Experimental Evaluation of Video Transmission Through LED Illumination Devices

J. Rufo, J. Rabadan, F. Delgado, C. Quintana, and R. Perez-Jimenez

Abstract — *In this paper we describe the implementation of a prototype of an optical wireless system based on visible white LED lamps, which allows a video broadcasting to reach a bit rate of 2 Mbps. This technology is usually called VLC or Visible Light Communications and presents several advantages as the robustness against EM interference, safety for human eye and security against undesired network access. These conditions make this system suitable for co-existing with commercial RF networks -WiFi, Bluetooth, etc.-, especially for in-house applications. For the uplink channel we have also included in the prototype an infrared 115 kbps transceiver. This VLC system could be used for supporting data transmission applied to low-speed sensor network connections as well. The electronic structure of a low-cost VLC transceiver, based on commercial off-the-shelf components and LED lamps is presented too. The modulation process and the Ethernet interface implemented in each access point are also described. Finally, some conclusions and application scenarios are drawn*[1].

Index Terms — Visible Light Communications, Optical Wireless Communications, CR-DPPM.

I. INTRODUCTION

Nowadays, there is a growing number of scenarios -in-house domestic applications, traffic lights, hospitals, hotels, etc.- where illumination devices based on visible LED lamps are used. This interest is not only motivated by economic reasons (as the price of individual lamps is still higher than that of traditional ones, although it is rapidly becoming cheaper and cheaper) but by energetic or environmental considerations. These lamps combine very low power consumption with an extremely long operational life, maintaining during all their operation the same chromaticity without significant changes. This paper is based on the fact that these devices can be also used as communications emitters without losing their main functionality as illumination sources. This technique (known as Visible Light Communications or VLC [1-2]) does not only maintain the usual capabilities of wireless optical transceivers (robustness against EM interference, absence of EM compatibility constraints and secure transmissions as radiation is confined by walls) but is also eye-safe (as it uses visible wavelengths). Additionally, as they are used as lamps, the amount of optical emitted power is enough to provide full transmission coverage over a regular size room. So we have a huge amount of low cost COTS (commercial off-the-shelf) optical emitters available that can be used wherever we need to provide illumination and to broadcast audio and video jointly.

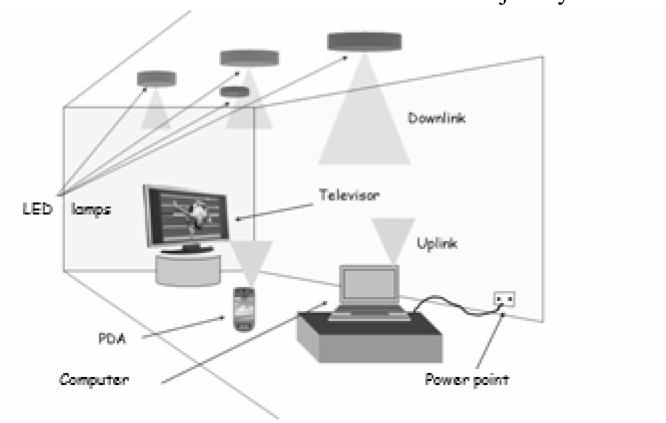

Fig. 1. Schematic view of indoor VLC system with a LED-array.

The illumination channel is nice for broadcasting transmission [3] or for addressing low speed communications for sensors (i.e. by means of polling protocols) [4]. It can be considered for several simultaneous OCDMA transmissions as well. Broadcasting information can be useful in several indoor application scenarios, as video/audio transmission for domestic in-home applications or wherever an EM constraint-free channel is needed (hospitals, nuclear or industrial plants, airplanes). It can be also used for outdoor broadcasting channels based on streetlamps, traffic lights, etc. Furthermore, it can be considered even in regular scenarios where RF use is allowed but commercial bands are rapidly becoming saturated. However, there are some constraints that must be taken into consideration. First, we should keep in mind that the primary use of the lamps is to provide illumination, so they should be able to transmit while maintaining the same optical emitted power, even when the lamp is off (emitting narrow pulses under eye detection capability). Thus, we shall have a four state switch for the lamp: off, off with data, on with data and on without transmission. The second problem to be solved is the uplink channel for commands (in the case of broadcasting transmission), for acknowledging the transmission, or for

[1] This work was supported in part by the Spanish Government (research & science and industry ministries, TEC2009-14059-c03-01 and TSI-020100-2009-175 projects. and GLOBALAN TELECOMUNICACIONES. C Quintana has received a PhD Grant from the Canary Island Regional Government. He has been also awarded by an INNOVA grant from FULP.

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Contributed Paper
Manuscript received 06/02/10
Current version published 09/23/10
Electronic version published 09/30/10.

providing the network with the required measured parameters (when considering sensors, actuators or addressed devices). There are several studies testing low/medium speed infrared channels [5-7], with which visible ones do not interfere. In those scenarios where RF use is allowed, we can also assume one of the several available commercial radiofrequency links (e.g. using commercial ZigBee strategies for sensor interconnection).

In this paper we present the results derived from the BALDUR project (see acknowledgements for details). This project has been developed so as to obtain real-time video transmission through visible light LED lamps. The final objective is to obtain an asymmetrical communications link which can be connected to a structured TCP/IP network, based on VLC for the downlink, while using infrared low-speed (up to 115 kb/s) for the uplink. This paper is organized as follows: the fundamentals of the VLC systems are described in the following section. The modulation techniques and the network interface are then shown. Sections IV and V describe the optical interface and some results derived from the operation of the prototype, respectively. Finally some conclusions and application scenarios are given.

II. VISIBLE LIGHT COMMUNICATIONS FUNDAMENTALS

A basic indoor VLC topology system is shown in Figure 1. Lighting and communications sources are provided by a number of LED arrays disposed on the room ceiling. An optical receiver is placed on a receiving plane, such as a desk, and data is received from the illuminating sources.

Natural white light contains all the colours in visible light spectrum. In LED illumination (also known as SSL -Solid State Lighting), a quasi-white light source is typically generated by using a combination of red/green/blue (RGB) or yellow-phosphor/blue (YB) LEDs [8]. The latter are being developed as an alternative white light source, where blue light is emitted from a single LED chip which is coated with a yellow phosphor layer [9]. The advantages of this YB-LED are low power consumption, high illumination efficiency and low production cost. However, the main drawback of this type of LED for communications is the narrow modulation bandwidth caused by the slow temporal response of phosphor emission compared with the blue LED raise and fall times [10]. Despite this fact, it is envisaged that a single chip YB-LED is the most likely candidate for the next generation of lighting technology.

A typical VLC transmitter is designed for both lighting and data communications. SSL 'lamps' typically use a number of LEDs connected in a chain to provide an appropriate resistance for the driver circuit. Assemblies may include LEDs in series and in parallel in order to achieve this [11]. In addition, a means to convert the AC main voltage into a high current low voltage DC source is required. Oscillator type converters are typically used to get this [12]. This voltage is typically fed directly to the devices, as the integrating effect of the eye removes the need to smooth these voltages.

Conventional optical wireless communications systems use intensity modulation and direct detection for data transmission and reception. In our case, IM/DD is also used, although different strategies are usually designed to provide both sufficient lighting and data communication and -as an additional requirement- to work even when the lamp is switched off (considering that the emitted light is significantly lower than in the "switched on" state) . Some authors suggest using Pulse Width Modulation (PWM), while others prefer Pulse-Position Modulation (PPM). Despite the bandwidth limitation in VLC, we have chosen PPM because of its capability to avoid the effects of symbol interference produced by the phosphor LEDs. As the received SNR is greater than 40 dB, the difficulty of obtaining the correct output levels is highly reduced. Almost any PIN photodiode without optical filter can be used due to the fact that they have a wide optical spectrum, which will allow to detect all the wavelength used by the VLC system.

III. MODULATION TECHNIQUES, VIDEO CODING AND ETHERNET INTERFACE

As already mentioned, we are using PPM to ensure correct data transmission in both operating modes: when the LED lamps are switched on and when they are turned off. This is achieved by emitting "positive" or "negative" pulses. "Positive" means that the lamp is off and we use short light pulses –ideally under eye sensitivity-, while "negative" means cutting the light flux during a short interval. In this case, 85% of the nominal optical power has been selected for the "turn on" mode and 15% for the "turn off" one. Moreover, this modulation technique reduces (almost completely in the "turn off" state) the lowest frequency components of the spectrum, making it suitable for avoiding interferences from incandescent and/or fluorescent lamps. The main drawback of this modulation technique is the necessity of a complex synchronism system to ensure correct detection. To alleviate this, Constant Rate-Differential Pulse Position Modulation (CR-DPPM) is used. This technique combines the non-coherent detection capability of classical DPPM schemes with a constant bit rate. Figure 2 shows the waveforms corresponding to the Pulse Position Modulations mentioned above.

This technique allows non-coherent detection at the receiver, ensuring that a symbol is received on each clock period. Symbol information is contained in the distance between two adjacent pulses, so detection is achieved counting clock samples (with a frequency 4 times higher than the PPM one) between rising edges. Correspondence between symbol and distances is shown in table 1. Both blocks have been programmed using VHDL (VHSIC Hardware Description Language) over a FPGA development kit.

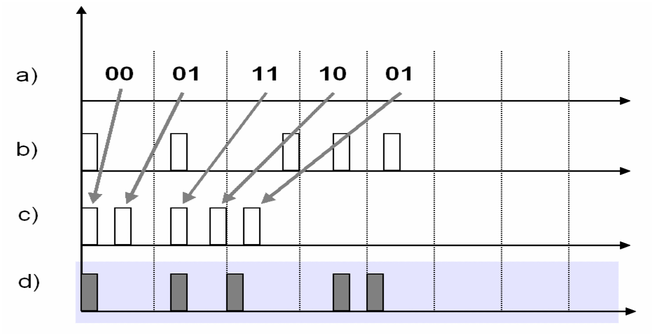


Fig. 2. Different pulse position modulations waveforms: a) Symbol b) PPM, c) DPPM, d) DPPM constant rate.

TABLE I
DPPM-CR SYMBOLS AND THEIR CORRESPONDING DISTANCES

Symbol	DISTANCE (CHIPS)
00	5
01	2 or 6
10	3 or7
11	4 or 8

The ceiling LED array does not only implement the subnet access point, but it also has additional functions such as flow control between Ethernet network and VLC (as the downlink VLC bit rate is limited to 2 Mbps due to lamp characteristics), MAC identification of all the room optical nodes, and modulation and demodulation of the optical signal. As the downlink VLC bit rate is limited, the access point should extract video components from the Ethernet frames so as to deliver them to any optical subnet node.

Moreover an interface of the Ethernet Media Access Controller/-Physical (MAC/PHY) and the VLC device has been developed so as to extract UDP payload from Ethernet frames and transmit them through the optical link. Only UDP packets addressed to the VLC subnet access point are transmitted. The Ethernet payload is re-encapsulated using a start-of-frame code in order to ensure packet reception. As the system frequency is 50MHz and the available speed of the bus used to communicate both modules is 62.5 MHz, this application can be easily extended to higher optical baud rates.

Server and client video streaming software applications have been developed for demonstration purposes. The video server can take a MPEG-TS (Transport Stream) codified video file and send the frames into UDP packets in constant bit rate mode (2 Mbps in this case). The FPGA in emitter mode extracts the payload and delivers the data to the VLC communications stage. In the reception block the FPGA takes serial data from the optical receptor and rebuilds the UDP packets. These packets are sent to the receiver computer by means of an Ethernet connection, where the video client collects the packets and reproduces the video.

IV. OPTICAL TRANSCEIVER

One of the biggest problems found in this implementation was driving enough current to the emitting LEDs fixture, in this case, a commercial battery fed lamp as shown in figure 3. This kind of lamps presents a parallel LED connection in order to get the LEDs forward voltage (about 4 V) with few batteries (3 1,5 V batteries for the lamp used in this work). In the lamps normal working state, the current driven to the led depends on the batteries capability, but when we use it as a VLC transmission device, we need to control the current level through the LEDs, so as to determinate precisely the emitted optical power.

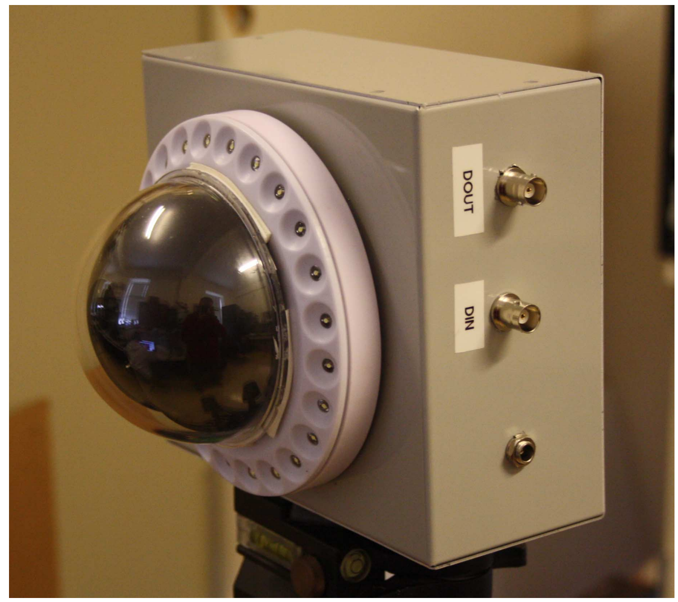


Fig. 3. Commercial LED lamp used as transmitter, it can be also observed the IR receiver under the dome.

Different driver configurations were tested, all of them based on open collector-logical gate chips. They are able to switch current values up to 100s of mW, as required for the illumination LED (especially in a parallel configuration, as is shown in Figure 3). Finally the implemented scheme makes use of several gates, each of them driving a group of 5 parallel connected LEDs, as is shown in figure 4. This configuration improves the current control and reduces the capacitive charge introduced by the LEDs, which decreases the available transmission bandwidth. The same circuit scheme can be used with other lamp configurations, as those which use groups of series-connected LEDs. In this case, the open collector output makes it possible to work with the needed voltages for the polarization of each group of LEDs (10-20 V).

Receiver structure is depicted in Figure 5. Two PIN photodiodes, with 15 MHz bandwidth, 0.45 A/W optical sensitivity at a 660 nm wavelength and an active area of 66 mm^2, perform the optical signal reception. After the photodiodes, there is a pre-amplifier in a trans-impedance configuration connected to a boost-trap circuit. Boost-trap is used to reduce the effect of spurious capacities in the photodiodes improving the frequency response, if a single photodiode is used, or maintaining the reception bandwidth, when several parallel connected photodiodes are needed to increase reception area. The second stage is composed by an amplification block and an active filter in sallen-key configuration for noise reduction. Finally the received signal is delivered to a ML detector.

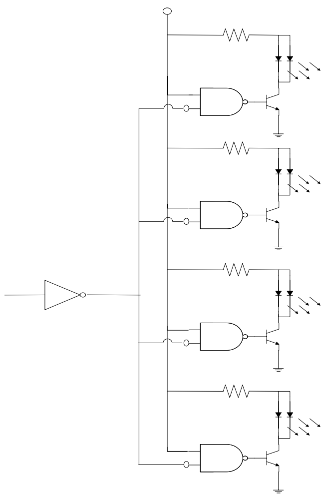
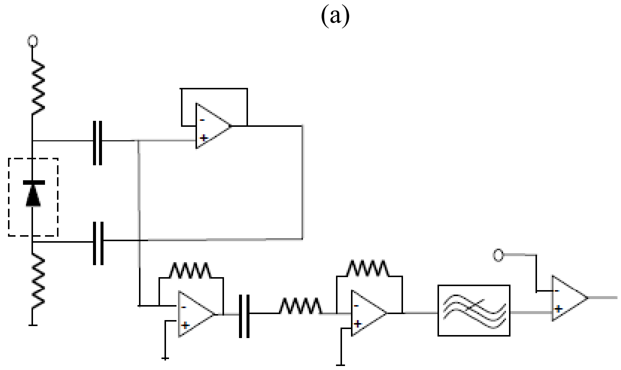


Fig. 4. Driver scheme for the LED lamps

(a)



(b)

Fig. 5. Receiver, with the photodiodes under the dome and the IR emitters (a), and the optical receiver block diagram (b)

The uplink implements a 115 kbps infrared link, using a set of eight IREDs as transmission system, at a wavelength of 950 nm. The driver scheme is similar to that used at the downlink, but in this case, we use four gates connected in parallel for driving more current through the IRED array. The circuit is presented in figure 6. Both receiver and downlink schemes are the same, but the latter uses a different optical headset, consisting of eight PIN photodiodes. In this case, these devices have their peak response at 850 nm and are coated with an optical filter for visible wavelengths, which is especially important in this system so as to reduce the effect of cross interference with the downlink VLC emitter. Additionally, we added a black coverage –transparent to infrared light- inside the dome used for protecting the infrared photodiodes from dust and humidity (see figure 5 for details). The uplink circuits have been designed to assure a reliable communications with the VLC access point node. Specifically, it gets link distances about 3 m with a field of view higher than 90º, enabling a wide area for positioning the mobile node.

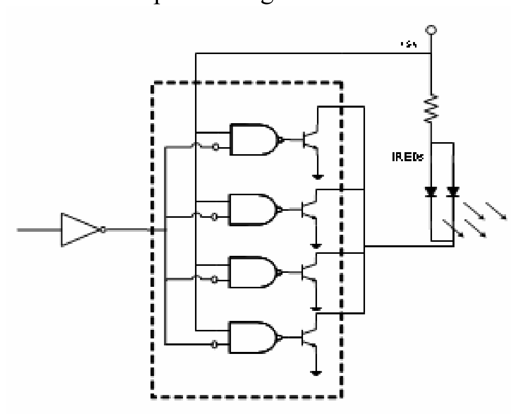


Fig. 6. Uplink block diagam

V. RESULTS

In order to test the system performance, we have carried outperformed several tests transmitting video from different sources coded in MPEG-TS (Transport Stream). It was extracted from a laptop through the Ethernet PC card at a baud rate of 2 Mbps. These data were CR-DPPM modulated and optically transmitted. First we transmitted echography signals (figure 7) from medical equipment regularly used in the Canary Islands Regional Health Service in order to test their capabilities under the supervision of medical personnel. Encouraged by the excellent performance of the optical link, we then began to use the link to transmit compressed video MPEG-TS codified file with a MPEG2 video compression bit rate of 200 Kbps and 64 Kbps audio rate, using video streaming software. The following figures show some of the preliminary results of the “on the table” laboratory testing. The performed experiment consists on the commercial phosphor LED lamp shown in figure 3 emitting at a distance over 4 meters to an array of 2 PIN photodiodes. Figure 8 represents for the “turn on” state (corresponding to a 95% of the nominal amount of optical power emitted by the lamp), the emitted and receiver signal (after being rectified)

The symbol error rate was estimated comparing emitted and received sequences of coded video. As we have transmitted several video fragments of 10^8 length and zero errors were found on them, we can estimate that error probability should be below 10^{-8} on a 4 meters link in the previous conditions.

Fig. 7. Performance test, transmission of an echography signal

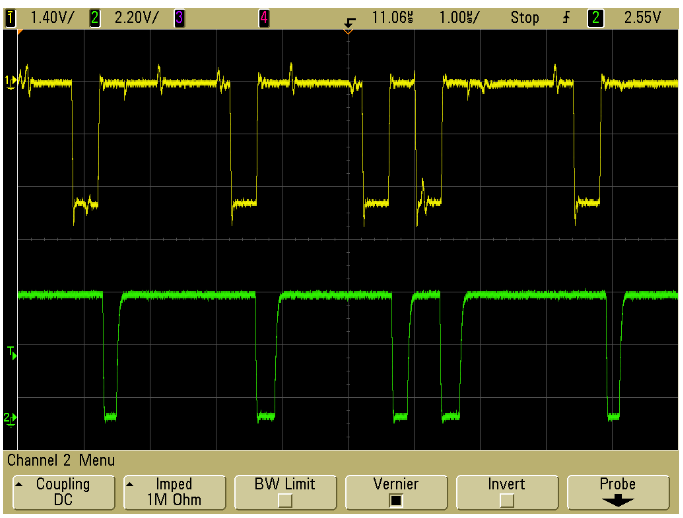


Fig 8. Experimental testing of the VLC prototype. Received signal for the link at 4 meters distance, (after being rectified). Emitted (up) and received (bottom) signal, "Turn on" state.

TABLE II
FRAMES LOST VERSUS TRANSMITTED IN THE PRESENCE/ABSENCE OF ARTIFICIAL LIGHTING

Darkness		Artificial Lighting	
Transmittted frames	**Lost frames**	**Transmittted frames**	**Lost frames**
1292	2	1128	1
1163	1	1128	4
1066	3	1255	4
1145	0	1477	4
1082	0	1320	0
1117	2	1409	1

When considering loss of frames we are testing transmission inside a room in two operative conditions: absence or presence of artificial lighting. We are using 30 second video segments

Table II shows that the average of lost frames is 0'116% in the absence of artificial lighting and 0'175% when using illumination devices (two 36 W fluorescent lamps), especially when switching on the lamps. We have also tested the transmission in the presence of interference (using a similar LED lamp emitting simultaneously but with different amplitudes, placed side by side with the VLC emitter). Table III shows the number of frames lost versus increasing signal-to-interference values, for a 30s video transmission.

TABLE III
FRAMES LOST VERSUS TRANSMITTED IN THE PRESENCE OF INTERFERENCE

SIR (dB)	Transmitted frames	Lost frames
No interference	1427	0
-4,67	1421	32
-9,91	1418	78
-12,62	1197	169
-20,22	1116	184

Figure 9 presents one captured image from the received video signal. Finally, we tested the possibility of using the implemented VLC link for sending real time video captured from a web camera. A delay of 3 seconds was reported due to the necessity of compressing and de-compressing the video signal. This delay can be reduced by increasing the available baud rate in the transmission.

Fig. 9. Received video capture, for a 4 m. link (from Snow White and the Seven Dwarfs, Walt Disney, 1937)

VI. CONCLUSION

The design of a visible light system suitable for transmitting video files has been shown. It is now able to transmit encrypted video at a baud rate up to 2 Mb/s. The same structure allows audio or raw data transmission without loss of generality. At a link distance over 3 meters the received SNR is over 40 dB, with a bit error rate extremely low (and even these remaining errors are corrected by the protocol itself). The system is suitable for video transmission while providing illumination levels from 85% to 15% of the nominal lamp emitted optical power value. Future work is oriented to test other lamps (e.g RGB lamps instead of phosphor ones) in order to achieve real-time video transmission or even symmetrical 10 Mbps Ethernet transmission (10BASE-T).

Many application scenarios can be considered for this models, as can be asynchronous data transmission in several areas where there are limitations to the use of RF signals (hospitals, industrial and nuclear facilities, etc.). It can be used also for in-house applications when WiFi channels are saturated or, simply, when we need interference-free (or secure) transmissions. Another interesting application to be considered is providing internet access in commercial flights without the limitations induced by the RF interferences with flight instrumentation.

ACKNOWLEDGMENT

Special thanks should be given to CeDInt-UPM for their technical support. BALDUR is a joint project of CeTIC, 07GLOBALAN and the Regional Health Service of the Canary Islands (SCS), supported in part by the Spanish Industry and Commerce Ministry, (projects TSI-020100-2008-660 & 2009-175). Previous research has been funded in part by the Spanish Science & Innovation Ministry (project COLIBRI TEC2009-14059-C03-01).

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