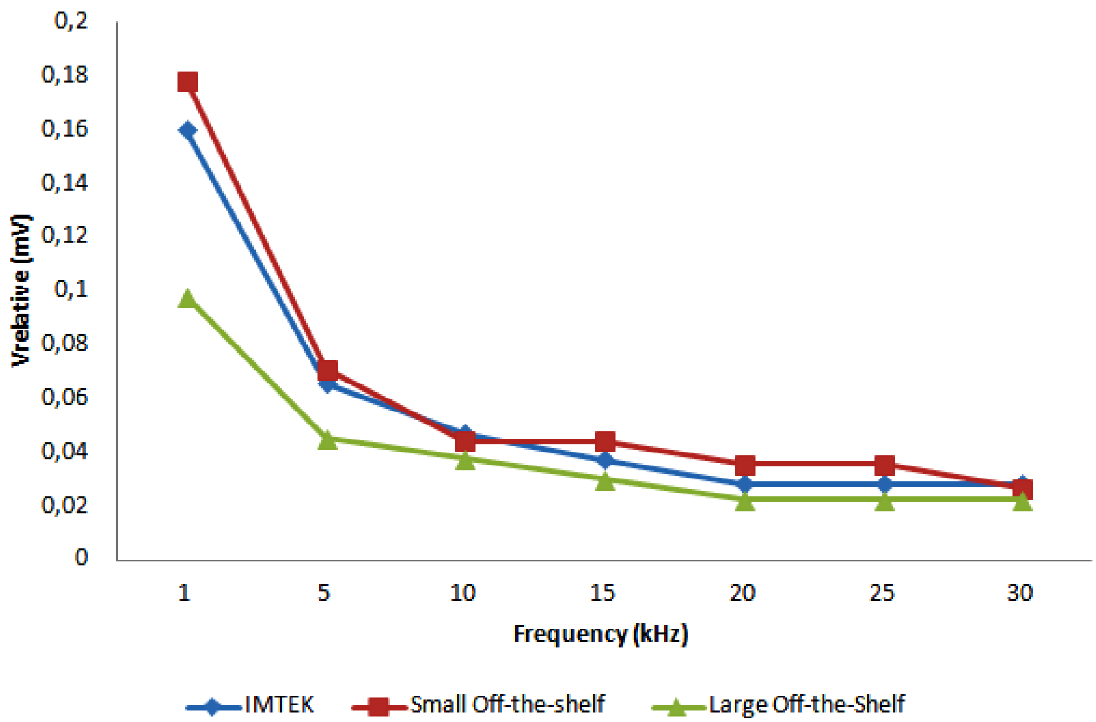


Figure 15. Response of the three indoor solar panels to different frequencies.

As seen in Figure 15, all three solar panels provide better relative voltage values at low frequencies than at high frequencies, being a similar behavior to the frequency response tests performed in [23]. Also, the differences between the three solar panels, in term of frequency response, are clearer at low frequencies than at high frequencies. Nevertheless, in general, for frequencies higher than 30 kHz the relative voltage values become too low. However, the Small Off-the-Shelf solar panel has the highest relative voltage for almost all the range of frequencies. As seen in the graph, the IMTEK solar panel has better relative voltage values compared to the Large Off-the-Shelf solar panel.

The results allowed us to know that the Small Off-the-Shelf solar panel is the right option in terms of frequency response and small size. Also, the Small Off-the-shelf solar panel provides a short circuit current of 34.6μA [5], this value is higher than the current consumption required by the receiver active component [25]. Although having these advantages, we evaluate additional criteria to decide the right choice to develop an energy-autonomous wake-up receiver, as detailed in the following subsections.

3.1.1.2 Testing power from solar panels

To develop an energy-autonomous wake-up receiver, it is necessary to use the resultant electric energy, provided by the solar panel, not just to carry the wake-up frame, but also to power the receiver active components. One of the resulting drawbacks from the system designed in [5] is the very long time required to charge the capacitor, a possibly infeasible time to wait until the system starts to work in a realistic scenario. Therefore, it is also important to select a solar panel capable of providing enough electrical energy to keep the receiver components powered and to charge a high capacity capacitor shortly. Figure 16 shows a view of the following tests, which will determine the best choice of solar panel for powering the receiver.

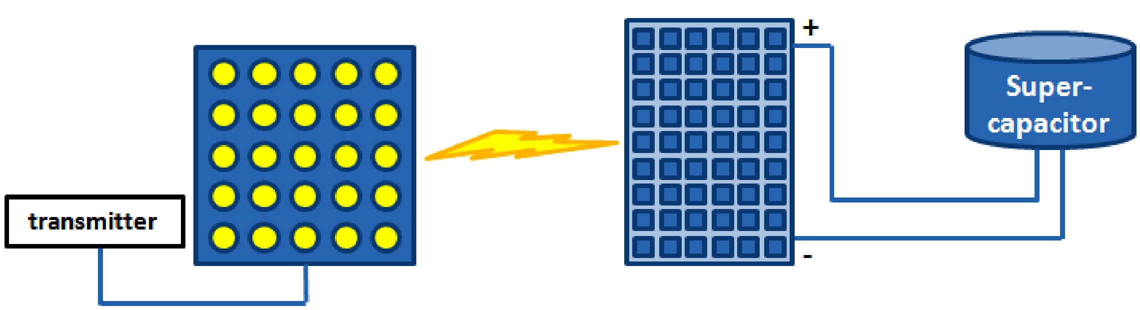


Figure 16. Charging super-capacitors test setup.

To have an idea of the energy efficiency of each of the three solar panels, the voltage level of super-capacitors fed by each of the solar panels was measured during the same time period. A 0.1F/5.5V and a 1F/5.5V super-capacitor were used in the tests and their voltage level was measured every 10 minutes during 1h for each solar panel. Wake-up calls were emitted from the LED with no other light interference, and the source supply for LED was set, as in previous test, at 31V to power the LED. The tests were done at certain distances according to light intensity standards [24]. The distance varied, firstly to achieve a light intensity standard for indoor general purposes of 200 lux, and secondly 400 lux, a light intensity standard for places, where some attention is required such as offices or some rooms at home [24]. Figure 17 shows the resulting graphs of the tests done at 200 lux, while Figure 18 shows the ones for 400 lux. The detailed data point values are provided in Appendix B.

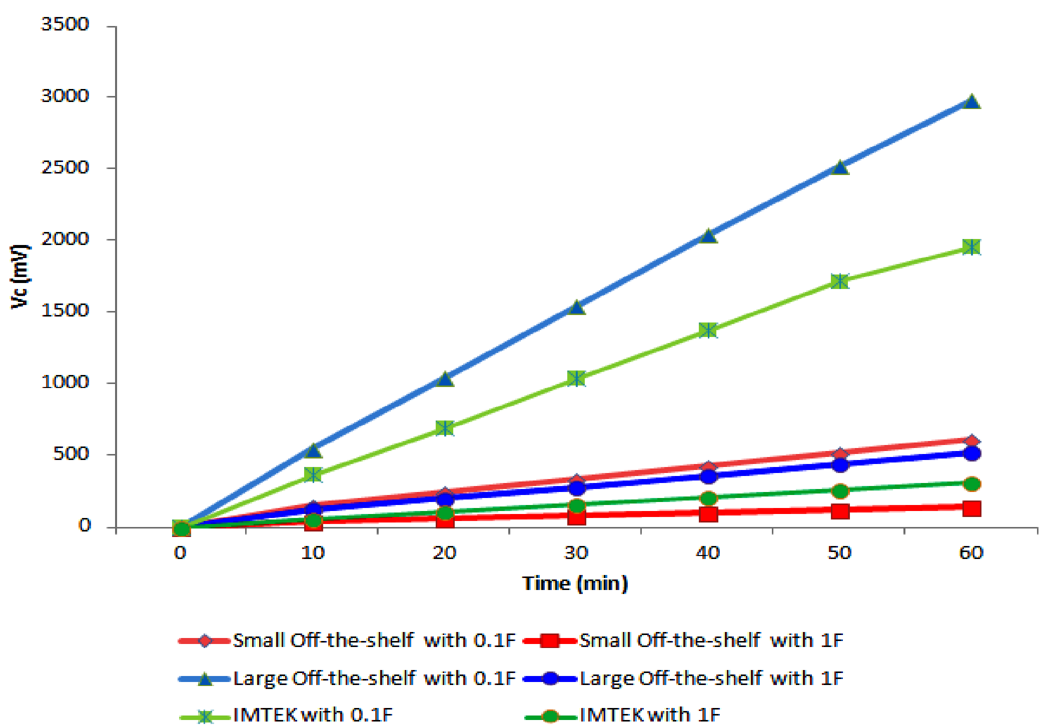


Figure 17. Capacitor voltages for the receiver system working at 200lux.

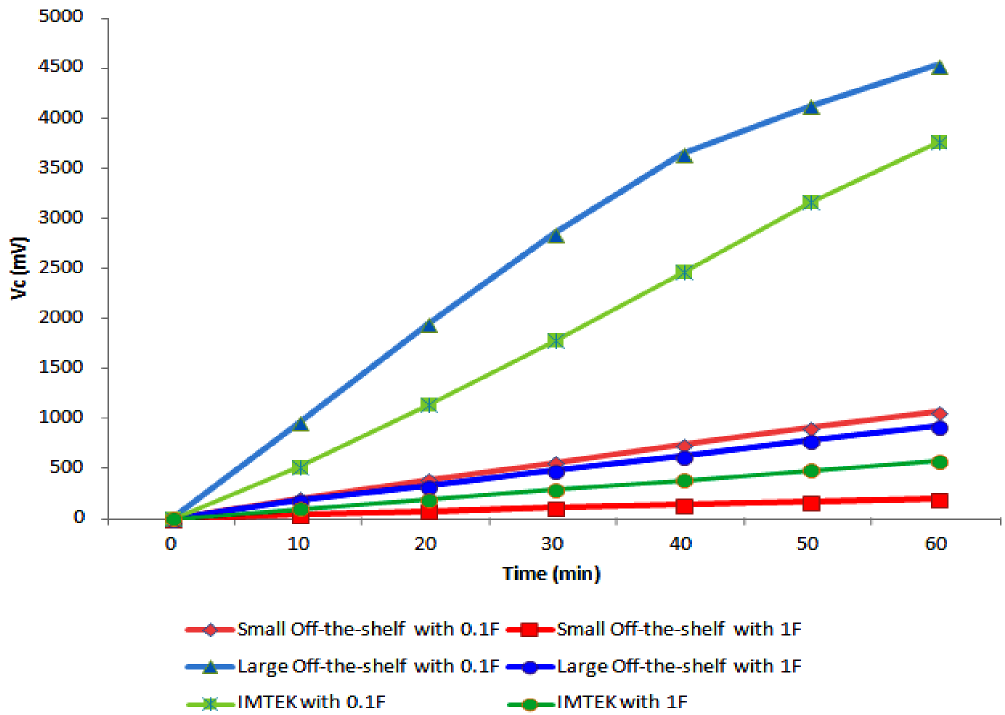


Figure 18. Capacitor voltages for the receiver system working at 400lux.

As seen in previous graphs (and Appendix B), the voltage values measured when the Large Off-the-shelf solar panel was used as source supply are always higher than those of IMTEK and Small Off-the-shelf solar panels. The same behavior can be seen in other tests when charging a super-capacitor using each of the three solar panels with equal light intensity level. Results also show that voltage values from IMTEK and Large Off-the-shelf solar panels are sometimes higher than voltage values from Small Off-the-shelf solar panel. Moreover, it can be noted that voltage values corresponding to the Large Off-the-shelf solar panel at 200lux, are even higher than voltage values corresponding to the Small Off-the-shelf solar panel at 400lux.

The results demonstrate that the Large Off-the-shelf solar panel can provide 3 or 4 times more electrical energy than Small Off-the-shelf solar panel. This energetic difference is proportionally related to the cell area size. In general, the set of tests performed to the solar panels allowed us to know that despite the Small Off-the-shelf solar panel has the best results in terms of frequency response, the Large Off-the-shelf solar panel provides the best energetic capabilities. This led us to choose the Large Off-the-shelf solar panel as the right choice for charging super-capacitors and powering the wake-up receiver, considering the application scenarios, where low light intensities or intermittent light exposure exist.

3.1.2 Super-capacitors

The AS3933, the active component used at the receiver side in this project, requires power to keep its configuration [25], but it is known that in many indoor applications light is not always needed. Therefore, storing the energy at the receiver side is needed to compensate the energy leakage occurring when the lights are off. To solve that requirement, we followed the idea of using a super-capacitor instead of using batteries, as energy storage of the energy-autonomous wake-up receiver. For that reason, it is also important to choose a suitable super-capacitor, with enough capacity to keep the receiver energized during long darkness periods. It is also necessary that the chosen capacitor has a low leakage current as this feature is related to the energy retaining ability.

In this set of tests, the capacity of retaining energy for longer time is measured in two super-capacitor choices. The tests are performed by measuring the voltage level of a 0.1F/5.5V and a 1F/5.5V super-capacitor in discharging process. Such values of capacitance are achieved thanks to modern manufacturing technologies in capacitors, and are large enough values to be used in the wake-up receiver. In the first tests, super-capacitors are previously charged at 3.6V (AS3933 maximum operating voltage) and the voltage levels of the super-capacitors are measured every 10 minutes during 1 hour. For the leakage tests, the receiver circuit is not included to evaluate only the self-discharge performances. The self-discharging results are shown in Figure 19.

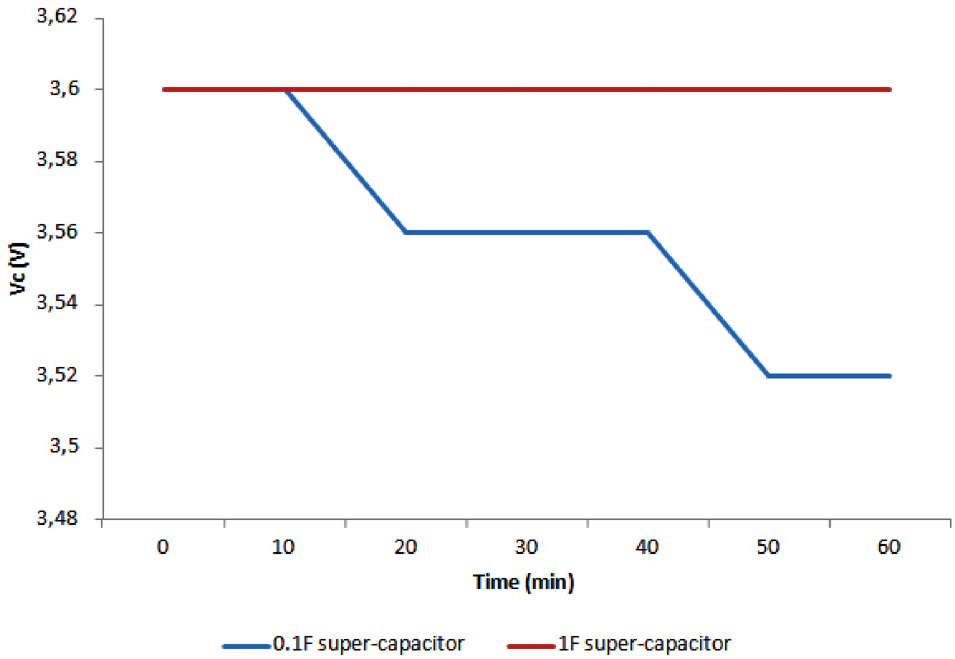


Figure 19. Super-capacitor leakage test results.

As seen in Figure 19 the 1F super-capacitor kept the same voltage during 1 hour, while the 0.1F super-capacitor voltage level decreased in around 80 mV after the same time. As expected, the results show, in spite of both super-capacitors having a large capacity for retaining energy for long periods, the 1F super-capacitor has lower influence of its leakage current when discharging, which means better capabilities for storing energy.

In a more realistic test, the receiver circuit is included as the discharging component, which allows us to know the best storage option to keep energized the AS3933 in darkness periods. Here again the values were obtained every 10 minutes during 1 hour, and the discharging processes started also at 3.6V with all light sources turned off. Figure 20 shows the correspondent results to these tests.

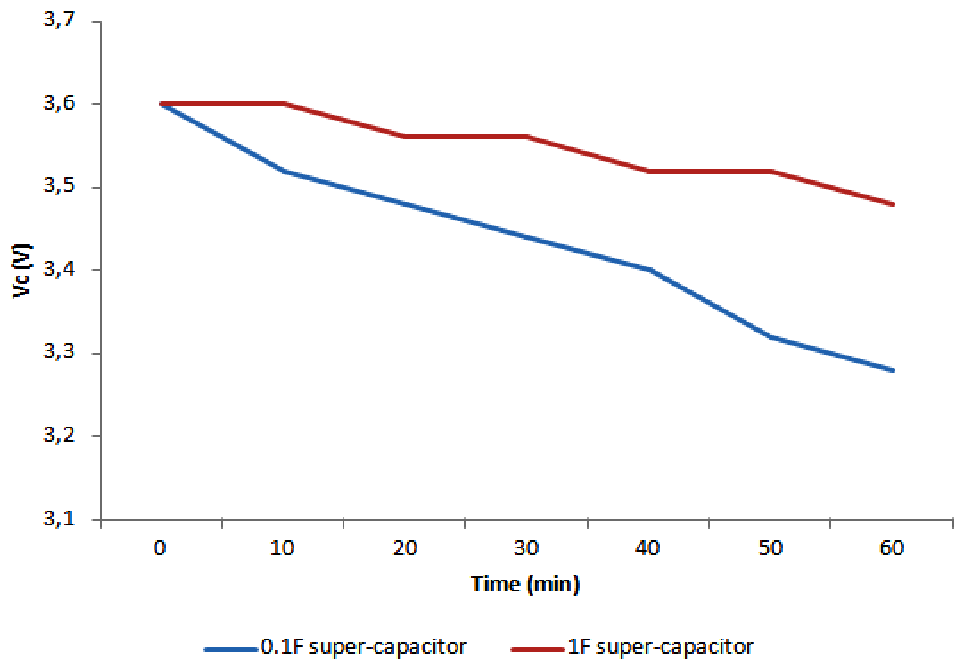


Figure 20. Super-capacitors discharging test being included in the receiver circuit.

As seen in Figure 20 a similar proportionality during the discharging process, is also seen when super-capacitors are included in the receiver circuit. After 1 hour the voltage level of 1F super-capacitor was dropped to 3.48V, while the 0.1F super-capacitor voltage level was dropped to 3.28V. As expected, the 1F super-capacitor discharging process is slower than the 0.1F super-capacitor, even including all receiver components and performing the same test. The results show, as previous test, that 1F super-capacitor can retain the energy for longer time, meaning a right solution for storing energy and powering the wake-up receiver circuit during long darkness time periods.

In general, the results of all performed tests led to the implementation of the Large Off-the-shelf solar panel along with the 1F super-capacitor as the right power solution. The option of using this couple of components makes possible to keep energized the wake-up receiver under almost any lighting situation in indoor environments. In spite of that, the 1F super-capacitor is still hard to be charged quickly as shown in Figure 17 and Figure 18.

Therefore, we propose a set of procedures that could be used for installing the energy-autonomous VLC wake-up system for the first time:

- Charge the 1F super-capacitor, by means of an external DC source supply, before installing the receiver
- Use the highest light intensity possible, also during idle hours, until the super-capacitor has been fully charged for the first time.

3.2 Transmitter

In the present work, the transmitter designed in [26] was adapted with several updates. The transmitter is composed of a Z1 low power wireless module from Zolertia [27], an adder, a LED driver and a 10W LED. Z1 device, shown in Figure 21, is a low cost, small footprint programmable module that is used as modulator.

Figure 21. Z1 from Zolertia.

Z1 can be configured, connecting a computer through its USB port, to compose a wake-up frame and modulate an OOK signal readable by the AS3933 at the receiver side. The modulated signal is delivered to the adder through three Z1 ports of 3V each, corresponding to JP.P4.0/TB0, JP.P4.2/TB2, JP.P4.7/TBCLK of JP1B ports, as shown in Figure 22. The adder performs the addition of the three input voltages, delivering a maximum of 9V to the LED driver when all ports are put at “1”. The LED driver is mainly composed by a general purpose transistor working in switching regime that drives the collector current and also the LED light according to the input OOK modulated signal.

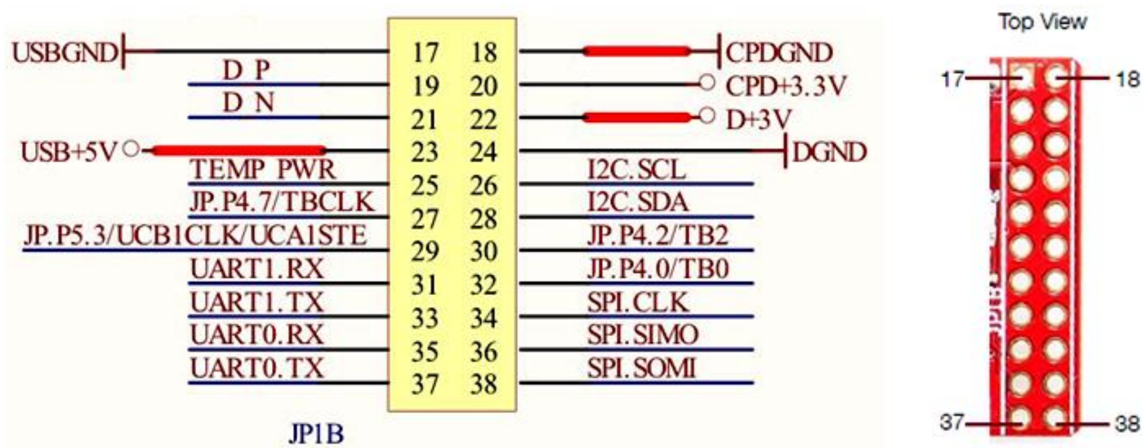


Figure 22. East port JP1B: diagram and real view.

Compared to the design in [26], a 15kΩ resistor was included between the negative pin of the operational amplifier and ground, working in parallel with other 15kΩ resistor. The new configuration of resistors improved the performance of the adder, providing better response at the output. Also, in the board in which the adder and the LED driver are built, a ground connection was included from the ground pin of the power supply that feed both circuits. The new connection improved the stability of the circuit and the system performance in general. The BC547A transistor included in the LED driver was also replaced by a 2N3904. The new transistor keeps the same driver performance but supports higher collector current avoiding any possible break up. Finally, the way to power the Zolertia Z1 module from the USB connection was changed to the pin 23 (USB+5V) and 24 (DGND) of the port JP1B, applying up to 5Vdc from the power supply. This change enabled to use the USB port just for configuring the Z1 module. This, in turn, removed the USB ground connection from the computer; solving the anomalies in the transmitted signal caused by the different ground sources. The detailed schema of the transmitter is shown in Figure 23.

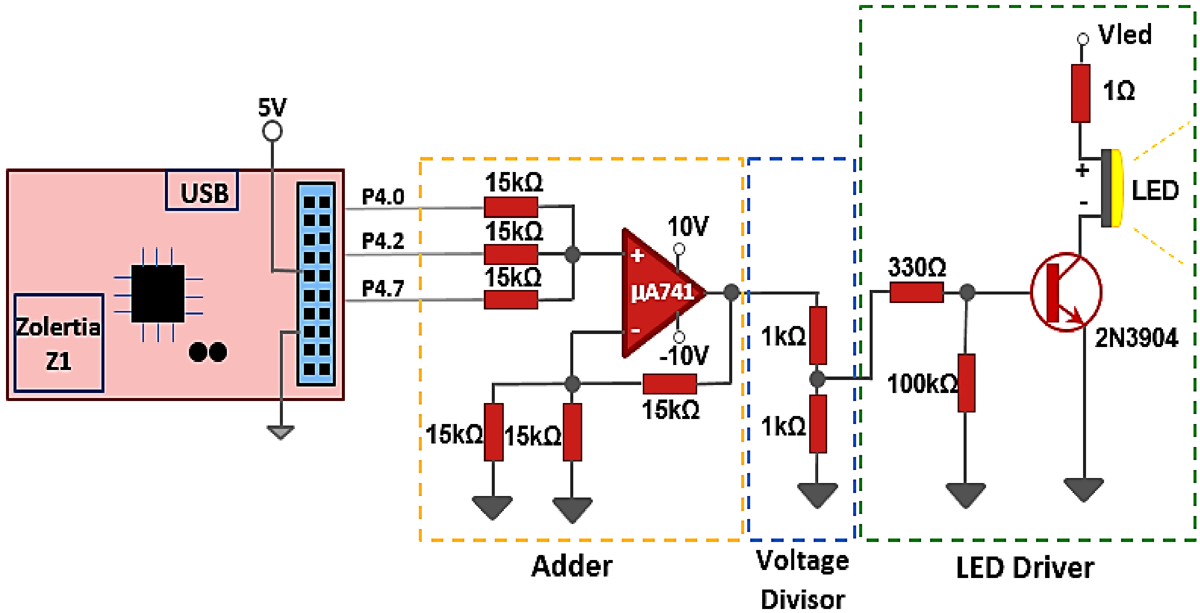


Figure 23. Circuit diagram of the wake-up transmitter.

3.2.1 Wake-up calls signal format

Austriamicrosystems provides in AS3933 datasheet [25], a wake-up call signal format shown in Figure 24. This format should be fully readable by the chip to activate the wake-up interruption. The wake-up frame is composed by: (1) a carrier burst, (2) a separation bit, (3) a preamble, (4) a pattern field and optionally (5) an optional data field.

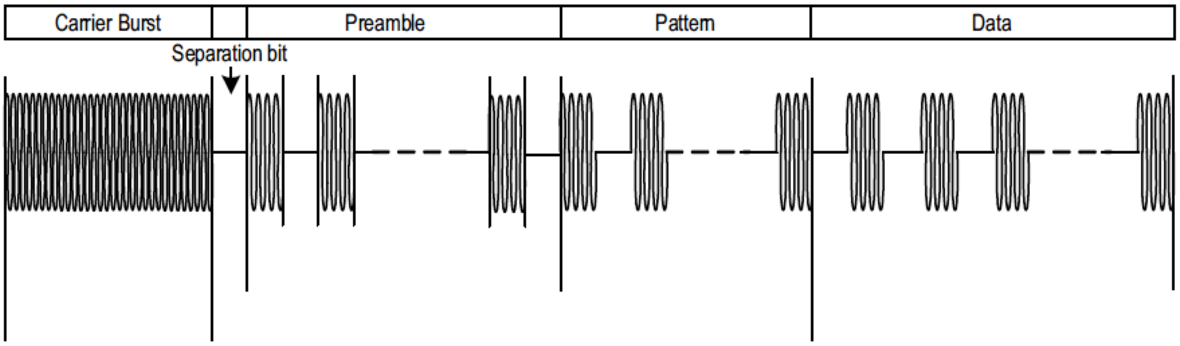


Figure 24. Austriamicrosystems wake-up signal format proposal.

In [26] an adaptation to the Austriamicrosystems wake-up signal format was purposed as shown in Figure 25. The length of the carrier burst and bit duration was set according to the period of the clock generator and the period of the frequency carrier. Also the signal was adapted for using Manchester coding and the data field was not used.

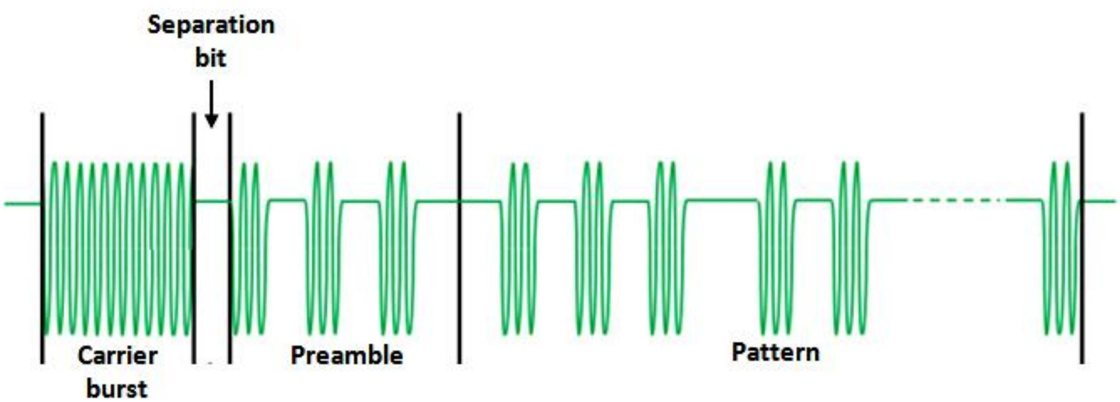


Figure 25. Wake-up signal format purposed in [26] and used in this project.

In this project the signal format purposed in [26] is maintained. As commented before, in the transmitter three Z1 ports of 3V each, are used as signal output (P4.0, P4.2 and P4.7), so the maximum voltage level achieved at the adder output is 9V. For the "1" logic bit signal, based in OOK modulation, the chosen Z1 ports are programmed to switch between 0V and 3V, meaning the LED light switching according the set frequency from the Z1 generator clock. For the "0" logic bit signal, two of the three ports (P4.0 and P4.2) are kept in "1" (3V) while the remaining port (P4.7) is kept in "0" (0V) during the bit duration. This means that when transmitting a "0" logic bit signal, the voltage at the adder output is 6V, avoiding the LED to keep in off during the bit duration and reducing the flickering effect. The code used in this project and elaborated in [26] for configuring the Z1 chip to perform the wake-up signal format was written in C language and it is presented in Appendix C of the current project.

4 PERFORMANCE EVALUATIONS OF THE WAKE-UP SYSTEM

Having tested and selected the right set of components to develop an energy-autonomous wake-up receiver, it is required to test the system performance. Distance and angle tests based on the light intensity, interferences tests and realistic common office hours tests are useful in knowing some characteristics, properties of functionality and reliability of the system under realistic indoor environments. In order to enumerate the success of the wake-up functionality of the system, the probability of detecting wake-ups was calculated in the following tests, relating the number of wake-up calls generated by the receiver with a known amount of 50 wake-ups frames sent by the transmitter. These tests and its results are detailed below.

4.1 Performance evaluation based on the light intensity

The set of tests to analyze the system performance metrics for different light intensity values observed in realistic indoor environments are described in this epigraph. Tests were firstly done at certain distances according to indoor lighting standards, secondly, the receiver was placed at the worst possible operating positions in an indoor space.

4.1.1 Performance evaluation based on indoor lighting standards

As the developed wake-up communication system uses VLC as media, it is important to relate the performance evaluation tests to the realistic light intensity values. Lighting standards allow knowing the right levels of light for any place and activity [24], and therefore, next performance evaluation tests are based on these indoor lighting standards. According to these standards, a 700lux level corresponds to the maximum level required for an office, 400lux is the normalized light intensity level for places where certain visual attention is required like most of the offices and some places at home, the standard for general lighting at home is 200lux and the minimum level permissible for general illumination at home is 50lux, i.e., used for corridors or stairs.

4.1.1.1 Testing the system for different distance and angles

In this test the receiver was placed in a straight line relative to the LED at different distances where the LED, sending OOK wake-up frames, can provide light intensity levels similar to those levels standardized for an office and for home. At approximately 0.4m a value of 700lux was achieved, a light intensity value of 400lux was measured at approximately 0.5m, 200lux was measured at 0.7m and 50lux were achieved at 1.4m. Also, at each point the solar panel was rotated to measure the light intensities and wake-up probabilities for varying angles and distances, while the LED was powered with 31V. The test setup is shown in Figure 26.

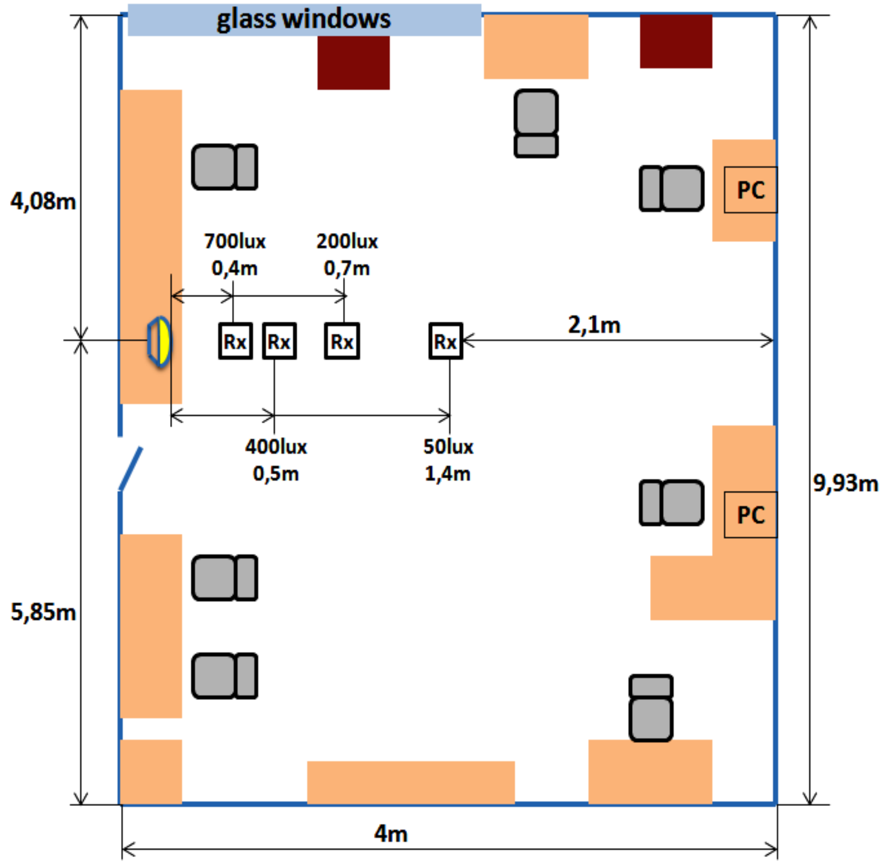


Figure 26. Distance and angle test setup for the indoor lighting standards.

In addition, the super-capacitor was previously charged using a DC source supply at a voltage level higher than 2,4V, corresponding to the AS3933 minimum operating voltage level [25]. Table 1 shows the obtained values for this test. In the table, measurements at 0° corresponds to the position of the solar panel directly facing the LED, then the solar panel was rotated clock-wise for measurements at 90°, 180° and 270°. In the table, columns "LI" correspond to the light intensity levels measured for every position and angle, using a lux-meter and given in lux, while "P" columns correspond to the computed probability of detecting wake-ups given as percentage, based on the number of wake-up interruptions generated by the receiver watched in an oscilloscope.

	Wake-up probability							
	0º		90º		180º		270º	
	LI(lux)	P(%)	LI(lux)	P(%)	LI(lux)	P(%)	LI(lux)	P(%)
IMTEK	50	18	8	84	3,8	92	3,6	92
	200	92	18	84	5	86	15	0
	400	90	22,8	2	5,8	4	23,2	0
	700	90	25	0	7,3	0	32	2
Small Off-the-Shelf	50	94	8	88	3,8	92	3,6	92
	200	94	18	92	5	92	15	94
	400	94	22,8	92	5,8	92	23,2	30
	700	94	25	0	7,3	90	32	4
Large Off-the-Shelf	50	88	8	94	3,8	92	3,6	4
	200	94	18	0	5	0	15	0
	400	94	22,8	0	5,8	0	23,2	0
	700	84	25	0	7,3	0	32	84

Table 1. Probability of detecting wake-up signals and light intensity values with varying distances and angles on a straight line.

Results show that the receiver is capable of detecting wake-ups at 0° for any of the standardized light intensity levels and using any of the solar panel types. High wake-up probability values, more than 80%, were measured at 0°, corresponding to the directed line-of-sight link configuration. The fact of detecting wake-ups calls at different angles than 0°, demonstrates an advantage of the developed system, i.e., being capable of detecting wake-ups from the reflected lights. This corresponds to the non-directed line-of-sight and non-directed non-line-of-sight settings and is very typical situation in indoor environments due to presence of walls and objects. Also, results demonstrated the high sensibility of the system through high wake-up probabilities achieved even at very low light intensity levels, for instance 92% of wake-up probability at 3.6lux.

At extreme cases of rotating the solar panel at 90°, 180° and 270°, sometimes high amount of wake-ups were detected, however not in accordance with the light intensity level. In some cases, for instance using the Small Off-the-Shelf solar panel rotated at 270°, placing the receiver closer to the transmitter, receiving higher light intensity from the transmitter LED, i.e. 4% at 32lux, the probability of detecting wake-ups is lower than placing the receiver at further distances, receiving lower light intensity levels from the transmitter LED, i.e. 92% at 3.6lux. Such behavior is related to the conditions of reflection for each position.

Differences can be observed between the wake-up probability values with respect to the solar panels. As the probability of detecting wake-ups is related to the frequency response property and the sensibility of the solar panels, the Small Off-the-Shelf provided the best results of wake-up probability as expected. Unexpected results can be noted when using IMTEK solar panel, the low probability of detecting wake-ups at 0°, i.e. 18% at 50lux, is lower than when the solar panel is rotated, receiving lower light intensity levels, i.e. 92% at 3,6lux at 270°. Such behavior could be related to the properties of the solar panel for detecting wake-up calls and also the conditions of reflections for each position. Although when using the Large Off-the-Shelf solar panel the receiver provided the lower wake-ups probability values, it is suitable for detecting wake-up calls at 0° under any standardized indoor light intensity level. Also using the Large Off-the-Shelf solar panel, the receiver provided probability values higher than 80% from reflected wake-ups at determined angles according to the light intensity level and condition of reflection of determined positions in this realistic indoor scenario evaluated.

4.1.1.2 Measuring supercapacitor maximum voltage level according to light intensity standards

Super-capacitor maximum voltage level depends on the powering properties of the used solar panel as well as the light intensity level arrived to the solar panel position. A set of tests was done to relate the standardized indoor light intensity levels with the super-capacitor maximum voltage level given by the solar panel at the super-capacitor position in the receiver circuit.

In these tests, the maximum voltage level that the super-capacitor should achieve at the end of any charging process is measured between the two connection points of the super-capacitor using an oscilloscope, but without including the super-capacitor. If the super-capacitor is included, the voltage level between their two connection points is set by the super-capacitor charge level in that moment, which very often does not correspond with the maximum voltage level. Also, as the solar panel position changes frequently along this tests, the super-capacitor charge will change giving non-accurate voltage values between the two tested points, therefore super-capacitor should be removed during these tests.

The tests were done using the three options of solar panels in independent way to compare the results. The receiver was placed at such distances, in straight line, at which the light intensity, measured with a lux-meter, corresponds to standardized indoor levels, similar to the previous test. At the transmitter side the Z1 was configured to transmit wake-up calls and the LED source supply was set at 31V, while other light sources were kept in off. The graphs of the Figure 27 show the tendency of the obtained results and all tests values are shown in Table 2.

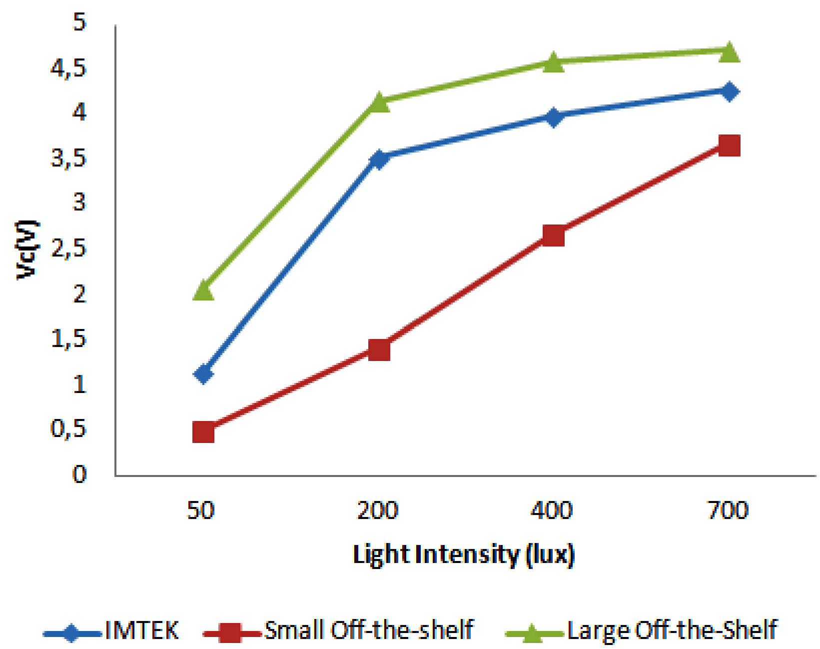


Figure 27. Super-capacitor maximum voltage levels according to light intensity standard levels using the three solar panels options.

	IMTEK	Small Off-the-Shelf	Large Off-the-Shelf
Light Intensity (lux)	Vc (V)	Vc (V)	Vc (V)
50	1,16	0,52	2,08
200	3,52	1,42	4,16
400	4,00	2,68	4,60
700	4,28	3,68	4,72

Table 2. Values of super-capacitor maximum voltage levels related to light intensity standard levels using the three solar panels options.

As expected, results show that the Large Off-the-Shelf solar panel provides the best voltage characteristics for powering the super-capacitor, while the Small Off-the-Shelf provides the lowest voltage levels at the different indoor light standards levels tested. These tests allowed to know under which normalized light intensity levels the receiver is capable to operate in energy-autonomous mode. Analyzing results of the TABLE can be seen that at 50lux, the lighting level does not allow any of the solar panels options to provide 2,4V at the super-capacitor position, corresponding to the AS3933 minimum operating voltage level

[25]. In this case, the receiver would need extra energy to operate. Also results show that the receiver is able to work in energy-autonomous mode from 200lux using IMTEK and Large Off-the-Shelf solar panels, and from 400lux when using the Small Off-the-Shelf solar panel, because under these lighting conditions the voltage level at the super-capacitor position exceeds 2,4V.

In addition, an extra test was done to find the light intensity threshold for each of the solar panels to make the wake-up receiver operational. From AS3933 datasheet [25], the minimum operating voltage level is 2.4V, meaning also the voltage level threshold for the receiver to work in energy autonomous way. Therefore, in this test the receiver was located such distance at which the voltage level at the super-capacitor position achieved 2.4V to find the light intensity level and the distance for the receiver to operate in energy autonomous manner using each of the three solar panels. In this test the conditions at the transmitter side were kept like in the previous tests, and also under no interference of other light sources. The voltage level of 2,4V at the super-capacitor position in the wake-up receiver was measured using an oscilloscope, moreover for each solar panel the distance between the transmitter and the solar panel was measured as well as light intensity level using a lux-meter. Table 3 shows the values corresponding to this test.

	Vc (V)	Distance (m)	Light Intensity (lux)
IMTEK	2.4	1,03	90
Small Off-the-Shelf	2.4	0,55	318
Large Off-the-Shelf	2.4	1,30	61

Table 3. Distance and light intensity values according to the AS3933 minimum operating voltage for each of the solar panels options.

As this test is related to the previous, results are proportional. The Large Off-the-Shelf achieves better results than the other two options, providing the threshold voltage value at

61lux, a light intensity level close to 50lux, the minimum normalized for indoor places, also the longest distance can be achieved for placing the receiver when using this solar panel, i.e. 1,30m. Using the IMTEK solar panel, the threshold voltage value is achieved at 90lux, which is also a light intensity level lower than 200lux, the level for general indoor lighting, but not when using the Small Off-the-Shelf solar panel. The Small Off-the-Shelf solar panel requires 318lux, the highest level of light intensity, to achieve the threshold voltage at the super-capacitor position, meaning a higher light intensity value than the level for general indoor lighting and the closest distance between the transmitter and the solar panel. In general, the Large Off-the-Shelf solar panel demonstrated again to provide the best powering properties, requiring the lowest condition in term of light intensity to provide a suitable level of electrical energy.

4.1.2 Testing the receiver at extreme cases of distances and angles

The following tests, placing the receiver in the worst possible conditions in a representative office environment were also performed to evaluate the system performance and to analyze more in depth the capabilities of the system. For these tests, the receiver was placed in different positions inside an office room, i.e., for different distances and angles, and rotating the solar panel from 0° to 90°, 180° and 270°. Tests were performed with the room lights turned off, and LED powered at 31V. In addition, the super-capacitor was previously charged using a DC source supply at a voltage level higher than 2,4V, corresponding to the AS3933 minimum operating voltage level [25]. The locations and angles tested within this office environment are shown in Figure 28. Table 4 shows the results of these tests, again including the "LI" columns, which correspond to the received light intensity values, measured with a lux-meter and given in lux, for each receiver position. In the table, "P" columns are also included, corresponding to the computed probability of detecting wake-ups given in percentage. Note that the angles in Table 4 are relative to the length of the room (vertical edge on the left in the figure) and hence angles relative to LED depend on the location.

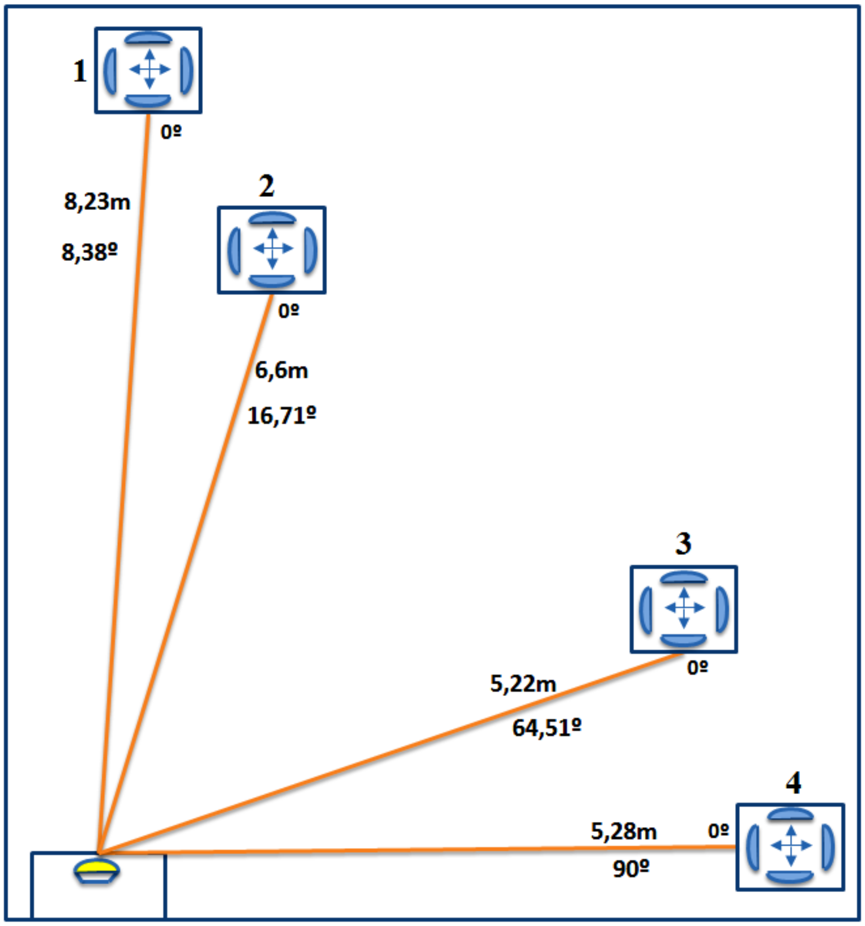


Figure 28. Positions (distance and angles) tested for probability of detecting wake-up frames.

	Small Off-the-Shelf							
	0°		90°		180°		270°	
Position	LI(lux)	P(%)	LI(lux)	P(%)	LI(lux)	P(%)	LI(lux)	P(%)
1	2	94	0,4	12	0,8	36	0,4	6
2	3,8	92	1,4	94	0,7	36	1,2	94
3	1,5	94	2,3	92	0,5	58	0,4	92
4	1,3	94	0,3	40	0,5	8	0,2	20

(a) Probability of detecting wake-ups and light intensity values using Small Off-the-Shelf solar panel.

	Large Off-the-Shelf							
	0°		90°		180°		270°	
Position	LI(lux)	P(%)	LI(lux)	P(%)	LI(lux)	P(%)	LI(lux)	P(%)
1	2	90	0,4	44	0,8	42	0,4	30
2	3,8	96	1,4	92	0,7	30	1,2	92
3	1,5	92	2,3	90	0,5	24	0,4	94
4	1,3	92	0,3	50	0,5	20	0,2	38

(b) Probability of detecting wake-ups and light intensity values using Large Off-the-Shelf solar panel.

	IMTEK							
	0°		90°		180°		270°	
Position	LI(lux)	P(%)	LI(lux)	P(%)	LI(lux)	P(%)	LI(lux)	P(%)
1	2	86	0,4	86	0,8	76	0,4	0
2	3,8	78	1,4	78	0,7	90	1,2	48
3	1,5	86	2,3	92	0,5	92	0,4	94
4	1,3	86	0,3	90	0,5	0	0,2	4

(c) Probability of detecting wake-ups and light intensity values using IMTEK solar panel.

Table 4. Probability of detecting wake-up signals and light intensity values with varying distances and angles at the locations of **Figure 28**.

Note that in most of the cases the probability of detecting wake-ups under extreme conditions is higher than the 50%, and even in certain positions the probability is close to or higher than 90%. Also it can be noted that the Large Off-the-Shelf solar panel, in spite of having shown the worst frequency response results, it provided suitable values of probability of detecting wake-ups under the conditions of this test.

Light intensity measures are useful to know under which light level conditions the system can work. Analyzing the light intensity tests, it is interesting to know that even for a light intensity of around 1lux, similar to a moonlit night, the receiver is able to work, demonstrating the high sensibility of the receiver wake-up signal detector. In spite of that, from previous test results, under these lighting condition no one of the solar panels options can provides enough energy to keep the super-capacitor charged at more than 2,4V [25]. This means that for all the receiver lighting conditions tested, the super-capacitor is in discharging process, so it is required extra energy to keep the receiver operational, also the lighting conditions do not allow the receiver to operate in energy-autonomous mode.

Other key aspect to be analyzed is that, as in the previous wake-up probability test, sometimes the number of detected wake-ups does not correlate with the distance, keeping the same angle of rotation. The reason is that the system demonstrated one more time that it is able to detect reflected wake-up signals, and in some cases the probability of detecting wake-ups depends also on the conditions of light reflection of the position. Such behavior of detecting reflected wake-up signals corresponds to the non-directed line-of-sight and non-directed non-line-of-sight settings, and was totally proved when the receiver generated wake-up interruptions at a rotation angle of 180°, facing opposite to the LED. Detecting reflections is an advantageous feature that increases the performance of the system even under unfavorable conditions, providing crucial flexibility for the potential user applications.

4.2 Efect of light interference

Another feature of indoor environments is the presence of interferences from different light sources. Indoor environments are normally illuminated using artificial light sources such as light powered with AC (alternating current) like fluorescent lamps, or LEDs powered with DC (direct current). Also indoor rooms could have windows facing outside, taking advantage of the sunlight as a natural light source to illuminate the rooms. The interference of any of such light sources in a place where a wake-up system using VLC is installed may affect the quality of the transmitted signal. Therefore, it is required to evaluate the wake-up system performance under the influence of other light sources.

To perform these tests, a sweep of the transmitter LED voltage was done in every test to vary the light intensity levels obtained at the receiver side, which was done by varying the LED source supply voltage from 25V to 31V measuring every 0.5V. Tests were done first, under no interference conditions, second, under AC light interference, third, under DC light interference and finally, under sunlight interference. The receiver was tested using the three options of solar panels, and the super-capacitor was previously charged using a DC source supply at a voltage level higher than 2,4V, corresponding to the AS3933 minimum operating voltage level [25]. In addition, the light intensity level was measured in every case along with the wake-up probability computation, following the same method of previous tests.

4.2.1 No light interference (base-line) performance

Firstly, the system was tested under no interference conditions, placing the receiver at 0.40m from the transmitter position. At this distance, setting the LED source supply at 31V, the light intensity level measured is around 700lux, the maximum standardized level for offices [24]. In this test the value of the ambient light intensity measured was around 0.3lux, keeping the room lights and transmitter LED turned off, such value is shown in Table C.1 in Appendix C in "LIo" column. The test starts setting the LED source supply at 25V, which means a level of lighting of 2.3lux at the solar panel position, and then the voltage of the LED source supply is increased up to 31V, performing tests every 0.5V. The values of voltage of the transmitter LED source supply, given in volt (V), are shown in the Table C.1 in Appendix C in "Vled" column. Figure 29 shows the respective results relating wake-up probability values for different LED source supply voltage levels , the light intensity values "LI" measured at the receiver side and the percentage of light intensity level "LIled" at the receiver side corresponding to the transmitter LED. The data values of the graph are provided in Table C.1 in Appendix C. "P" values correspond to the wake-up probability given in percent and "LI" values correspond to the light intensity levels measured at the receiver positions. Measured light intensity levels, given in lux, are the result of the addition of the light from any interferer source and the transmitter LED light for every voltage level of the transmitter LED source supply. “LIled” gives the percentage of the light intensity level coming from the transmitter LED of the total light intensity level measured at the receiver side. For this test, values of the “LIled” are high and most of them close to 100%, demonstrating that in this case the level of interfering light is almost imperceptible.

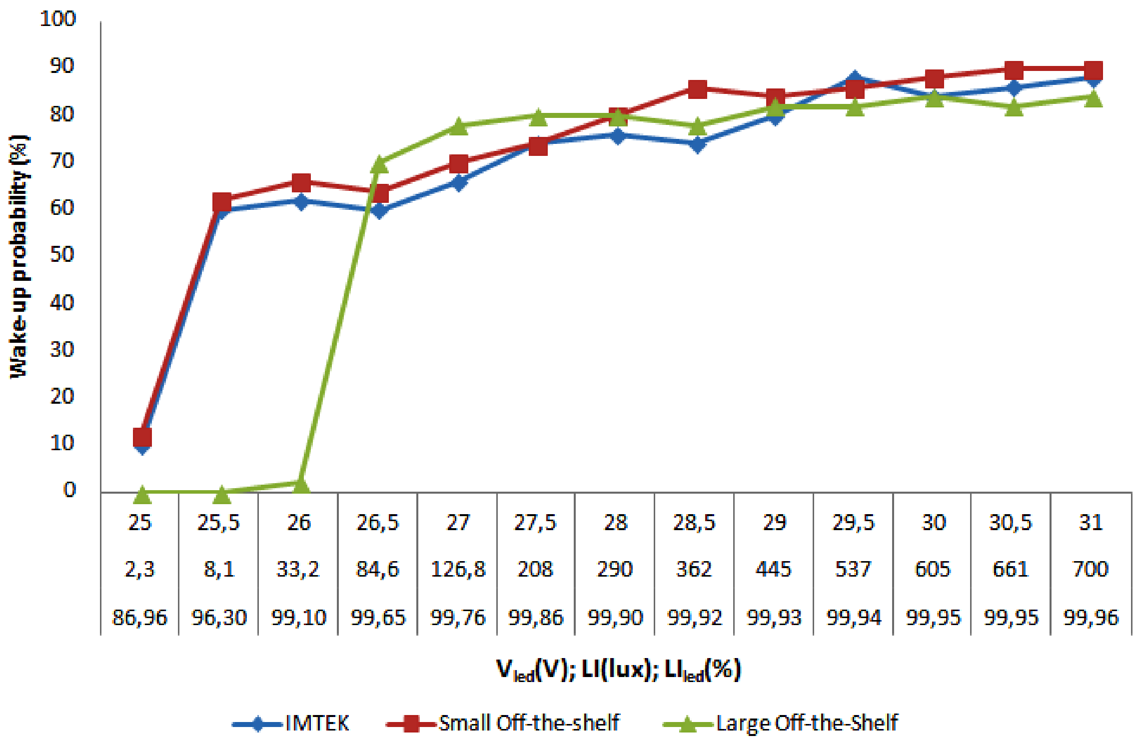


Figure 29. Probability of detecting wake-ups under no interference conditions.

In the figure, it can be seen that, when using IMTEK or the Small Off-the-Shelf solar panels, the probability of the receiver for detecting wake-up calls starts and achieves a value higher than 50% at lower light intensity levels than when using Large Off-the-Shelf solar panel. Also, analyzing more in depth the graph, it can be seen that Small Off-the-Shelf provides even higher probability values, at almost every light intensity level, than IMTEK solar panel.

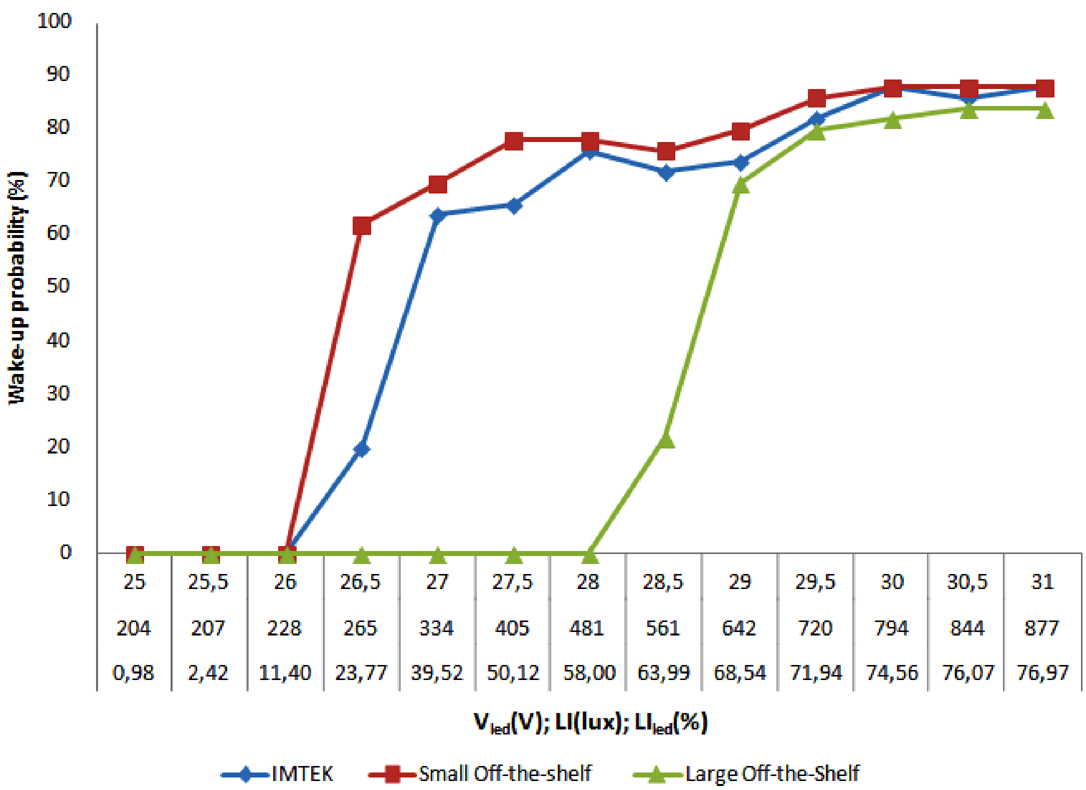
The behavior of the tested solar panels is related to the property of delivering a more readable wake-up signal to the receiver signal processor, so it depends on the frequency response characteristic of each of the solar panel. Therefore, results are, as expected, in correspondence to the frequency response values obtained previously. However, it can be seen that all of these solar panels options provide a suitable behavior for the receiver to detect wake-up calls in realistic indoor environments without the interference of other light sources. For instance, when setting the LED source supply at 27.5V, which corresponds to a light intensity level of 208lux, a value very close to the standardized level for general indoor lighting [24], the probability of detecting wake-up calls is higher than 70% using any of the solar panels options.

4.2.2 AC and DC lights interference tests

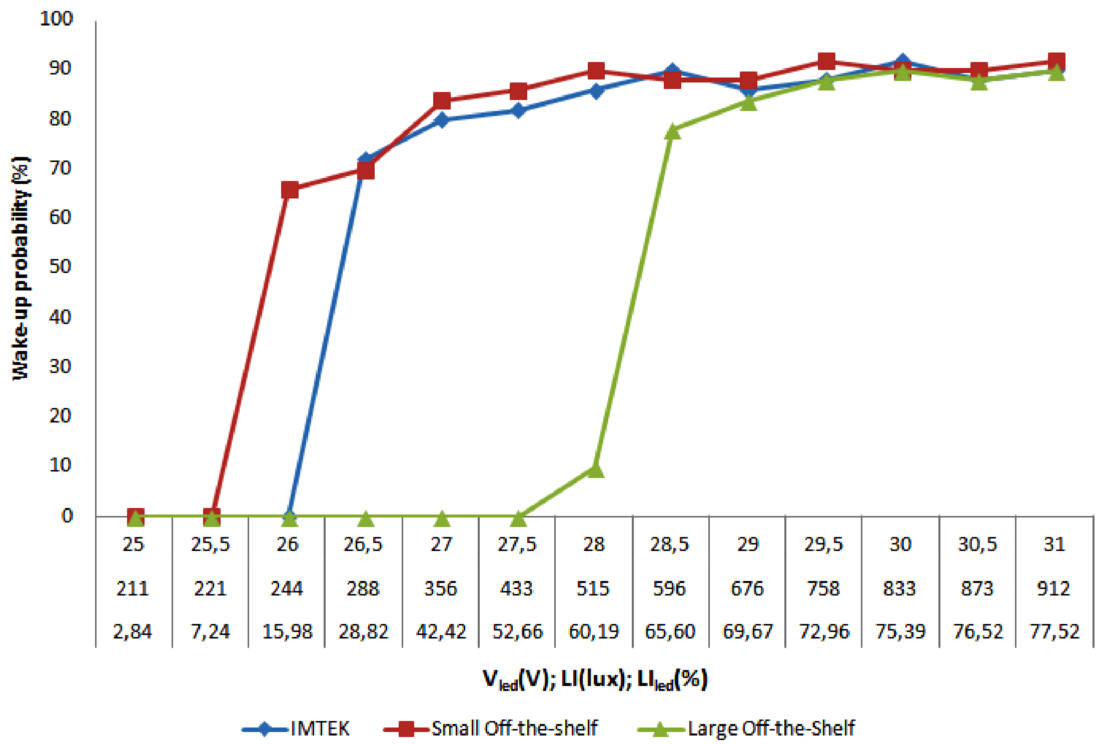
Secondly, the system was tested under interference of AC and DC light sources, placing the receiver at 0.40m from the transmitter, following the previous test conditions according to the office lighting standard. For these tests, an office florescent lamp was used as AC light source interferer and another LED light was used as DC light source interferer. The interferer LED lamp was located close to the transmitter LED and directed toward the solar panel.

In addition, the interferer light sources were located in such way that the receiver perceived around 200lux from such interferer light sources, according to the standard for indoor general light level. This level of light corresponds to the initial light level of the tests, measured when the transmitter LED was still turned off and is shown in Table C.2 and C.3 at Appendix C as “LIo” columns given in lux. The lighting level of the AC interferer light source, measured with a lux-meter, was exactly 202lux, while the lighting level of the DC interferer light source was exactly 205lux. Tests started setting the transmitter LED source supply at 25V, corresponding to a total of 204lux when AC lights were interfering and 211lux when DC light was interfering. The voltage level of the transmitter LED source supply was increased and wake-up interruptions were counted every 0.5V up to a maximum of 31V, meaning a total of 877lux under AC light interference and 912lux under DC light interference.

Figure 30 show the results of the tests, relating wake-up probability values with the LED source supply voltage levels, the light intensity values “LI” measured at the receiver side and the percentage of light intensity level “LIled” at the receiver side corresponding to the transmitter LED. Tables C.2 and C.3 at Appendix C show more in detail the values of these tests. In these tests, the values related with light intensity levels are different from the previous test because of the presence of light interference. For instance, the increase of the “LIo” values to approximately 200lux, increases the values of the “LI” columns but reduces the percentage values of the “LIled” columns.



(a) Probability of detecting wake-ups under AC interference conditions for the received interferer light intensity of 202lux.



(b) Probability of detecting wake-ups under DC interference conditions for the received interferer light intensity of 205lux.

Figure 30. Probability of detecting wake-ups under AC and DC interference conditions.

Tests results demonstrated that the developed wake-up receiver is capable of detecting wake-up calls even under interference of artificial light sources, being another advantageous property that enhances the system performance. Also, as in the previous test, it can be seen that when using IMTEK and the Small Off-the-Shelf solar panels the receiver provides better wake-up probability at lower light intensity levels than when using the Large Off-the-Shelf solar panel. Moreover, when using the Small Off-the-Shelf solar panel, the receiver provides the best wake-up probability values of the three options under artificial light interference conditions. This behavior was also expected due to the frequency response properties of each of the solar panels.

However, it can be seen that the wake-up probability values, even when using the Large Off-the-Shelf, are acceptable for the receiver to operate in realistic indoor scenarios, under interference of artificial light sources at standardized light intensity values. For instance, when setting the LED source supply at 29V, corresponding to light intensity levels higher than 600lux for both interference conditions, the probability of detecting wake-up calls is equal to or higher than 70% using any of the solar panels options. Such levels of light intensity are higher than the threshold light intensity level for any of the solar panels, found in section 4.1.1.2, meaning that the system can work in energy-autonomous mode. In addition, these values demonstrate that the developed energy-autonomous receiver can be operational even in cases with more than 30% of interferer light intensity level from artificial sources.

In addition, in spite of the AC and DC interference tests were done at the same interferer light intensity and at the same distance between transmitter LED and receiver, there are small differences in the results when using each solar panel. In every case, under LED light interference, the receiver starts detecting wake-ups with a lower voltage than under fluorescent light interference. A study of the AC fluorescent light waveform shows that, the signal received by solar panel, is nonlinear but oscillates at a frequency of around 100Hz. Therefore, the transmitter LED light must be strong enough to overcome the interference, as the LED signal and fluorescent light signals are mixed, the wake-up frames becomes more difficult to be detected by the AS3933. On the other hand, the LED interfering light has a linear waveform, being less problematic for the receiver to detect the wake-up frames when mixed with such interfering DC light. This behavior is due to that the AS3933 uses an envelope detector to perform the OOK demodulation.

4.2.3 Sunlight interference tests

Thirdly, the system was tested under the worst possible condition of interference, i.e., with sunlight interference. The transmitter was placed close to a glass window, illuminating toward inside the room, while the receiver was located in straight line facing the transmitter, as shown in Figure 31. Also tests were done at around midday, when the sun is in zenith position and its light is more intense. It is known that sunlight intensity can change between days and can change frequently during a day according to cloudiness behavior, also high building and tree shadows can vary the incidence of sunlight in indoor places with windows. These tests were done in different days, measuring and indicating the corresponding light intensity levels of the received sunlight.

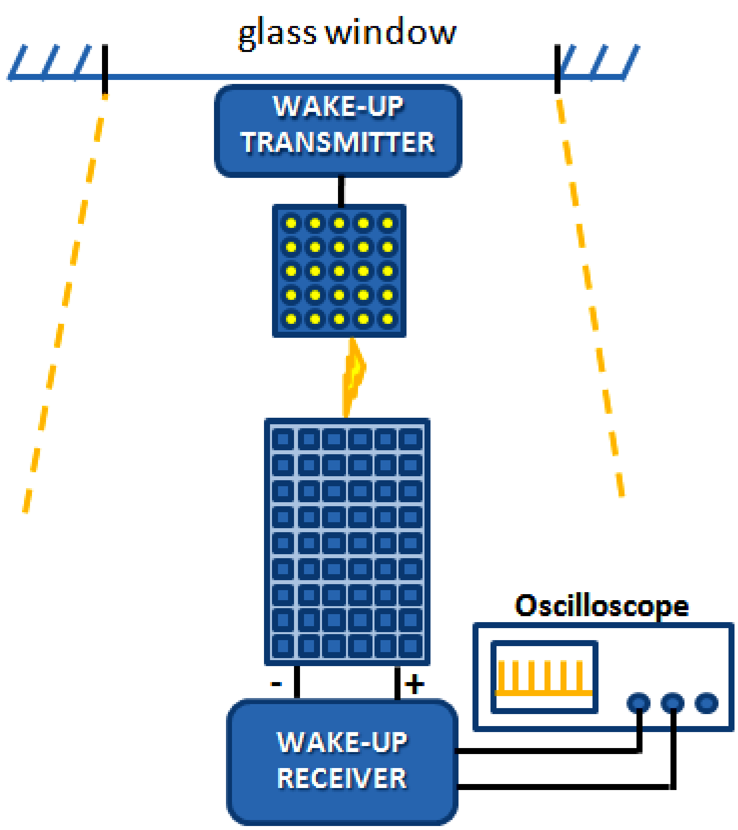
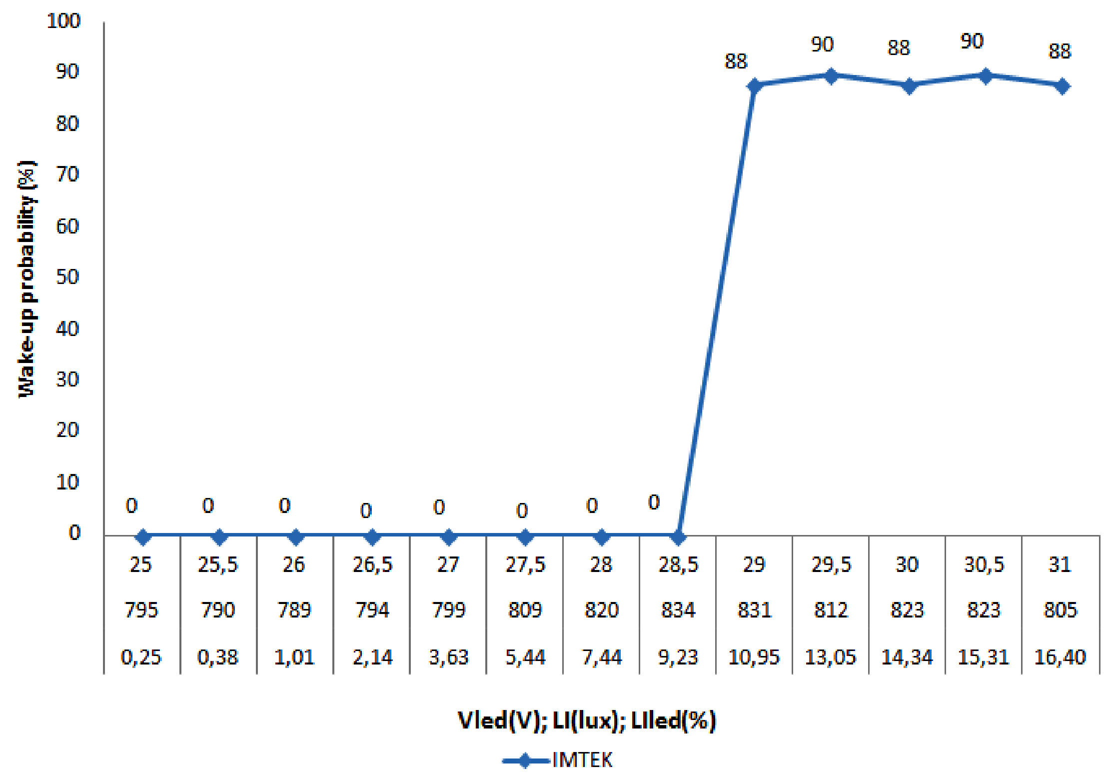
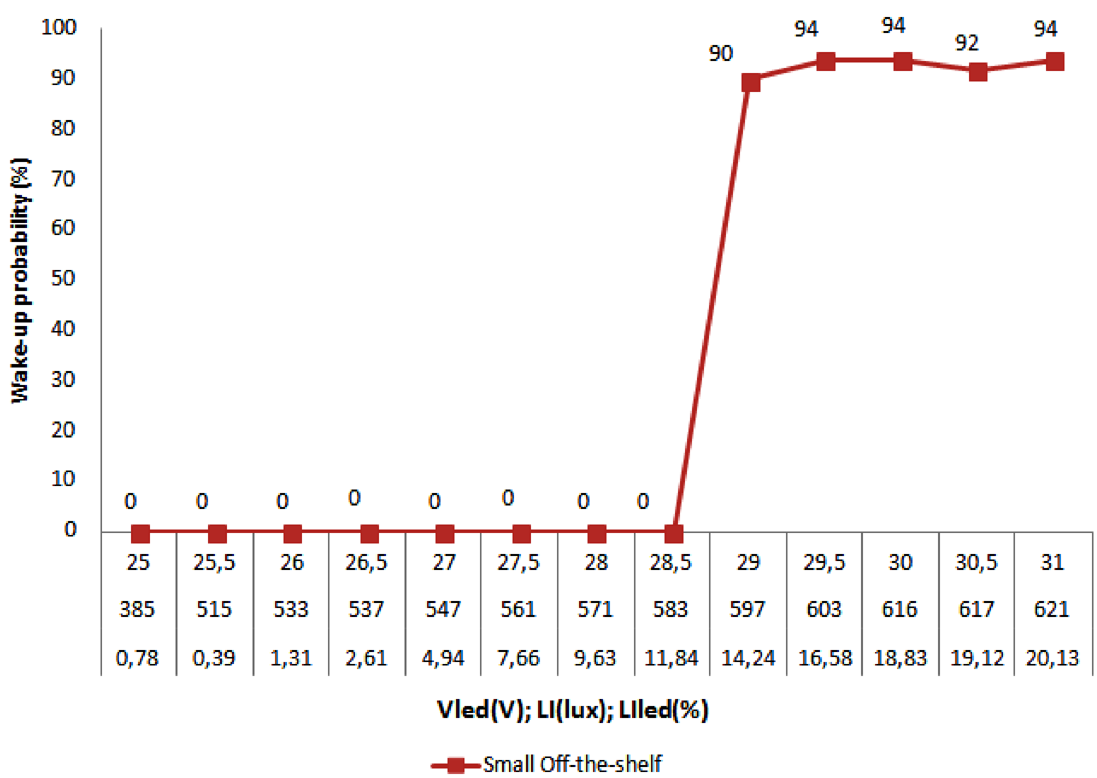


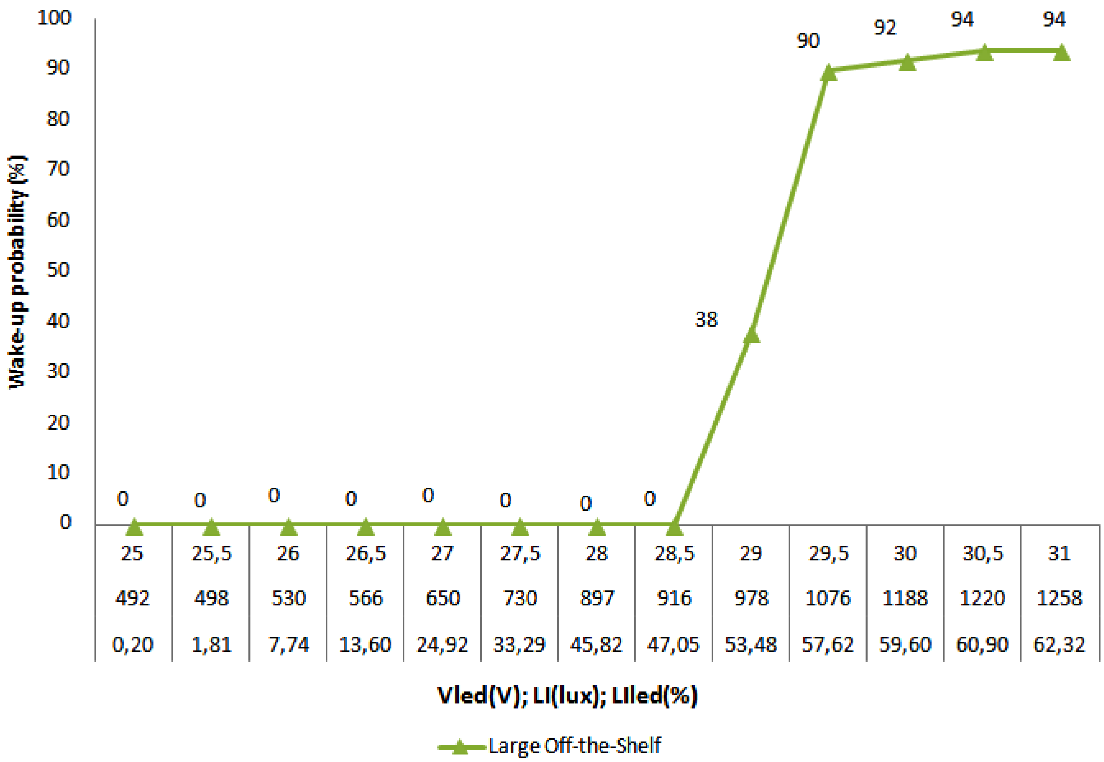
Figure 31. Wake-up probability test under sunlight interference conditions.

The presence of sunlight interference makes the conditions harder for the different solar panels to provide a clear wake-up signal to the receiver signal processor, making the performance of the three solar panels very difficult to compare. Therefore, sunlight interference tests were performed with different setups than previous interference tests. Receiver positions were set at such distances at which the receiver started detecting wake-up transmitted signals, setting the LED source supply at 29V, keeping a margin of voltage up to the maximum level supported by the LED source supply. The receiver was placed at 0.80m when using Small Off-the-shelf solar panel, at 0.65m when using IMTEK solar panel and at 0.30m when using Large Off-the-shelf solar panel. Also, an additional test was done by turning on the room lamps, adding AC interferer light to the sunlight interference tests, keeping the distance set for the receiver when using each solar panel. Figure 32 shows the results of this set of tests, relating wake-up probability values with the LED source supply voltage levels, the light intensity values "LI" measured at the receiver side and the percentage of light intensity level "LIled" at the receiver side corresponding to the transmitter LED.

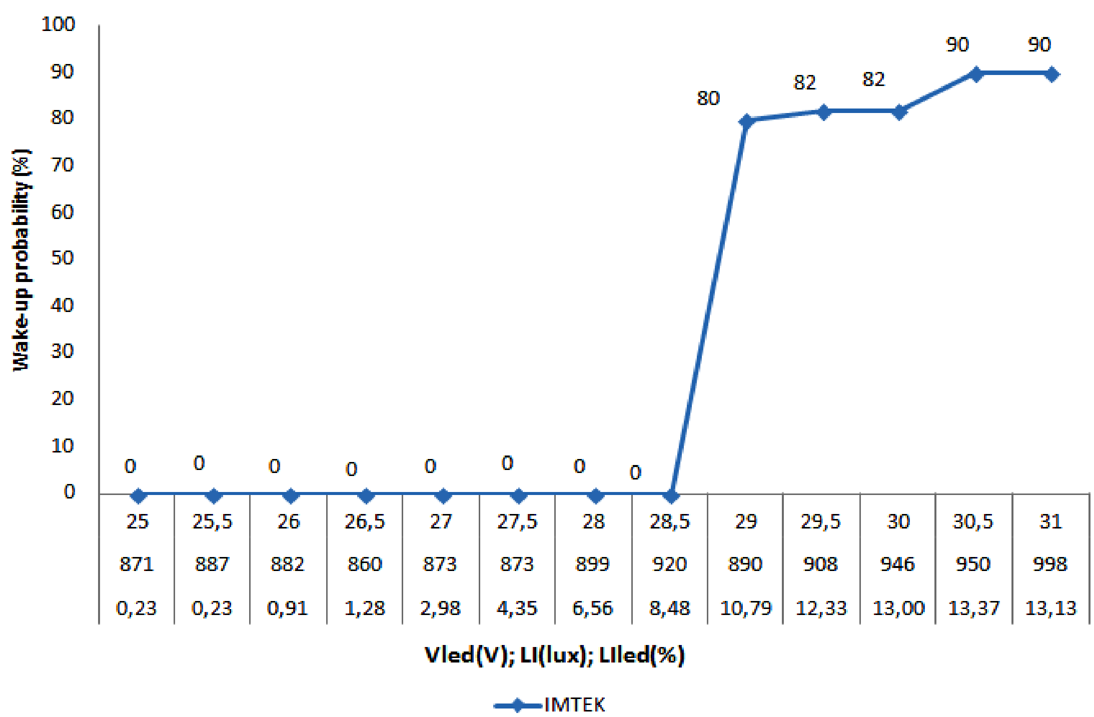
Some characteristics from previous interference tests were also applied in sunlight interference tests, for instance the variation of the voltage level of the LED source supply, also the way of measuring light intensity levels, using a lux-meter placed at the same position of the solar panels. Methods for counting wake-up interrupts and computing the probability of detecting wake-up calls were the same used in previous interference tests. Therefore, Tables C.4 and C.5 at Appendix C show all tests values, including the same columns parameters of the previous interference tests. For sunlight interference tests, the values of "LIo" columns change according to the frequent variation of the sunlight intensity, making other columns related to light intensity levels, like "LI" and "LIled", also to vary their values.

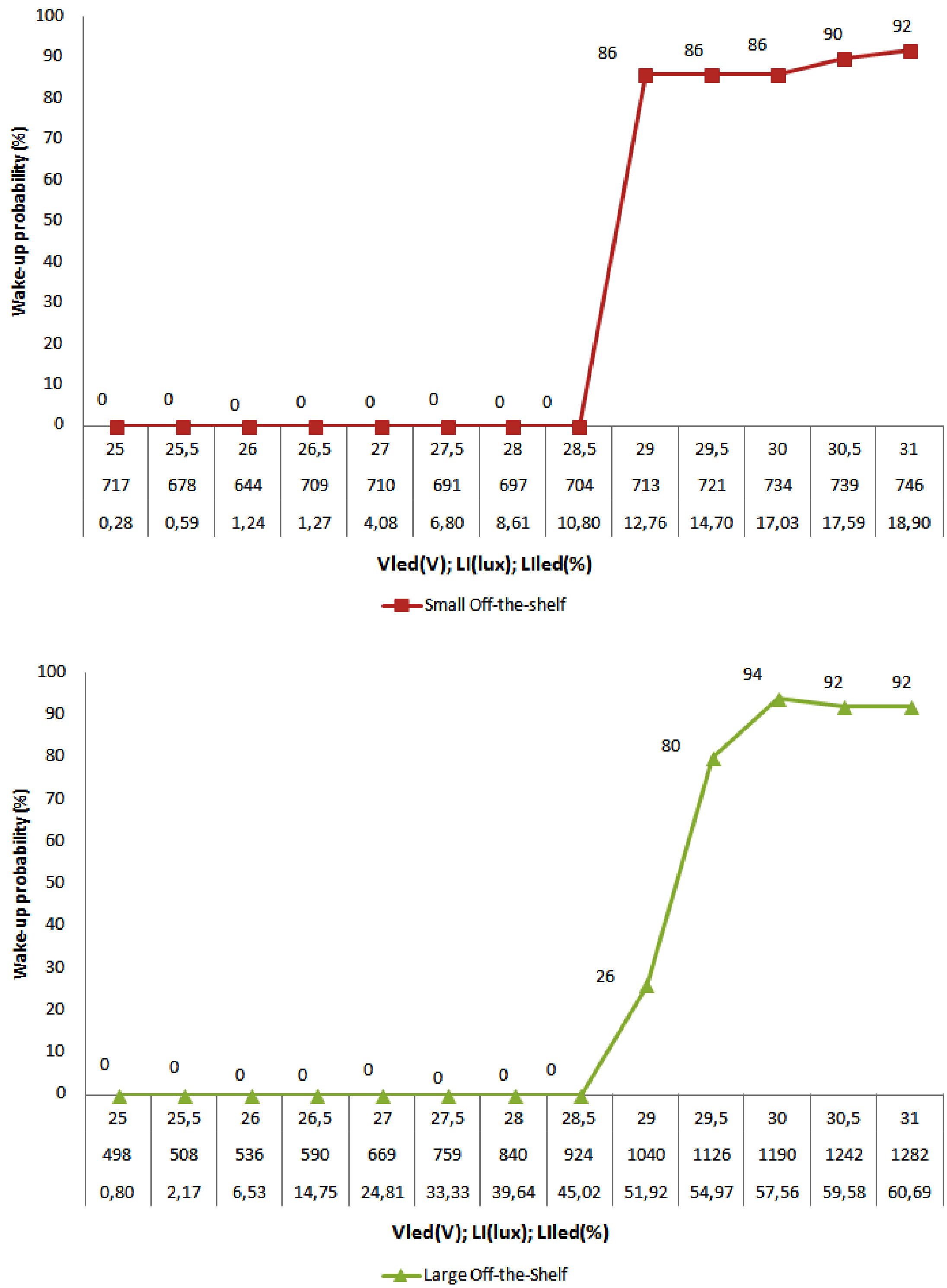

Wake-up probability (%)
100
90
80
70
60
50
40
30
20
10
0
0 0 0 0 0 0 0 0 88 90 88 90 88
25 25,5 26 26,5 27 27,5 28 28,5 29 29,5 30 30,5 31
795 790 789 794 799 809 820 834 831 812 823 823 805
0,25 0,38 1,01 2,14 3,63 5,44 7,44 9,23 10,95 13,05 14,34 15,31 16,40
Vled(V); LI(lux); LIled(%)
IMTEK


Wake-up probability (%)
100
90
80
70
60
50
40
30
20
10
0
0 0 0 0 0 0 0 0 90 94 94 92 94
25 25,5 26 26,5 27 27,5 28 28,5 29 29,5 30 30,5 31
385 515 533 537 547 561 571 583 597 603 616 617 621
0,78 0,39 1,31 2,61 4,94 7,66 9,63 11,84 14,24 16,58 18,83 19,12 20,13
Vled(V); LI(lux); LIled(%)
Small Off-the-shelf



(a) Probability of detecting wake-ups under sunlight interference conditions.





(b) Probability of detecting wake-ups under sunlight + AC interference conditions.

Figure 32. Probability of detecting wake-ups under sunlight and sunlight + AC interference conditions.

Results from sunlight interference tests demonstrated that the developed wake-up receiver is capable of detecting wake-up calls even under sunlight interference using any of the solar panel options. These tests allowed knowing another advantageous property that enhances the system performance. Also, as expected, results show that when using Small Off-the-Shelf and IMTEK solar panels the receiver provides better performance for detecting wake-up calls than when using the Large Off-the-Shelf solar panel. Moreover, best results were obtained when using the Small Off-the-Shelf solar panel, even taking into account that the receiver was tested at the highest distance when using this solar panel.

The results show that for any of the solar panels used, the light intensity levels at which the receiver starts operating are higher than the threshold light intensity levels found in section 4.1.1.2. Such conditions means that, in term of powering, the developed wake-up receiver can operate in energy-autonomous mode. It is also shown that when using IMTEK and Small Off-the-Shelf solar panels the receiver can detect wake-up calls with probability values equal to or higher than 80% having less than 15% of light intensity level from the transmitter LED. This behavior demonstrates the high sensibility of the receiver signal processor, being capable of operating even with up to 89,2% of interference. In the case of using the Large Off-the-Shelf solar panel the receiver requires more than 50% of light intensity level from the transmitter LED to operate. In this case the requirements in terms of light intensity levels are considerably higher than when using any of the other two solar panels options, but the receiver also demonstrated to operate in presence of approximately 50% corresponding to sunlight interference.

In general, interference tests demonstrated that the developed wake-up system requires better conditions in terms of distance and light intensity levels from the transmitter LED to operate in presence of interference of other light sources. The differences between light intensity values and the type of interference source affect the results of the tests significantly.

Moreover, the results were also very dependent on the solar panels used. Small Off-the-Shelf solar panel provided the best wake-up probability results for all performed interference tests, demonstrating to be most resilient against light interferences. Large Off-the-Shelf solar panel demonstrated to be weaker for detecting wake-up calls under light interferences. It provided low wake-up probability results and required better conditions during sunlight interferences tests. Such differences are related to the frequency response characteristics of each solar panel, which are also different, as was shown previously in section 3.1.1.1, corresponding to frequency response tests.

On the other hand, a key positive aspect proved in interference tests, is that the developed wake-up receiver is capable to detect wake-up transmitted signals in presence of other light sources. In spite of requiring better conditions for certain tests, the receiver detected wake-up calls using any of the three solar panel options. Also, it can be noted that the light intensity ratio for the receiver to detect wake-up calls starts around 50% of light intensity level from the transmitter LED, this respect to the total light intensity measured at the receiver side during sunlight interference tests. In case of artificial light interference tests, the required light intensity ratio is lower, starting at around 40% of light intensity level from the transmitter LED, when using the Large Off-the-Shelf solar panel. In general, the set of interference tests was another way to identify additional system properties and to know more about the system performance and functionality in realistic indoor scenarios.

4.3 Energy autonomy of the wake-up system for common office hours

Lights are not always needed in realistic indoor scenarios such as offices and homes. For instance, lights at home are normally switched on at evening and night hours, and their use show random behavior according to the frequency and duration of use of the different rooms. In offices, the use of lights is more regular, normally during the day hours between

8:00 and 19:00. Due to these characteristics of indoor places, the energy-autonomous wake-up system developed was tested for typical lights usage in an office environment, in order to know if the system properties fit with such lighting features. For this test, the energy levels at the receiver side was needed to know, therefore the super-capacitor voltage level was measured at certain key moments during the test. As this test is related to energy efficiency properties, the Large Off-the-Shelf solar panel was used at the receiver side. Such selection was done since this solar panel provided the best powering properties in previous tests for energizing the receiver, for instance as tests in section 4.1.1.2 described.

In this test, the Z1 device, at the transmitter side was configured for sending wake-up frames constantly and source supply for powering the transmitter LED was set at 31V keeping the rest of the room lights in off. The receiver was located at such distance at which the light intensity level is around 400lux, according to the minimum light intensity level standardized for offices. The 1F/5,5V super-capacitor was firstly totally discharged (0V) and included in the receiver at 8:00 of the first day. The transmitter LED was kept switched on up to 19:00, simulating typical office working hours. At 19:00 the super-capacitor voltage level was measured using an oscilloscope, after 11 hours of charging process, and the transmitter LED was switched off. Finally, next day, at 8:00 the super-capacitor voltage level was also measured, after 13 hours of discharging process. The results of the super-capacitor voltage levels measurements are shown in the Table 5 presented below.

Hour	Vs-cap (V)
First day at 8:00	0
11 hours of charging process	
First day at 19:00	4,32
13 hours of discharging process	
Second day at 8:00	3,76

Table 5. Voltage levels of wake-up receiver super-capacitor during realistic office working hours using the Large Off-the-Shelf solar panel.

Results show firstly, a voltage value higher than the AS3933 minimum operating voltage level (2,4V) after 11 hours of charging process. This means that using the Large Off-the-Shelf solar panel under these realistic conditions, the receiver needs less than the whole time of working hours to be operative, even starting at 0V of super-capacitor voltage level. Secondly, it can be noted that the voltage level, after 13 hours of discharging process, is still higher than the AS3933 minimum operating voltage level. Analyzing the table results, can be found, that the receiver consumed less than 1V, mainly to keep the AS3933 configuration, after 13 hours of darkness. This behavior means that the energy level of the super-capacitor after the discharging process still allows the receiver to be operative from 8:00, the first working hour of the second day.

This test allows to know that the receiver provides a very high energy efficiency when using the Large Off-the-Shelf solar panel along with the 1F super-capacitor. Also, the receiver configuration and the use of the AS3933 as wake-up signal processor are key aspects that help to achieve the high energy efficiency level. Finally, test results proved that the developed wake-up receiver is completely able to work as an energy-autonomous system in realistic indoor scenarios.

4.4 Alternative system designs to improve the system performance

Analysis and tests of new options for the receiver circuit configuration become frequent when it is necessary to look for a more energy efficient wake-up system. As the receiver circuit design developed in [26] is simple, it is easy to analyze and find options for enhancing the energetic performance of the receiver. Therefore, as in the previous test, section 4.3, the developed energy-autonomous wake-up system was tested for common lights usage in an office environment to evaluate the system performance for these conditions, but using two solar panels instead of one.

4.4.1 Large and Small Off-the-Shelf solar panels during common office hours: first configuration

In this test the Small Off-the-Shelf solar panel was included in the receiver circuit, placed in parallel to the Large Off-the-Shelf solar panel. A diagram of the current configuration is presented in Figure 33. The test was done expecting a more efficient receiver configuration due to the current increase provided by using both solar panels together. This configuration should allow the super-capacitor to be charged faster at operating voltage level and to achieve higher voltage level at the end of the charging process.

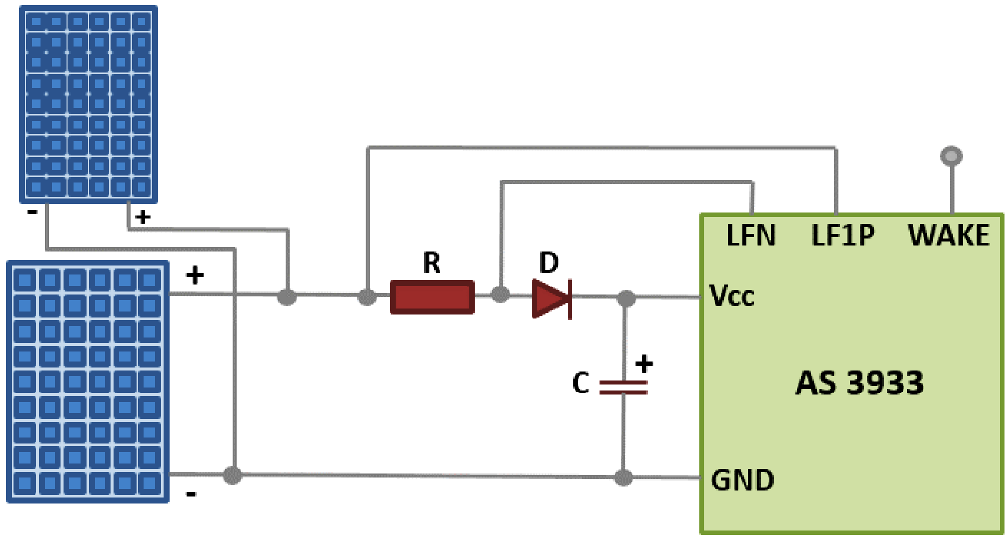


Figure 33. Circuit diagram using Large and Small Off-the-Shelf solar panel in parallel.

As in previous test, the Z1 device, at the transmitter side was configured for sending wake-up frames constantly and source supply for powering the transmitter LED was set at 31V keeping the rest of the room lights in off. At the receiver side, the Small Off-the-Shelf and Large Off-the-Shelf solar panels were located at such distance at which the light intensity level is around 400lux, according to the minimum light intensity level standardized for offices. The 1F/5,5V super-capacitor was firstly totally discharged (0V) and included in the receiver at 8:00 of the first day. The transmitter LED was kept switched on up to 19:00, simulating typical office working hours. At 19:00 the super-capacitor voltage level was measured using an oscilloscope, after 11 hours of charging process, and then the transmitter LED was switched off. Finally, next day, at 8:00 the super-capacitor voltage level was also measured, after 13 hours of discharging process. The results of the super-capacitor voltage levels measurements are shown in the Table 6.

Hour	Vs-cap (V)
First day at 8:00	0
11 hours of charging process	
First day at 19:00	4,4
13 hours of discharging process	
Second day at 8:00	3,8

Table 6. Super-capacitor voltage levels during realistic office working hours using the Large and Small Off-the-Shelf solar panels in parallel.

Results show, as expected, a little higher voltage level of the super-capacitor after 11 hours of charging process compared to the results gathered in previous test. According to the results, this configuration demonstrated to be more energy efficient in charging process. Also, as expected, the super-capacitor voltage level measured after 13 hours of discharging process is higher than the obtained value in previous test. This means that using the current configuration the receiver also lost less than 1V during the darkness period. Yet, it is not advantageous to increase considerably the solar cell area, broking the minimalist volume of the receiver by including an extra solar panel, just to obtain 80mV more after one-day of charging process.

4.4.2 Large and Small Off-the-Shelf solar panels during common office hours: second configuration

Following the same method of the previous one, an alternative idea for the receiver configuration is presented in Figure 34. In this configuration, the connections points of the AS3933 signal input ports (LF1P and LFN) were removed from both side of the resistor and connected directly to Small Off-the-Shelf solar panel pins. The main reason is to avoid energy loss through LF1P and LFN ports, allowing the Large Off-the-Shelf solar panel to deliver more energy to the super-capacitor during charging processes. This configuration, like the previous one, should allow the super-capacitor to be charged faster at operating voltage level and to achieve higher voltage level at the end of the charging process.

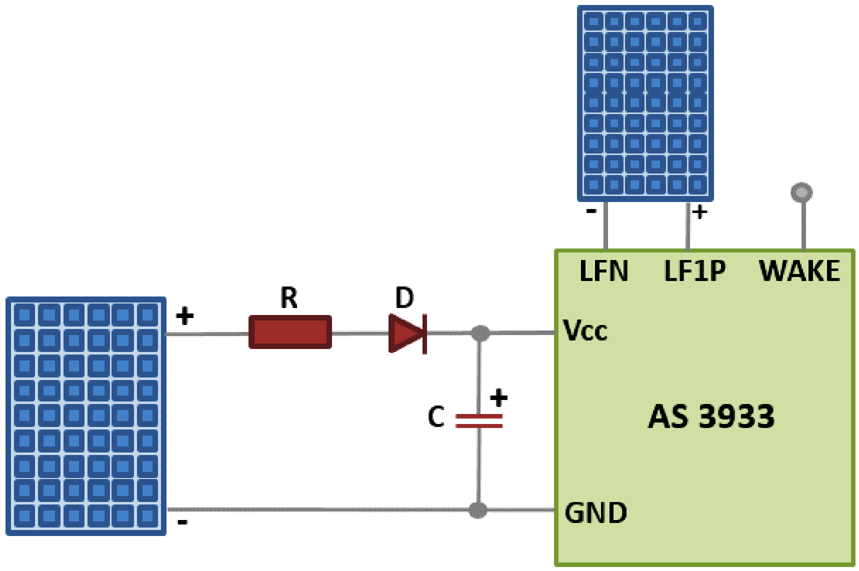


Figure 34. Circuit diagram connecting the Small Off-the-Shelf solar panel directly to AS3933 signal input ports.

In this test, the Z1 device, at the transmitter side was configured for sending wake-up frames constantly and source supply for powering the transmitter LED was set at 31V keeping the rest of the room lights in off. The receiver was located at such distance at which the light intensity is around 400lux, according to the minimum light intensity level standardized for offices. The 1F/5,5V super-capacitor was firstly totally discharged (0V) and included in the receiver at 8:00 of the first day. The transmitter LED was kept switched on up to 19:00, simulating typical office working hours. At 19:00 the super-capacitor voltage level was measured using an oscilloscope, after 11 hours of charging process, and then the transmitter LED was switched off. Finally, next day, at 8:00 the super-capacitor voltage level was also measured, after 13 hours of discharging process. The results of the super-capacitor voltage levels measurements are shown in the Table 7.

Hour	Vs-cap (V)
First day at 8:00	0
11 hours of charging process	
First day at 19:00	4,4
13 hours of discharging process	
Second day at 8:00	3,68

Table 7. Super-capacitor voltage levels during realistic office working hours using the Small Off-the-Shelf solar panel directly connected to the AS3933 signal input ports.

Results show, as expected, that the super-capacitor voltage level achieved after 11 hours of charging process is similar to the level achieved in the previous test. According to the results, this configuration demonstrated to be more energy efficient in charging process. But the super-capacitor voltage level measured after 13 hours of discharging process is the lowest, compared to the results of the previous tests of office working hours simulations. This behavior could be due to the current position of the Small Off-the-Shelf solar panel adds certain load to the super-capacitor during discharging process. Although, the obtained value is still much higher than the AS3933 minimum operating voltage level, and means that using the current configuration the receiver also lost less than 1V during the darkness period. In general, using this configuration the wake-up receiver demonstrated to be less energy efficient and less profitable in terms of size compared to the configurations previously tested.

5 CONCLUSIONS AND FUTURE WORK

In this study, an existing wake-up communication system using VLC was adapted to work as an energy-autonomous system. This means that a more energy efficient system could be created, taking advantages of the environmental resources (the light energy), and maintaining a high quality and availability of the system. To develop a more energy efficient system, an indoor solar panel was used as both VLC communication receiver and light energy harvester; also a super-capacitor was included in the receiver as energy storage. Different solar panels and super-capacitor choices were tested, with respect to functional and energetic parameters, to choose the proper options to be included in the receiver.

From devices tests, the Large Off-the-shelf solar panel showed not the best frequency response properties and to be weak in presence of light interference. However, using the Large Off-the-shelf solar panel at the low operational frequency in performance evaluations tests, the receiver was able to detect wake-ups in realistic office environments. Therefore, because of its high cell efficiency, the Large Off-the-shelf solar panel was selected as the right option to be included in the receiver, being capable of harvesting more energy than the other choices and charging the 1F super-capacitor in a short and feasible time.

Moreover, certain details were improved at the transmitter side providing a better system stability. In this way, it is recommended to continue working on improving the wake-up transmitter in term of the flickering mitigation, testing more realistic approaches and trying to include data into the wake-up frame. For example, different options of programmable devices can be tested as wake-up frame generator using different VLC modulation methods, and a commercial ceiling LED lamp can be used as light signal transmitter. Also, it is important to declare that the current system was designed and developed using commercial components instead of customized devices, making the system more easy to implement and maintain.

The developed system built on the selected element options was evaluated in realistic indoor environments. Tests of varying distance and angles, adding various interference sources and tests simulating office working hours were done to study the system properties and its behavior under difficult conditions and situations. The results show an operational distance of this energy-autonomous receiver of more than 8m, higher than the standard longitude for VLC communications (7m). This means that the system can cover the most usual distances of indoor places. A very interesting advantage noted in these tests is the possibility to detect reflected wake-up light signals, potentially eliminating the need for a direct line of sight between the transmitter LED and the receiver.

In addition, the results of the simulation of an office working hours in a typical day, demonstrated that the receiver is capable of self-energizing and storing the energy in an autonomous way. This behavior, achieved by the careful devices and configuration selection, avoids the core system receiver to share its energy source with the wake-up receiver, and avoids incorporating and maintaining a specific energy source for the wake-up receiver. Also, as an experience taken from testing the energetic behavior of the wake-up receiver, using the current configuration, the total amount of light intensity at the receiver side should be kept lower than 900 lux. Although, this is a non-common light intensity value, too high for indoor places, it corresponds to a voltage level at the LF1P pin close to 5V, the maximum voltage level supported by the AS3933 [25], so it is recommended not to be overcomed. Moreover, in general, tests results demonstrated that the developed energy-autonomous wake-up receiver using VLC is ready to work in applications installed in the most common indoor environments.

In this way, it is recommended for future works to test other possible receiver designs. Searching and testing more solar panel options, with better frequency response and even more cell efficiency, to be included in the receiver. Trying and testing more receiver configuration options even looking for more energy efficiency, for instance replacing the resistor by another diode. Also some challenging ideas could be performed in next projects, for example making the receiver to be capable of keeping its configuration after a weekend time under darkness conditions. Finally, the developed wake-up system using VLC, being ready to operate in realistic indoor applications, can be installed attached to an indoor wireless link to test its objective.

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Appendices

Appendix A.

Table corresponding to the frequency response tests, using the three solar panel options setting the transmitter LED at different frequencies.

	IMTEK			Small Off-the-Shelf			Large Off-the-Shelf		
Frequency (kHz)	Vpp (mV) absolute	VDC (mV)	Vpp (relative)	Vpp (mV) absolute	VDC (mV)	Vpp (relative)	Vpp (mV) absolute	VDC (mV)	Vpp (relative)
1	680	4240	0,160377358	800	4480	0,178571429	520	5280	0,098484848
5	280	4240	0,066037736	320	4480	0,071428571	240	5280	0,045454545
10	200	4240	0,047169811	200	4480	0,044642857	200	5280	0,037878788
15	160	4240	0,037735849	200	4480	0,044642857	160	5280	0,03030303
20	120	4240	0,028301887	160	4480	0,035714286	120	5280	0,022727273
25	120	4240	0,028301887	160	4480	0,035714286	120	5280	0,022727273
30	120	4240	0,028301887	120	4480	0,026785714	120	5280	0,022727273

Appendix B.

At 200 lux	Small Off-the-Shelf		Large Off-the-Shelf		IMTEK	
	0,1F	1F	0,1F	1F	0,1F	1F
Time(min)	voltage (mV)	voltage (mV)	voltage (mV)	voltage (mV)	voltage (mV)	voltage (mV)
0	0	0	0	0	0	0
10	146	37	544	120	364	56
20	242	59	1040	198	696	108
30	336	80	1540	276	1040	160
40	424	100	2040	356	1380	214
50	520	120	2520	440	1720	262
60	608	138	2980	520	1960	312

Table B.1. Voltages values when charging the 0,1F and 1F super-capacitors at 200lux using three indoor solar panel options.

At 400 lux	Small Off-the-Shelf		Large Off-the-Shelf		IMTEK	
	0,1F	1F	0,1F	1F	0,1F	1F
Time(min)	voltage (mV)	voltage (mV)	voltage (mV)	voltage (mV)	voltage (mV)	voltage (mV)
0	0	0	0	0	0	0
10	202	40	952	174	516	102
20	384	74	1940	324	1140	198
30	556	105	2840	480	1780	292
40	736	136	3640	624	2460	384
50	904	166	4120	774	3160	484
60	1060	194	4520	920	3760	576

Table B.2. Voltages values when charging the 0,1F and 1F super-capacitors at 400lux using three indoor solar panel options.

Appendix C.

Tables of results of performed interference tests, including tests under no light interference and tests under different situations of light interference from artificial lights sources and sunlight. For this set of tables, “Vled” columns show the voltage levels, given in volt (V), at which the transmitter LED source supply was set, from 25V up to 31V. Values of the “LIo” columns, given in lux, correspond to the initial light level of the tests when the transmitter LED was still turned off. Values of the “LI” columns, given in lux, correspond to the light intensity levels measured at the receiver position. These values are the result of the addition of the light intensity level of any interferer source and the transmitter LED light intensity level for every voltage level of the transmitter LED source supply. Values of the “LIled” columns, given in percent, correspond to the percentage of the light intensity level coming from the transmitter LED of the total light intensity level measured at the receiver side. Values of the “P” columns, given in percent, correspond to the probability of the receiver for generating wake-up interruptions due to wake-up calls detection.

				IMTEK	Small Off-the-Shelf	Large Off-the-Shelf
Vled(V)	Lio(lux)	LI(lux)	LI_{led}(%)	P(%)	P(%)	P(%)
25	0,3	2,3	86,96	10	12	0
25,5	0,3	8,1	96,30	60	62	0
26	0,3	33,2	99,10	62	66	2
26,5	0,3	84,6	99,65	60	64	70
27	0,3	126,8	99,76	66	70	78
27,5	0,3	208	99,86	74	74	80
28	0,3	290	99,90	76	80	80
28,5	0,3	362	99,92	74	86	78
29	0,3	445	99,93	80	84	82
29,5	0,3	537	99,94	88	86	82
30	0,3	605	99,95	84	88	84
30,5	0,3	661	99,95	86	90	82
31	0,3	700	99,96	88	90	84

Table C.1. Probability of detecting wake-ups under no interference conditions.

				IMTEK	Small Off-the-Shelf	Large Off-the-Shelf
Vled(V)	**Lio(lux)**	**Ll(lux)**	**Ll$_{led}$(%)**	**P(%)**	**P(%)**	**P(%)**
25	202	204	0,98	0	0	0
25,5	202	207	2,42	0	0	0
26	202	228	11,40	0	0	0
26,5	202	265	23,77	20	62	0
27	202	334	39,52	64	70	0
27,5	202	405	50,12	66	78	0
28	202	481	58,00	76	78	0
28,5	202	561	63,99	72	76	22
29	202	642	68,54	74	80	70
29,5	202	720	71,94	82	86	80
30	202	794	74,56	88	88	82
30,5	202	844	76,07	86	88	84
31	202	877	76,97	88	88	84

Table C.2. Probability of detecting wake-ups under AC interference conditions.

				IMTEK	Small Off-the-Shelf	Large Off-the-Shelf
Vled(V)	**Lio(lux)**	**Ll(lux)**	**Ll$_{led}$(%)**	**P(%)**	**P(%)**	**P(%)**
25	205	211	2,84	0	0	0
25,5	205	221	7,24	0	0	0
26	205	244	15,98	0	66	0
26,5	205	288	28,82	72	70	0
27	205	356	42,42	80	84	0
27,5	205	433	52,66	82	86	0
28	205	515	60,19	86	90	10
28,5	205	596	65,60	90	88	78
29	205	676	69,67	86	88	84
29,5	205	758	72,96	88	92	88
30	205	833	75,39	92	90	90
30,5	205	873	76,52	88	90	88
31	205	912	77,52	90	92	90

Table C.3. Probability of detecting wake-ups under DC interference conditions.

	IMTEK				Small Off-the-Shelf				Large Off-the-Shelf			
Vled(V)	Lio(lux)	Ll(lux)	Ll_{led}(%)	P(%)	Lio(lux)	Ll(lux)	Ll_{led}(%)	P(%)	Lio(lux)	Ll(lux)	Ll_{led}(%)	P(%)
25	793	795	0,25	0	382	385	0,78	0	491	492	0,20	0
25,5	787	790	0,38	0	513	515	0,39	0	489	498	1,81	0
26	781	789	1,01	0	526	533	1,31	0	489	530	7,74	0
26,5	777	794	2,14	0	523	537	2,61	0	489	566	13,60	0
27	770	799	3,63	0	520	547	4,94	0	488	650	24,92	0
27,5	765	809	5,44	0	518	561	7,66	0	487	730	33,29	0
28	759	820	7,44	0	516	571	9,63	0	486	897	45,82	0
28,5	757	834	9,23	0	514	583	11,84	0	485	916	47,05	0
29	740	831	10,95	88	512	597	14,24	90	455	978	53,48	38
29,5	706	812	13,05	90	503	603	16,58	94	456	1076	57,62	90
30	705	823	14,34	88	500	616	18,83	94	480	1188	59,60	92
30,5	697	823	15,31	90	499	617	19,12	92	477	1220	60,90	94
31	673	805	16,40	88	496	621	20,13	94	474	1258	62,32	94

Table C.4. Probability of detecting wake-ups under sunlight interference conditions.

	IMTEK				Small Off-the-Shelf				Large Off-the-Shelf			
Vled(V)	Lio(lux)	Ll(lux)	Ll_{led}(%)	P(%)	Lio(lux)	Ll(lux)	Ll_{led}(%)	P(%)	Lio(lux)	Ll(lux)	Ll_{led}(%)	P(%)
25	869	871	0,23	0	715	717	0,28	0	494	498	0,80	0
25,5	885	887	0,23	0	674	678	0,59	0	497	508	2,17	0
26	874	882	0,91	0	636	644	1,24	0	501	536	6,53	0
26,5	849	860	1,28	0	700	709	1,27	0	503	590	14,75	0
27	847	873	2,98	0	681	710	4,08	0	503	669	24,81	0
27,5	835	873	4,35	0	644	691	6,80	0	506	759	33,33	0
28	840	899	6,56	0	637	697	8,61	0	507	840	39,64	0
28,5	842	920	8,48	0	628	704	10,80	0	508	924	45,02	0
29	794	890	10,79	80	622	713	12,76	86	500	1040	51,92	26
29,5	796	908	12,33	82	615	721	14,70	86	507	1126	54,97	80
30	823	946	13,00	82	609	734	17,03	86	505	1190	57,56	94
30,5	823	950	13,37	90	609	739	17,59	90	502	1242	59,58	92
31	867	998	13,13	90	605	746	18,90	92	504	1282	60,69	92

Table C.5. Probability of detecting wake-ups under sunlight + AC interference conditions.

Glossary

AC	Alternating Current
API	Application Programmer Interfaces
ASK	Amplitude Shift Keying
CPU	Central Processing Unit
CSK	Color Shift Keying
DC	Direct Current
EMI	Electromagnetic Interference
FFT	Fast Fourier Transform
FSK	Frequency Shift Keying
GSM	Global System for Mobile Communication
IFFT	Inverse Fast Fourier Transform
IoT	Internet of Things
IP	Internet Protocol
IR	Infrared
LD	Laser Diode
LED	Light Emitting Diodes
LOS	Line of Sight
MAC	MAC Layer
MCU	Microcontroller Unit
MEMS	Microelectromechanical Systems

OFDM	Orthogonal Frequency Division Multiplexing
OWC	Optical Wireless Communication
PHY	Physic Layer
RF	Radio Frequency
RFID	Radio Frequency Identification
RGB	Red-Green-Blue
Vpp	Peak-to-Peak Voltage
VPPM	Variable Pulse Position Modulation
WiFi	Wireless Fidelity
WSN	Wireless Sensor Networks