Development of IEEE802.15.7 based ITS services using low cost embedded systems

Alessio Bellè
TeCIP Institute - Scuola Superiore Sant'Anna
Via G.Moruzzi, 1 - 56124 Pisa, Italy
alessio.belle@gmail.com
Mariano Falcitelli, Matteo Petracca and Paolo Pagano
CNIT - National Laboratory of Photonic Networks
Via G.Moruzzi, 1 - 56124 Pisa, Italy
{mariano.falcitelli, matteo.petracca, paolo.pagano}@cnit.it

Abstract

Visible Light Communication (VLC) is the technique adopting electromagnetic frequencies in the visible spectrum for free space optical communications. Although its practical use is still at early stages, in the last few years research activities have been exploring different solutions to achieve high data rates and reliable links using common LEDs and light sensors. VLC can be used in a variety of applications or end user segments, exploiting already existing lighting infrastructures and thus making VLC a cheap communication system. Among these applications, a prominent case study is that of ITS (Intelligent Transportation Systems), where car headlamps and traffic lights can be used to communicate and fulfill the requirements of road safety applications. This option turns to be particularly effective in short range direct communications to exploit its line-of-sight feature and overcome the issues related to the isotropic nature of radio waves. Recently IEEE undertook standardization activities on VLC, resulting in the IEEE802.15.7 standard, which disciplines PHY and MAC layer services for Visible-light Personal Area Networks (VPANs). This paper shows the development of a VLC prototype based on IEEE802.15.7 standard, using low cost embedded systems as the target platforms. The aim is to get a device suitable to be integrated in existing PANs, or to cooperate with other wireless networks to provide communication services in complex architectures like ITS.

Keywords

Intelligent Transportation Systems, Visible Light Communication, IEEE802.15.7, Wireless Sensor Network, Free Space Optical Communication.

I. Introduction

In recent years, Intelligent Transportation Systems (ITS) have attracted a considerable interest among government institutions and in the research community, due to the effective solutions they can provide for improving citizens' lifestyle and drivers' security. A fully integrated approach for travel planning, transport demand, traffic management, emergency management, road pricing, and use of parking and transport facilities is demanded to the new generation of ITS systems. This requirement has taken the floor in the activities promoted by academia, industrial stakeholders, Standard Development Organizations, and public authorities, seeking for a set of solutions in Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication, permitting to provide added value to transportation, stimulate economy, and enable for new services to the final users (notably the citizens). Vehicular Ad-hoc NETworks (VANETs) are at the focus of research efforts for safety and non-safety critical applications in ITS; particularly, there is a broad scientific and industrial interest in collecting needs and requirements, specifying and developing safety applications based on cooperative systems [1].

Radio-Frequency (R/F) solutions have largely been considered the key technology for vehicular communications. By far IEEE802.11-based protocols are the most adopted solutions in the DSRC (Dedicated Short Range Communications) / WAVE (Wireless Access in Vehicle Environments) protocol suite for ITS. Equipment in the DSRC Service is comprised of On Board Units (OBUs) and Roadside Units (RSUs). An OBU is a board that is normally mounted in or on a vehicle, while an RSU is a board mounted along a road or pedestrian passageway. RSUs and OBUs exchange data with others RSUs and OBUs within communication range. The general approach is that of addressing safety by exchanging and processing messages, mainly between the roadside units and the on-board units with possible V2V communications.

Strict real-time behavior and safety guarantees are typically very difficult to attain in ad-hoc networks. Consider an example of emergency data transmission, when a critical event, that involves a large number of vehicles, occurs: in a wireless ad-hoc network, multi-hop relaying is used whenever we need to disseminate information to an area greater than the one covered by the transmission range of a node. The simplest way to perform multi-hop relaying is by flooding a packet. In this situation, when a node receives a broadcast message for the first time, the node re-transmits the message. Nevertheless at the physical layer, the R/F isotropic transmission can produce a broadcast storm, where there are several nodes broadcasting at high frequency, effectively jamming the wireless space. Thus, in a high density scenario, many real-time safety-critical applications may not be satisfied. In a situation like this and in many others Visible-Light Communication (VLC) systems can offer real advantages.

VLC transmits data via free-space optical (FSO) medium by intensity modulating light sources, such as light emitting diodes (LEDs) and laser diodes (LDs), faster than the persistence of the human eye. In the past few years, LEDs improvements in switching rates, brightness increase, and large scale diffusion drew the attention of research communities, which started looking at visible light as a new communication medium, complementary to radio frequencies, which are becoming more and more congested. LED devices have benefits such as energy savings, long life, low maintenance cost, low temperature generation, better visibility and high brightness, all compared to those of the incandescent lights or fluorescent lights. For these reasons traffic signals and vehicles are gradually changing from electric light bulbs to LED lights. These new lights have the potential to be used as transmitters of information, e.g. with signals transmitted by infrastructure lights and detected by receivers mounted in vehicles (V2I communications). RSUs such as LED-based traffic lights are well suited for information broadcast in vehicular communication systems in V2I mode. Traffic safety related information can be continuously broadcasted without extra power usage, enhancing smooth traffic flow as well as reducing accidents and fatalities. Since light goes straight on, high directional communication is possible, for instance different information can be transmitted for every lane of a road. It is also possible for cars to exchange data with adjacent vehicles (V2V communication), using head, tail and brake lights; in a V2V scenario example, a vehicle in front of a traffic light receives the information and relays it using the brake lights to the vehicle running behind. Using this reasoning it is possible to establish a visible-light vehicular ad-hoc network. Some of these funcionalities are represented in Fig. 1. LED light is directional, so high density cars scenarios would see an increment in the number of links between vehicles, which could improve data delivery since multiple paths become available as more vehicles gets connected together with optical links. On the contrary, in such a situation, R/F communications are likely to get into performance issues due to broadcast storms, disrupting real-time safety-critical information tasks.

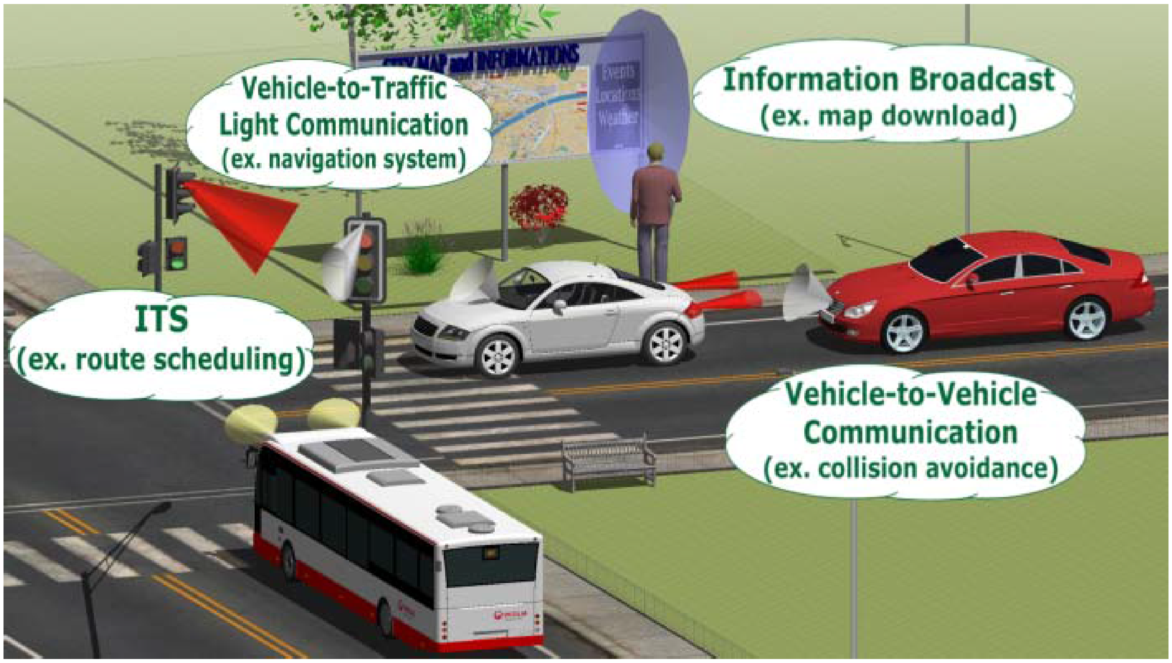

Fig. 1. An overview of VLC network applications in ITS.

Of course, outdoor mobile optical networks pose some further technical issues and challenges for research, with respect to indoor VLC: (i) relative mobility between vehicles or between infrastructure and vehicles is likely to disrupt Line of Sight links; (ii) outdoor VLC is largely affected by natural and artificial lights, mainly sun light, which adds noise and interference to the received signal. The first problem could be addressed by optimizing fixed and mobile (on vehicle) lighting positioning, while interferences may be minimized by using optical filters and optimized electronics. Anyhow, these problems pose an effective limit on the communication range; several experiments and simulations results showed that a reliable communication is possible when a VLC transmitter and a VLC receiver are no farther than 40-50m (see Section II). An interesting hybrid solution would employ VLC for short range, high density communication scenarios, with R/F being used for long range communications ($>$100 m).

Recently, IEEE undertook standardization activities on VLC, resulting in the IEEE802.15.7 standard, which disciplines PHY and MAC layer services for Visible-light Personal Area Networks (VPANs). This paper shows the development of a VLC prototype based on IEEE802.15.7 standard, using low cost embedded systems as the target platforms. The aim is to get a device suitable to be integrated in existing PANs, or to cooperate with other wireless networks to provide communication services in complex architectures like ITS.

The remainder of this paper is organized as follows: in Section II the research activities on VLC methodologies and related ITS-systems prototypes are reviewed together with a description of the salient achievements from standardization working groups. Section III shows the design of a new embedded VLC system based on the IEEE802.15.7 standard; the functional blocks of this system are presented and their implementation is described. In Section IV the experimental characterization of the prototype is introduced: the performance verification by means of specific measurements is realized and the results are discussed. Lastly, Section V summarizes the results and illustrates a road-map for future developments.

II. Related Works

Since the first study employing VLC in ITS, which date back to the early 2000s [2], many others R&D groups explored this new technology and different prototypes were built for both research and demonstration purposes. Long distance communications have been considered in [3], where a reception system with transmitter-tracking mechanism composed by two cameras and two galvanometer mirrors was developed. The two cameras were used to acquire images and track the transmitter light, that information in turn is used to control the galvanometer mirrors and keep transmitter and receiver aligned. Outdoor experiments were conducted at distances from 20 m to 100 m with data rates of 1 Mbps and 2 Mbps, showing that it is possible to communicate if the receiver is maximum 40 m far from the transmitter.

Another related work [4] focused on a road to vehicle communication system using an high-speed camera receiver. LED traffic lights on the road are used as transmitters, while a on-vehicle high-speed camera is used as a receiver. The transmitter is a 16 x 16 LED array, blinking at 500 Hz. Multiple LEDs were used synchronously to enforce the light signal of the transmitter. Experiments were conducted outdoor at a distance between 20 m and 70 m from the transmitter. Images were captured while driving the vehicle at 30$\div$40 km/h towards the transmitter. Experiments showed that it is possible to achieve data transmission at rate of 32 kbps, within 40 m.

D.-R. Kim et al. [5] tested an outdoor VLC system based on Controller Area Network (CAN) which is normally used in cars and many other industrial devices. Data were transmitted with

ON-OFF Keying (OOK) modulation at 500 kBaud. Total communication distance was 20 m in the daytime outdoor condition.

A VLC system suitable for outdoor applications has been developed and tested by [6], who analyzed the performance of a new modulation scheme, based on Direct Sequence Spread Spectrum (DSSS) technique. DSSS enables multiple data transmission at the same time: since its demodulation is based on signal correlation with a specific Pseudo-Noise (PN) sequence, multiple broadcasting sources may use different PN codes to modulate data. Outdoor experiments were conducted in both daylight and nighttime scenarios, also with movements and side shifts, simulating the distance between two road lanes. They showed that the prototype can ensure data transmission at the rate of 20 kbps and drive an array of 242 high-brightness LEDs. On the receiver side, data were sampled by an analog-to-digital converter at 1 Mhz. Signal processing parts of both the transmitter and the receiver are implemented in FPGAs.

Simulations have been performed by [7] to evaluate the feasibility of FSO communication for the broadcast of safety messaging in high density scenarios. Mathematical modeling, in strong agreement with real-world experiments, analytically showed the potential trade-offs between utilizing 802.11 radios versus using short-range, directional communication implemented by VLC.

From the side of standard development organizations the most important contribution comes from the IEEE 802.15 WG (Working Group) - Personal Area Network standards for short distance wireless networks (a.k.a. WPANs) - who released the first official VLC standard in the second half of 2011 [8]. This standard covers both the physical layer (PHY) air interface and the medium-access control (MAC). The IEEE802.15.7 standard is significant for VLC community, because it represents the basis for developing products with guaranteed functionalities. It also provides a minimum benchmark for future developments. The standard is being proposed for a variety of VLC applications relating to Wireless Personal Area Networks (WPAN). The MAC currently supports three multiple access topologies; peer-to-peer, star configuration and broadcast mode. The MAC also handles physical layer management issues such as addressing, collision avoidance and data acknowledgment protocol. The MAC layer could be considered in more detail in later articles but for now it is important to focus on the main features of the physical layer, since this is the bit that actually uses the visible light.

The physical layer is divided into three types; PHY I, II & III, and these employ a combination of different modulation schemes. For ITS application the PHY I type is the most convenient, since it is designed specifically for outdoor applications. It provides data rates in the range 12÷267 kbit/s. Convolutional and Reed-Solomon codes are used for forward error correction, and OOK or Variable Pulse Position Modulation (VPPM) are used for modulation. With OOK, as the name suggests, the data is conveyed by turning the LED off and on. In its simplest form a digital '1' is represented by the light 'on' state and a digital '0' is represented by the light 'off' state. The beauty of this method is that it is really simple to generate and decode. The 802.15.7 standard uses Manchester Coding to ensure the period of positive pulses is the same as the negative ones but this also doubles the bandwidth required for OOK transmission. Alternatively, for higher bit rates run length limited (RLL) coding is used which is more spectrally efficient. Dimming is supported by adding an OOK extension which adjusts the aggregate output to the correct level. At bit rates higher than 100 kbit/s IEEE802.15.7 prescribes for the PHY I layer the VPPM modulation scheme. Pulse position modulation (PPM) encodes the data using the position of the pulse within a set time period. The duration of the period containing the pulse must be long enough to allow different positions to be identified, e.g. a '0' is represented by a positive pulse at the beginning of the period followed by a negative pulse, and a '1' is represented by a negative pulse at the beginning of the period followed by a positive pulse. VPPM is similar to PPM but it allows the pulse width to be controlled from light dimming support.

So far, none of the proposed solutions for using VLC in ITS are actually compliant with the IEEE802.15.7 standard. The main reason lies in the fact that the standard is subsequent to the majority of the studies carried out as yet. Moreover, common feature of the so far developed prototypes is that they adopted high cost camera and optics, which is a strong potential drawback for a wide-scale diffusion.

In the present paper, a preliminary analysis of a VLC system designed for V2V message delivery [9] is extended to a system IEEE802.15.7 conform. Compared to that work, the purpose to adopt low cost hardware is kept, but a different board with a more efficient CPU is used.

III. VLC PROTOTYPE DESIGN

This section shows the features of the developed VLC prototype on embedded systems. The unit board was chosen because of its low-cost off-the-shelf components, as the target is to develop scalable and pervasive systems capable to cover a large ratio of the sensitive environment, with large market penetration rates, eligible to be integrated in more complex systems like ITS. Public licensed software has been used as tool for the development. Also, the prototype comprises IEEE802.15.7 standard-compliant MAC and PHY communication layers. Below, an overview of both the hardware and the software used for the implementation and testing of the prototype is given. Special attention is devoted to the design of the optical transmitter/receiver and to the IEEE802.15.7-based software protocol stack, because those features represent the most innovative aspects of the proposed set up.

A. The Reference Model

Because of the strong novelty of the design, ASICs with optical transceivers suitable for the SEED-EYE board were not available on the market at that time. To overcome this limitation and starting a process having the final goal of producing a microchip dedicated to that purpose, transmitter and receiver functional blocks were implemented as firmware libraries of a board, which acts either as a transmitter or receiver. To build up the prototype we start from the wireless node [10], the SEED-EYE board, developed within a previous work and embedding an IEEE802.15.4 ASIC transceiver. The board will be described in some detail in the following section. A half-duplex prototype will be set up connecting two pairs of two boards. As it will be specified further in the SW subsection, namely the MAC layer with the management PHY functions have been assigned to the control board, while PHY encoding/decoding and transmission tasks have been assigned to transmitter/receivers boards. Thus, in order to distinguish between boards with different tasks, the following terminology is used:

- TX/RX Control Board: a SEED-EYE implementing application-level tasks, MAC and PHY services;
- Transmitter/Receiver Board: a SEED-EYE implementing the optical devices; its tasks are data encoding/decoding and data transmission/reception over the visible light medium.

Control Board and Transmitter/Receiver Board share communication tasks via SPI interface. Fig. 2 shows the functional blocks of the IEEE802.15.7 half-duplex system, highlighting the implementation level of the various MAC and PHY services, either done as new library of the OS (called μLight), or as raw code. A picture of the complete system is reported in Fig. 3. In the next sections some details of the hardware and software design are deepened.

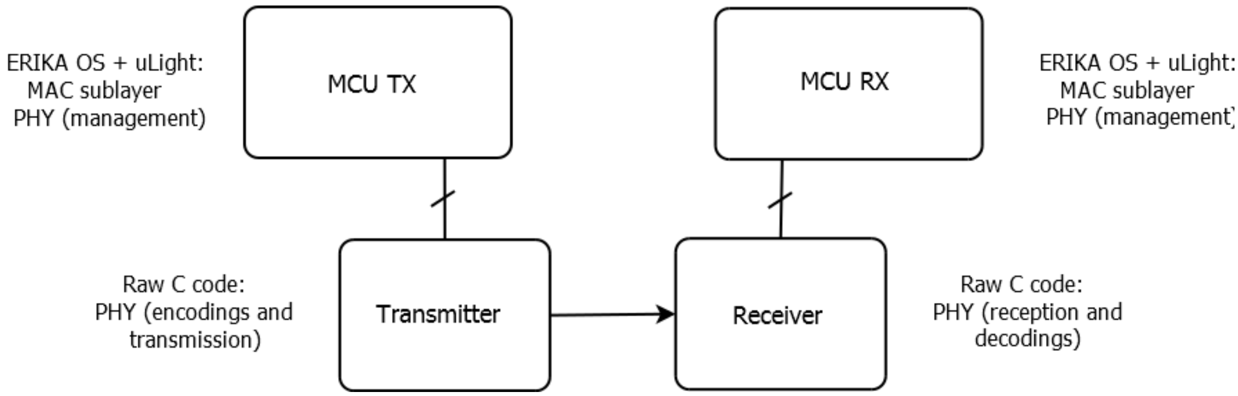

Fig. 2. The VLC IEEE802.15.7 functions, as implemented in the system.

B. The Hardware Components of the System

The board used as basic brick of the system was designed within the IPERMOB project [11], targeted to a large-scale prototype deployed and tested on the land-side of the Pisa International Airport. The SEED-EYE board [10] is an advanced Wireless Sensor Network (WSN) node specifically thought for ITS applications [12]. It comes with full software support, including porting for Contiki OS [13] and ERIKA Enterprise RTOS [14], the latter of which was used in the present work. This device is equipped with an 80 MHz PIC32 micro-controller with built-in 128 KB of RAM and 512 KB of Flash ROM. It implements in hardware IrDA, SPI, I2C, UART, USB, and CAN communication protocols easing the connection with external units; the operative voltage of the chip ranges from 2.3V to 3.6V and some power sleeping modes (RUN,

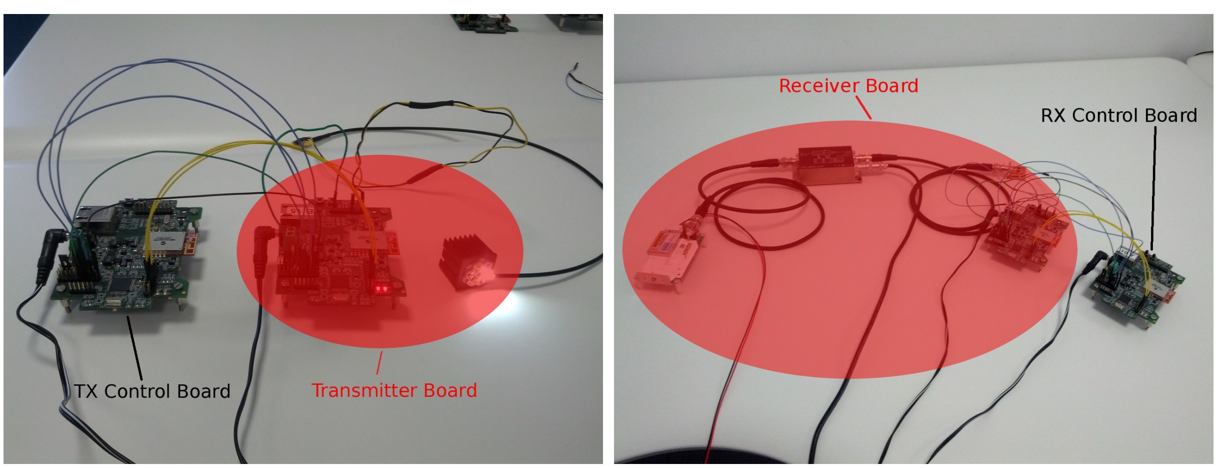

Fig. 3. Complete system: TX Control Board and Transmitter Board (up), RX Control Board and Receiver Board (down).

IDLE, and SLEEP modes) are allowed, along with multiple switchable clock modes useful for the development of power saving policies. From the point of view of the network layer and radio communications, SEED-EYE embeds a Microchip MRF24J40B transceiver. This transceiver is IEEE 802.15.4 compliant and operates in the 2.4 GHz ISM unlicensed band. It has an extremely high coverage (up to 100 m in open space at max power) and it is highly configurable. The R/F communication interface was not used in this work, but its functionality is kept on the board in order to enable, as next developments, a vertical handover between IEEE802.15.7 VLC and IEEE802.15.4 R/F technologies.

1) Optical components: On the transmitter side, only two components are needed: LED and optical lens. The LED was a commercially available phosphor-white OSTAR LED, commonly used as luminous source, generating a radiation flux with a divergence angle of around 120°; the optical lens right after the LED has the purpose to reduce the beam divergence at 18°. On the receiver side, more components are needed as listed below:

- a custom Avalanche Photo-Diode (APD) (Hamamatsu C 5331-11 [15]), with a tiny (1 mm^2) active area and a frequency bandwidth ranging from 4 kHz to 100 MHz;
- an amplifier (FEMTO HVA-200M-40-B [15]), which receives the electrical signal from the APD and amplifies it by a factor of 10 or 100 (switchable gain 20dB / 40dB).
- an adaptation circuitry composed by two standard avalanche fiberglass diodes BYW54 [15]; it is necessary because the output of the amplifier is a voltage falling in the range [-5 V,+5 V], but the inputs of the SEED-EYE generally require a voltage between -0.3V and 3.6 V (some pins are 5 V-tolerant). The adaptation circuitry cuts the negative part of the signal and reduces the maximum positive voltage;
- two optical lenses: a Thorlabs LMR1/M, with a focal length of 1” used for low-range tests, and a Thorlabs LMR2/M, with a focal length of 2”, used for medium-range tests ($\geq$ 10 m). They are used to increase communication distance by placing them in front of the APD and focusing the light on the active area of the detector.

In Fig. 4, all the components of the transmitter/receiver are illustrated.

C. The Software Components of the System

The software stack was developed using either the API (Application Programming Interface) of the ERIKA open source Real-Time Operative System (RTOS) for TX/RX Control Boards,

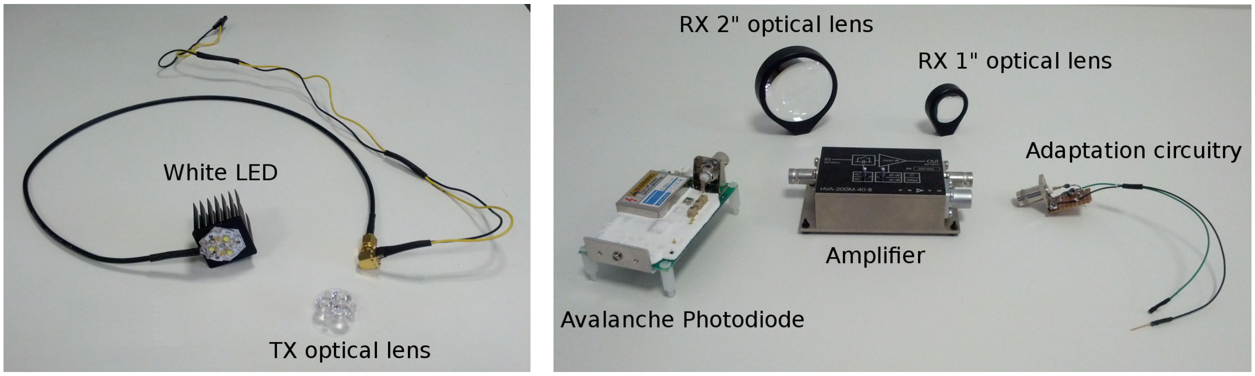

Fig. 4. Optical equipment: Transmitter (left), Receiver (right).

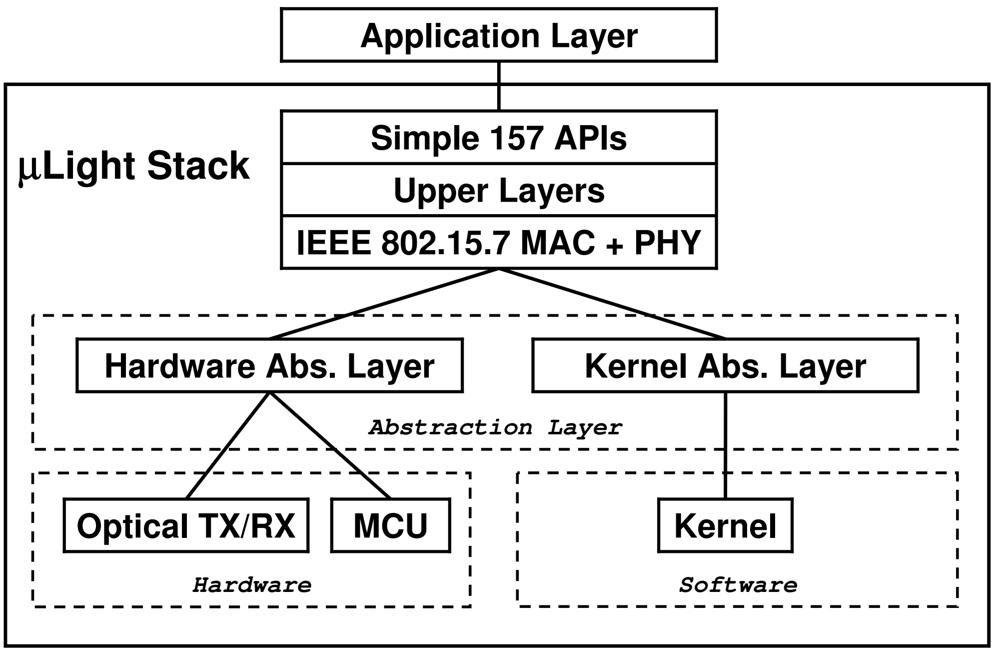

Fig. 5. μLight Architecture.

or the MPLAB® Official Microchip Integrated Development Environment (IDE) for the VLC transmitter/receiver boards.

1) μLight Stack: Using the highly modular ERIKA API framework, and inspired by the experience in the IEEE802.15.4 MAC and PHY implementation acquired during previous works [16], an IEEE802.15.7-compliant network stack was programmed for the TX/RX Control Boards. The resulting software library, μLight, follows a layered approach, as shown in Fig. 5, conform to a VPAN device. To describe the details of software library is out of the scope of the present paper, below only a brief outline is presented. The Hardware Abstraction Layer is basically a wrapper for the functions of the transmitter/receiver driver (Optical TX/RX driver) that is beneath. With some extra functions added, it is responsible for keeping track of the transmitter/receiver state. The MAC and PHY layers accommodate a partial implementation of the IEEE802.15.7 stack, on the one hand almost all the PHY I Service Access Point (SAP) primitives were implemented, on the other hand a minimal set of MAC SAP was implemented to allow easier and meaningful testing at this developing step. Over the MAC layer, μLight has a small high level library used for simple applications where IEEE802.15.7 is required: to initialize the board as a VPAN coordinator and starts a new VPAN, to initialize the board as a VPAN device and seeking for a coordinator, to set some function to be called when a frame is received from MAC layer, etc. Eventually a very simple Device Management Entity has been implemented, with the purpose of enabling and disabling the idle pattern dimming and setting a dimming level. The μLight software library required a driver to control the optical transmitter/receiver, so a new driver has also been added to ERIKA OS. This driver implements the Control Board side of the SPI protocol described in the next paragraph.

2) Optical transmitter/receiver: The transmitter/receiver was developed to perform three main tasks:

1) provide an interface for the Control Board to transfer data and configuring the transmitter/receiver itself (enable/disable transmission/reception, set data rate, etc.),
2) encode/decode data,
3) transmit/receive data within constrained timing.

The SPI peripheral is used for transmission and reception; both transmitter and receiver units are configured as SPI slaves. The optical transmitter/receiver is seen by the Control Board as a stack of addressable control registers and a stack of TX/RX data buffers. All control registers are 8 bit wide, though some of them are significant in pairs. They are addressable by a 6 bit address (short address). TX and RX buffers are 1025 bytes wide: the first two bytes hold the length of the data, while the other 1023 bytes hold the actual data. They are addressable by a 13 bit address (long address). The implemented communication protocol allows only the PHY I level of the standard to perform. This PHY type is intended for outdoor usage with low data rate applications, therefore it is suitable eg. for devices deployed to roadside ITS Stations. For the current prototype only the OOK modulation format was used. Data transmission is done at a maximum data rate of

100 kbps, while the header is always sent at 11.67 kbps. The IEEE802.15.7 standard prescribes some error correction techniques to maximize fail-safe communications in noisy environments. Thus, Reed Solomon encoding, Convolutional Codes, Manchester encoding and CRC-16 have been implemented on the Transmitter Board; similarly, Reed Solomon decoding, Viterbi decoder and Manchester decoding have been implemented on the Receiver Board. The codes are based on publicly available sources, and has been adapted and optimized for the specific needs.

IV. VLC PROTOTYPE PERFORMANCES

The proposed solution was experimentally investigated performing two kind of measurements: on the first the devices were characterized on the laboratory test bench in terms of processing times of the signal and measurement of the physical layer throughput. Then the system was arranged in a free-access and bright corridor of the laboratory building, in order to represent typical noisy outdoor conditions (e.g. V2I communication of a roadside ITS Station). In that condition Bit Error Rate (BER) measurements were performed. Eventually, since one of the main design goal is to utilize low cost embedded systems, then an estimation of the costs was attempted.

A. Test Bench Measurements

Each task of the communication chain committed to the Transmitter/Receiver Boards has been characterized in terms of processing times. The source code of Transceiver Boards firmware has been compiled with MPLAB®XC32 Compiler v1.20, with the lowest level of optimization, because the freeware version was used. Time measurement are done by sampling the low-to-high and high-to-low transitions of a debug pin on the Transmitter/Receiver Boards; this debug pin switches whenever a task starts and finishes; results, shown in Tab. I are averaged over multiple repetitions of the same task. On the transmitter side, the signal delays due to the standard processing protocols are in the expected range, that is very close to the physical limit allowed by the prescribed clock frequency (200 kHz). On the receiver side, the data clearly shows that Viterbi algorithm is really slow. Also in the case of RS(15,7) blocks with correction of all errors, the convolutional decoding time is ten times slower than the others. For that cases the performance of the current system are so far from a satisfactory degree, as to indicate clearly the need of radically changing the architecture of some electronic component. For eg. remaining on low cost readily available devices, all the VLC transceiver functions can be implemented on FPGA, where thanks to its strong parallel processing capabilities, multiple Reed-Solomon blocks can be computed at the same time and Viterbi algorithm can be heavily parallelized.

Some kind of measurement of the PHY layer throughput was performed, to further assess the efficiency of the VLC device. Throughput tests were performed by sending and receiving multiple packets and measuring the time between the start of a packet transmission and the end of a packet reception. Time measurements account for the encoding, transmission, reception and decoding of a complete Presentation Protocol Data Unit (PPDU), which according to IEEE 802.15.7 is formed in turn by the series of Synchronization HeadeR (SHR), Physical layer HeadeR (PHR), and PHY Service Data Unit (PSDU). In these tests the two variables are the PSDU length and the data transmission rate. It is worth to note that the PHY I variable data rate applies to the PSDU only, since the SHR (which is 8 byte long in these tests) is transmitted at 200 kHz, and the PHR is always sent at 11.67 kbps. The results are shown in Fig. 6 where the throughput efficiency is plotted for different PPDU and data rate. The throughput efficiency is computed as the ratio between real throughput and reference throughput. Real throughput is computed with the formula: $\frac{PSDU\ length}{total\ transmission\ time}$, where "total transmission time" refers to the PPDU transmission time (SHR and PHR are thus considered overhead). The reference throughput is the maximum theoretical value achievable with an ideal ultra fast microchip, not introducing

TABLE I. OPTICAL TRANSCEIVER PROCESSING TIMES.

Board	Task	Processing Time (μs)
Transmitter	SPI optical transmission ISR	2.6
	RS(15,7) block encoding	20
	RS(15,11) block encoding	16
Receiver	Viterbi single iteration	15
	Viterbi complete decoding *	268000
	RS(15,7) block decoding without errors	32
	RS(15,7) block decoding with errors	72
	RS(15,7) complete decoding with errors **	21096
	RS(15,11) block decoding without errors	18
	RS(15,11) block decoding with errors	40

(*)=1023 B PSDU + RS(15,7); (**)=1023 B PSDU.

any delay respect to the nominal data rate of SHR, PHR and PSDU. Also in this case the worsening of the performances is evident in conditions where the Red-Solomon and Viterbi algorithms are requested by the standard (from 11.67 kbps to 48.89 kbps). On other hand, when convolutional codes are not requested by the standard as in the 73.3 kbps (where only RS(15.11) is working) and in the 100 kbps (none noise correction) cases, the real throughput is close to the ideal state.

B. BER Measurements

The VLC system was arranged in a free-access and bright corridor of the laboratory building, in order to test its communication performance in a noisy environment. The optical alignment between transmitter and receiver was made by hand, without pursuing high precision, because the goal of the test was to reproduce real life conditions.

Several tests were performed in order to find out on the first the maximum achievable distance between the TX and the RX, and then to measure the BER. The latter is the number of bit errors divided by the total number of transferred bits during a given time interval of transmission. Ten different system configuration were considered at each tested distance (0.5 m, 1.8 m, 2.8 m, 5.1 m, 10.2 m), where the variables were the 5 implemented data rates and 2 packet sizes: small packet (127 B PSDU length) and large packet (950 B PSDU length). An error-free communication was achieved up to 5.1 m, while communications at 10.2 m showed some errors, as presented in Fig. 7. Different symbols refer to the different packet sizes. Comparing the two plots at 10.2 m a common BER degree can be found only at 100 kbps, when none error correction protocol are working; while at the other data rate, the BER scatters above and below 100 kbps value without a coherent behavior respect to payload and data rate. This could be due to the accidental nature of noise generation combined to the ability of the protocols to recover some errors instead of others.

C. Cost estimation

The potential of deployment of the here proposed technology on ITS networks depends on a number of economical factors. Besides equipment and maintenance low costs, a likewise valuable key factor for its affirmation is the compatibility with previous legacy systems and other ITS appliances which have already been installed in the vehicular traffic environment. These issues does not fit the scopes of the present work, but are worth analyzing by further peculiar studies.

Nevertheless an estimation of the costs of the prototype is given below, because that would summarize the present advantages of the designed prototype with existing approaches. The cost of the various components is specified, in order to show also the margins of further savings. SEED-EYE board costs about 100 €, its cost directly depends on the actual small volume of production. If the demand for VLC systems will be high, prices will eventually fall as a consequence of mass production. The same rationale holds for Lens, LED and Avalanche Photo-Diode that have an overall cost of about 100 €. A different argument applies to the voltage amplifier. The device used in the current setup is very expensive compared to the other components, since it costs more than 1 k€. It was used because, despite being over-sized for the purposes of work, it was already available in the laboratory. Presently, the use of less expensive voltage amplifiers is being evaluated. The following Tab. II summarizes the current characteristics of the prototype showing experimental results and costs. Strong further savings are expecting from the RX side, simply using different off-the-shelf components.

TABLE II. EXPERIMENTAL RESULTS AND COSTS OF THE PROTOTYPE.

Max TX/RX distance (m)	Throughput eff. (%)	Data rate $(kbps)$	TX Cost (€)	RX Cost (€)
10.2	$49 \div 98$	$11.67 \div 100.0$	~ 250	> 1500

V. Conclusion

A half-duplex VLC prototype for ITS applications has been realized. The device implements PHY I and MAC layers such as conform to the IEEE802.15.7 standard. The experimental characterization has shown that successful message delivery is very close to the reference case at highest bit rates, when convolutional codes are not used. Faster electronic devices are needed to handle in a suitable way the error correction protocols prescribed by IEEE802.15.7 when the communication occurs at slow rates. The quality of signal transmission is found to be acceptable within 10 meters. It is influenced mainly by the optical alignment system, which was not particularly accurate during the trials. Photo-diodes with a larger active area or telescopic systems on the receiver can improve these performances. At now, referring to ITS domain, only I2I communications services are feasible with the current prototype. Improved equipments will allow to implement ITS V2I and V2V communication services via VLC.

Future work will be addressed to improve and increase the implementation of IEEE802.15.7 functionalities in the system. It is expected to achieve great performance improvements, transferring the Optical Transmitter/Receiver functions on a FPGA. In fact dedicated HW architectures with parallel processing capability, could overcome the signal delay limitations due to the processing time of the general purpose CPU used at present. Moreover the design of an adaptation layer between IPv6 and IEEE802.15.7 would be effective to allow the access of VLC technology to the Internet of Things infrastructure. After the functional verification of IEEE802.15.7-conform VLC technologies, it could be interesting to evaluate the possibility to realize the vertical handover between R/F and VLC communication systems, in order to extend the range of application in providing cooperative ITS services. Beside that, many others specific applications could be designed in the broad field of Cooperative Intelligent Transport Systems, together with the promotion of standardization initiatives at ISO and ETSI working groups will be pursued.

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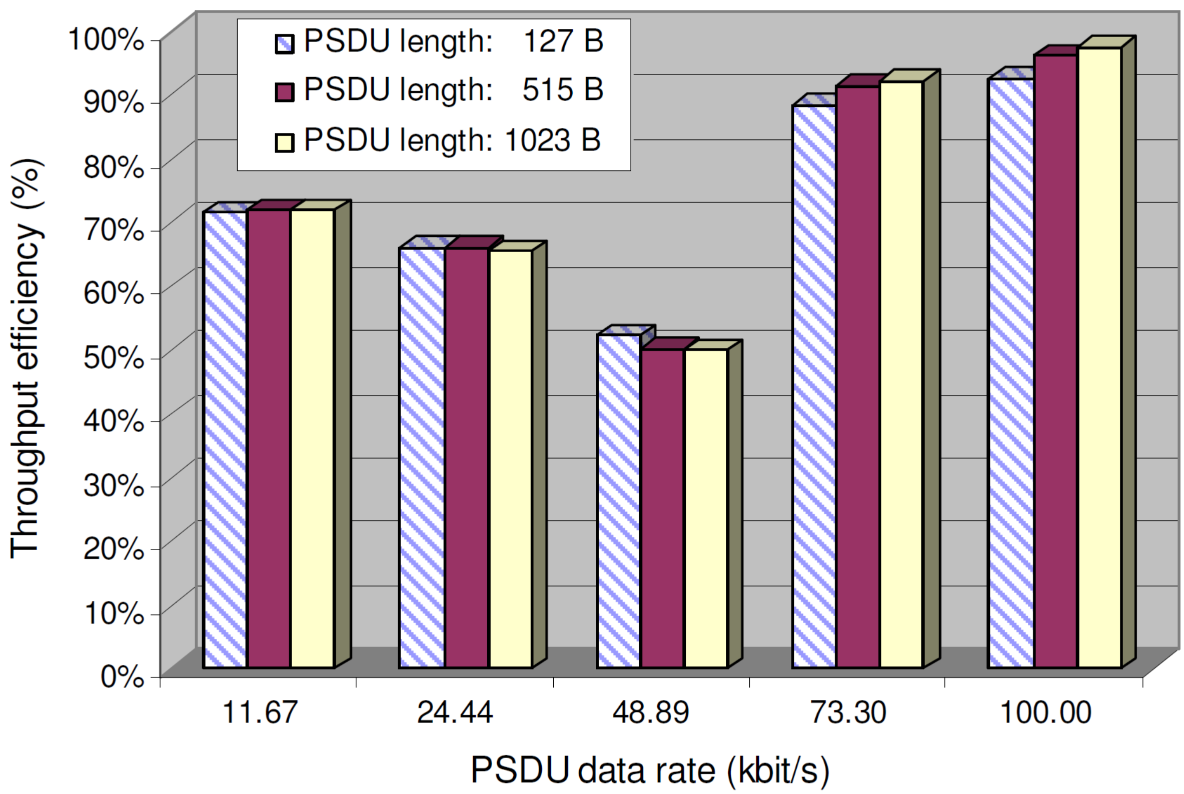

Fig. 6. Throughput efficiency of the VLC system.

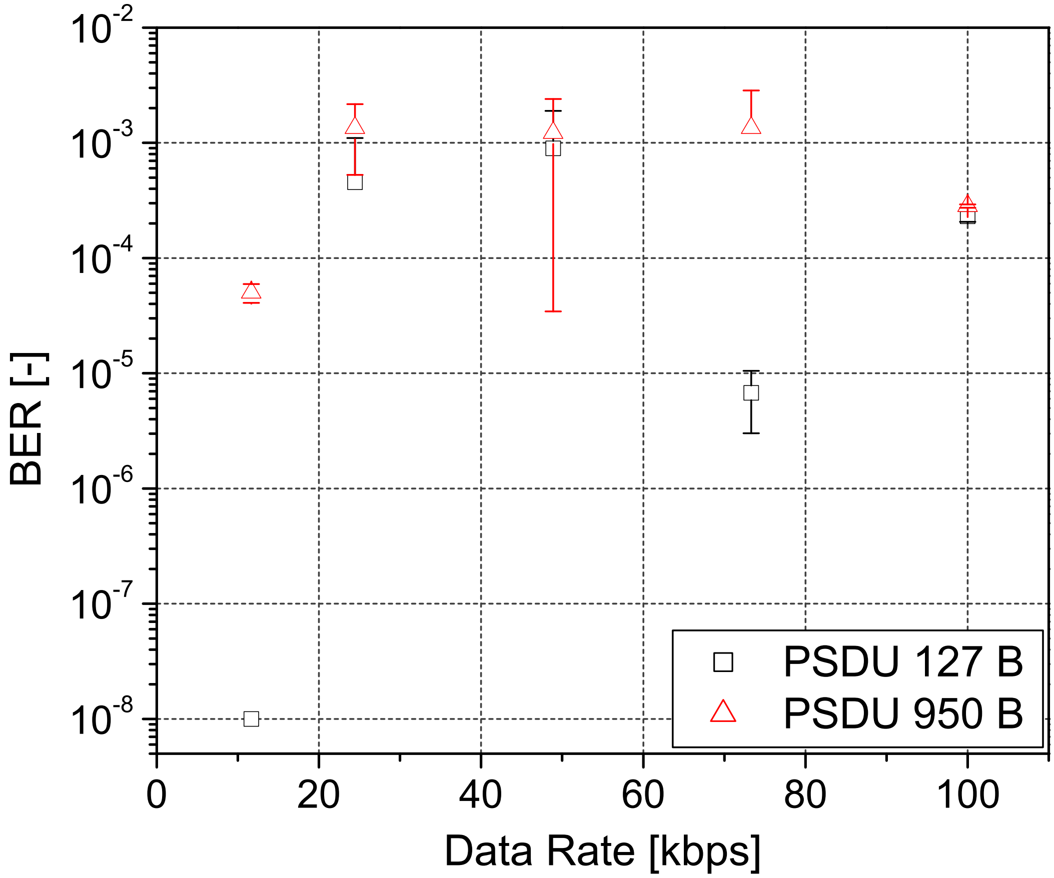

Fig. 7. BER at 10.2 m of distance between the TX and the RX. Two payloads are plotted (127 B PSDU, 950 B PSDU) vs. data rate.