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VISIBLE LIGHT COMMUNICATION CHANNEL FOR AN INTELLIGENT PHOTOELECTRIC SENSOR MODULE

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Abstract

In conventional wireless communication technology the gradual saturation of the RF spectrum driving the need for alternative technologies. The problem of spectrum scarcity becomes more essential in monitoring of technical processes of manufacturing equipment and IoT devices, where a large amount of autonomous sensors are used. We present a visible light communication channel as an alternative to traditional RF technology for an intelligent photoelectric sensor module. The paper describes the arising design issues during the construction of a light communication channel for miniature devices and the possible solutions for improving the quality of the received signal under different disturbing conditions, such as noise and light interference.

INTRODUCTION

With an increasing popularity of utilization of wireless radio frequency (RF) communication technologies in all kinds of electronic devices, such as smartphones, smart TVs, wristwatches, wireless headphones, IoT gadgets, etc., the issue of electromagnetic interference between those, which operate on unlicensed 2.4 GHz band, becomes more essential. The rapid development in the field of lighting and illumination afforded an opportunity of applying Light Emitting Diodes (LEDs) as an alternative to a conventional RF technology. Unlike other illumination sources, LEDs allow switching light intensity levels at a very high rate. This capability can be used to encode transmitted data. Apart from the fact, that the optical spectrum contains hundreds of terahertz of license free bandwidth, the communication by means of light offers a set of advantages. It is intrinsically safe, does not pose a health threat as long as eye safety regulations are fulfilled. It can be harmlessly used in environments, where RF emission is forbidden or restricted, e.g. chemical and nuclear plants. Light also allows propagation through water with lower attenuation than the radio waves, which makes underwater data transmission possible.

In this paper we present an opportunity of visible light utilization for a fully-optical autonomous sensor module, which is able to take measurements and emit information by external wake up (Figure 1). The power autonomy of the module is intended to be achieved by energy harvesting, where the ambient optical energy is converted into electrical energy by means of a solar cell, which can be also used as a receiver of light signal. A matrix-like arrangement of several such modules comprises a wireless sensor network, which can be used as an individually adapted sensor system. The size of each module is intended to be small-scale and mainly depends on the solar cell used as a power supply.

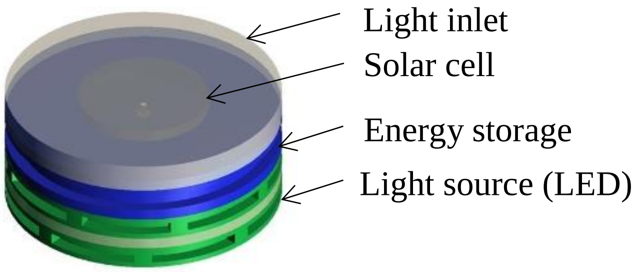


Fig.1. The concept of fully-optical autonomous sensor module

This paper is aimed to analyse special design aspects of light communication channel for miniature devices, in particular for autonomous sensor module. The main factors degrading the signal quality are considered and the possible solutions for its improvement are proposed.

STATE OF THE ART

Optical communication can be realised in three alternatives depending on a type of the emitter: it can either be a laser, an infrared or a white LED. A comprehensive review of the first two technologies has been given in [1] and [2] respectively. In this paper we are concentrating on visible light communication (VLC) approach in particular. A lot of interesting applications in this field were proposed. In [3] an implementation of downlink communication for new electronic services for healthcare in hospitals was done by integrating a power line network with conventional LED lamps, used for illumination purposes. In such a way the power manipulates the light intensity of the lamp, transmitting a data signal. Authors from [4] introduced a VLC for pose, position and range estimation by using an image sensor as a receiver instead of a photodiode and successfully implemented their approach in bridge-shape monitoring. An all-encompassing survey was given by [5] on the challenges and possibilities of using VLC under water, whether itself or in combination with acoustic methods. Another noteworthy application to Intelligent Transportation Systems was proposed by [6], where a possibility of vehicle-to-vehicle VLC based on LED headlamps was investigated with respect to lighting distribution regulation of headlamps under daytime conditions. The research on VLC is full of interesting ideas and concepts, however, the miniature sensor modules and the possible networks of them are till now not comprehensively explored.

Optical Communication Link

The general optical communication setup (Figure 2) is determined by the radiation properties of a transmitter and detection characteristics of the receiver as well as by their arrangement. The light radiated by the transmitter can be incident on a the receiver in direct way (line-of-sight) or can be bounced from many surfaces (non-line-of-sight). The transmitter consists of a driving electric circuit with a digital-to-analog converter (DAC), which is responsible for modulation of information bits, presented in digital form, and their conversion to analog current signal. Then the information-carrying current signal drives the optical emission of an LED, manipulating its intensity with a high frequency, not visible to human eye. Adjustment of a transmitted beam shape can be achieved by applying additional optical system, which can consist of an optical amplifier lens, a collimator or a diffusor. During the optical signal transmission over a wireless channel, the optical energy is either absorbed or reflected by the objects and walls. The light signal impinging the receiver surface can also be passed through an optical system, in order to reduce the ambient light interference by a filter, and amplified by collimator lenses for optimal detection. Then the photodetector, represented either as a photodiode, an image sensor or a solar cell, converts the optical signal back into electrical current. The receiver’s electric circuit amplifies the current signal by means of

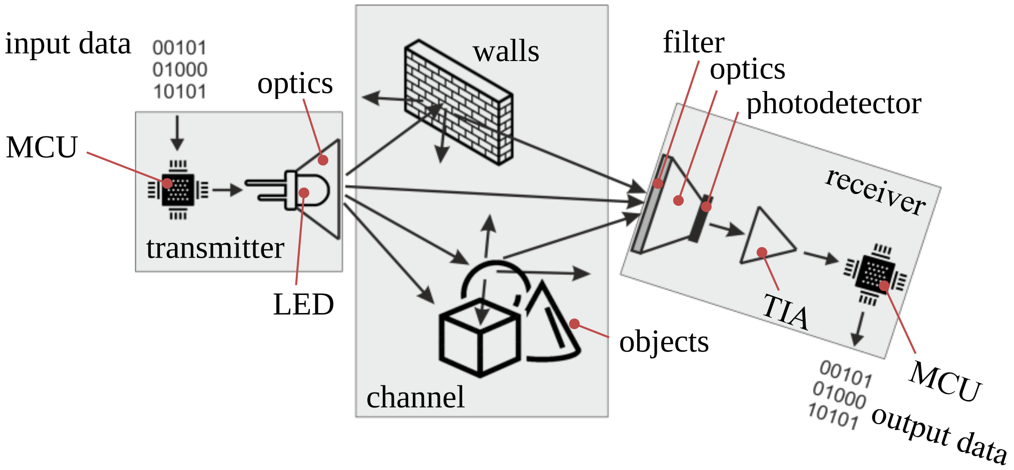


Fig.2. The general building blocks of optical communication link

transimpedance amplifier (TIA), transforms the analog signal into digital by integrated analog-to-digital converter (ADC) and demodulates the digital signal to initial data. [7]

Modulation Techniques

Unlike RF in VLC it is not possible to encode data in phase of the light signal. Therefore all the modulation methods for VLC are based on varying the intensity of the emitting light and can be divided in two groups: single-carrier techniques and multi-carrier techniques. In single-carrier modulation the information can be encoded whether in pulse duration (PWM), position (PPM) and amplitude (PAM) or as a binary on-off-keying (OOK). These methods have an advantage in VLC of robust and low-complexity transmission at very low signal-to-noise ratio (SNR) in the flat fading channel. However, in the dispersive channel for high data rate, the pulse bandwidth exceeds the channel's coherence bandwidth. This causes the root-mean-squared (RMS) delay, spread of the optical wireless channel, to exceed the pulse duration, which leads to inter-symbol interference, limiting the throughput. This issue is solved by multi-carrier modulation, where the symbol duration is significantly longer than the RMS delay of the channel. Multi-carrier transmission allows delivering very high data rates and is resistant to low-frequency distortion from background light noise. Two common examples are O-OFDM (optical orthogonal frequency division multiplexing) and CSK (colour-shift-keying) modulations. In O-OFDM the channel is divided into multiple orthogonal subcarriers and the data is sent in parallel sub-streams modulated over the subcarriers. CSK relies on the colour space chromacity diagram (RGB constellation triangle), mapping data bits to chromacity values, determining the intensities of RGB LEDs [8]. The disadvantage of the multi-carrier techniques is in their high implementation complexity and in increased power requirements.

VLC CHALLENGES IN PHOTOELECTRIC SENSOR MODULE DESIGN

The design of VLC for an autonomous device of a small-scale size (1-3 cm in diameter), such as photoelectric sensor module, imposes some certain constraints on the ability of the energy harvesting source to supply enough power during communication. It is important to notice that in the case of sensor node the maximum amount of reading cycles per second is more relevant than the rate of transmission of any single sensor reading (data rate). Therefore, the device must consume as little power as possible on a full-scale of whole communication process, minimizing power, which is necessary during modulation and demodulation (1); light emission (2); filtering and amplification the received signal (3).

With respect to power consumption limitations and device dimensions miniaturisation, the following challenges are relevant for the implementation of visible light communication for an intelligent photoelectric sensor module.

Noise and Interference

In the context of energy harvesting for autonomous sensor module the solar radiation is a very useful energy source. However, within the framework of wireless light communication it is a source of noise, which has to be filtered in the receiver. Additional noise comes from artificial illumination sources,

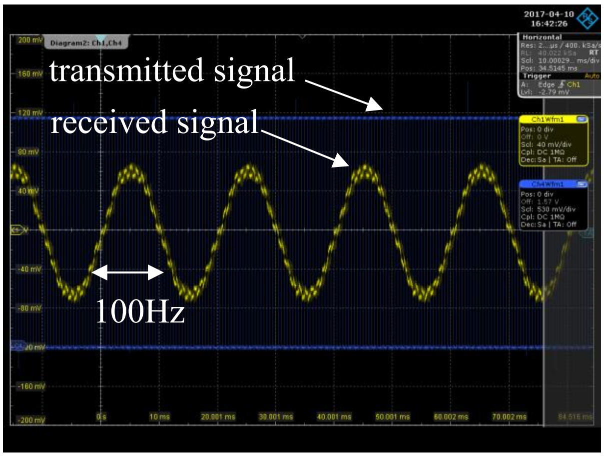
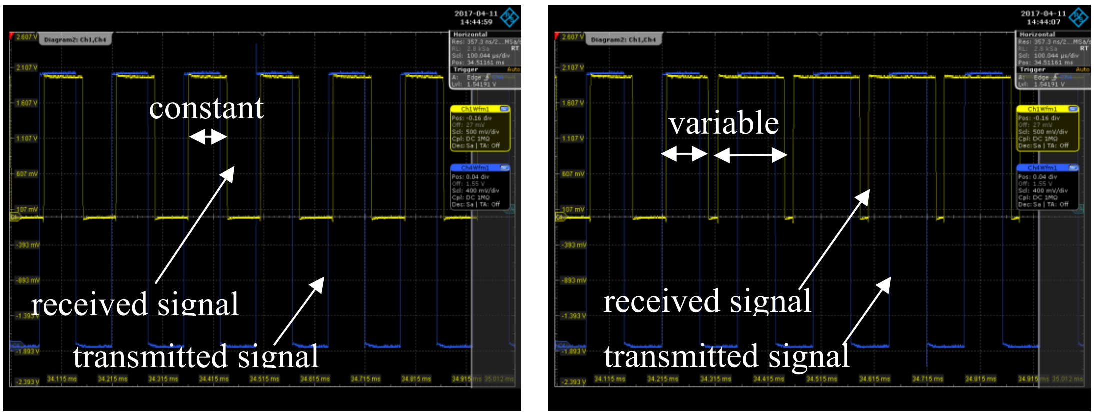


Fig.3. Behaviour of received signal with the presence of interference from fluorescent lamp without filter

which are powered from alternating current (AC) at 50 Hz (in Europe) and therefore experience a voltage decrease 100 times a second (twice per line cycle), producing 100Hz flickering. Such light changing intensity is also sensed by a photodetector and has to be filtered out (Figure 3). This effect can be mitigated by using an electrical high pass filter. However, the complete elimination of the interference component presents a significant challenge and requires very precise adjustment of the filter parameters. Figure 4 illustrates the resulting received signal without (a) and with (b) presence of fluorescent lamp interference.



(a) (b)

Fig.4. Behaviour of received signal without (a) and with (b) the presence of interference from fluorescent lamp with filter

Additional noise is induced in the photodetector by the signal and ambient light (shot noise) and on electrical pre-amplifier stage (thermal noise). They depend on the photodetector area, on the room temperature and amount of ambient light and can usually be filtered out by a low-pass filter.

Saturation of photodetector outdoors

An exposure of the photoelectric sensor under direct sunlight in outdoor environment can pose an issue of saturation of the photoelement. Photodiode saturates when the output photovoltage approaches the reverse bias voltage. Since photodiode outputs a current, the saturation limit can be adjusted by modifying the reverse bias voltage (within specification) or reducing the load resistance [9]. Based on this principle authors of [10] designed an adaptive transimpedance amplifier, which changes its gain value according to the level of incident light. This can be a good solution of the saturation issue of the photoelectric sensor in case of possibility of implementing the electric circuit in mm-scale.

Spatial Communication

Several autonomous photoelectric sensor modules can comprise a wireless sensor network, where each node communicates with its neighbors by means of light. In this scenario unlike for RF communication the position of every node requires precise adjustment and preliminary simulation for each application, since the quality of the transmitted signal is very sensitive to incident and to irradiation angle (Figure 5) and the inter-channel interference can occur. Such ray-tracing simulation and path loss calculation example was given in [7] for modelling a light-communication-based cellular network in aircraft cabin. Another challenging task in spatial communication of sensor nodes involves implementation of MIMO (Multi-Input Multi-Output) transmission. Compared to RF systems, which have multiple spatial paths that

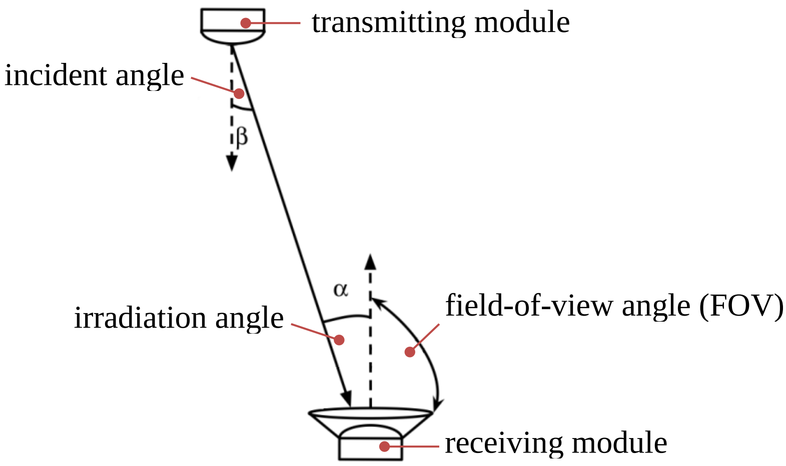


Fig.5. Incident and irradiation angles in spatial communication between two autonomous sensor nodes

diverse in nature, in VLC such diversity gains are limited, since the paths for transmitters and emitters are very similar and can interfere with each other. A solution can be in utilization of an image sensor as a photodetector instead of a single photodiode. A specific advantage of the image sensor is its ability to spatially distinguish light sources, since massive number of pixels is available

CONCLUSION

In this study the challenges of visible light communication were analysed with respect to its implementation in fully-optical autonomous sensor module, which is capable of self-powering, taking measurements and communicating with environment by means of light. The VLC for such application was chosen as an alternative to RF for the environments, where electromagnetic waves are unwanted or unsuitable. The general issues of the VLC link design, such as noise and interference on the receiver, saturation of photodetector, limited spatial path diversity in wireless sensor network, were identified and the possible solutions were proposed. To sum up, the design of a network of autonomous sensor modules communication in terms of light is an demanding task, however, a lot of research in VLC field is bringing new sophisticated ideas, which are likely to follow in near future.

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