Chapter 2
Visible Light Communication for Cooperative ITS

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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 fulfil 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 IEEE 802.15.7 standard, which disciplines PHY and MAC layer services for Visible-light Personal Area Networks (VPANs). This chapter shows the recent achievements of the experimental research in the scope of VLC prototyping for ITS. Special attention is devoted to the development of a VLC prototype based on IEEE 802.15.7 standard, using low cost embedded systems as the target platforms. The aim is to provide useful considerations for achieving devices suitable to be integrated in existing PANs, or to cooperate with other wireless networks to provide communication services in complex architectures like ITS.

2.1 Introduction

Visible light communication (VLC) is an emergent wireless communication technology, which uses white or coloured LEDs to provide information through visible light as the communication medium. VLC transmits data using all the frequencies

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between 400 THz (750 nm) and 800 THz (375 nm) by intensity modulating the light sources 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.

High power 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 the traffic signals and the head lamps of the vehicles are gradually changing from electric light bulbs to LED lights.

The combined lighting and switching feature of LEDs has a strong innovative potential and it will produce important applications. For example LED-based traffic lights and vehicular VLC systems can become an integrated component of ITS and play a key role in road safety applications by broadcasting traffic information in advance to drivers running vehicles which will incorporate low cost VLC receivers.

Under certain aspects VLC can be considered to be relative to infrared (IR) optical wireless optical communication (OWC). The latter had a slow but constant evolution during the last century, bringing applications in the scope of short-range and low-data-rate communication. The infrared light can be found in our daily life, where the best known example is the remote control of electronic domestic devices. Nevertheless so far, IR wireless communication remains of secondary importance respect to short range RF based technologies, such as Bluetooth, and it have not evolved into broader scope, such as dependable alternative for broadband access networks (Fig. 2.1).

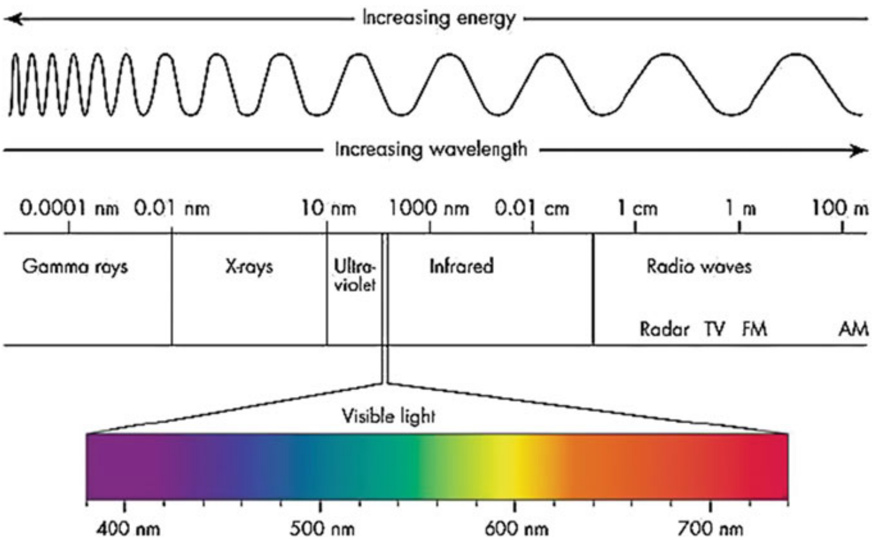

Fig. 2.1 Visible light spectrum

VLC is really a subset of OWC that has become a technology in itself because, in this case, the signal carrier can be seen by the human eye. As distinguishing feature, VLC provides illumination as well as communication, while traditionally OWC has been concerned just with communications. On the other hand VLC systems must operate through illuminating devices with eye safety constraints and they should be able to provide communication also when the illuminating light is dimmed or even turned off.

The potential use of the same device for simultaneous data transmission and illumination is tempting and fascinating. At first glance, the power and money already invested in providing illumination could be reused to facilitate high-data-rate communication between light sources and users. LED luminaries could act as network access points, turning VLC into a direct competitor to broadband radio technologies such as WiFi, fourth/fifth generation (4G/5G) systems and WiGig. The Visible Light (VL) spectrum is unlicensed and currently largely unused for communication, the availability of this free spectrum creates an opportunity for low-cost broadband communication that can help the more used bands. About this, indoor hybrid systems, comprised of RF technology and VLC links, in which directional broadcast VLC channels are exploited to supplement conventional RF channels start to be considered and investigated by means of simulation studies [7, 27]. Nevertheless, to date there are still no assessed solutions for the seamless integration of VLC with conventional wireless networks. The design of VLC systems is still challenging, because the specific properties of the medium offer both new problems and new possibilities. The most important VLC features are outlined below.

Line of Sight (LoS). In order to establish an optical link, LoS is requested between the transmitter and the receiver. This could be a major issue, as devices mobility or obstacles moving between transmitter and receiver can disrupt communications. Moreover, natural and artificial lights add noise and interference to the channel. When used outdoor, bad weather conditions like rain, snow, fog can further alter light signal.

Unlicensed spectrum. Visible light is an unrestricted very large (400 THz wide) spectrum available worldwide. This is in contrast with infrared light (IR) or radio frequency (R/F) technologies, which are limited by law and limited in band; many R/F frequencies are restricted for special applications (military, aircraft, etc.).

Healthy. Visible light is safe to human body, which makes it possible to transmit with high power, while radio waves are concerned to be dangerous to human body and infrared light may be harmful to human eyes.

No electromagnetic interference. VLC is resistant to electromagnetic noise and in turn does not cause electrosmog. It can be used in places where radio waves cannot be used, for examples, hospitals and areas around precision machines.

Security. Visible light communication requires LoS, and don't penetrate through walls, while radio frequencies do. Communication is then limited to the area in which it originates. This property can be exploited to hide data communications from potential eavesdroppers.

High spatial reuse. Consider circumstances where many devices compete for wireless medium access, for instance classrooms, conference halls and other assembly spaces. Traditional wireless can hardly handle lots of users, which in turn experience degraded performances. Since VLC is high directional, a single optical link could for instance originate from a lamp in the ceiling pointing directly to the floor, so that only a few users share the link. Spacial reuse allows then to accommodate larger number of VLC devices without interference as in the wireless case.

Ubiquitous computing. VLC can be used as a communications medium for ubiquitous computing, because light producing devices, such as indoor lamps, commercial displays, traffic lights, outdoor lamps, etc. are used everywhere.

2.2 VLC Architecture and Expected Applications

A typical VLC architecture, as shown in Fig. 2.2 comprises transmitter entities and receiver entities, communicating by modulated visible light. Communicating entities can be end devices such as mobile personal devices, vehicles, and infrastructure lights. Each entity transmits and receives data by means of a VLC emitter and a VLC receiver, respectively. The VLC emitter is an optoelectronic transducer that transmits information using visible light as the physical transmission medium; high brightness LEDs are commonly used. LEDs are modulated at such high frequencies that human eye cannot perceive any difference in lighting compared to that when there is not modulation. As a result, VLC transmitters can be used for lighting and data communication simultaneously. The VLC receiver is an optoelectronic transducer (PIN photodiode or avalanche photodiode or CMOS sensor) that receives information, previously modulated in the visible light spectrum, and converts it into electrical signals than can be processed by a demodulator/decoder.

Three types of topologies are possible for the VLC link: directed Line-of-Sight (LOS), non-directed LOS, diffused non-LOS. As depicted in Fig. 2.3, the directed LOS allows the highest intensity for the received signal and thus it has the highest bitrate and the longest distance are achieved at the expense of severe demand of precise alignment; in the non-directed LOS the receiver has a wider field of view, the alignment is simpler, but the intensity of the signal is at medium level, so shorter

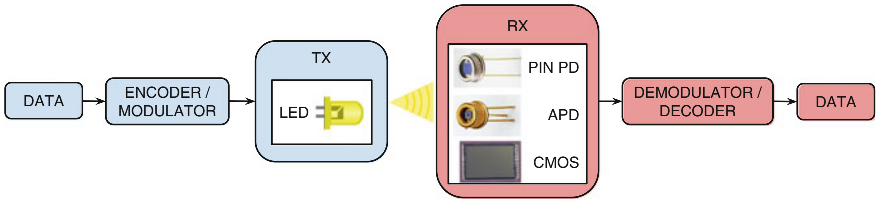

Fig. 2.2 Architecture of VLC system: transmission-reception chain

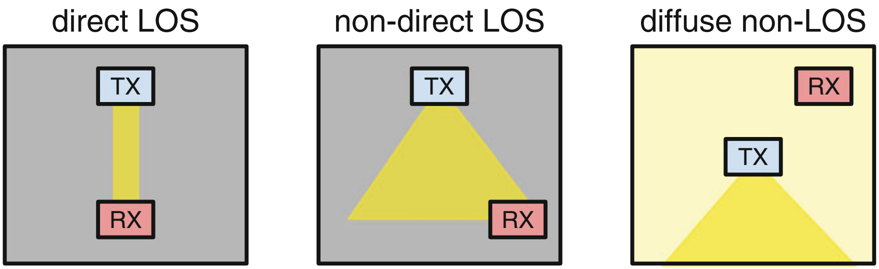

Fig. 2.3 Possible topologies of the VLC link

distances are achievable together with high/medium bitrate; the diffuse non-LOS is free form alignment issues, but it is suitable only in closed environments and it shows the lowest bitrate.

VLC technology is still in the introductory phase and substantial efforts are needed before it can be widely deployed for practical applications. Nevertheless a number of LED based applications are expected to be ready in few years in many sectors: from inner satellite to military purpose, from hospitals (where electromagnetic interference must be avoided) to aircraft, from lighting to automobiles. A short list follows.

Aviation: Radio waves cannot be used by passengers in aircraft. LED-based lights are already used in aircraft cabins and each of these lights could be potentials VLC transmitters to provide both illumination and media services for passengers. Furthermore, this will reduce the aircraft construction costs and its weight.

Smart Lighting: Smart buildings require aesthetic lighting. Smart lighting with VLC provides the infrastructure for both lighting and communication and reduces the circuitry and energy consumption within an edifice.

Hazardous Environments: In environments such as petrochemical plants, mines, etc., RF is potentially dangerous because there are explosion risks, so communication becomes difficult. VLC can be used in this area as it is a safe technology and provides illumination and communication at the same time.

Device Connectivity: By directing a visible light at a device one can have a very high speed data link and security because a beam of light is shined in a controlled way.

Defense and Security: VLC can enable secure and high data rate wireless communications within military vehicles and aircraft.

Hospitals: In hospitals, some equipment is prone to interference with radio waves, so using VLC has many advantages in this area.

Underwater Communications: VLC can support high data rates beneath the water, where other wireless technologies like RF do not work. Thus, communications between divers or remote operated vehicles are possible.

Vehicle and Transportation: Traffic lights and many cars use LED-based lights. Cars can communicate with each other to prevent accidents and also traffic lights can communicate with the car to ensure road safety. The role that VLC can play in this field will be deepened in the next section.

2.3 ITS Scenario

The most recent achievements of the activities in the area of intelligent transportation systems (ITS) promoted by academia, industrial stakeholders and Standard Development Organizations (SDO) are the so called Cooperative ITS (C-ITS) [15]. Their goal is to use and plan communication and sensor infrastructure to increase road safety. Communication cooperation on the road includes car-to-car, car-to-infrastructure, and vice versa. Data available from vehicles and road side units can be either consumed locally in the boundary of a geolocalized network or transmitted to a server for central fusion and processing. These data can be used to detect events such as road works, traffic jam, approaching emergency vehicle, etc. Such data are processed in order to produce driving recommendation dedicated to a single or a specific group of drivers and transmitted wirelessly to vehicles.

The development of the C-ITS has been driven by usage scenarios that see a great extent the use of radio wave technology, as depicted in Fig. 2.4. In this broad and more general framework we can identify a number of use cases where the unique characteristics of VLC devices can be exploited in more effective ways as compared to traditional radio wave technology. However, it is worth emphasizing that compared to the mature RF based technology, VLC is still in the introductory phase and substantial efforts are needed before it can be widely deployed for short-range ITSs applications.

It is worth to mentioning that before the onset of LED based VLC, a series of infrared (IR) optical devices have been used successfully in several ITS projects in Korea and Malaysia (electronic toll collection), Japan (Vehicle Information and Communication System [VICS]), and Germany (Truck Tolling Scheme), among others [11]. The lesson learned by those projects suggested that near IR can be used for broadcasting messages in line of sight from RSUs to vehicles and for receiving beacon frame from vehicles to RSUs, while far-infrared can be used for video surveillance [23]. Over 50 thousands IR VICS transceivers are already installed on the surface road in Japan and most of them are connected to Traffic Management Center. The maximum range of infrared VICS beacons is up to 10 m with the maximum data rate of 1 Mbps and the maximum packet data size of 59 bytes [18].

Both IR as well as VLC are used to be included in the so called ITS Infrastructureless Technologies. This category holds the technologies that do not require any traditional telecommunication infrastructure to operate [11]. Indeed, unlike cellular communications that rely on base stations and a large number of antennas deployed throughout a territory, the Infrastructureless Technologies are easy to install adapting the existing roadside settlement and they become ready to use within short time. About this, VLC is even cheaper than IR, because the light signal transmitters are

Fig. 2.4 ITS scenario [14]

the existing LED traffic lights and LED car headlamps, therefore if VLC is adopted in ITS applications instead of IR, there is no need to put ad hoc IR emitters in the environment.

2.3.1 VLC in ITS

Traffic signals and vehicles are gradually changing from electric light bulbs to LED lights because of their merits of energy saving, long life, low maintenance cost, better visibility and low temperature generation. These new lights have the potential to be used as transmitters of information, with signals transmitted by infrastructure lights and detected by receivers mounted in vehicles (I2V communications). RSUs such as LED-based traffic lights are well suited for information broadcast in vehicular communication systems in I2V 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

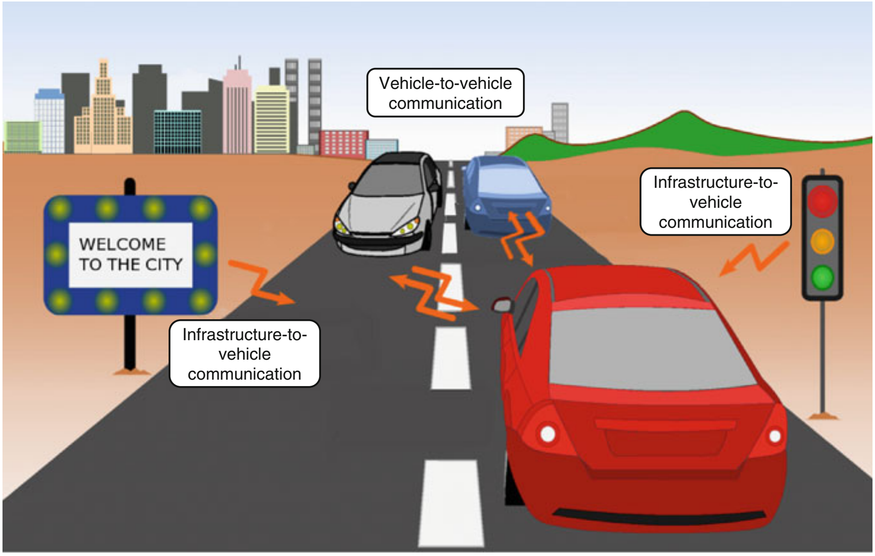

Fig. 2.5 Example of vehicular communication enabled by VLC

brake lights to the vehicle running behind. From the perspective of the vehicular ad-hoc network, VLC can be seen as a new access channel next to the RF existing ones. As shown in Fig. 2.5, potential applications of V2X systems are the same as those for RF channels, including active road safety, traffic efficiency, local services and Internet based services. Obviously the latency and reachability constraints for data exchanges are tighter for safety critical applications respect to the other kinds, but recent studies showed that they can be fitted by VLC also with off-the-shelf components [22].

Outdoor VLC links depend on the existence of an uninterrupted line of sight (LOS), 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. Conversely, in such a situation, R/F communications are likely to get into performance issues due to broadcast storms, disrupting real-time safety-critical applications and information dissemination [2].

Of course, outdoor mobile optical networks pose some technical issues and challenges with respect to indoor VLC: (i) relative mobility between vehicles or between infrastructure and vehicles is likely to disrupt LOS 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 interference may be minimized by using optical filters and optimized electronics. Anyhow, these problems pose an effective limit on the communication range; a number of experimental results and simulations showed that a reliable communication is possible when a VLC transmitter and a VLC receiver are no farther than 40–50 m [22].

A large number of analytical studies based on numerical simulations have been performed investigating the benefit of using VLC complementing RF DSCR messages to enable ITS related technologies, such as platooning [1], Cooperative Adaptive Cruise Control (CACC) [31] and Advanced Driver Assistance System (ADAS) [19], among others. Besides that strong efforts have been devoted for developing and testing experimental prototypes, as will be deepened in the next section.

2.4 Research and Prototypes for VLC in ITS

As soon as the high power LED technology was beginning to emerge, one of the first patented applications of VLC was in the scope on ITS. Indeed, utilization of LED traffic lights to transmit information have been patented very earlier in USA [16], even before the research was developed in that field. Afterwards, at the beginning of 2000s, many research group started to investigate this new technology and a number of prototypes was developed extending the field of application from I2V to V2V communication. At the same time, the interest in VLC grew and other field of applications have been explored. That motivated the set up of a special IEEE working group for the standardization of VLC for personal area networks, which at the end of 2011 released the first official version of the standard IEEE 802.15.7 [17].

Although none VLC commercial technology arrived in the domain of ITS so far, a series of prototypes exists that can be roughly classified in two classes: those resulting from research started before the publication of the IEEE 802.15.7 standard and those made after the IEEE 802.15.7 standard, trying to demonstrate how it can be exploited for ITS applications. This section contains the most significant results achieved by the researchers before the standard, while in the next sections the standard and its latest attempts of application in ITS will be introduced.

Starting from I2V communication, the basic performance of a LED based traffic light in terms of suitable modulation, required SNR, and the amount of receivable information was initially analyzed by Akanegawa et al. [3]. More recently a prototype of LED traffic lights was designed using discrete components for the opto-electronic parts and FPGA digital circuits for the signal processing parts for both the transmitter and the receiver [20, 21]. The modulation scheme used for this system was based on direct sequence spread spectrum techniques. The test trials on the prototype showed that the bottleneck for the data rate was the transmitter, where a data rate of 200 kbps was achieved. On the other hand the receiver was able to sample the signal 5-times higher at a maximum of 1 Mbps. The limitation of data rate occurs at the transmitter side because the traffic light needs a high amperage current load, but switching on and off such a current at high frequency is still challenging.

A system for transmitting messages from traffic light to cars was prototyped also by researchers of the University of Versailles [8]. The main application for the system that they patented [4] is the communication between the traffic lights and the car in

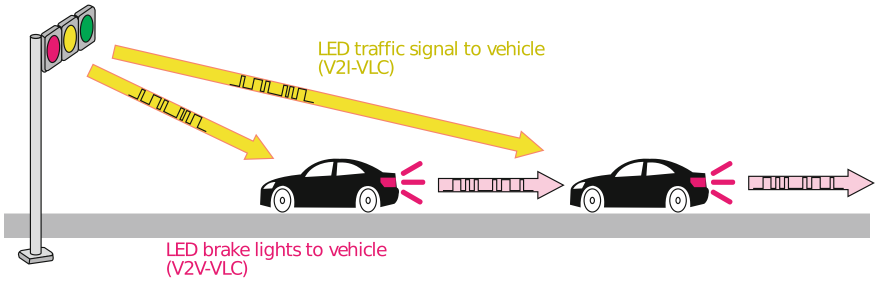

Fig. 2.6 VLC enhanced traffic light use case

order to transmit, for example, the countdown before the next traffic light signal change, as depicted in Fig. 2.6. The interest is also to alert the vehicles and to control the engine for a fast restart or for trigger the green wave.

The system consists of a broadcast station unit represented by a LED-based traffic light and a photodiode based receiver. Both emitter and receiver are interfaced with PCs. The emitter module was developed based on a commercial LED-based traffic light in order to investigate up until what point any traffic light can become a data broadcast unit with little modifications and at the lower cost. The same low cost constraints were used also to design the circuits and choising the electronic components for both the emitter and the receiver sides. Going more into details, the logic is implemented with 8 bit microcontrollers at both the transmitter and the receiver side. The receiver uses a PIN photodiode whose signal is amplified with an Automatic Gain Control (AGC), in order to receive data for both short and long distance. AGC is especially useful at short distance because of it prevents the saturation of the photodetector module. An optical component in front of the photodiode reduces the FOV angle of the receiver to $\pm 10°$. The system is robust, but non suitable to implement complex network stack. Indeed basic modulation coding schemes are used, such as the Manchester code and the Miller code. Both the codes use OOK (On-Off Keying) amplitude modulation which is simple and well suited for data transmissions at frequencies of tens of kilohertz.

The experimental tests have been conducted with a traffic light (red and green lights) installed in the corridor of the laboratory or outdoor. Basically, the message transmitted during the experiments is sent to the emitter and the frame indicates if Miller or Manchester code is selected. The receiver decodes the data in real-time and an algorithm allows post-processing or calculation of errors. For first experiments, a specific message made by 7 ACSII characters is sent continuously using a modulation frequency of 15 kHz. Error free trasmission (BER 10^{-7}) has been detected up to 50 m Outdoor with daylight and up to 20 m indoor with artificial light.

The use of VLC for V2V communication has been investigated by many research groups: it is believed that VLC could provide both accurate positioning and enforce vehicle safety. The architecture of such devices has been depicted with different degrees of detalis in many studies. Also, many numerical simulation have been performed in order to estimate the performance of that systems compared with RF DSCR. However a much less number of prototypes have been realized and tested, showing altought promising features of this technology. As we will see, some of them uses low cost components, while some others uses more sofisticated devices such as high speed cameras and dedicated CMOS imaging sensors.

An interesting example of low cost devices is the prototyping effort to implement a VLC system on scooters, using commercially available LED taillights and software defined radios (SDRs) [31].

Figure 2.7 shows the system block diagram of the prototype. On the transmitting end, the electronic control unit (ECU) connector periodically collects information

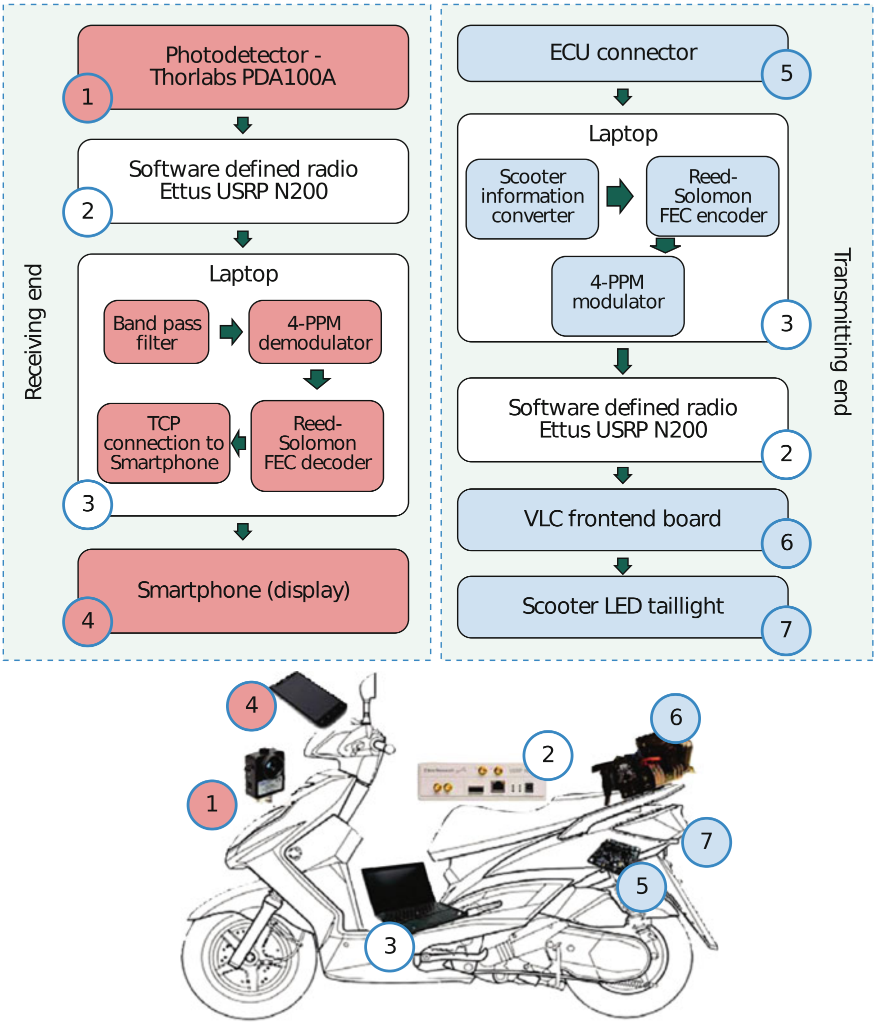

Fig. 2.7 Functional architecture of the VLC prototype implemented on scooters

such as current speed, engine revolution, brake status, and turning signal status from the scooter, and sends it to a laptop. In the laptop, digital packets with the information as the payload and a footer with forward error correction (FEC) code is created, and then modulated with 4-pulse position modulation (4-PPM). The packet goes through a digital-to-analog conversion in a SDR and is passed to the VLC frontend, which changes the light intensity of the LED taillight according to the input analog signal. On the receiving end, the photodetector converts the received optical signal to an electric signal, which goes through an analog-to-digital conversion in SDR. The laptop then performs the demodulation and decode processes to obtain the scooter information in the original packet. Finally, the information is sent to a smartphone mounted on the handlebar of the scooter. The smartphone presents a warning, and the information of a preceding scooter to the driver when a collision with this scooter is possible.

The choice to use the SDR is motivated because it allows the flexibility to easily change various physical layer designs and networking protocols during prototyping. Afterwards when the design of the devices will be focused on a commercial product, these designs can be transferred to a field programmable gate array (FPGA) or an application-specific integrated circuit (ASIC) to reduce costs.

The road trials have been performed with a one-way link, implemented between two scooters in such a way that the taillight of the scooter ahead transmitted data to a photodetector placed on the front of the chasing scooter. None lens was used in front of the photodetector, resulting in a wide 90° field-of-view (FOV) angle, while on the transmitter side the beam angle was more narrow (about 20°).

The experiments were carried out on a sunny day with no rain or fog. Both scooters operated in a real-world road at speeds between 10 and 40 km/h. A 20-byte packets that contain information about the current speed, brake status, and so on were continuously broadcasted from the taillight at a data rate of 10 kb/s. The measured packet loss on the reception side showed an acceptable level when the distance between the scooters was in the range of about 4–14 m.

Moving from low-cost systems to more sophisticated systems, the development of image-sensor-based VLC for automotive applications shows unique characteristics that deserve to be described. It is an alternate approach trying to integrate a special receiver function into a conventional image sensor. This V2V communication system investigated at Toyota Central R&D Laboratories uses an LED transmitter capable of sending various data by 10 Mb/s optical signals and a camera receiver, which employs a special CMOS image sensor, i.e., an optical communication image sensor (OCI) [29].

As shown in Fig. 2.8 the OCI has an array of non-conventional pixel, so called communication pixel (CPx), which is specialized for high-speed optical signal reception. Additionally, it has an output circuit producing a "1-bit flag image," which only reacts to high-intensity light sources such as LEDs and thus facilitates the LED detection in outdoor environments. By using the OCI, the camera receiver has obtained 10 Mb/s optical signal reception and accurate LED detection capabilities in various experiments under real world driving conditions. The experiments were performed with

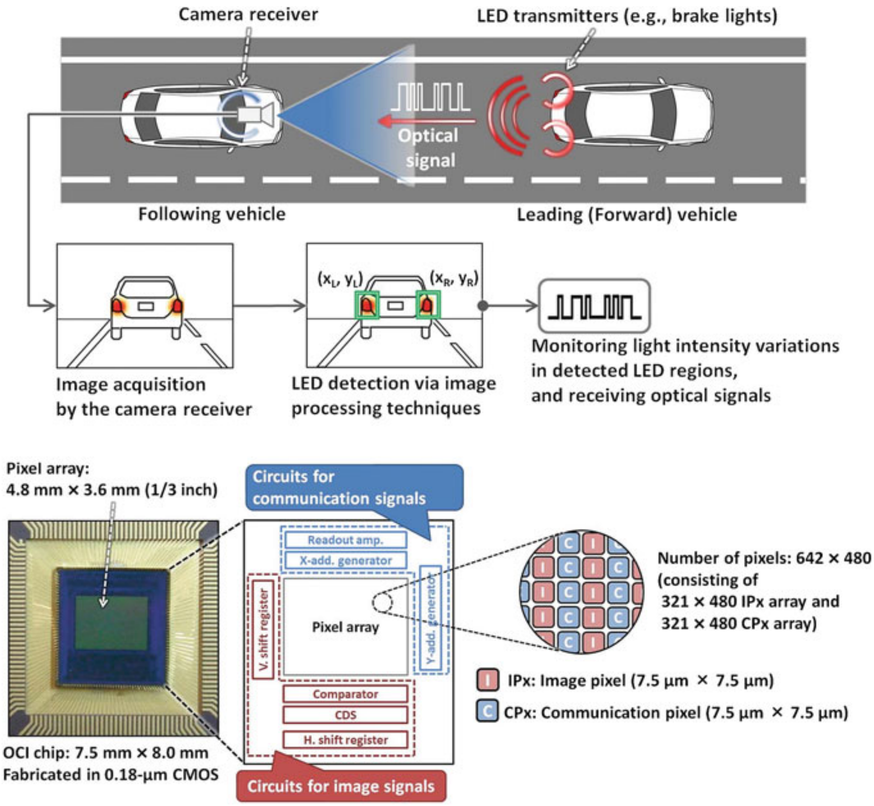

Fig. 2.8 OCI based V2V communication system (up) and structure of the OCI (down)

the optical V2V communication system consisting of two LED transmitters mounted on a leading vehicle and one camera receiver mounted on a following vehicle.

The transmitter system consisted of an LED array unit controlled by a PC. The controller aggregates data caming from the vehicle and from the front camera, generates packets of 2464 bits, encodes the packets with Manchester, block interleave and BCH code for up to 3 error correction and send the data to the LED array unit. The latter has a driver circuit and 10 × 10 LEDs emitting up to 4 W of optical power. It is important to stress that the system did not use current automotive taillight LEDs, but 870-nm nearinfrared (NIR) LEDs capable of being modulated at high speed. Therefore the system is not yet a proper VLC device, because the comunication carrier was in the IR spectrum, although the results of this attempt will facilitate the extension of this technology in the visible.

For confirming the performances and potential of this system, many experiments have been conducted under real driving and outdoor lighting conditions. The test trials showed that the LED detection method using the flag image effectively eliminates most unnecessary objects in images and achieves correct and real-time LED detection even in challenging outdoor environments. In data transmission experiments, the leading veichle simultaneously sent both a set of data about the driving conditions of the veichle (such as vehicle ID and speed) and a stream of color image data (320×240 pixels) up to 20 fps. The measurements proved that the following vehicle received these data with acceptable packet loss, i.e. the front-view image stream is received with an efficiency rate of 87 % in the daytime and 89 % at nighttime.

2.5 Standardization

The achievement of VLC devices for ITS applications may be accelerated by standardization initiatives. There are currently two entities involved in VLC standardization: the Visible Light Communication Consortium (VLCC) in Japan and the IEEE 802.15 WPAN Task Group 7. The former proposed two standards at JEITA in 2007: one is Visible Light Communication System Standard (JEITA CP-1221), mainly focused on position detection applications, and the other is Visible Light ID System Standard (JEITA CP-1222), but they have not been commercially exploited.

The most important contribution came from the IEEE 802.15 WPAN Task Group 7, who released the first official VLC standard in the second half of 2011 [17]. This standard covers both the physical layer (PHY) air interface and the medium-access control (MAC). The IEEE 802.15.7 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 intends to support a variety of expected applications, relating to VLC Personal Area Networks (VPAN).

As we can see in Table 2.1, three classes of devices are considered for VLC: infrastructure, mobile and vehicle. According to their physical properties and capabilities—limitations like physical mobility, power supply and of course their applications, their specifications such as range and data rates are defined. For instance infrastructure has “unlimited” power supply, while vehicle moderate and mobile terminals very limited. These yield higher power light sources for infrastructures and vehicles and furthermore potentially higher range. Regarding mobility, only

Table 2.1 Classification of IEEE 802.15.7 devices

	Infrastructure	Mobile	Vehicle
Fixed coordinator	Yes	No	No
Power supply	Ample	Limited	Moderate
Form factor	Uncostrained	Constrained	Uncostrained
Light source	Intense	Weak	Intense
Physical mobility	No	Yes	Yes
Range	Short/long	Short	Long
Data rates	High/low	High	Low

the infrastructure type has no physical mobility. Based in their applications vehicle devices need low data rates/long range for exchanging information about traffic for example, while mobile and infrastructure devices can reach much higher rates within shorter distance for exchanging multimedia like high definition videos, online gaming etc.

This standard defines a PHY and MAC layer for short-range optical wireless communications using visible light in optically transparent media. It is capable of delivering data rates sufficient to support audio and video multimedia services and also considers mobility of the visible link, compatibility with visible-light infrastructures, impairments due to noise and interference from sources like ambient light and a MAC layer that accommodates visible links. Furthermore, the standard adheres to applicable eye safety regulations.

The IEEE 802.15.7 standard supports three multiple access topologies: peer-to-peer, star configuration and broadcast mode; with data rates ranging from 11.67 kb/s to 96 Mb/s for indoor and outdoor applications. The architecture of a generic VLC standard conform device, as shown in Fig. 2.9 besides the ISO OSI stack, is defined in terms of a number of layers and sublayers; each layer offers services to the higher layers.

A VPAN device comprises a physical layer (PHY), which contains the light emitter/receiver along with its low-level control mechanism, and a medium access control (MAC) sublayer that provides access to the physical channel for all types of transfers. A logical link control (LLC) layer can access the MAC sublayer through the service-specific convergence sublayer (SSCS). A device management entity (DME) is also supported in the architecture. The DME can talk to the PLME (Physical Layer Management Entity) and MLME (MAC Link Management Entity) for the purposes of

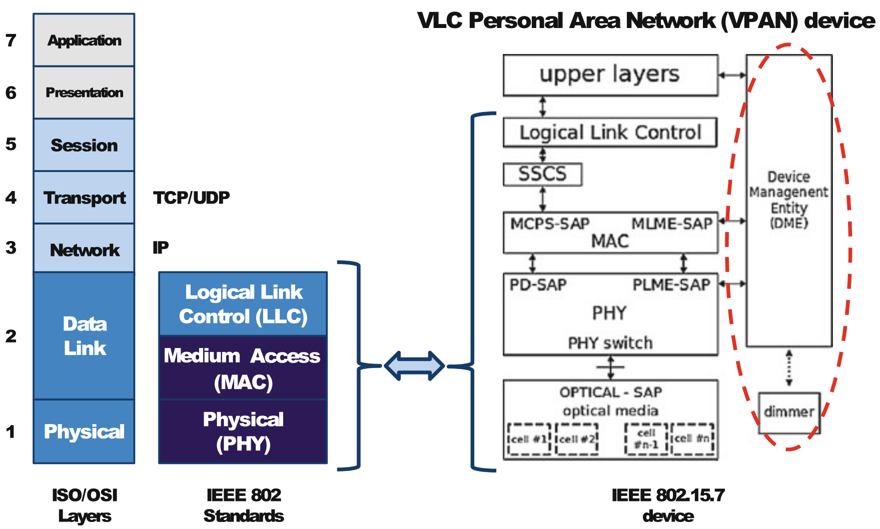

Fig. 2.9 IEEE 802.15.7 VPAN device architecture

interfacing the MAC and PHY with a dimmer. The DME can access certain dimmer related attributes from the MLME and PLME in order to provide dimming information to the MAC and PHY. The DME can also control the PHY switch using the PLME for selection of the optical sources and photodetectors.

The MAC layer handles physical layer management issues such as addressing, collision avoidance and data acknowledgment protocol. Many features of the MAC sublayer are shared with the IEEE 802.15.4 specifications, such as beacon management, channel access, guaranteed time slot (GTS) management, frame validation, acknowledged frame delivery, association, and disassociation. However some functions are peculiar of the visible light medium such as visibility, flicker-mitigation and dimming support.

Visibility support is provided across all topologies to maintain the illumination function in the absence of communication or in the idle or receive modes of operation. The purpose of this function is to maintain illumination and mitigate flickering.

The physical layer is divided into three types; PHY I, II & III, and these employ a combination of different modulation schemes.

PHY I operates from 11.67 to 266.6 kb/s, PHY II operates from 1.25 to 96 Mb/s and PHY III operates between 12 and 96 Mb/s. PHY I and PHY II are defined for a single light source, and they support on-off keying (OOK) and variable pulse-position modulation (VPPM). PHY III uses multiple optical sources with different frequencies (colors) and uses a particular modulation format called color shift keying (CSK).

Each PHY mode contains mechanisms for modulating the light source, run length limited (RLL) line coding, and channel coding for forward error correction (FEC).

RLL line codes are used to avoid long runs of 1 and 0 s that could potentially cause flicker and clock and data recovery (CDR) detection problems. RLL line codes take in random data symbols at input and guarantee DC balance with equal 1 and 0 s at the output for every symbol. Various RLL line codes such as Manchester, 4B6B, and 8B10B are defined in the standard, and provide tradeoffs between coding overhead and ease of implementation.

For ITS application the PHY I type is the most convenient, since it is designed specifically for outdoor applications. Although it provide the slowest data rates, robust convolutional and Reed-Salomon codes are used for forward error correction to overcome the additional path loss due to longer distance and potential interference introduced by optical noise sources such as daylight and fluorescent lighting.

PHY I modulation mode are two: on-off keying (OOK) and variable pulse-position modulation (VPPM). Each one has an associated optical clock rate which is "divided down" by the various coding schemes to obtain the final resulting data rates, as shown in Table 2.2.

The optical clock rate for PHY I is chosen to be no higher than 400 kHz to account for the fact that LEDs used in applications such as traffic lights require high currents to drive the LEDs and therefore switch slowly.

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. At the slowest optical clock, the

Table 2.2 PHY I operating modes

Modulation	RLL code	Optical clock rate (kHz)	FEC		Data rate (kb/s)
			Outer code (RS)	Inner code (CC)	
OOK	Manchester	200	(15,7)	1/4	11.67
			(15,11)	1/3	24.44
			(15,11)	2/3	48.89
			(15,11)	None	73.3
			None	None	100
VPPM	4B6B	400	(15,2)	None	35.56
			(15,4)	None	71.11
			(15,7)	None	124.4
			None	None	266.6

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.

Dimming is supported by adding an OOK extension which adjusts the aggregate output to the correct level. Light dimming is defined as controlling the perceived brightness of the light source according to the user's requirement and is a cross layer function between the PHY and the MAC. An idle pattern can be transmitted during MAC idle or RX states from infrastructure light sources for dimming support. This is important since it is desired to maintain visibility during idle or RX periods at the infrastructure. The idle pattern has the same duty cycle that is used during the active data communication so that there is no flicker seen during idle periods. The standard also supports dimming during data transmission: for instance, dimmed OOK modulation breaks the frame into subframes, inserting compensation symbols before each subframe in order to increase or reduce perceived brightness.

At bit rates higher than 100 kbit/s IEEE 802.15.7 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. when the position are two (2-PPM) 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 2-PPM but it was tailored in such a way as the pulse width is controlled from the light dimming support: pulse amplitude is kept constant, while pulse width varies according to the desired dimming level. Figure 2.10 shows examples of two "0" and one "1" with different dimming levels (T is the symbol period).

The transmitter chain of the VPPM mode sees the input data sent through an RS FEC encoder for error protection, followed by a 4B6B RLL code for DC balance and flicker mitigation. The 4B6B coding takes a 4-bit symbol and changes it into a DC

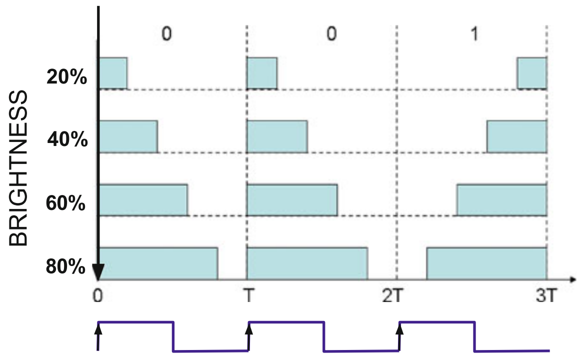

Fig. 2.10 Variable pulse position modulation

balanced 6-bit code, according to a tabular scheme. The counts of 1 and 0 in every VPPM encoded symbol are always equal to 3. Since the bit rate is constant regardless of the requested dimming level, as the light is dimmed, the range decreases with the dimming level.

So far, none of the proposed solutions for using VLC in ITS are actually compliant with the IEEE 802.15.7 standard. The main reason lies in the fact that the standard is subsequent to the majority of the studies carried out about VLC for ITS.

In the next section, the analysis of a IEEE 802.15.7 conform VLC prototype for V2X message delivery is presented.

2.6 VLC IEEE 802.15.7 System for ITS Applications

This section shows the features of the IEEE 802.15.7 conform VLC prototype developed at CNIT as enhancing extension of an embedded ITS station. The aim of this section is to provide some guidelines to develop a low-cost VLC system using commercial off-the-shelf (COTS) devices suitable for ITS applications.

2.6.1 VLC Prototype Design

The SEED-EYE board was used as developing board: it is a Wireless Sensor Network (WSN) node in house developed for multimedia ITS services [28]. It hosts the high performance Microchip PIC32, and has a full set of communication interfaces such as Ethernet, IEEE 802.15.4/ZigBee, and USB. The computational resources of the micro-controller are also devoted to process the images from a low cost CMOS Camera, making it an unique WSN node with high efficient image processing capabilities, tailored for ITS applications such as parking slot detection, traffic flow monitoring, etc. [26]. The SEED-EYE Board comes with full software support, including an

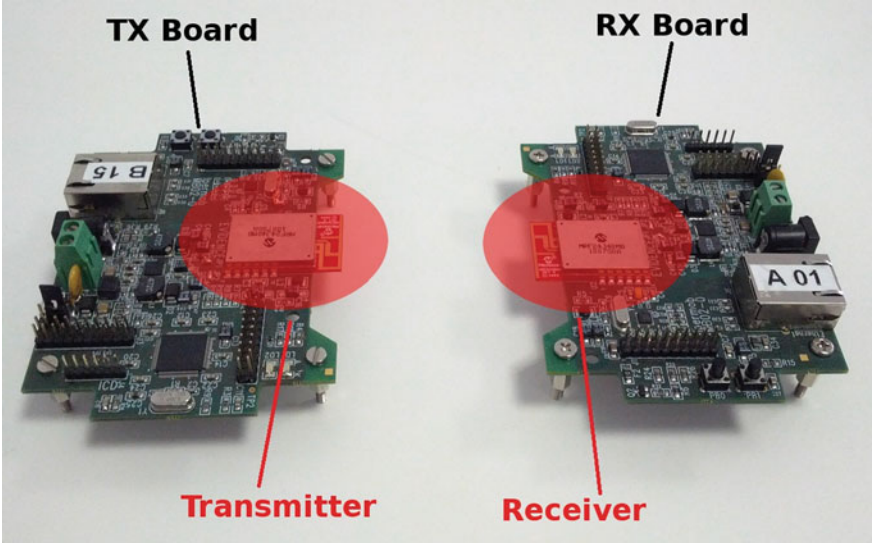

Fig. 2.11 The R/F IEEE 802.15.4 unidirectional system

open source OSEK/VDX Real Time OS for small micro-controllers for automotive applications, (ERIKA Enterprise Real Time OS [13]). A picture of that reference system is showed in Fig. 2.11.

This board was chosen for three main reasons: (1) it is made by 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; (2) a fully-customized firmware for the IEEE 802.15.4 transceiver was available [25] and this was used as reference guide for implementing the IEEE 802.15.7 protocols, especially for what concerns the MAC layer; (3) although the IEEE 802.15.4 transceiver was not used in the present work, its functionality is kept on the board in order to enable, as next developments, a vertical handover between IEEE 802.15.7 VLC and IEEE 802.15.4 R/F technologies.

2.6.1.1 The Reference Model

Because of the strong novelty of the design, ASICs with VLC 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 VLC dedicated component to be included in next releases of the board, the VLC transceiver functions were implemented on software blocks running on an extended architecture which even uses twin boards.

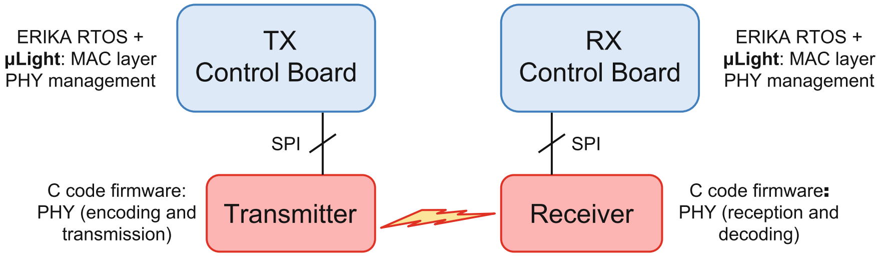

Fig. 2.12 The VLC IEEE 802.15.7 functions, as implemented in the system

This extended architecture is shown in Fig. 2.12: 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. 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. Figure 2.12 shows the functional blocks of the IEEE 802.15.7 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. 2.13. In the next sections some details of the hardware end software design are deepened.

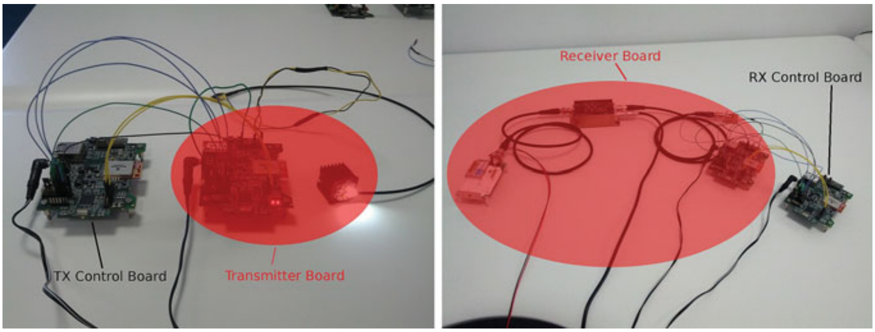

Fig. 2.13 Complete system: TX Control Board and Transmitter Board (*left*), RX Control Board and Receiver Board (*right*)

2.6.1.2 The Hardware Prototypes

The board used as basic brick of the system was designed within the IPERMOB project [30], targeted to a large-scale prototype deployed and tested on the land-side of the Pisa International Airport. The SEED-EYE board [28] is an advanced Wireless Sensor Network (WSN) node specifically thought for ITS applications [5]. It comes with full software support, including porting for Contiki OS [12] and ERIKA Enterprise RTOS [13], 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 2.3 to 3.6 V and some power sleeping modes (RUN, IDLE, and SLEEP modes) are allowed, along with multiple switchable clock modes useful for the development of power saving policies. Moreover a CMOS Camera is embedded on the board, what makes this device suitable to implement next generation imaging WSN [10]. 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 IEEE 802.15.7 VLC and IEEE 802.15.4 R/F technologies.

2.6.1.3 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, many components were needed:

- a custom Avalanche Photo-Diode (APD) (Hamamatsu C 5331-11 [6]), with a tiny (1 mm^2) active area (the surface which can receive the light signal) and a frequency bandwidth ranging from 4 kHz to 100 MHz;
- an amplifier (FEMTO HVA-200M-40-B [6]), which receives the electrical signal from the APD and amplifies it by a factor of 10 or 100 (switchable gain 20 dB/40 dB);
- an adaptation circuitry composed by two standard avalanche fiberglass diodes BYW54 [6]; 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 −0.3 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;

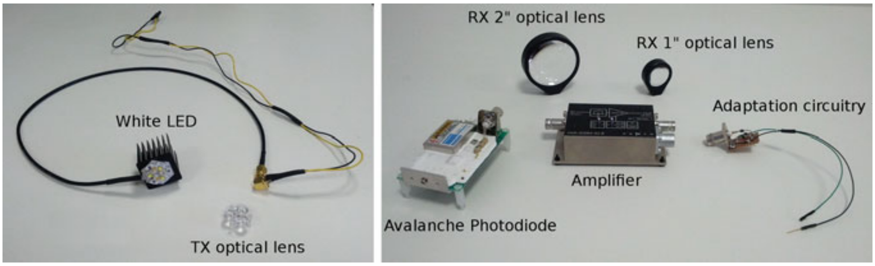

Fig. 2.14 Optical equipment: Transmitter (*left*), Receiver (*right*)

- 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. 2.14, all the components of the transmitter/receiver are illustrated.

2.6.1.4 The Software Prototypes

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

2.6.1.5 μLight Stack

Using the highly modular ERIKA API framework, and inspired by the experience in the IEEE 802.15.4 MAC and PHY implementation acquired during previous works [24], an IEEE 802.15.7-compliant network stack was programmed for the TX/RX Control Boards. The resulting software library, μLight, follows a layered approach, as shown in Fig. 2.15, conform to a VPAN device. To describe the details of software library is out of the scope of the present paper, below is presented only a brief outline. 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 IEEE 802.15.7 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 IEEE 802.15.7 is required: to initialize the board as a VPAN coordinator and

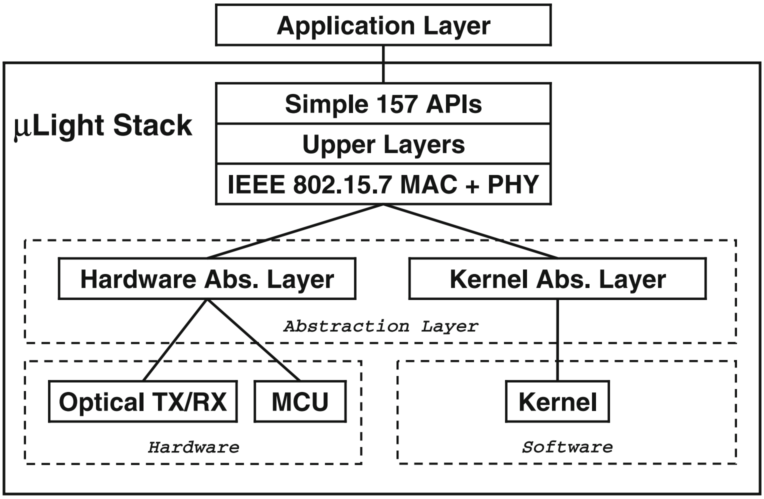

Fig. 2.15 μLight Architecture

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.

2.6.1.6 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 e.g. 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 IEEE 802.15.7 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.

2.6.2 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.

2.6.2.1 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 Table 2.3 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 e.g. remaining on low cost readily available

Table 2.3 VLC transceiver processing times

Board	Task	Processing time (μs)
Transmitter	SPI oprical transmission ISR	2.6
	RS(15,7) block encoding	20
	RS(15,11) block encoding	16
Receiver	Viterbi single iteration	15
	Viterbi complete decoding[a]	0.27×10^6
	RS(15,7) block decoding without errors	32
	RS(15,7) block decoding with errors	72
	RS(15,7) block decoding with errors[b]	0.021×10^6
	RS(15,11) block decoding without errors	18
	RS(15,11) block decoding with errors	40

[a] 1023 B PSDU + RS(15,7)
[b] 1023 B PSDU

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. 2.16 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 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 to 48.89 kbps). On other hand,

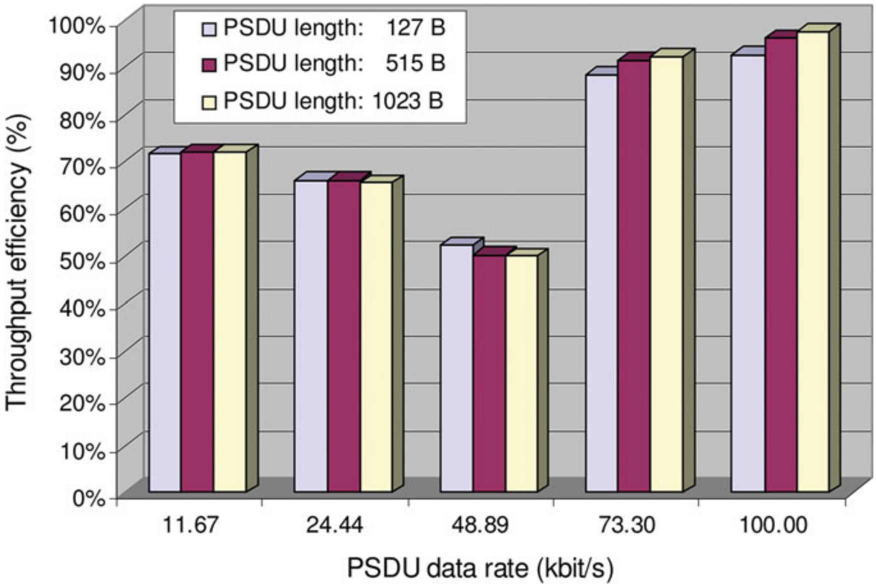

Fig. 2.16 Throughput efficiency of the VLC system

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.

2.6.2.2 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 (see Fig. 2.17). 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, 1.8, 2.8, 5.1 and 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). Figure 2.18 shows the measured BER for both the small and the long packet transmission scenario; an error-free communication was achieved up to 5.1 m, while communications at 10.2 m showed some errors. 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

Fig. 2.17 Experimental setup for BER measurement

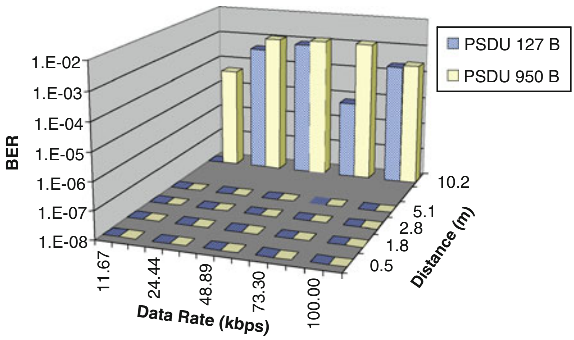

Fig. 2.18 BER at many data rate and distance values and two payloads: 127 B PSDU, 950 B PSDU

protocol are working; while at the other data rate, the BER scatters above and below 100 kbps value without a coherent behaviour 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.

2.7 Conclusion

A simplex VLC prototype for ITS applications has been realized. The device implements PHY I and MAC layers such as conform to the IEEE 802.15.7 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 IEEE 802.15.7 when the communication occurs at slow rates.

The quality of signal transmission is found to be acceptable within 10 m. 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 equipment will allow to implement ITS V2I and V2V communication services via VLC.

Future work will be addressed to improve and increase the implementation of IEEE 802.15.7 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 could overcome the signal delay limitations due to the processing time of the general purpose CPU used at present [9]. Moreover the design of an adaptation layer between IPv6 and IEEE 802.15.7 would be effective to allow the access of VLC technology to the Internet of Things infrastructure. After the functional verification of IEEE 802.15.7-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.

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