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DEVELOPMENT OF A VISIBLE LIGHT COMMUNICATIONS VERSATILE RESEARCH PLATFORM WITH POTENTIAL APPLICATION ON VEHICULAR NETWORKS

MEMORIA PARA OPTAR AL TÍTULO DE
INGENIERO CIVIL ELÉCTRICO

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RESUMEN DE LA MEMORIA PARA OPTAR
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Las redes vehiculares ad-hoc (VANets) son un nuevo paradigma en comunicación móvil que se plantea que podría permitir el despliegue de sistemas de transporte inteligente (ITS), más seguros, eficientes y amigables con el medioambiente. Se cuenta con el estándar DSRC de comunicaciones vehiculares pero no está comprobado que sea capaz de ofrecer la robustez y seguridad que necesitan los ITS.

Las comunicaciones por luz visible (VLCs), son tecnologías de comunicación inalámbricas basadas en la modulación de intensidad de luz. Se realizan con dispositivos opto-electrónicos como diodos LED y foto-diodos. Se plantea que éstas podrían complementar a las radio-frecuencias (RF), como las del protocolo DSRC, por ejemplo, y permitir a las VANets entregar un mejor servicio, sobre todo en ambientes congestionados.

En el presente trabajo, se realizó el desarrollo de una plataforma con herramientas para prototipado de enlaces VLC con aplicación en VANets bajo la hipótesis que las tecnologías existentes de illuminación en automóviles y señales de tránsito son una infraestructura que permite implementar VLCs en ambientes vehiculares.

Primero se consultó el estado del arte de VANets y de VLCs, enfocado en entender el origen del interés por la implementación de redes vehiculares, así como sus desafíos y cómo las VLCs pueden mejorar el desempeño de dichos sistemas.

Se estudiaron tecnologías aplicables a los sistemas de información y comunicaciones de las redes vehiculares con enfoque en las VLC. Un grupo fueron las plataformas de hardware programable como radios definidas por *software* (SDRs) y las placas *Arduino*. Otro tema fue la red de control interna de los vehículos y cómo existen interfaces para acceder a ella y obtener mediciones de los sensores e incluso dar instrucciones a los actuadores del auto. También, se revisaron los transductores de una red VLC: los diodos LED y fotodiodos, incluyendo la electrónica necesaria para su funcionamiento.

Finalmente, se implementó un sistema de comunicaciones por VLC, basado en SDRs y optoelectrónica, y también un sistema adquisición de datos para la red de control del vehículo, basado en Arduino y un circuito integrado ELM327. Ambos sistemas se diseñaron modulares y se construyeron robustos. Se logró con ellos la transmisión de datos por luz y la lectura de datos del area de control del vehículo.

Actualmente, el sistema desarrollado está en manos de un grupo de investigación que se dedica a estudiar las tecnologías de comunicación vehicular. También se está trabajando en una publicación con la evaluación de los sistemas implementados.

A mi familia, Gloria Icaza, Francisco Matus, Francisca Matus, Sofía y Dominga Arduiz, Camila Garrido y mis abuelas y abuelos.

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Contents

Introduction

Motivation

Wireless digital communications are a very hot topic in technology and research because they are rapidly expanding Internet's boundaries towards the interconnection of every person and every machine. The electromagnetic spectrum is a valuable resource and the way networking exploits it is evolving in order to make the changes faster.

The LED technology is replacing every incandescent and fluorescent lamp because of its high durability and low power consuption. This kind of lamps allow high speed modulation of their illuminance, making posible to implement wireless digital communications with them. This is a growing field of research that has released Li-Fi technology and many applications are emerging.

This work started in a frame of several projects related to the visible light communications (VLCs) and their applicability as an alternative technology that can complement radio frequency (RF). One is project ERANet-LAC RETRACT (enabling REsilient urban TRAnsportation systems in smart CiTies), released by organizations from four countries from Europe and Latin America: National Council for Science and Technological Research (CONICYT), Chile, National Council for Science and Technology (CONACYT), Mexico, State Education Development Agency (VIAA), Latvia, and Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI), Romania.

Simultaneously, the First South American Colloquium on Visible Light Communications (SACVLC) occurred in Santiago, Chile, in November 2016, gathering various investigators that were looking for applications on robotics, e-health, intelligent transportation systems, Internet of things, smart-city/smart-building.

This motivated the initiation on research in a technology that has the potential of taking advantage of existing urban illumination infrastructure whose costs are covered by basic needs, that can be innocuous to life, that can improve other technologies by complementing capabilities.

The idea is also related to the new advances in car automation technologies and traffic control applications, that are taking big steps towards self-driving cars and that need a safe network to communicate.

Objectives

Overall Objective

To develop a research platform of prototyping tools to investigate visible light communications and their vehicular networking applicability.

Specific Objectives

- To understand the interest and the challenges on implementing vehicular networks and the capabilities of visible light communications applicable to improving the performance of such systems.
- To review the technologies for prototyping vehicular communication and information technologies based on visible light communications.
- To implement visible light vehicular networking system prototypes, based on the most versatile technologies and capable of dealing with the most critical issues detected.

Hipothesis

The existing vehicular illumination infrastructure allows the implementation of visible light communications based vehicular ad-hoc networking.

Structure of the Thesis

Chapters 1 to 3 will discuss the design, development and implementation of the prototyping platform as follows:

- In chapter 1, theoretical and practical state of the art of VLCs and its impact in vehicular networks are shown.
- In chapter 2, the hardware and the chosen devices to implement the system are described.
- Chapter 3 shows the implementation of the platform, divided into software development and hardware implementation and modification, done to the SDRs and the LED.

Finally a conclusion is developed, exposing the highlights of the platform and giving some recommendations for the future research.

Chapter 1

Background and State of the Art

Introduction

This chapter reviews two concepts: vehicular ad-hoc networks (VANets) the visible light communications (VLCs), and the relationship between them. In the first part, the need for VANets is supported by describing the concept of intelligent transportation systems (ITS), a control network that uses VANets as mean of communication and whose deployment could help solving transportation's most harmful issues. The architecture, standards and late research on VANets is then discussed. One important problem on VANets is observed: the spectrum to establish wireless links in vehicular conditions is shared by too many other technologies, threatening VANets' requisites of robustness and resilience. This challenge arises the opportunity to apply VLCs to VANets taking advantage of the widely deployed LEDs in road and car infrastructure. This is discussed in Section 1.2, first explaining the context that triggered a boom of research on VLCs, and then showing the capabilities of the technology in the vehicular scenario. The chapter ends with a summary of the optical channel model theory focused on the vehicular setting.

1.1 Vehicular Networks

During the last years, lots of projects coming from a wide variety of fields had been started aiming to develop technologies for the implementation of intelligent transportation systems (ITS). Such developments promise great improvements on the performance of existing transportation systems in terms of traffic management and efficient use of transportation infrastructure, reducing travel times, improving road safety, and protecting the environment and people's health. Congestion and accidents are a worldwide phenomenon that translates into considerable economic costs [1] and the impairment of life quality in big cities. It also translates into the loss of human lives, especially in highways. All these problems could be greatly reduced through the implementation of ITS, which are essentially massive-distributed control networks of heterogeneous means of transport.

In the field of information and communication technologies (ICTs), research on ITS has been focused on the production of a paradigm for the vehicular ad-hoc networks (VANets), which represent the wireless local area networks (WLANs) that allow the dissemination of the control network relevant data and also infotainment streams. The uniqueness of a vehicular scenario has lead to the development of specific tools for VANets' research. In a 2008 and a 2014 surveys ([2], [3] respectively), the potential applications, the design challenges, the simulation tools available, a review of the standards, a discussion about security and privacy issues, and a summary of the state-of-the-art of VANets are presented. In these works, one key challenge of VANets is shown: the scarce spectrum. The following description of a vehicular scenario and the definition of the standards adopted, and then the review of the context of radio-frequency (RF) communications at Section 1.2 will help to picture the importance of finding solutions for spectral scarcity.

1.1.1 Architecture of Vehicular Ad-hoc Networks (VANets)

The scientific community uses the term vehicular ad-hoc networks (VANets) (a subset of mobile ad-hoc networks (MANets)) to group two fundamental vehicular wireless communication schemes: vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). Note that *ad-hoc* is a latin expression, literally translated as "for this", and it means that the connections are made ephemerally between two nodes with no centralized coordination.

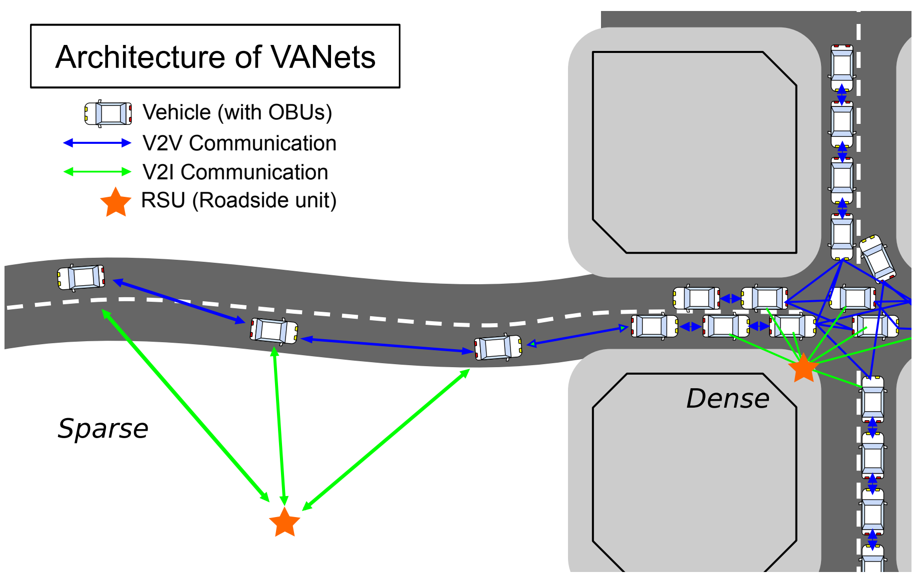

Figure 1.1: VANets diagram showing basic networking concepts: V2V and V2I communications, OBUs and RSUs, and sparse and dense conditions. .

The nodes in a VANet do packet transmission, reception, and routing and can be vehicles, equipped with "On-Board Units" (OBUs), and special road infrastructure called "Roadside Units" (RSUs). Kinematic information of the traffic entities is gathered and disseminated securely and privately by the nodes. The exchange of this information allows the network to take precautionary measures and warn life-threatening traffic conditions to drivers and self-driving cars, as one of the key applications of VANets [3].

The architecture of VANets usually has two variants depending on traffic levels and congestion: "sparse" and "dense" conditions. They have their own challenges and vehicular networking technologies must work properly on both [2]. In sparse conditions, nodes need to reach each other within two hundred meters of distance, and communications will probably be less affected by interference, especially in the countryside. In turn, in dense conditions, nodes can be just a few meters apart and spectrum needs to be highly reusable to avoid packet collisions and interference. These differences impact in which band of frequencies and how much power is used by the wireless communication technology the VANet will be defined to work with.

1.1.2 Standards for VANets

The efforts on standardization of VANets come from a wide variety of actors: government organisms, car manufacturers, car industry entities and the scientific community. The Federal Communications Commission (FCC) (USA) kicked off this process when a 75 MHz-wide allocation was made in the band of 5.9 GHz for dedicated short range communications (DSRC) for safety-related applications of VANets. This project has been joined by the Vehicle Safety Communications Consortium (VSCC) (USA) and the European Communication Commission (ECC) and many other projects have proliferated from it [3]. Several technologies and techniques for vehicular communication have been investigated and tested, but most efforts focus on dedicated short range communications (DSRC) and standard IEEE (1609) 802.11p, which establishes the regulations for wireless access in vehicular environments (WAVE). DSRC comprises now 75 MHz of spectrum in the USA and 30 MHz of spectrum in the EU, both in the 5.9 GHz band [4], [5]. It was meant as a global vehicular networks communication standard, but there are still many issues to solve to make it popular.

1.1.3 Need for New Alternative and Hybrid Schemes for VANets

There has been ongoing research about how other complementary technologies can work together to make transport communications more resilient and improve their performance. [6] proposes a set of rules to use 3 technologies (LTE, 802.11p, and DSRC) simultaneously, reducing latency and increasing throughput.

Investigations by Eze, E. *et al.* in 2015 [7] and Pagadarai *et al.* in 2009 [8] pointed out the availability of "spectrum holes" in television broadcasting networks in rural and urban areas, a profitable resource for vehicular networks. These publications where later followed by the release of cognitive radio (CR) assisted vehicular networks (CRAVNets) research, summarized in Eze, J. *et alii*'s survey [9]. It mentions that CRAVNets can be very attractive but spectrum availability is still low in highly populated areas.

A more resilient solution for VANets will need to incorporate other parts of the electromagnetic spectrum to support the scene of dense areas. This is when the use of visible light communications gains real interest, as a complementary technology to be applied specially in urban VANet communications. Next section explores this idea.

1.2 Visible Light Communications applied to VANets

Wireless communications have continuously increased their popularity and deployment levels, exceeding one device per capita today in the world and expecting an increase up to 1.5 mobile connections per capita in 2021 ([11]). The standard mobile connections such as Wi-Fi and 4G need complementary technologies in order to grow in capacity because the radio-frequency (RF) spectrum is overcrowded. To illustrate this, Figure 1.2 shows the $DC - 300[GHz]$ spectrum allocation in USA, *i.e.*, the bands licensed for different services, such as TV and radio-stations broadcast, radioastronomy, radio amateurs, cellular network, maritime-land-aerial navigation, satellite, and so on, with lots of them working simultaneously in some bands (Note that the lower frequency bands look freer but they are narrower). In particular, DSRC (IEEE 802.11p) standard for VANets (discussed in Section 1.1.2) is highlighted in the band of 5.9 GHz.

Visible light communications (VLCs) are now a major topic in alternative communications technologies research. VLCs use signals at hundreds of Terahertz, the highest frequency of the spectrum that can be allowed (a higher one would mean, UV, X rays, and γ rays, that are harmful "ionizing" rays). The main technologies for transmission and reception are light emitting diodes (LEDs) and positive-intrinsic-negative doped diodes (or p-i-n diodes), respectively. Avalanche photo-diodes (APDs) and LASER diodes (LDs) are used too. These semiconductor technologies allow modulation of intensity and direct detection (IM-DD) schemes at reported rates of a few GHz. A recent survey [12] provides a wide view of VLC research and technology to the date by reviewing the literature about components, physical layer characteristics, multiple access issues, programmable platforms, and indoor and outdoor applications.

In November 2011, IEEE established the 802.15.7 standard for Li-Fi (*Light Fidelity*, like *Wireless Fidelity* or Wi-Fi). The actual version of the standard states an operating frequency of arround 375 [THz] and speed higher than 1 [Gbps]. The diagram shown in Figure 1.2 elaborates the categories of the communication technologies that use the spectrum of light, where we can see the traditional fiber optics communications along with a variety of optical wireless communications that form the Li-Fi technology and the free space optics (FSO) technologies.

Visible light communications (VLCs) appear to have the required transmission rates to meet VANets' goals [13], and are also a cost-effective alternative [14] because LEDs are widely deployed in traffic and car lights. As shown in [15], researchers have reported data rates higher than 10 Gbit/s for short-range VLC, but for a longer than 10 m range, Wu *et al.* [15] reached 34.13 Mbit/s with a bit error ratio (BER) of 10^{-6}.

1.2.1 Vehicular Optical Wireless Channel Modeling

The characterization of the optical wireless channel in an outdoor setting will be discussed now in order understand the physical dynamics of the light signal propagation between vehicles. Math fundamentals of Lambertian propagation theory are first reviewed.

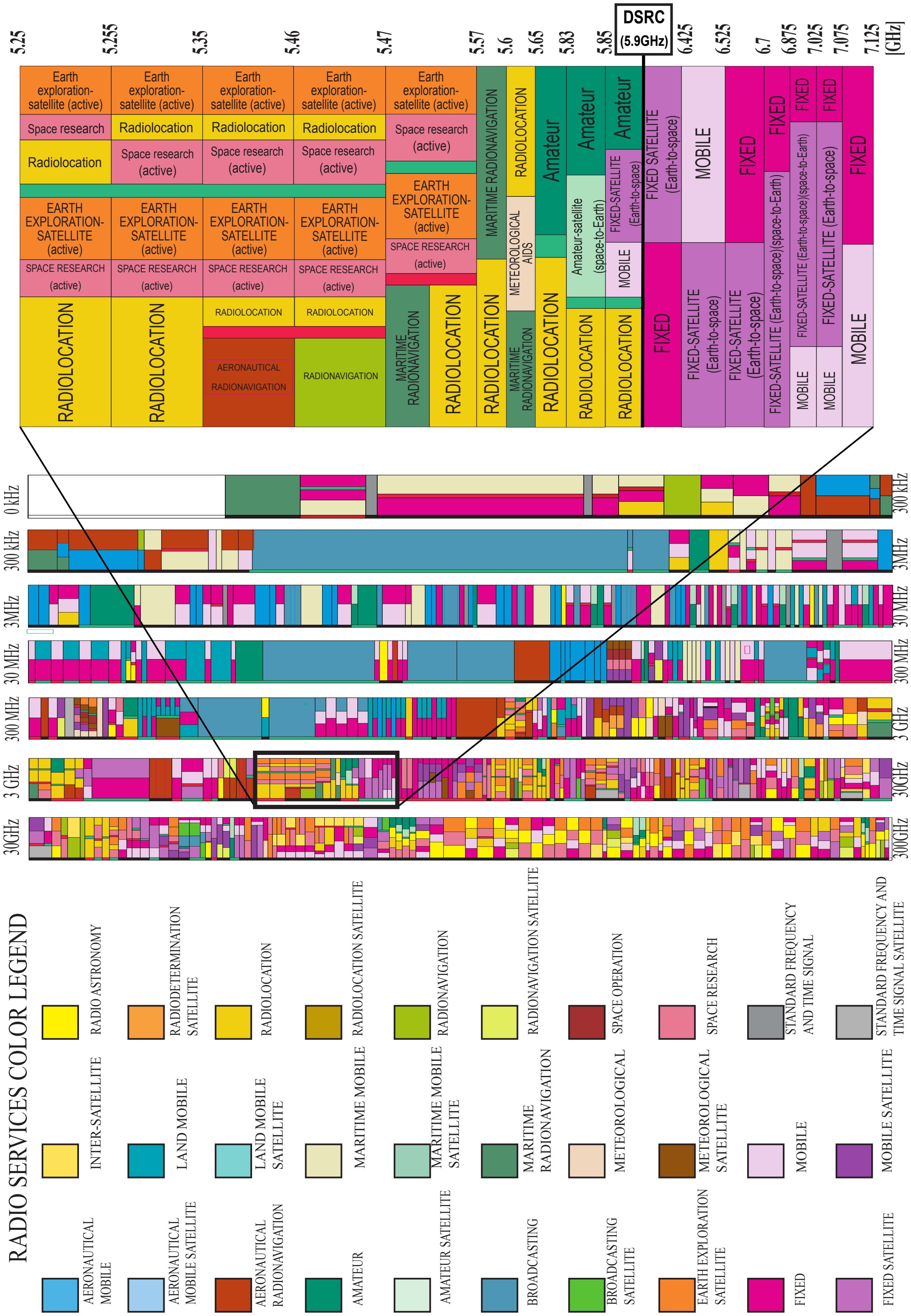

Figure 1.2: United States' spectrum allocation chart of year 2016 illustrating the spectral scarcity that the DSRC standard and RF communications in general are facing. VLCs location is beyond the chart's maximum. Source: Adapted from [10].

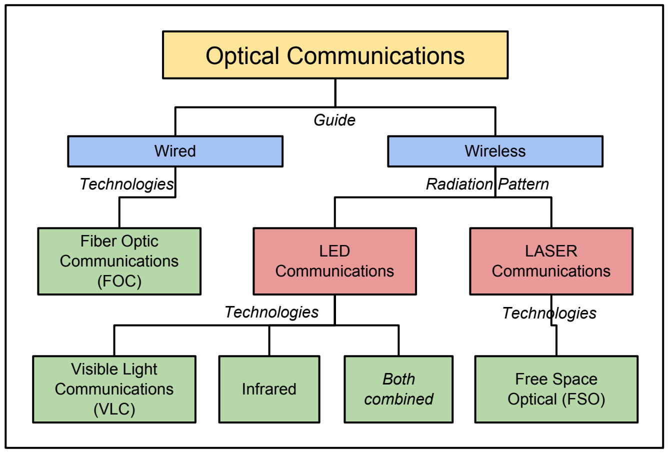

Figure 1.3: Diagram of the different optic communication technologies around the Li-Fi (802.15.7) standard. Source: Oledcomm.

In [16], the third chapter is dedicated to VLC channel modeling but focused in the indoor case. It points out important facts of any optic communication. First, the propagation modes considered in an optical wireless communication are discussed, starting the study of the signal in line-of-sight (LoS) and then including the non-line-of-sight (NLOS) components. Then, the indoor model is discussed for single and multiple sources. Limitations derived from the photodetectors and LEDs technologies, and also from the multipath-induced inter-symbol interference (ISI) are then discussed and the end of the chapter is a multiple-input multiple-output (MIMO) VLC system design.

Line-of-sight (LoS) refers to the part of the signal from the transmitter that directly reaches the receiver. In the case of VLC, a light radiating element is the source with a luminous flux Φ. It is assumed that the radiation follows a m-order Lambertian pattern given by:

$$I(\phi) = \frac{m+1}{2\pi} I(0) cos^m(\phi), \phi \in [-\frac{\pi}{2}, \frac{\pi}{2}], \tag{1.1}$$

where ϕ is the angle formed by the light beam and the LED's axis of symmetry and m is given by [17], [16].

Light radiated by the LED then passes through a number of optical elements (air, lenses, etc.) and is reflected in diffuse and specular ways, depending on the environment's boundaries. At the end, the whole setting can be modeled as a system with an impulse response $h(t)$, that is called the channel impulse response (CIR). In other words, the CIR captures all the processes or systems the signal goes accross. At the end of the channel, a part of the light from the source impacts the surface of a photo-detector (PD), wich has an area A_{PD} and a responsivity R and is exposed to a noise $n(t)$.

The whole system just described is illustrated in Figure 1.2.1, where $x(t)$ is the optical power signal coming from the LED and $y(t)$ is the current signal emitted by the photodiode. These relationship between both is described by:

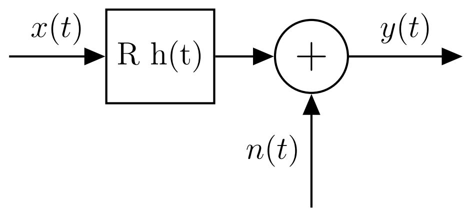

Figure 1.4: (Baseband) model for a visible light communications channel using an intensity modulation with direct detection (IM-DD) scheme. Source: [16]

$$y(t) = Rx(t) \circledast h(t) + n(t) \tag{1.2}$$

The vehicular setting shown in Figure 1.5 is derived in [16], chapter 8, assuming the asphalt has Lambertian order $m = 1$. All analysis are made in function of the semi-angle of the diffuse reflecting surfaces and optic devices. It is the vector perpendicular to the plane of the reflecting area the light beam impacts.

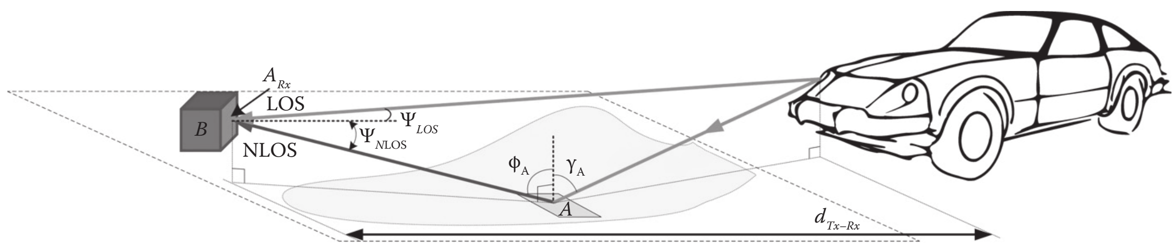

Figure 1.5: LoS signal and first reflection propagation from right side head lamp's light from the vehicle to a receiver. Source: adapted from [16].

Conclusion

The concept of vehicular networks was visited in an integral way, understanding how a health issue motivates their implementation and requires their robustness. This robustness is threatened by the lack of spectral availability. The trend towards solving the radio frequency spectral scarcity is generalized in all radio-frequency communications, and the scientific community has been studying better ways to exploit this resource through the concepts of cognitive radio networking and visible light communications. This last one offers the possibility to reuse infrastructure available in vehicular environments and promises good performance in dense areas.

Chapter 2

Materials and Methods

Introduction

This chapter focuses in the most important tools found to be useful for the implementation of wireless data links using visible light communications (VLCs). Programmable radio hardware and related software tools are described.

Optical devices, part of the visible light communications electronic elements will be reviewed: a commercially available photo detector (PD), consisting of a photo-diode and a trans-impedance amplifier (TIA), and a circuit design of a transistor-based LED communications driver.

Finally some of the simplest control and automation hardware for vehicle data acquisition is summarized.

2.1 Software Defined Radios

Software defined radios (SDRs) are programmable communications hardware based on field programmable gate arrays (FPGAs). They count with voltage controlled oscilators (VCOs), pashe-locked loops (PLLs), signal mixers, analog-to-digital and digital-to-analog converters (ADCs and DACs), amplifiers and other digital signal processing modules. These components' parameters are configurable by code, allowing rapid implementation of communication systems of any kind. In particular, a pair of SDRs along with off-the-shelf electronic components such as an LED and a Photodetector can implement full VLC systems.

2.1.1 Ettus Research (National Instruments) - Universal Software Radio Peripheral (USRP)

National Instruments (NI) Universal Software Radio Peripheral (USRP) is a family of SDRs designed to be programmed with NI LabView software. It was originally developed by Ettus Research and then NI bought the company. The USRPs model 2922, available at DEE U. Chile, come from a family of SDRs known as USRP2 that share the same motherboard and change daughterboards depending on what band of frequencies the VCOs work. The USRP 2922 work within the band from 400 MHz to 4.4 GHz in a pass-band scheme with 20 MHz bandwidth. This hardware is not directly compatible with VLCs, because intensity-modulation with direct-detection (IM-DD) schemes use low frequency or baseband signals, so a replacement of the original oscillators or having the base-band signal available at I/O is needed.

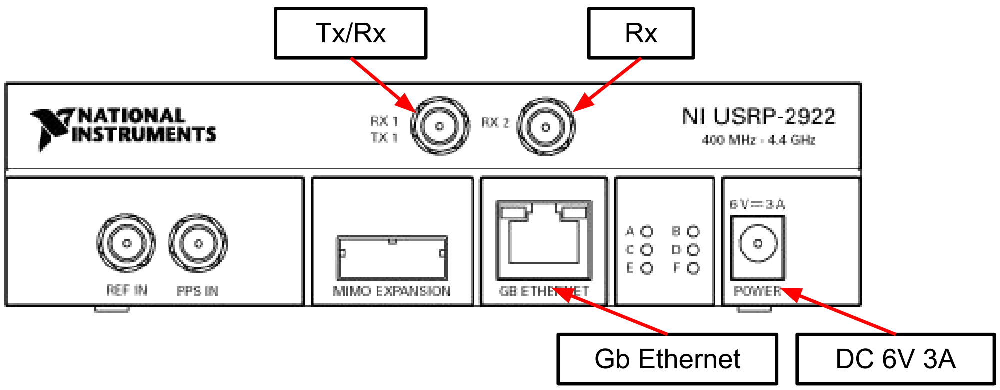

Figure 2.1: Ettus (NI) USRP 2922 front panel.

2.1.2 GNU Radio SDR Programming Software

GNU Radio (See 2.2) is a modular programming software for digital communications that is actively used and supported by scientists, the radio amateur community and the radio industry. In particular, USRPs are GNU Radio compatible through Ettus' USRP Hardware Driver (UHD).

This software counts with a library of blocks for digital signal processing that can be arranged and programmed in a graphical-flowchart framework called GNU Radio Companion (GRC). The final program can have a graphical user interface (GUI) with tools like Fourier Transform plots, sliders to chose parameters' values, and more.

GNU Radio
THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

Figure 2.2: Logo of GNU Radio

GRC has a python language tool to export a system defined by blocks in to a python script, allowing the programmer to define new blocks and to make them interact with any other python library. This can be used to compliment the computational capabilities of the system with the PC, or to communicate the system with other embedded computing devices.

2.2 VLC Channel Elements

2.2.1 Signal Combining Circuit for LED

LED lamps are made with a fixed-current driver that has to be chosen to meet the current defined by the LED's manufacturer. Some accept dimming by lowering the fixed-current value but dimmers are not always suitable to make fluctuate the LED's intensity at high speeds, so a variable-current driver is needed. As these devices aren't still commercially available, different techniques for implementing them will be now discussed.

The first chapter of [16], dedicated to review lighting and communications devices and systems, proposes circuits for the translation of the modulating signal into LED intensity modulation. It is proposed to be "biased", ending with a direct-current (DC) offset that turns the LED on.

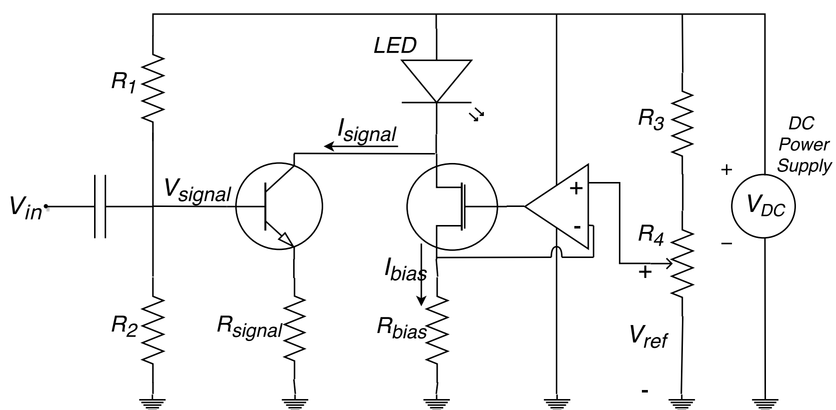

Figure 2.3: Signal Combinator. It receives the DC and AC signals coming from the LED's DC power supply and the SDR output, respectively, and sends the sum of both signals to the LED. Source: Adapted from [16]

.

There are RLC based passive circuits known as "bias-tee" that are low cost solutions and can perform well in VLC [18], but they can be easily contaminated with noise because they couple with electromagnetic fields and better design (in terms of noise) of a is proposed by [16]. It's called a signal combining circuit (SCC) or signal combinator.

The electric design of the SCC can be seen in Fig. 2.3. The circuit has two blocks or sub-circuits: (1) a fixed-current source based on a MOSFET controlled by an OPAMP and (2) a variable-current source based on BJT whose current is set by the communication signal.

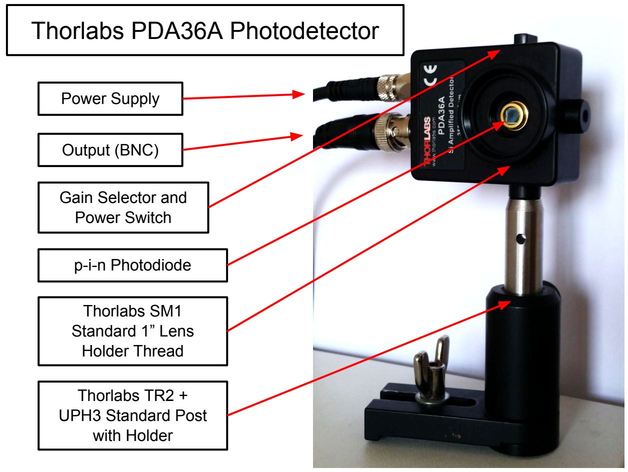

Figure 2.4: Diagram of the Thorlabs PDA36A: switchable-gain photodetector based on p-i-n photodiode and trans-impedance amplifier.

The DC block of the SCC also can act as a dimmer of the LED by changing the input of the OPAMP V_{ref}, then the fixed-current I_{bias} will be:

$$I_{bias} = \frac{V_{ref}}{R_{bias}} \tag{2.1}$$

The variable-current I_{signal} changes in fuction of the communication signal V_{in}, assuming the transistor is operating in the active region and its collector current is approximately equal to its emitter current (*i.e.* the current gain $\alpha = \frac{\beta}{\beta+1}$ is unitary), is given by:

$$I_{signal}(V_{\text{in}}) \approx \frac{V_{signal} - 0.7[V]}{R_{signal}} = \frac{V_{\text{in}} + V_{DC}\frac{R_2}{R_1+R_2} - 0.7[V]}{R_{signal}} \tag{2.2}$$

2.2.2 Thorlabs PDA36A Photodetector (PD)

This photodetector (PD) is a silicon p_{type}-intrinsic-n_{type} (p-i-n) photodiode with a switchable gain trans-impedance amplifier (TIA). It has an active surface of 3.6[mm] by 3.6[mm], centered in a Thorlabs SM1 patented thread to hold lenses and other optical elements. It's also mounted in a Thorlabs TR2 patented post with imperial metrics thread (Note that decimal metrics poles are labeled with a ring on top). Figure 2.2.2 shows the PDA36A mounted.

An important constant of a PD is its responsivity, measured in [A/W] and is a function of factors like wavelength (λ), temperature, and more. The PDA36A's responsivity against wavelength curve is shown in Figure 2.5 showing the PDA36A works in ultra violet-visible-near infrared spectrum (UV-VIS-NIR). Peak responsivity of 6.5 [A/W] is reached at 960 [nm] and the best performance of the PD is in the NIR (near-infrared) spectrum.

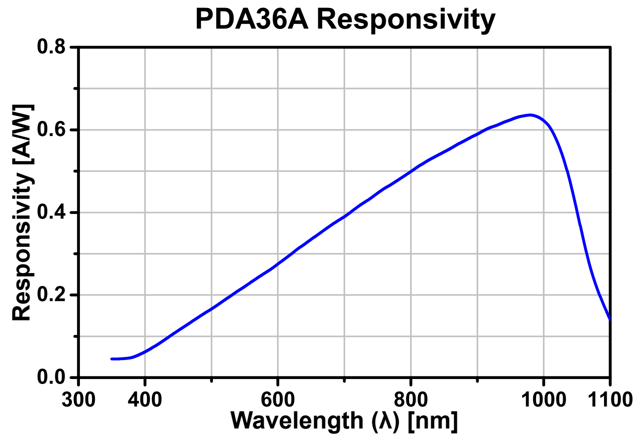

Figure 2.5: Responsivity-wavelength curve of the Thorlabs PDA36A Photodetector. Source: Thorlabs PDA36A User's Guide.

2.3 Vehicle Control and Automation Communication Technologies

The dawn of the era of electric vehicles, together with driving assistance systems included in sophisticated cars, have brought huge advances in the development of self-driving vehicles. Tesla Motors company had already released models including what they call *autopilot hardware*, that can drive the vehicle with no people's intervention in some certain environments. Another company, called Comma.ai, has released a universal open-source self-driving platform that also can drive a growing list of cars autonomously in similar conditions. The principle involving these systems is to control the vehicle's sensors and actuators with an artificial intelligence.

Control Area Network Bus (CAN Bus) is a bus-architecture (shared medium) network existing inside modern vehicles where all the digital sensors and actuators (or control units) interact. It's a family of communication protocols released by the International Organization for Standardization (ISO) and the Society of Automotive Engineers (SAE). CAN reading would allow On-board Units (OBUs) to gather kinetic data direct from local sensors, such as instantaneous velocity, acceleration and even failure codes like airbag operation, thus, taking advantage of an existing infrastructure and saving the installation of new sensors. Also, CAN writing could provide traffic control services such as emergency braking or synchronized acceleration and deceleration in dense conditions.

2.3.1 Control Area Network Bus (CAN Bus) Interfaces

All modern vehicles count with up to 3 CAN buses that are accessible by an On-Board Device Port, version II (OBD-II Port), usually located inside the cabin and close to the steering wheel. In a recent work from 2016, a VLC system exploiting CAN Bus through OBD-II port was successfully built [19]. Some well-known integrated circuit to read and write CAN Bus data are the ELM327 and the MCP2515, that work as a universal CAN protocol interpreter and a modem for the CAN Bus physical layer protocol respectively. A newer interface is the Comma.ai Panda, that's part of a platform for controlling vehicles with artificial intelligence. It runs with a python library and connects to the computer through a Wi-Fi hotspot that it implements using an ESP8266 communications board. Sparkfun CAN-Bus Shield (for Arduino UNO) is an MCP2515 based CAN Bus interface. It also counts with a microSD interface, GPS port, and other non-considered features. A typical implementation of the ELM327 is Bluetooth and WiFi dongles. These technologies mentioned are shown in Figure 2.6.

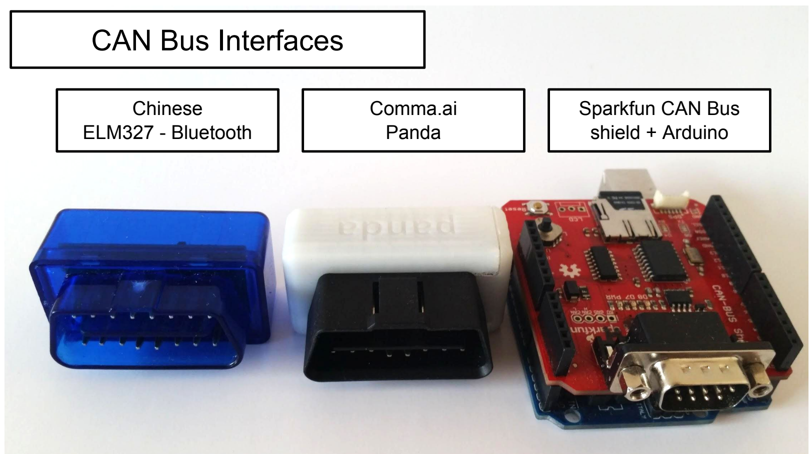

Figure 2.6: CAN Bus reading and writing interfaces.

2.4 Arduino Nano: Open Source Microcontroller and Serial Interface

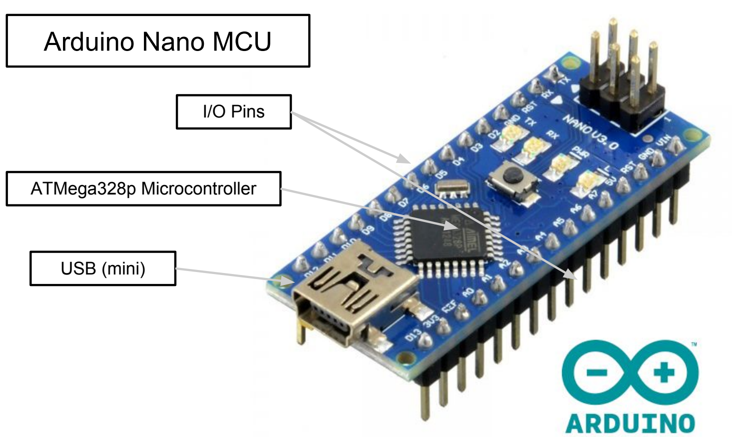

Figure 2.7: Arduino Nano board, featuring an ATMega328p microcontroller and a USB interface to easily interact with a computer.

An Arduino board is a microcontroller unit (MCU), that, along with a computer running Arduino IDE (Integrated Development Environment), and electronic elements can implement embedded computing devices. The Arduino IDE is based on Processing programming language, that allows the MCU to share computing resources with the PC, for example, making a GUI in the pc with Processing and using the Arduino as I/O and controller, like a programmable logic controller (PLC) with human-to-machine interface (HMI).

The model Arduino Nano board (See Figure 2.7) is based on an ATMega328p microcontroller at 16MHz, with 8 analog inputs and 12 digital I/O pins. It also has a CH340 Serial-to-USB interface to easily connect the board to a computer. It is capable of turning two digital pins into a serial UART (Universal Asynchronous Receiver-Transmitter) interface at up to 115200 [bauds/s]. The smallest official board available now is the Arduino Pro Mini but it has no USB interface, so the Arduino Nano is the simplest to use.

Conclusion

Two programmable hardware platforms were discussed, the software defined radios (SDRs) to implement communication's chain of blocks and Arduino to interface/acquire data from other devices.

Visible light communications (VLCs) fundamental components were studied: a signal combinator, that has to be self-made, to modulate the LED's intensity, and a photodetector (PD) based on a p-i-n photodiode and a trans-impedance amplifier (TIA).

Control area network bus (CAN Bus) interfaces act as the gateways to connect to the control network of the car, allowing to tap into the car's sensors and actuators data.

Chapter 3

Implementation

Introduction

The intelligent transportation systems (ITS) are application-layer systems of a network where nodes are vehicles or parts of the urban and rural infrastructure that share kinetic and control data through ephemeral *ad-hoc* links that can be classified as vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communications, as discussed in Chapter 1.

This chapter discusses the implementation of two systems for research on vehicular communications based on visible light communications (VLCs) . A data acquisition system for control area network bus (CAN Bus) interface based on ELM327, and an optical wireless channel system based on software defined radios (SDRs) a modified LED and an off-the-shelf photodetector.

First, the general idea of the system is described by designing V2V and V2I communication schemes with three basic modules, two for transmitting and receiving and one for data acquisition. After the implementation of a signal combining circuit (SCC) to replace an LED's driver, and the configuration of a pair of software defined radios (SDRs), a wide-band FM scheme is used to transmit audio data through a VLC channel.

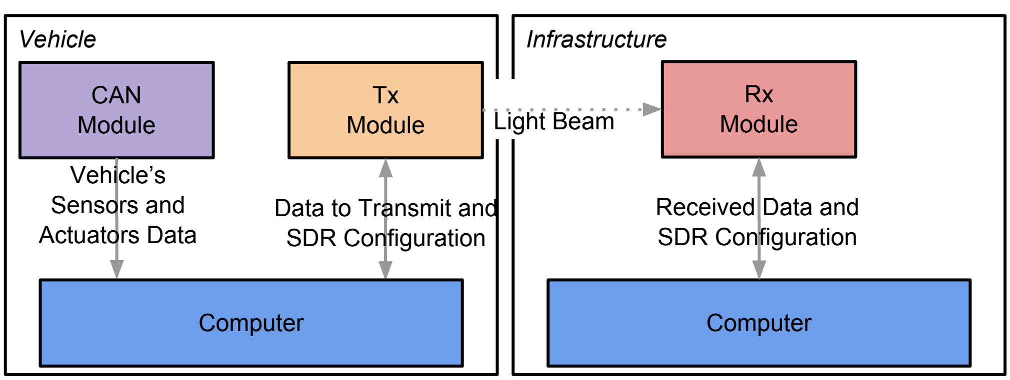

Figure 3.1: V2I platform configuration.

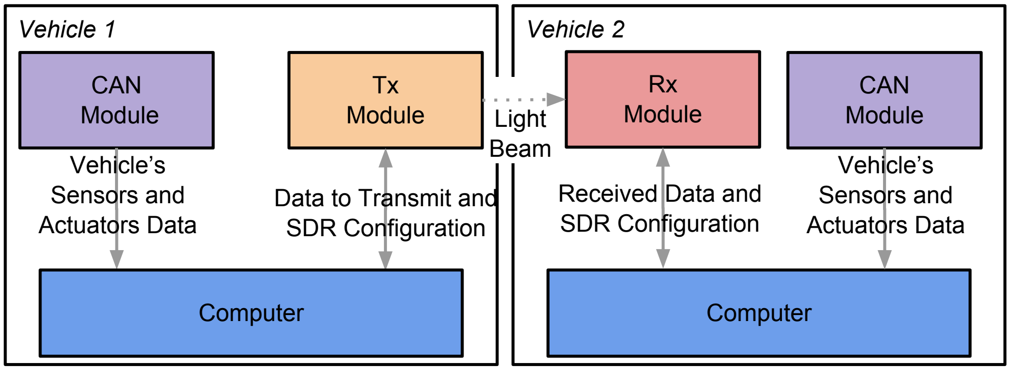

Figure 3.2: V2V platform configuration.

The platform is both a VLC link and a CAN Bus interface that can be arranged in different configurations. It's formed by three main modules: Tx, Rx, and CAN. Both, Tx and Rx modules are based on USRP2 with a Chinese LED floodlight and a Thorlabs PDA36A p-i-n photodiode respectively. The CAN module is based on a ELM327-Bluetooth dongle along with an Arduino nano microcontroller with a HC-05 Bluetooth circuit.

As seen in Fig. 3.7, the connection between the PDA36A photodetector and the USRP in the receiver side is direct, since the Trans-Impedance Amplifier (TIA) is integrated within the PDA36A. In the transmitter side, however, an AC+DC signal combinator is needed in order for the LED to transmit an intensity-modulated signal. This signal combining circuit (SCC) receives the LED's DC power supply and the USRP's AC signal as inputs.

As shown in Fig. 3.1, a computer controls the CAN interface and the VLC Tx subsystem inside the vehicle. This computer will filter the data stream coming from the CAN interface and will communicate to the Rx subsystem through visible light.

3.1 CAN Module Implementation

In order to gather kinetic data from the vehicle, like in Figure 3.3, a CAN Bus interfacing module was developed using Arduino Nano, an HC-05 bluetooth interface and a wire less (bluetooth) ELM327 OBD interface. The chain of blocks needed to implement the this modules shown in Fig. 3.4. Communication with VLC Tx and/or Rx module would be by a serial interface block in GNU Radio Companion (GRC) software or by programming serial reads and writes in the python code generated by GRC.

The Arduino is connected to the ELM327 by a wireless bluetooth serial gate that works like a cable. The ELM327 is connected to the vehicle's OBD-II port and left clear. The CAN module is connected to a laptop through USB port.

The code of the Arduino is organized in Figure 3.5 begins with a pre-configuration that consists of telling the ELM327 to automatically choose the CAN Bus protocol. The sensors data requests of the ELM327 consist of an ID that is sent by de Arduino. Then, the ELM327

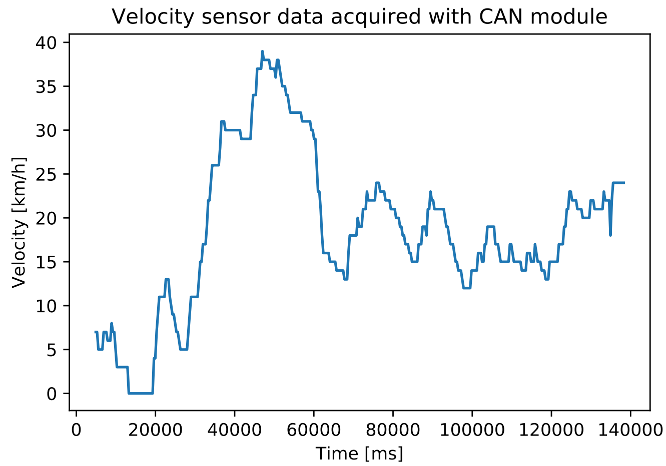

Figure 3.3: Car velocity measured by its own sensor using the CAN module.

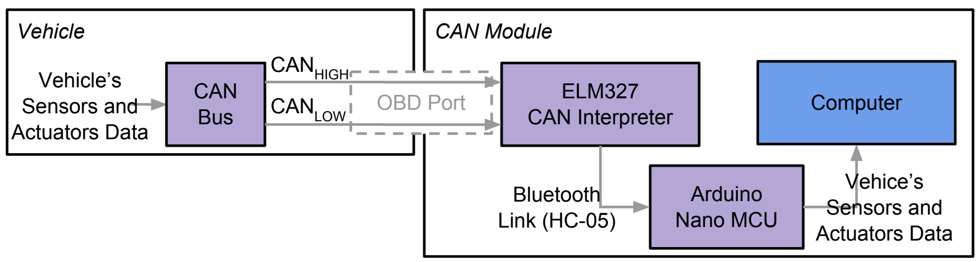

Figure 3.4: CAN platform subsystem capable of reading the data of the CAN Bus.

answers a string of bytes that has to be translated to data using the sensor's equation.

Figure 3.6 show the final construction of the CAN module. It was built with a SIM800L module for other project's purposes. A DC jack was installed to connect the module to the car's battery. A 9[V] regulator was also installed in order to protect the Arduino's voltage regulator from the car.

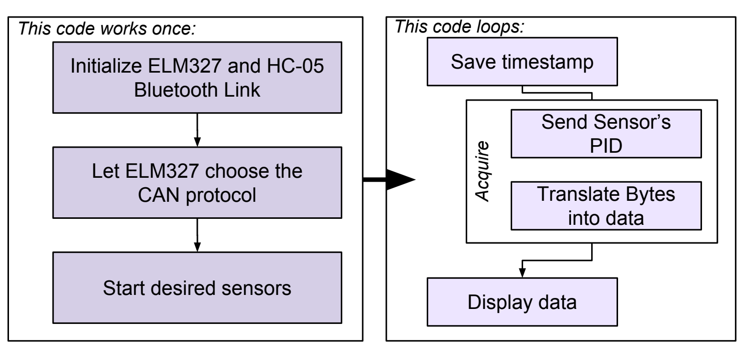

Figure 3.5: Flow chart of the Arduino nano program to request kinetic data to the ELM327.

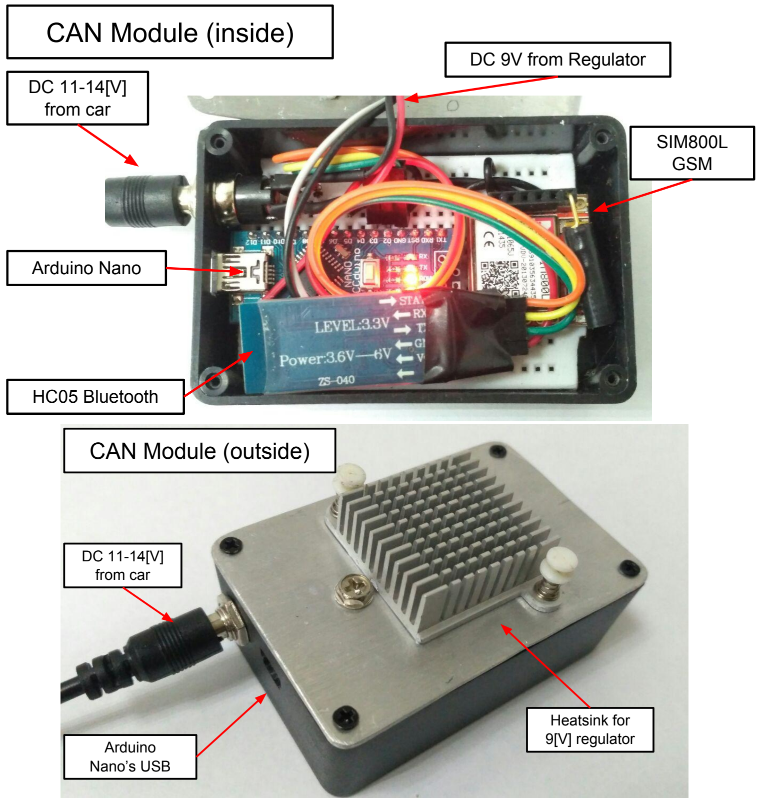

Figure 3.6: CAN module implementation.

3.2 VLC Link Implementation

The VLC module consists of a transmitter, connecting a USRP NI2922 with a LED lamp through a signal combinator, and a receiver, using a USRP NI2922 connected to a PD36A photodetector, as shown in Figure 3.7. The VLC Tx and Rx subsystems are designed to work in base-band or low frequency, as opposed to the default USRP scheme which is a pass-band scheme.

3.2.1 SDRs Hardware and Software Configuration

Because of high integration within the USRPs, it's not possible to access the base-band signal before it's mixed with the local oscillator's signal. Therefore, an internal hardware modification of the NI2922 was performed. Both radios' default pass-band daughterboard was replaced by two low frequency daughterboards that act as receiver and transmitter, namely Ettus Research LFTX/LFRX 0-30 MHz. Such replacement was made in order to improve the transmission rates and to make the system compatible with visible light spectrum transmission. This modification can be appreciated in Fig. 3.8.

The implementation of the software of the system was done in a Debian operating system runing GNU Radio Companion (GRC) and with Ettus USRP Hardware Driver (UHD) installed correctly. IP address changes were made to the USRPs. Then, a wide-band frequency

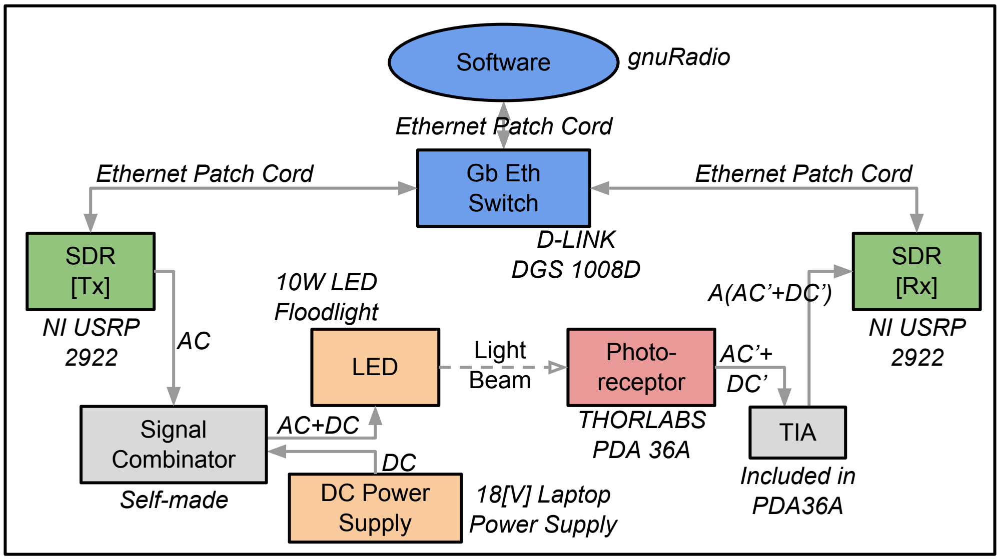

Figure 3.7: Block diagram of the VLC system.

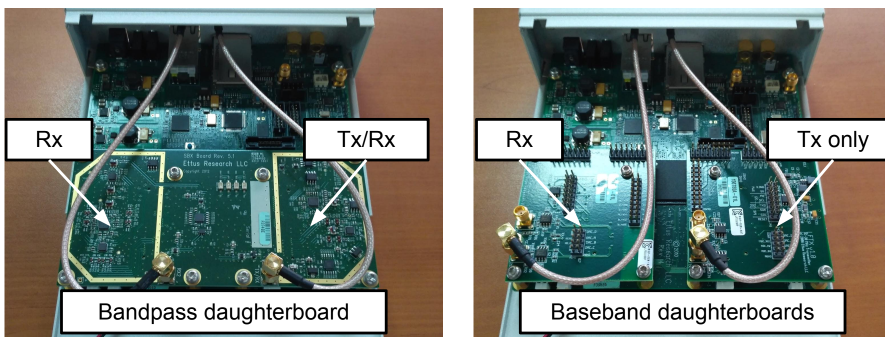

Figure 3.8: Modification of the NI USRP 2922 original daughterboard (which works in bandpass) [left side] to baseband daughterboards [right side]

modulation (WBFM) was implemented to transmit sound (*wav* files or the computer's microphone input) through the VLC channel and listen to the received using a speaker as it's illustrated in Figure 3.11. This configuration works as a demonstration of the system capabilities since the performance can be judged (qualitatively) by the ear. To quantitatively evaluate the performance, *.wav* files can be saved at input and output to compare digitally.

3.2.2 Signal Combining Circuit Implementation

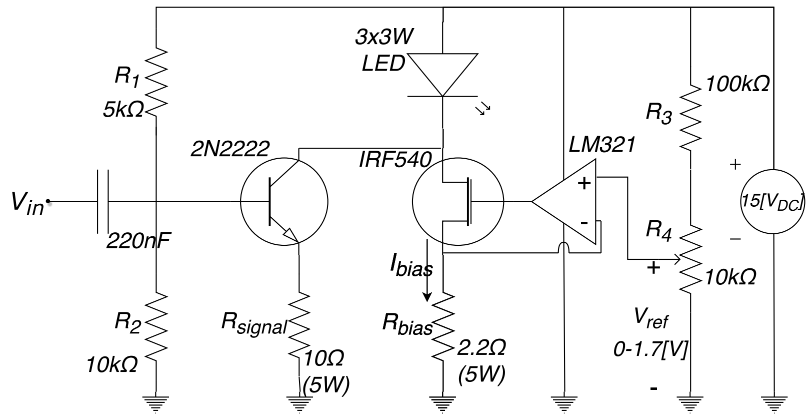

Figure 3.9: Final design of the Signal Combining Circuit (SCC).

The SDR Tx signal is translated into subtle changes of the LED's intensity by a signal combinator, or signal combining circuit (SCC). This circuit is a voltage-controlled current source. It has two main blocks: (1) a DC current source based on MOSFET and OPAMP and (2) an AC current source based on BJT. The circuit design and component's values are presented in Figure 3.9.

Figure 3.10 shows the process of implementation of the SCC board in a standard LED, taking advantage of the chassis of the lamp, made to refrigerate the LED and its original driver.

Other components, not shown in the schematic of the circuit are: BNC and DC jack connector, a laptop power supply and a 15[V] DC regulator as the source of energy of the circuit. Also, the OPAMP LM321 was changed by a quad-OPAMP LM324 that has the same integrated circuit replicated four times. One of the three OPAMPs left was adapted to make an input LED indicator, that turns on when the SDR is sending current to the LED.

Conclusion

The implementation of hardware for prototyping visible light communication (VLC) technology and car automation interfaces was described in this chapter. A circuit for the intensity modulation of an LED was built using transistors and electronics. Software configuration of SDRs and Arduino was carried out. The final GNU Radio code is shown in 3.11.

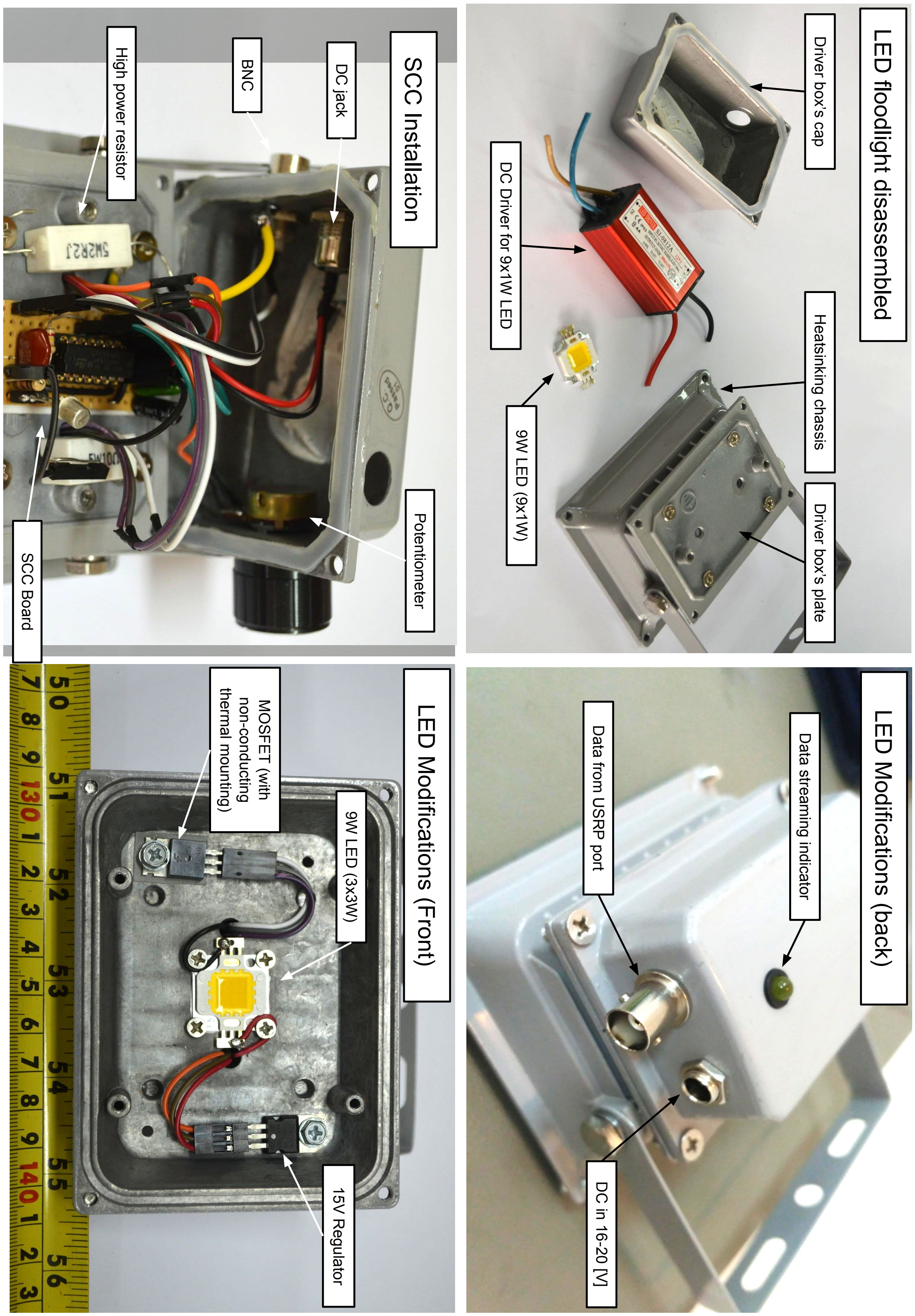

Figure 3.10: Implementation of the signal combining circuit (SCC) board

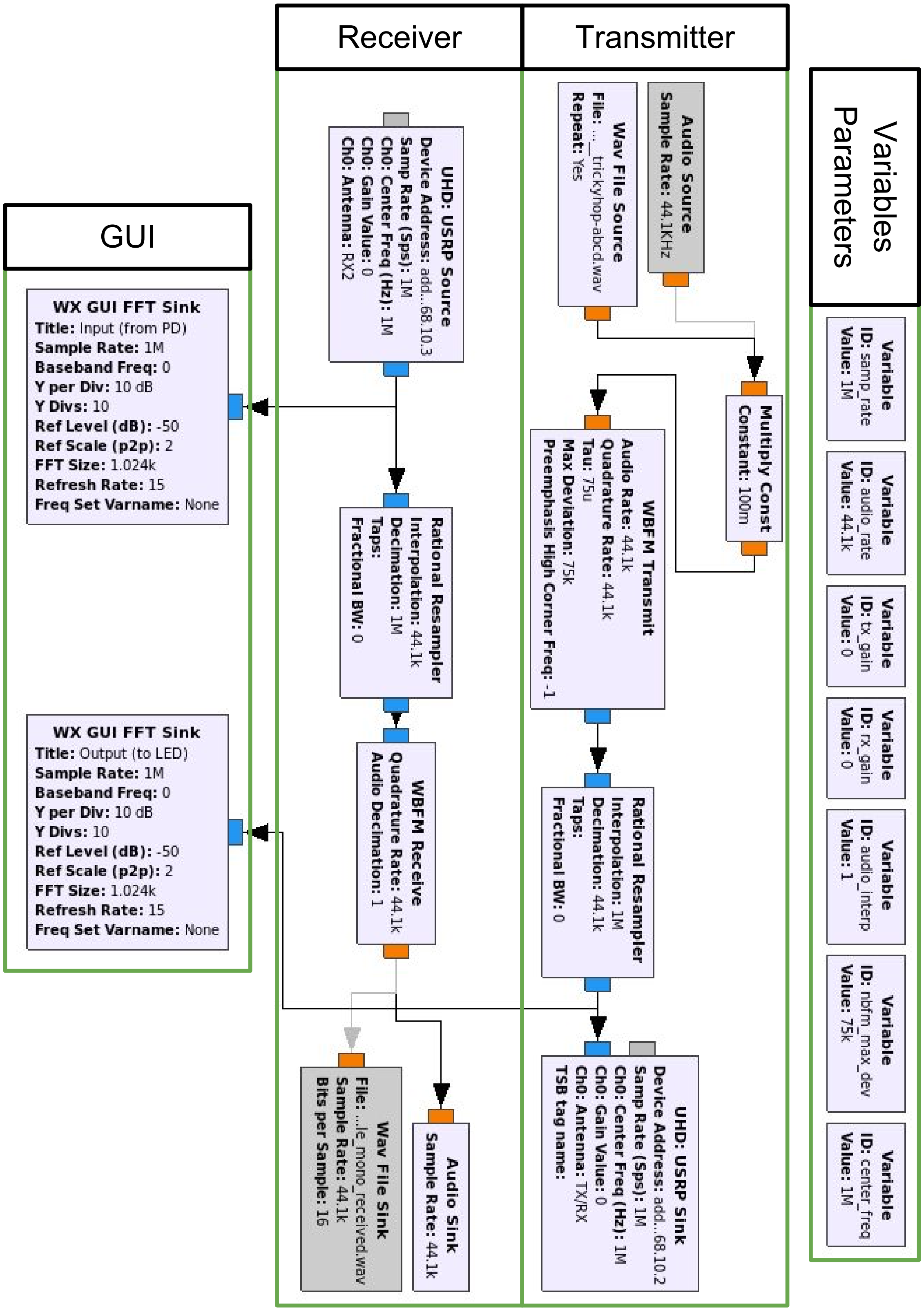

Figure 3.11: GRC graphical software program of the VLC module based on WBFM

Conclusion

Visible light communications (VLCs) are a wireless technology that is based on the principle of modulating light intensity of an illumination device like an LED and detecting it with a photonic device like a photo-diode, under a scheme called intensity modulation with direct detection (IM/DD), and where radiation follows Lambertian patterns. The approach of a model for a vehicular setting was reviewed from bibliography.

The data rates that VLCs can reach are determined not by the width of the visible light band, which is about 400 [THz], but by the LED's capacity to switch intensity and the resposivity of the photodetectors and today are in the Gbps rates in indoor settings. The implementation of a VLC transmitting device was done using a standard LED lamp and an electronic circuit known as signal combinator or signal combining circuit (SCC). The light intensity switching rate reached was of about 1 [MHz], which is the typical rate of a phospor-coated LED. The implemented device was arranged with a Thorlabs PDA36A photodetector and two software defined radios (SDRs) Ettus USRP2922, and using GNU Radio SDR programming software it was possible to stablish a wide-band FM audio communication.

Vehicular ad-hoc networks (VANets) are an emerging wireless communications paradigm in which vehicles carrying on-board units (OBUs), and road-side units (RSUs) placed in the streets, exchange information like: kinetic measurements, automatization instructions, infotainment streams. These networks enable traffic control techniques denoted intelligent transportation systems (ITS) where machines and people drive the vehicles, promising to take better decisions in all cases, especially in emergencies, improving health and environmental impacts of the use of transportation means. An approach to a OBU was built using the programmable platform Arduino and an ELM327 based device. The device is able to read the velocity sensor of the car and report the data to a computer through USB.

The hypothesis of this work was the idea that VLCs can implement VANets. It wasn't tested in the real setting since the integrity of laboratory implements is needed and valuation of the capabilities in vehicular environments of the systems implemented has to be done. What was found, is that VANets need to be robust in order to support critical applications such as ITS,. VLCs are not capable of implementing robust VANets alone because they fail in long distances. VLCs are indicated for ranges of a few meters, where other technologies found a lot of congestion. Thus, complementing VLCs with cognitive radio networking (CRN) and the existing dedicated short-range communications (DSRCs) can support the widest variety of cases.

Recommendations and Future Work

The new paths this investigation can follow are not restricted to VLCs or to VANets. For example, SDR capabilities in cognitive networks can be studied using the GNU Radio software and USRP hardware that was configured, also, the CAN module could be tested with RF standard VANEts technology in order to give access to kinetic and control data of the vehicle.

To evaluate the capabilities of VLC in a real VANet scenario, a car headlight should be adapted with a SCC designed in this work. It also could be directly integrated to the vehicle's CAN Bus. The implemented systems should be arranged in an outdoor static setting to approach that evaluation. The experimentation along with DSRC technologies still remains far.

More advanced silicon technologies and photonic and optical techniques should be studied. Red-Green-Blue (RGB) LEDs, as well as separated LEDs of more than five different colors are commercially available and could exploit wavelength division schemes by replicating the implementations of this work for each channel and using optical elements such as a triangular prism.

The implementation of photodetectors based on p-i-n Photodiodes could also be studied, similarly to the SCC implementation of this work but implementing trans-impedance amplifiers. This could be implemented in car tail lamps in order to complete the vehicular setting studied in this work and ultimately studying the multiple-input multiple-output (MIMO) scheme by replicating the setting to four car's lamps.

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Appendix A: List of Publications

Conference Publications

1. Vicente Matus, Nicolás Maturana, Cesar Azurdia-Meza, Samuel Montejo, Javier Rojas, "Hardware Design of a Prototyping Platform for Vehicular VLC Using SDR and Exploiting Vehicles CAN Bus", accepted in *First South American Colloquium on Visible Light Communications*, Santiago de Chile, November 2017.

Submitted Articles

1. Vicente Matus, Cesar Azurdia-Meza, Samuel Montejo, Pablo Ortega, Sandra Céspedes, "Evaluation of the Applicability of VLCs on VANets using Existing Vehicular Infrastructures", to be submitted to the 11^{th} *International Symposium on Communication Systems, Networks, and Digital Signal Processing.*, Budapest, Hungary, July 2018.

Appendix B: Codes

The codes written for the Arduino in the CAN module and the USRPs in the VLC system were uploaded to a *GitHub* repository. To access the repository and get the latest version of the codes, enter the following website:

`https://github.com/LaboratorioTICs-UChile/`

The versions used in this work are available in the following links:

Arduino Code

`https://github.com/LaboratorioTICs-UChile/OBD-monitor/blob/master/CANmodule_VMatusThesis.ino`

GNU Radio Companion Code

`https://github.com/LaboratorioTICs-UChile/SDR_based_VLC/blob/master/wbfm_transceiver.py`