Implementation of a Low-Cost Vehicular VLC System and CAN Bus Interface

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***Abstract*—Vehicular communication networks are one of the essential technologies needed to implement intelligent transportation systems in smart cities. In such networks, available/licensed technologies still need to develop robustness and resilience in order to support critical applications for safety and efficiency. One alternative technology, complementary to radio-frequency, is visible light communications (VLC), which has the potential of taking advantage of light emitting diodes (LEDs) that are widely deployed in car lamps and traffic lights. Control area network bus (CAN Bus), the control network of all modern cars, can be read through the on-board diagnostics (OBD) port available inside the cabin. Data from sensors and actuators of the car can be robustly acquired from the bus and can be shared to allow the vehicular network cooperatively build knowledge of the kinetic data of each car through beaconing. In this work, a low-cost VLC system based on white LED technology, which is the most commonly used technology within the cars headlamps, is implemented and validated in laboratory conditions at a distance up to 1.5 meters between the transmitter and receiver. Further, the implementation of a low-cost CAN Bus interface is shown and velocity data acquisition is validated by testing the system against a global positioning system (GPS) device. The proposed low-cost CAN Bus interface achieved high reproducibility of the GPS estimations and was validated with a 0.9979 Lin's concordance correlation coefficient.**

***Keywords*—Control area network bus (CAN Bus), software defined radios (SDRs), vehicular networks, visible light communications (VLCs).**

I. Introduction

Vehicular communications networks are a particular and challenging case of wireless communications, where cars host mobile nodes called on-board units (OBUs) and streets host fixed nodes called road-side units (RSUs) [1]. These devices communicate in inter-vehicular schemes usually called vehicle-to-vehicle (V2V) communications, and in road-vehicle schemes, usually called vehicle-to-infrastructure (V2I) communications, as shown in Fig. 1. The nodes of a vehicular network share data; such as car kinetic variables, control and automation instructions, and infotainment streams. The exchange of kinetic data is done by the transmission of *beacons* [2], [3], that allow OBUs and RSUs to cooperatively build the map of their surroundings [4], forming the web needed to implement intelligent transportation systems (ITS), that are a vast control network intended to improve road safety and traffic efficiency [1].

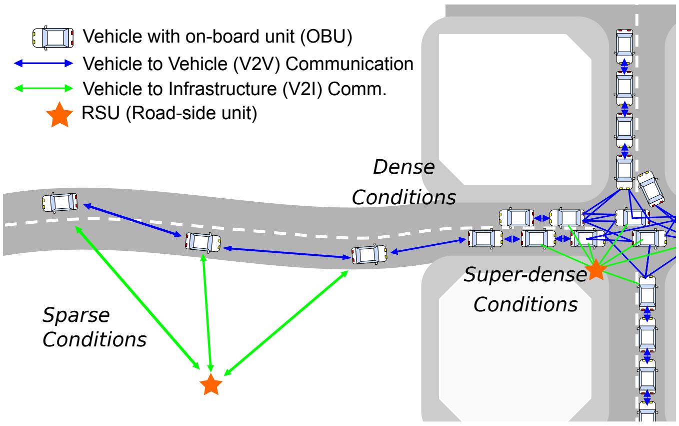

Fig. 1. Basic architecture of vehicular networks, conformed by on-board units (OBUs) inside cars, and road-side units (RSUs) hosted by the vehicular infrastructure that communicate under vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) schemes.

The dedicated short-range communications (DSRC) standard and wireless access in vehicular environments (WAVE) family of standards for vehicular communications are based on IEEE 802.11OCB, technologies based on orthogonal-frequency division multiplexing (OFDM) at the physical layer, in the 5.9[GHz] band, and licensing up to a bandwidth of 75[MHz] depending on the country. Just as all other cases of wireless communications, vehicular networks face an important issue of spectral scarcity [5], which has lead to different approaches to solve the problem.

The application of cognitive radio (CR) networking has been studied [6] in order to allow vehicular communications to take advantage of existing spectrum holes that can be used in an opportunistic way, without compromising the experience of the licensed users. Investigations by Eze, E. *et al.* in 2015 [7] and Pagadarai *et al.* in 2009 [8], characterized the available spectrum in television broadcasting networks in rural and urban areas, that open an alternative for sparse conditions. In [9], the authors proposed a framework to temporarily add channels to improve a DSRC vehicular ad-hoc network

TABLE I
COMPLEMENTARY TECHNOLOGIES THAT CAN FORM WIRELESS LINKS IN DIFFERENT TRAFFIC CONDITIONS

Traffic Conditions	Proposed Technologies
Sparse	RF (DSRC), CR
Dense	RF (DSRC), CR, mmW
Super-dense	mmW, VLCs

(VANET) by the use of CR.

Vehicular communications occur in a wide range of proximity conditions, from sparse to super-dense (see Fig. 1), and must work properly in all of them [5]. For the densest scenarios, bands of higher frequencies, such as millimeter waves (mmW) [10] and visible light, that have a higher directionality degree and a shorter range than radio frequencies (RFs), can be considered. As shown in [11], visible light communications (VLCs) work better in heavy traffic conditions, where DSRC usually fails. A robust and resilient technology for vehicular communications networks should mix different technologies and use each in the best conditions. Table I summarizes the conditions and technologies discussed so far.

Modern vehicles include LED technology that could be used to deploy VLC in vehicular communication. LEDs are usually built using Silicon, but as well as other elements like Gallium, and Nitrogen. Chemical compounds formed by them emit light in very narrow bands of a few tens of nanometers. For example, an Aluminum-Indium-Gallium Phosphate (AlInGaP) LED will emit red light approximately in the band of 620-650[nm] [12]. To generate white color, or some colors that are not available as single compounds, coatings are used. Most modern cars use white phosphor-coated blue LED technology in its headlamps, and red and yellow (non-coated) LEDs in tail-lamps. The coating has lower switching rates than the LED itself. A single non-coated LED can be modulated at a 60 [MHz] bandwidth [13], while a white phosphor-coated blue LED can be modulated by the order of 3 [MHz] without filtering, and up to 20 [MHz] if the blue component is optically isolated [14].

The objective of this work is to integrate widely-available white LED technology with communications hardware and vehicular control networks in order to implement a test bed for VLCs based vehicular communications.

The structure of the paper is organized as follows. In Section II, the description and implementation of the designed system blocks are shown. The experiments made with the test bed are shown and discussed in Section III. Finally, conclusions are given in Section IV.

II. PROPOSED INTEGRATED VLC SYSTEM

In previous work [15], the modular design of the system was presented. Whereas in this manuscript, the main objective is to integrate widely-available white LED technology with communications hardware and vehicular control networks in order to implement a low cost VLC based vehicular communications system. The main idea is that an on-board computer gathers kinetic information of the vehicle using its control area network bus (CAN Bus, which communicates to the computer of the car), then the information is transmitted with a light emitting diode (LED) to a photo-diode (PD), and finally the information is received. The system then consists of two modules: (1) a visible light communications (VLC) transmitter (Tx) and receiver (Rx), based on phosphor-coated light emitting diode (LED) and based on p-i-n (p-type, intrinsic, n-type) photo-diode (PIN PD) respectively, and (2), a vehicle control area network (CAN) interface based on a universal protocol interpreter and a micro-controller. To make the system as versatile as possible, Tx and Rx are designed based on software defined radios (SDRs), which are programmable radio hardware. The final list of parts chosen to implement the modules of the system is shown in Table II. Next subsections discusses the implementation of each module.

TABLE II
MAIN HARDWARE PIECES USED TO IMPLEMENT THE MODULES.
*: SIM800L INSTALLED FOR VEHICLE-TO-CLOUD (V2C) COMMUNICATIONS THROUGH GENERAL PACKET RADIO SERVICE (GPRS)

Module of the System	Hardware Used (cables excluded)
VLC Module	2 x National Instruments USRP 2922 2 x Ettus LFRX 2 x Ettus LFTX 1 x Thorlabs PDA36A 1 x Generic 10W LED Floodlight 1 x Self-made Signal Combining Circuit
CAN Module	1 x ELM327 Bluetooth Dongle 1 x Arduino Nano 1 x HC-05 Bluetooth 1 x SIM800L (unused*)
Integration of modules	1 x Laptop (GNU Radio, Arduino IDE) 1 x Gb Ethernet Switch

A. VLC Module

The VLC module consists of a transmitter, connecting a USRP NI2922 with a LED lamp, and a receiver, using a USRP NI2922 connected to a PD36A photo-detector. The block diagram of the module is shown in Fig. 2 and its final implementation is shown in Fig. 3. 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. In our previous work [15], the modification of the USRP internal daughter-boards was performed, and Ettus low frequency cards LFTX and LFRX were installed. The range of operation of the oscillator within the Ettus low frequency cards is from DC to 30[Mhz].

Thorlabs PDA36A photo-detector, based on P-type, intrinsic, N-type (PIN) Photo-diode works in the visible spectrum and ultraviolet and infrared bands. Peak responsivity is reached at 960 [nm] with a value of 6.5 [A/W], whereas the best performance of the PD is in the near-infrared spectrum.

The LED's original power source or driver was replaced by a self-made signal combining circuit (SCC). It sets a fixed current to turn the LED on and a variable current to modulate the LED's intensity in function of a signal received from the communications blocks implemented in the SDR.

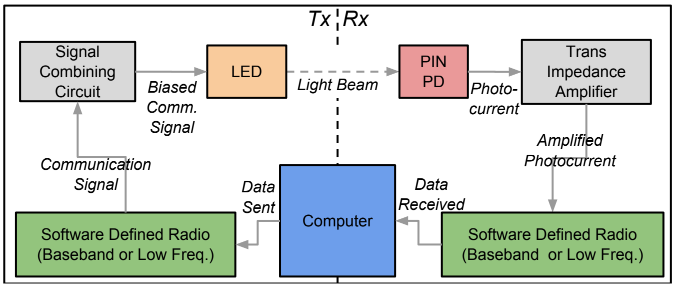

Fig. 2. VLC module blocks.

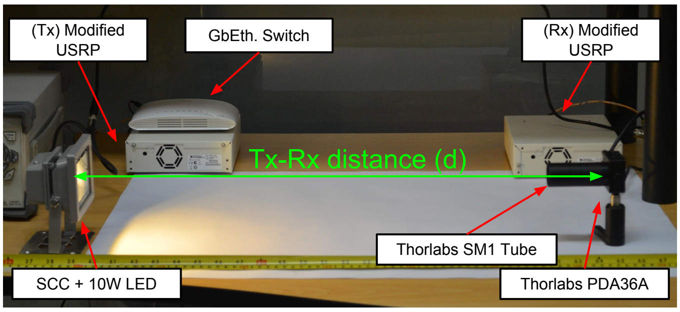

Fig. 3. A laboratory setup of the VLC module.

The electric design of the SCC was based on the topology proposed by [16]. The final schematic is shown in Fig. 4. 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 a BJT whose current is set by the communication signal. The DC block of the SCC can also act as a dimmer of the LED by changing the input of the OPAMP V_{ref}, then the fixed-current I_{bias} will be

$$I_{bias} = \frac{V_{ref}}{R_{bias}}. \quad (1)$$

The variable-current I_{signal} changes in function of the communication signal V_{in}. Assuming the 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), I_{signal} is given by

$$I_{signal} \approx \frac{V_{signal} - 0.7[V]}{R_{signal}} = \frac{V_{in} + \frac{V_{DC}R_2}{R_1+R_2} - 0.7[V]}{R_{signal}}. \quad (2)$$

B. CAN Module

The 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 is a family of communication protocols released by the International Organization for Standardization (ISO) and the Society of Automotive Engineers (SAE). CAN reading allows a controller to gather kinetic data directly from the vehicle's sensors, taking advantage of an existing infrastructure and sparing the installation of new sensors.

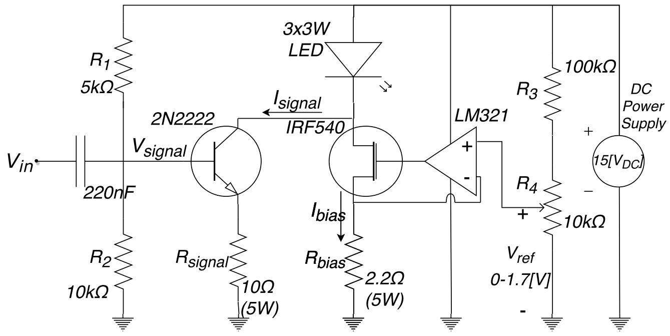

Fig. 4. Implemented Signal Combining Circuit (SCC).

To read the CAN Bus, an interface for the on-board diagnostics (OBD) port of the car is needed. The alternatives for such interface found so far in this work are the following: OpenXC Vehicle Interface, Comma.ai Panda, ELM327 based *dongles* and circuits, STN1110 based *dongles* and circuits, and MCP2515-MCP2551 based circuits. The ELM327 is one with the lowest-cost and widely available circuits, whereas the Comma.ai Panda has the most advanced hardware, designed to implement self-driving cars.

The CAN Module of the proposed system consists of an ELM327 based OBD interface and an Arduino Nano microcontroller. The systems are communicated via Bluetooth, as shown in Fig. 5. Figure 6 shows the final construction of the CAN module.

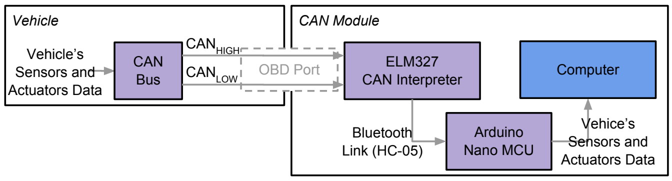

Fig. 5. CAN platform subsystem capable of reading the data of the CAN Bus.

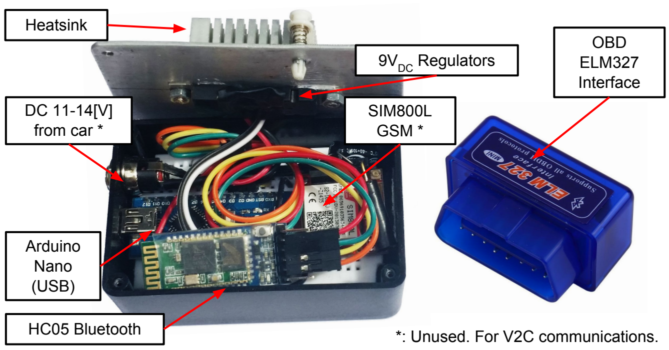

Fig. 6. CAN module implementation using Arduino Nano, HC05 Bluetooth circuit, SIM800L GSM circuit (for vehicle-to-cloud communication purposes), and an OBD interface based on ELM327 circuit.

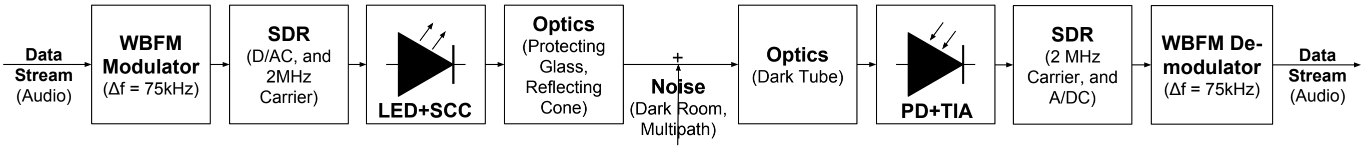

Fig. 7. Block diagram of the software developed in GNU Radio for the SDRs along with the VLC hardware implemented.

TABLE III
PARAMETERS OF THE ANALOG COMMUNICATION EXPERIMENT

Parameter	Value	Unit
Tx Gain	0	[dB]
Rx Gain	30*	[dB]
FM Center Frequency	2M	[Hz]
FM Frequency Max. Deviation	75k	[Hz]
SDR 32bit-wide Sample Rate	1M	[Samp./s]
Sound Card 16bit-wide Sample Rate	44.1k	[Samp./s]

*: Rx Gain set using photodetector's own amplifier.

C. Analog VLC Communication System

The implementation of the software for the computer of the system was done in a Debian operating system running GNU Radio Companion (GRC) with Ettus USRP Hardware Driver (UHD). A wide-band frequency modulation (WBFM) was implemented to transmit sound (*wav* files or the computer's microphone input) through the VLC channel, and listened at the receiver side using a speaker, as illustrated in Fig. 7. This configuration works as a demonstration of the system capabilities to transfer information via VLC, since the performance can be judged (qualitatively) by the ear. To quantitatively evaluate the performance of the system, *.wav* input and output files can be saved, and later compared using digital techniques. Final codes of the software implementation are available in the *GitHub* project's repository[1].

III. RESULTS AND DISCUSSION

The VLC module was set to send a pure tone of 1 [kHz] at different distances between the transmitter and the receiver. The parameters of this experiments are shown in Table III. The demodulated signal was saved to observe the distortion introduced by the distance. Normalized curves are shown in Fig. 8. Note that the experiment was done in conditions of total darkness, except for the system's LED, and the non-line-of-sight (NLoS) signal was blocked by the use of Thorlabs SM1 dark tube (see Fig. 3).

In order to also validate the performance of the CAN module, it was mounted on a vehicle and operated simultaneously with an Arada LocoME On-board Unit (OBU) with integrated GPS. Both platforms measured the velocity of the car in motion by their own means: the CAN module acquired data from the CAN Bus of the car, whereas the OBU made an estimation based on GPS location measurements. The car was driven in an open area in order to have the best GPS performance. The results of 191 measurements are shown in Fig. 9. The Lin's concordance correlation coefficient [17] between both measurements is 0.9979 with a 95% confidence interval between 0.9972 and 0.9984, denoting high reproducibility of the GPS velocity estimation with the CAN module data acquisition.

[1]Github Repository link: https://www.github.com/LaboratorioTICs-UChile/CSNDSP-paper_codes

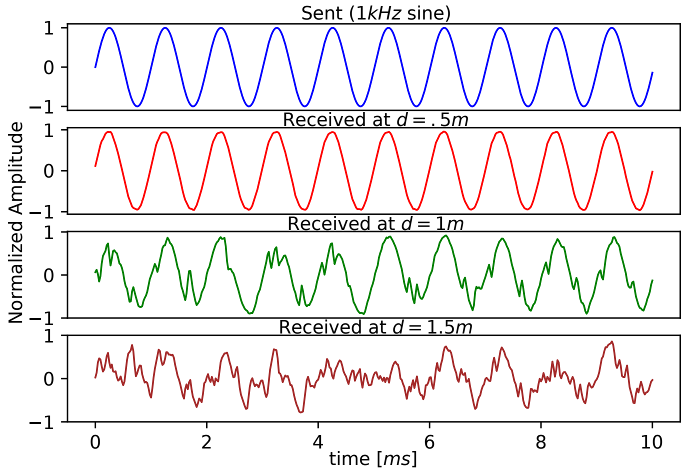

Fig. 8. Comparison of 1kHz sine communicated through the VLC module varying Tx-Rx distance d.

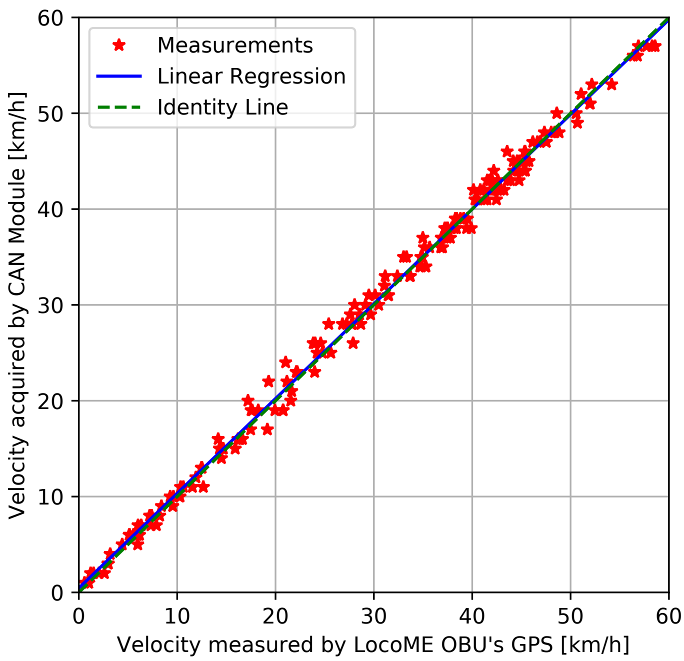

Fig. 9. Velocity data acquired with CAN module and estimated by the GPS of an Arada Systems LocoMate ME OBU.

The main differences between the OBU and the CAN module measurements are that CAN data comes in integer values, while the OBU has a resolution of one-hundredth of [km/h], thus, the OBU can be more precise. On the other hand, GPS devices usually fail when the satellite signal faces obstacles, like inside tunnels, whereas the CAN Bus data is designed to always be available since the control of the vehicle depends on it. Therefore, the use of kinetic data read from the CAN module and transmitted via VLC, as proposed by the system described in this work, is a viable solution to guarantee the short-distance delivery of critical information in vehicular networks, specially when the main communication technology (*i.e.*, DSRC) fails.

Finally, and as future work, and in order to evaluate the capabilities of VLC in a real vehicular scenario, the headlight of the car should be adapted with the SCC designed in this work. The proposed system could also be directly integrated to the vehicle's CAN Bus. Further, the implemented systems should be arranged in an outdoor static setting.

IV. Conclusion

The implementation of a low-cost VLC transmitting system was done using a standard LED lamp and a self-made electronic circuit known as SCC that modulates the LED's luminous intensity. The carrier of the modulated signal was set at 2 [MHz], which is in the typical range of a phosphor-coated LED switching rate capacity. The system was implemented and validated in laboratory conditions at a distance of up to 1.5 meters between the transmitter and receiver. It was found that vehicular networks need to be robust in order to support critical applications such as ITS. VLC systems are not capable of implementing robust links alone because they fail in long distances. VLC systems are indicated for a communication range of a few meters, where other technologies find a lot of congestion. Thus, complementing VLC with cognitive radio networking (CRN) based on RF and mmW, and the existing DSRC standard could support the widest variety of cases.

In parallel, a low-cost CAN Bus interface was implemented in order to have a way to gather kinetic data from the vehicle without the need of implementing sensors in the car. The complementary use of the CAN module and a GPS device can provide precise and reliable car velocity information, that is needed for DSRC beaconing and further for traffic control algorithms. The proposed low-cost CAN Bus interface achieved high reproducibility of the GPS estimations and was validated with a 0.9979 Lin's concordance correlation coefficient.

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