VLCLighting - A Collaborative Research Project on Visible Light Communication

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***Abstract* — This paper describes a collaborative research project on Visible Light Communications for lighting infrastructures. It is being developed by the Integrated Circuits and Mobile Network groups in Instituto de Telecomunicações, Aveiro site, and expects to deliver a VLC demonstrator transmitting video and data in real-time by the end of 2016. Another main goal is to develop this system to be modular in order to enable collaboration with other groups with interest in this field, offering the academic community a real-time test bed to evaluate the performance of different modules, algorithms and optical front-ends, which is currently not available.**

Keywords — Visible Light Communications; DCO-OFDM; ACO-OFDM; Smart Lighting Infractructures

I. INTRODUCTION

The ramping up of LED technology brought new opportunities for energy savings and reduced maintenance costs in illumination systems [1]. Thus, the replacement of traditional illumination devices by LEDs is a rapidly growing trend [2], which has been enabling service providers to reduce power consumption, maintenance and installation costs. For instance, it is possible to combine sensory information, like motion detection or background illumination and react to environmental demands. Lighting quality manipulation as also been considered by means of color temperature adjustment. Relevant research on these topics has been reported in [3, 4].

Lighting infrastructures offer a great potential for value added service support. Being a ubiquitous infrastructure, lighting systems can support new service opportunities, like night surveillance, infotainment and advertising, among other possibilities. For this end, Visible Light Communication (VLC) stands as a very interesting candidate as it exploits the existing lighting infrastructure and is not constrained by international regulations regarding bandwidth usage. The exploitation of LEDs as information broadcasting devices has been an active research topic in the last decade [5], but there are still many important aspects in free space optical communication systems to be addressed, since most of the reported research focuses on indoor systems and short range communications, opposite to the proposed application.

Project VLCLighting is a multidisciplinary project, aiming at the exploitation of VLC concepts, for broadcast services, in public street lighting infrastructures. This application scenario has its inherent specificities, such as a significant distance between emitter-receiver, presence of non-negligible optical noise and interference sources and regulated lighting requirements. These constraints are not considered in most published research on VLC systems, which has been mainly focused on indoor applications where environmental conditions can be conveniently controlled [6]. Thus, this project will have to face several research challenges, namely: i) demonstrate the viability of these concepts and disclose the conditions for nurturing new economic opportunities; ii) find effective means to combine dimming (based on sensor information) and data modulation in high power LEDs, which have intrinsic bandwidth limitations; iii) addressing methods to reduce the impact of non-uniform illumination conditions on humans due to data modulation; and iv) implement a cost effective VLC transceiver enable to demonstrate the feasibility to introduce value added services as a new design variable. Another major goal of this project, which is the focus of paper, is to build a test-bed for the deployment of VLC concepts in lighting infrastructures. This test-bed should provide experimental evidence on the suitability of these concepts and be amenable to collaboration among different research projects. This means that the transceiver's architecture should be modular in order to ease the adding/removing of modules developed by different research teams. Different modulation schemes and signal processing units can therefore be easily tested, their performance evaluated and compared to alternative solutions. To make this possible, the VLC transceiver is being implemented in a Field Programmable Gate Array (FPGA), with elastic buffers between modules.

This paper is composed by five sections. Section I has provided a general introduction to project VLCLighting, while major constraints and opportunities are discussed in section II. Section III describes the VLC system's architecture and implementation details. Preliminary results are given in section IV and conclusions discussed in section V.

II. CONSTRAINTS AND OPPORTUNITIES

A. System Constraints

Bandwidth and power limitations are dependent on the available devices and targeted applications [7]. LEDs for

This work is funded by FCT/MEC through national funds and when applicable co-funded by FEDER – PT2020 partnership agreement under the project UID/EEA/50008/2013.

lighting applications usually require high output flux per chip, which translates into high forward currents, reaching over 1A. Switching these devices between on and off states, pose fundamental limitations on the achievable bandwidth, which constrain the support of high data rate services unless evolved modulations schemes are applied. However, these schemes are typically based in continuous wave modulations, which can be distorted by the LED's limited dynamic range.

On the other hand, dimming is a mandatory attribute in public lighting infrastructures in order to reduce power consumption, but their superposition with evolved modulation schemes may bring out new issues. High optical power may also raise additional issues. Considering point-to-point communications, high optical power translates into high signal to noise ratios, thus a performance improvement. However, considering multi-point communication, where multiple luminaries may access the channel at the same time, high optical power leads to higher interference levels between neighbors. Once more, evolved modulation and coding schemes, able to mitigate interference in multiple user scenarios, must be applied.

B. *Oportunities*

In recent years, OFDM-based modulation schemes have been considered as promising techniques for VLC systems [8]. Their ability to mitigate the effects of the deep fading and interference, while achieving high data rates, justify their popularity. However, modulating the light of LEDs with data generates non-uniform illumination conditions, which have not been conveniently addressed before. Techniques able to mitigate these effects or reduce their impact on public comfort and visibility issues need to be considered.

Usually, digital modulation formats combined with pulse width modulation (PWM) are the most popular for driving LEDs as they avoid distortion induced by the LED's limited dynamic range. However, from the spectral efficiency view point, these formats are rather limited, given the above mentioned constraints. A promising venue consists of exploring optical digital to analog conversion promoted by the usage of LED arrays and chip on board LEDs, thus reducing the illumination non-uniformity effects and promoting bandwidth enhancement with more advanced modulation formats [9]. Project VLCLighting is using Optical Digital to Analog Conversion (ODAC) concepts to avoid distortion when single LEDs are modulated with a high Peak-to-Average Power Ratio (PAPR) modulation such as OFDM. In ODACs, the light output is produced by turning on, or off, a number of LEDs rather than driving a single LED with an analog signal.

III. Transceiver Architecture

The transceiver is being implemented in a Virtex-6 FPGA, available in Xilinx ML605 development board. Beyond usual advantages of prototyping with FPGAs, it is especially suited for this project because: i) the availability of system level tools (e.g., Xilinx System Generator) that eases the hardware design learning curve, especially for researchers used to MATLAB and Simulink; ii) the easiness of introducing new modules, and testing their performance in simulation, co-simulation and real-

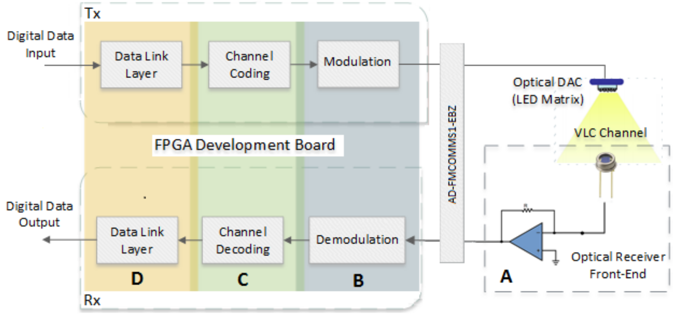

Figure 1 - VLCLighting high-level transceiver architecture

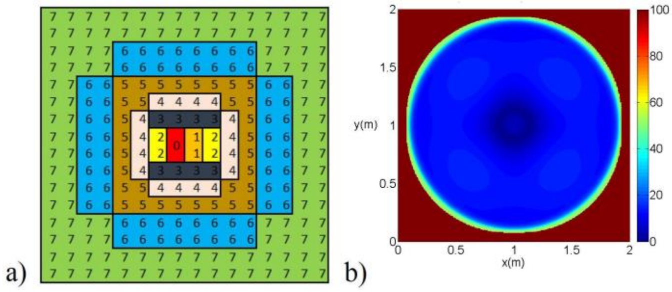

Figure 2 - ODAC a) layout; and b) mean square error when receiving a sinusoidal signal

time; iii) the availability of sophisticated hardware debug tools, such as Xilinx ChipScope Pro; iv) the reasonable cost when compared to existing real-time VLC demonstrators (relying on arbitrary waveform generators); and finally, v) the possibility to integrate the transceiver with a microprocessor with Linux support (e.g., Microblaze) which enables full system integration with high level data services.

The VLCLighting high-level transceiver architecture is shown in Figure 1. It comprises an optical front-end, a DAC/ADC board from Analogue Devices (AD-FMCOMMS1-EBZ, in baseband configuration), and a FPGA based transceiver. Note that the DAC on FMCOMMS1 board is necessary only when the ODAC is not used – for preliminary transceiver testing and comparison purposes. In the following sections, the main system modules are further described.

A. *Optical Front-End*

The optical front-end comprises an ODAC transmitter and a receiver from Hamamatsu (C1270-11). The ODAC was built with 255 blue Suprflux LEDs (OVA-1033). Figure 2a) shows the final layout, with least significant bits driving the inner LEDs and the most significant bits driving the outer regions. This configuration has been evaluated through MATLAB simulation. The spatial distribution of the mean square error when receiving a sinusoidal signal is shown in Figure 2b), considering a receiver with a receiving angle of 60º and at a distance of 50cm from the source. It shows that although the ODAC is rectangular in shape, the coverage is similar to what we would expect from a single point source.

Beyond the LEDs and transistor drivers, the board also includes: eight current buffers to provide the current that FPGA outputs cannot deliver; one FPGA Mezzanine Card (FMC) connector; and impedance balanced inputs, with similar path lengths, guaranteeing similar delays for each bit in the input

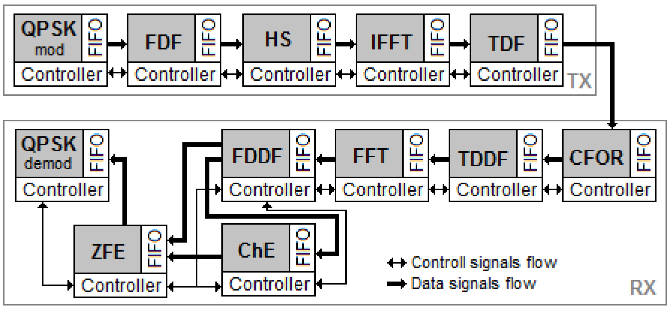

Figure 3 – DCO-OFDM transceiver architecture.

bus. Also, the board has been implemented to be compatible with both ML605 and KC705 development boards.

B. Modulation

DC biased optical OFDM (DCO-OFDM) is the modulation currently implemented in transceiver. The analogue signal is made real and positive by constraining the input vector to the transmitter inverse fast Fourier transform (IFFT) to have Hermitian symmetry and by adding a DC bias in the analogue domain. Other popular techniques to generate OFDM include asymmetrically clipped optical OFDM (ACO-OFDM) and PAM-modulated discrete multitoned (PAM-DMT), although other hybrid and modified solutions have been proposed in literature. Due to its popularity and efficiency, DCO-OFDM was selected to be implemented in this transceiver.

The transceiver's block diagram is presented in Figure 3. The transmitter (TX) includes: a QPSK modulator; a frequency domain framing (FDF) unit; a Hermitian symmetry (HS) unit; an IFFT unit; and a time domain framing (TDF) unit. The transmitted frame is composed of 4 OFDM symbols, each with 1024 carriers. Due to bandwidth limitations and AC coupled paths in the optical front-end, we are currently using only 300 carriers, starting at 600kHz, with a carrier separation of 30kHz (6MHz bandwidth). Pilots are inserted in odd symbols, evenly spaced with a separation of 4 carriers. The TDF unit is then responsible to append a high autocorrelation time domain synchronization symbol and a 256 samples cyclic prefix (CP). The receiver (RX) includes: a module to estimate and remove the carrier frequency offset (CFOR) and estimate the start of frame; a time domain deframing (TDDF) unit to remove the CP; a FFT module; a frequency domain deframing (FDDF) unit, to separate pilots from data; a Channel Estimator (ChE) module; a Zero Forcing Equalizer (ZFE) module; and a QPSK demodulator.

The interface between main blocks includes elastic buffers that implement an asynchronous handshake protocol, as shown in Figure 4. Each processing module is attached to a buffer and a controller. The controller keeps track of local and previous buffer fill levels and enables the processing module so that the local buffer is never full or empty. As long this architecture is respected, it is very straightforward to add/remove blocks without concerns about synchronism and latencies.

C. Channel Encoder

In the considered scenario, the system's reliability can be compromised by noise and interference, namely: i) ambient light, coming from the sun or other lighting sources; ii) atmospheric attenuation, which depends not only on the distance between the emitter and the receiver but also on the atmospheric conditions such as fog and rain, which are relevant even for medium range distances found in public lighting systems; iii) channel blockage, induced by obstacles in the LOS channel; iv) multipath, due to the reflections of surrounding buildings. Random and burst errors induced by these phenomena must be handled in order to guarantee a minimum system performance.

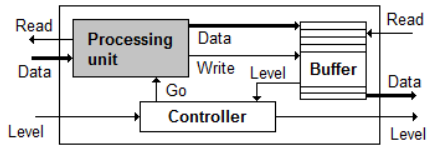

Figure 4 – Elastic buffer block architecture.

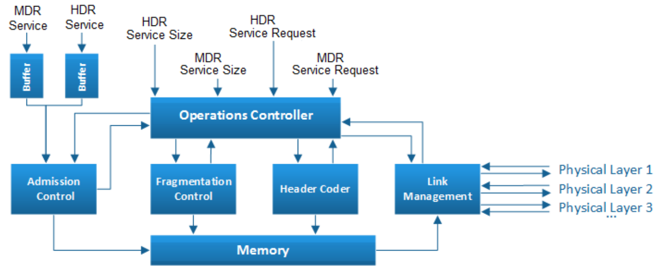

Figure 5 – Data Link Layer block diagram.

In the proposed broadcast VLC system, Forward Error Correction (FEC) techniques should be employed, such as Reed-Solomon (RS) and/or convolutional codes, to provide the receiver error detection and correction capabilities. While convolutional codes handle random errors better, RS codes can be effective for both random and burst errors. However, these are more complex to implement and use bigger code words (for the same performance). Also, for both codes, there is always a compromise between robustness and overhead. Thus, our approach is to use RS and Interleaving, which minimizes the impact of burst errors, and resort to a more robust code in the frame header and a lighter code in the payload. Above 7dB the RS(255,239), with an efficiency of 93.7%, has better performance when compared to an Convolutional that has 50% of efficiency, therefore we included it in the project.

D. Data-Link Layer

This project has identified two types of value added services to be introduced in public lighting systems: i) Moderate Data Rate (MDR) – to furnish adequate means for control and management, advertising and infotainment services; and ii) High Data Rate (HDR) – for video broadcast. The Data Link Layer (DLL) is responsible for fragmenting and routing these data while maintaining a continuous transmission flow to assure the lighting and transceiver functionality.

The principal function of the DLL is to provide a reliable protocol that assures frame sequencing and final encapsulation of higher layer messages into frames, while prioritizing and combining multiple services into the same physical layer. With these purposes in mind, the proposed DLL (figure 5) includes: an Admission Control block that is responsible for controlling the payload admission; Fragmentation Control block that

freq (MHz)	LSB_{ref}							MSB
0,01	1	2	4	9	19	36	66	108
0,1	1	2	4	9	19	37	68	110
1	1	2	4	9	20	38	71	111
2	1	2	4	9	20	38	65	113
5	1	3	7	13	24	42	49	78
10	1	2	6	12	15	22	40	62

a) b)

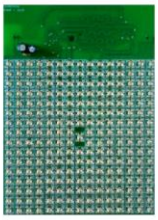

Figure 6 – ODAC a) table with the voltage ratio between bits with different frequencies (LSB as reference); b) picture of produced board.

fragments and generates the sequencing of frames; Header Coder block that computes the frame header; and Link Management block that establishes the bridge with lower layers. Operations Controller block has the ability to manage and control these blocks to ensure the well-functioning of all operations.

IV. RESULTS

This section presents preliminary results regarding the individual ODAC and transceiver performances.

A. Optical Front-End

To evaluate the correct operation of the ODAC we used square waves to drive each bit on its digital input pins and measure the received signal. By repeating this procedure with increasing frequencies the table in Figure 6a) has been obtained. As expected for this type of converter, results showed that neighboring input bits have approximately a difference of a double. In this table we can observe the low frequency response has a consequence on the optical bandwidth limitations imposed by the LEDs. Figure 6b) shows the ODAC board picture.

B. DCO-OFDM Transceiver

The implemented OFDM transceiver was tested at different levels of the implementation flow. First, its performance was evaluated through simulation, using the tools available in System Generator and Simulink. Once the correct operation was verified, functionality was evaluated in real-time, with the analog transmitted signal connected to the receiver's ADC with an SMA cable. Results were obtained by resorting to four Chipscope Integrated Logic Analyzers (ILAs) implemented in key locations in the transceiver. This enabled us to observe the received signal constellation after the equalizer and evaluate the system's performance. Figure 7 shows the real-time signal constellation superimposed to the simulated constellation (obtained within System Generator).

Simulation results show a negligible signal to distortion noise (SNRd= 68.9dB), which results from the resolution used in the current implementation (32 bits in most data processing blocks) and inherent imperfections of the algorithms used for data manipulation. Higher performance can be obtained at the cost of implementation area. Real-time results show also an excellent transceiver performance (SNRd= 55.7dB), which can be easily upgraded to accommodate higher order constellations.

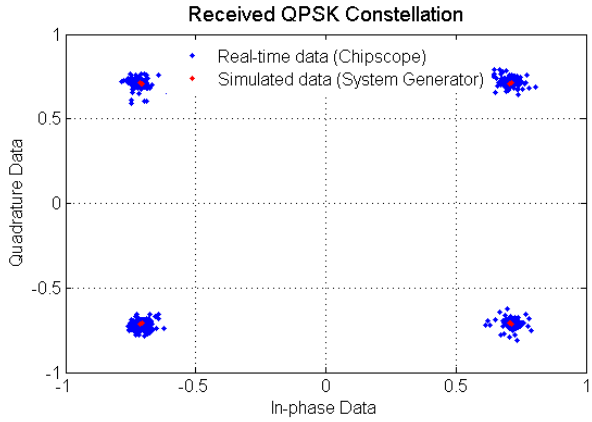

Figure 7 – Received signal constellation.

V. CONCLUSIONS

This paper described project VLCLighting, aiming to develop a real-time demonstrator, amenable to collaboration with other research teams in the field of visible light communications. Up to now, two collaborations have been established and are expected to contribute to the system with alternative modulation schemes and a real-time optical channel emulator for VLC. Preliminary transceiver results show an excellent performance, which can be explored to increase spectral efficiency. Also, ODAC has shown to perform as expected, with a reasonable bandwidth. Dimming integration and quality of light shall be addressed in future work.

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