Vehicular Visible Light Communication:

An Integrated I2V2V2I Connected Car Concept

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Abstract—**This paper investigates the connected vehicle concept at intersections with traffic signals control and proposes the use of Visible Light Communication (VLC) in Vehicular Communication Systems for vehicle safety applications. A smart vehicle lighting system that combines the functions of illumination, signaling, communications, and positioning is presented. A generic model of cooperative transmissions for vehicular communications services is established. Three specific vehicular communications systems are analyzed. One is for Infrastructure-to-Vehicle communications from the street lamps, located on roadside, to the vehicles; the other is for in line Vehicle-to-Vehicle communications and the last for Vehicle-to-Infrastructure communications from cars to the traffic lights, at the crossroad. An on-off code is used to transmit data. The encoded message contains the ID code of each emitter concomitantly with a traffic message that is received, decoded and resent to another vehicle or to traffic light, in the crossroad. An algorithm to decode the information is established. A phasing traffic flow is presented as a proof of concept.**

Keywords- I2V, V2I and V2V Vehicular Communication; Connected Cars; Visible Light Communication; Emitters/Receivers, White LEDs; SiC photodetectors; OOK modulation; Traffic control.

I. INTRODUCTION

The communication through visible light holds special importance when compared to existing forms of wireless communications. The visible light spectrum is completely untapped for communication and can complement the RF-based mobile communication systems.

Recently the demand for the solution of road traffic problems such as accidents, congestion and the associated environmental pollution has significantly increased. By enabling wireless communication among vehicles and between vehicles and infrastructure, the safety and the efficiency of road traffic can be substantially improved. Highway and local roads are becoming more congested every year due to insufficient road development to accommodate the growing number of vehicles. In order to reduce accidents, congestion and offer smooth traffic flow, several solutions are being adopted. Solutions such as: intelligent traffic control systems, providing communication infrastructures along the road; vehicular communication and likewise, are currently research trends under the area of Intelligent Transportation Systems (ITS) [1, 2, 3, 4]. Modern vehicles are equipped with many electronic sensors, which monitor the vehicle's speed, position, heading, and lateral and longitudinal acceleration. Although the technology already exists, vehicles rarely communicate this information wirelessly to other vehicles or roadside infrastructure. The goal of the cooperative intelligent transport system (C-ITS) is to provide a vehicular communication system that can enable quick, cost-effective means to distribute data in order to ensure safety, traffic efficiency, driver comfort, and so forth. Researchers are anticipating the deployment of wireless vehicle communication, and have begun developing applications that use this new technology to improve safety and reduce congestion. This use case is known as connected vehicles. Recently, the transportation lighting infrastructure such as street lamps, traffic lights, automotive lamps, etc., is changing to LEDs. Therefore, in the case of an ITS based on VLC, it will be possible to make use of the conventional automotive and traffic LEDs. Consequently, the cost incurred in building the ITS infrastructure will be reduced. Secondly, the electromagnetic compatibility problem, which is a very serious problem in ITSs based on RF signals, will be minimized since visible light and the conventional RF signals occupy different parts of the electromagnetic spectrum. Visible light represents a new communication opportunity for vehicular networking applications. Compared to RF-based communications, VLC offers robustness against jamming attacks, a smaller interference domain, and a large license-free spectrum [5, 6, 7].

Vehicular Communication Systems are an emerging type of network in which vehicles and roadside units are the communicating nodes, providing each other with information, such as safety warnings and traffic information [8].The vehicular communication for C-ITS is composed of infrastructure-to-vehicle (I2V), vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. The I2V applications focus on utilizing the traffic related infrastructure, such as traffic light or streetlight to communicate useful information. So, VLC can be realized as a secondary application in LED arrays that are placed for lighting. In this way, some of the wireless traffic can be sent using light, with less cost and less carbon footprint.

Recently, LED-based optical wireless communication has been also proposed for car-to-car message delivery. LEDs are highly reliable, energy efficient and have a life-cycle that exceeds by far the classical light sources leading to the replacement of classical halogen lamps with LED lighting [9]. This option turned out to be particularly effective in short range direct communications to explore Line-of-sight (LoS) and overcome the issues related to the isotropic nature of radio waves. One additional benefit of LEDs is that they can switch to different light intensities at a very fast rate. This functionality has given rise to a novel communication technology (Visible Light Communication - VLC), where LED luminaires can be used for high speed data transfer [10, 11, 12]. VLC is a low cost technology and is easy to implement. VLC seems to be appropriate for providing wireless data exchange for automotive applications in the context in which the LED lighting began to be widespread in transportation, being integrated in traffic infrastructures (in traffic lights, street lighting and traffic signals) and in the vehicle lighting systems.

In the recent past, we have developed a WDM device that enhances the transmission capacity of the optical communications in the visible range. The device was based on tandem a-SiC:H/a-Si:H pin/pin light controlled filter with two optical gates to select different channel wavelengths. When different visible signals are encoded in the same optical transmission path [13, 14], the device multiplexes the different optical channels, performs different filtering processes (amplification, switching, and wavelength conversion) and finally decodes the encoded signals recovering the transmitted information. This device can be used as receiver, and helps developing automated vehicle technologies that allow vehicles to communicate with the surrounding 'environment' [15].

The proposed smart vehicle lighting system involves wireless communication, computer based algorithms, smart sensor and optical sources network, which constitutes a transdisciplinary approach framed in cyber-physical systems.

An introduction to the paper is given. The rest of the paper is structured as follows: In Section II, a traffic scenario is established and the transmitters and receivers are characterized. The performance of a cooperative driving system is evaluated in Section III. In Section IV, as proof of concept, a traffic scenario is presented and tested. Finally, in Section V, the conclusions are addressed.

II. CONNECTED VEHICLES MODEL

A VLC system mainly consists of a VLC transmitter that modulates the light produced by LEDs and a VLC receiver, based on a photosensitive element that is used to extract the transmitted modulated signal.

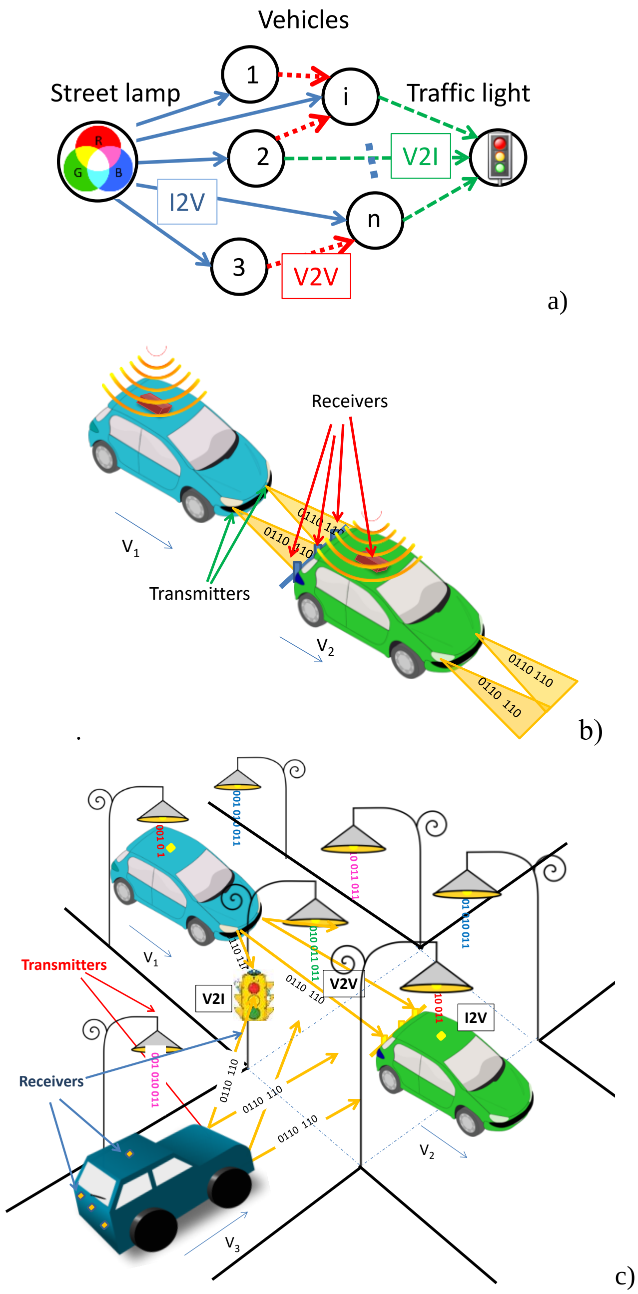


Figure 1. Illustration of the proposed V2V, V2I and I2Vcommunication scenario: a) Generic model for cooperative vehicular communications. b) vehicles emitters/receivers. c) Connected vehicles communication in a crossroad.

The transmitter and the receiver are physically separated, but connected through the VLC channel. For VLC systems, LoS is a mandatory condition.An infrastructure-to-vehicle followed by vehicle-to-vehicle and by vehicle-to-infrastructure communication was simulated. The illustration of the proposed scenario, for a light traffic controlled crossroad, is displayed in Figure 1. In Figure 1a, the generic cooperative vehicular model is shown, in figure 1b the emitters and receivers in the vehicles are depicted and in Figure 1c, the proposed scenario, is illustrated. Using the I2V communication, each street lamp (transmitter) sends a message received and analyzed by a SiC receiver, located at the rooftop of the vehicle. Using the headlights as transmitters, the information is resent to a leader vehicle (V2V) or directly to a crossroad receiver (V2I), at the traffic light, interconnected to a local controller that feeds one or more signal heads.

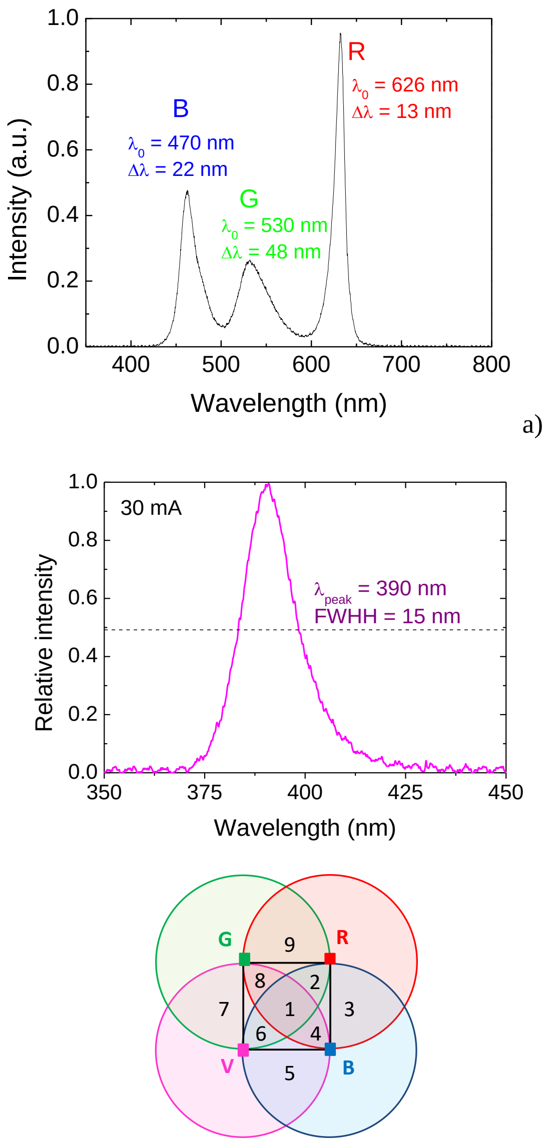


Figure 2. Unit cell (LED array = RGBV color spots).

Along the roads, street lamps are distributed in a square topology, for data transmission and lighting purposes. They are based on commercially available violet (V: 400 nm) and white RGB-LEDs. The white LEDs require three separate driver circuits to realize the white light. To decrease this complexity at each node, only one chip of the LED is modulated for data transmission, the Red (R:626 nm), the Green (G:530 nm) or the Blue (B:470 nm) while the other two are provided constant current for illumination. The luminous intensity is regulated by the driving current for white perception. In Figure 2a and Figure 2b the optical spectrum of the used LEDs is presented. A four-code assignment for the LEDs was used. The unit cell employs four R, G, B and V LED located at the corners of a square grid, as shown in Figure 2c.

The estimated distance from the street lamps to the receivers is used to generate a circle around each transmitter (see Figure 2), on which the receiver must be located in order to receive the transmitted information. The grid size was chosen in order to avoid an overlap in the receiver from the data from adjacent grid points. The geometric scenario used for calculation uses, for calibration, a smaller size square grid (2 cm)**,** to improve its practicality. To receive the information from several transmitters, the device must be positioned where the circles from each transmitter overlap, producing, at the receiver, a MUX signal that after demultiplexing, acts twofold as a positioning system and a data transmitter.

Table I Lighting plans.

Footprint regions	**Overlaps**
#1	**RGBV**
#2	**RGB**
#3	**RB**
#4	**RBV**
#5	**BV**
#6	**GBV**
#7	**GV**
#8	**RGV**
#9	**RB**

The nine generated regions, defined onwards as footprints, are presented in Figure 2. Assuming that only one of the RGB chip LEDs is modulated at each corner, it is presented in Table I, the nine possible allowed overlaps. If the signal comes only from one LED, the position of the LED is assigned to the device's reference point. If the device receives multiple signals, *i.e.*, if it is in an overlapping region of two or more LEDs, it finds the centroid of the received coordinates and stores it as the reference point. So, inside the cell, nine reference points are considered. Thus, the overlap region is used as an advantage to increase the accuracy in position estimation because more overlapping region means more reference points.

A large-dimension environment, like a road network surrounding (Figure 1b), is analysed by dividing the space into unit navigation cells (see Figure 2) with an appropriate side length giving the geographical position assigned to each node as displayed in Figure 3a (LED array = RGBV colour spots).

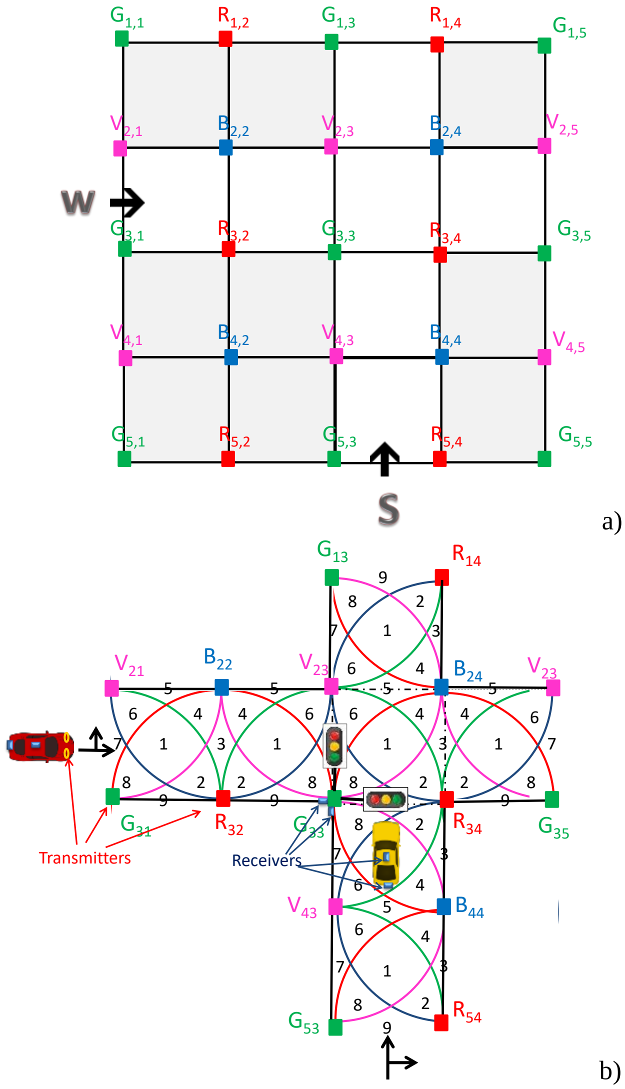


Figure 3. Topology: a) Cluster with sixteen cells (square topology) having each one four modulated RGBV-LEDs located at the corners of the square grid. b) Lighting plan and generated joint footprints in a crossroad.

To build the vehicular VLC system, a simplified cluster of cells for the streetlights is used. The analysed crossroad is located in the interception of line 2 with column 3 (white cells in Figure 3a). Two traffic flows are considered, one in the horizontal (W) and the other on the vertical direction (S). Each streetlight sends traffic message that includes the synchronism, its physical ID and traffic information. Each node, $X_{i,j}$, carries its own colour, X, (RGBV), as well as its horizontal and vertical ID position in the surrounding network (*i,j*).In the I2V communication, the emitters are located along the roadside. Each lamp transmits data during the time slot it occupies, *i.e.*, the individual LED lamp transmits its own data depending on the area it locates. The transmitted information is received and decoded at an external SiC pi'npin receiver, located on the rooftop of the car (Figure 1b). When a probe vehicle enters the streetlight´s capture range, the receivers respond to light signal and its unique ID and the traffic message are assigned.

To build the V2V system between a leader and a follower vehicle, the follower sends the message that is received by the leader and can be retransmitted to the next car [16, 17] or to the infrastructure. The follower vehicle is equipped with two headlamps transmitters. The leader vehicle is assumed to be equipped with three SiC pi'npin receivers, symmetrically distributed at the tails, to detect optical messages. The leader receives three signals, compares them and, based on their intensities infers the drive distance and the relative speed between both [18], and can send again the information to a next car (V2V) or to an infrastructure (V2I). Therefore, each probe vehicle receives two different messages; the one transmitted by the streetlight (I2V) and the one coming from the follow vehicle (V2V) and can compare them (Figure 1b). This system uses an approach in which a sequence of cellular locations is matched to a route segment along the road network that appears to be the most probable. All observations for a single section are analysed together to produce an estimate of the lane occupied and travel time along that section.

The introduction of wireless communication between vehicles and the infrastructure, referred to as V2I communication, has the potential to address the limitations of point detection. Instead of estimating exact vehicle position, speed, and queues from detector actuations, V2I communication allows the direct measurement of these values. In the V2I communication, two interconnect receivers are located at the same traffic light, facing the cross roads, and the emitters at the headlights of the moving cars approaching the interception. When a car enters in the infrastructure´s capture range of the receivers, an approach message is received and decoded by the corresponding optical pi'npin receiver. So, each driver, approaching the intersection area from S, W or both sends an approach request, that are compared by the intersection manager (local controller of the traffic light). Those messages contain the assigned ID positions, speeds, and flow direction of the vehicles that approach the intersection. The requests are labelled either with a W (West) or S (South) label, depending on the flow they belong to. The vehicle service time depends on its flow and on the flow of the following vehicle. The problem that the intersection manager has to solve is allocating the reservations among a set of drivers in a way that a specific objective is maximized. This goal can be, for instance, minimizing the average delay caused by the presence of the regulated intersection. In particular, V2V communication is useful to enhance the action space of a driver, *e.g.*, through the option of dynamically joining groups of vehicles, based on the idea of platoons.

III. CODING/DECODING TECHNIQUES

A. *Modulation scheme*

A dedicated four channel LED driver, with multiple outputs, was developed to modulate the optical signals. The modulator converts the coded message into a modulated driving current signal that actuates the emitters of each violet and tri-chromatic LEDs. A graphical user interface allows the control of the system, which includes the setting of the driving current, bit sequence and frequency of each emitter.

We have considered a network composed of a single access point (vehicle) and several nodes that periodically generate data, at different rates. The optical signals are synchronized and include the transmission of information related to the ID position of the transmitters and the message to broadcast. So, in a time slot, each node has a packet to transmit.

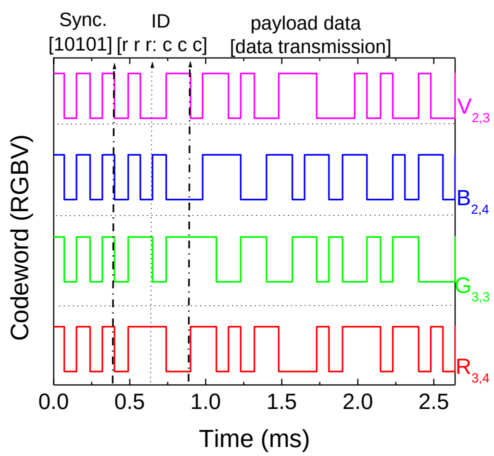


Figure 4. Frame structure. Representation of one original encoded message [10101: rrr ccc: XY….]. $R_{3,4}$, $G_{3,3}$, $B_{2,4}$ and $V_{2,3}$ are the transmitted node packet, in a time slot, from the crossroad in the network.

Each frame is a word of 32 bits, divided into three blocks: the synchronism (5 bits), the binary node address, (6 bits) and the traffic message (payload data). In Figure 4, an example of the codification of the digital optical signals is illustrated. We assigned the first five bits to the synchronization in a [10101] pattern. It corresponds to the simultaneous transmission of the four nodes in a time slot. Each colour signal carries its own ID-BIT [rrr;ccc] where the first three bits give the ID binary code of the line and the next three the ID binary code of the column. For instance, an ID_BIT [011 100] for the $R_{3,4}$ streetlight is sent whereas in case of $G_{3,3}$, an ID_BIT [011 011] is generated by the green LED. Thus, $R_{3,4}$, $G_{3,3}$, $B_{2,4}$ and $V_{2,3}$ are the transmitted node packets, in a time slot, inside the crossroad. With perfect information, this method will give an exact, unique answer, i.e., the unit cell location in the cluster and for each unit navigation, the correspondent footprint.

B. *The pi´npin receiver*

The receiver module is the sub-system at the reception end of the communication link that extracts information from the transmitted modulated light signals. It transforms the light signal into an electrical signal that is subsequently decoded to extract the transmitted information. The VLC receiver is a tandem, p-i'(a-SiC:H)-n/p-i(a-Si:H)-n heterostructure sandwiched between two transparent conductive contacts (TCO).

The device configuration and operation is shown in Figure 5a. The intrinsic layer of the front p-i'-n photodiode in made of a-SiC:H while the back intrinsic layer is based on a-Si:H. The deposition conditions and optoelectronic characterization of the single layers and device as well as their optimization were described previously [13, 19]. Due to the different absorption coefficient of the active absorption layers, both front and back diodes act as optical filters confining, respectively, the optical carrier produced by the blue and red photons. The optical carriers generated by the green photons are absorbed across both (see arrow in Figure 5a).

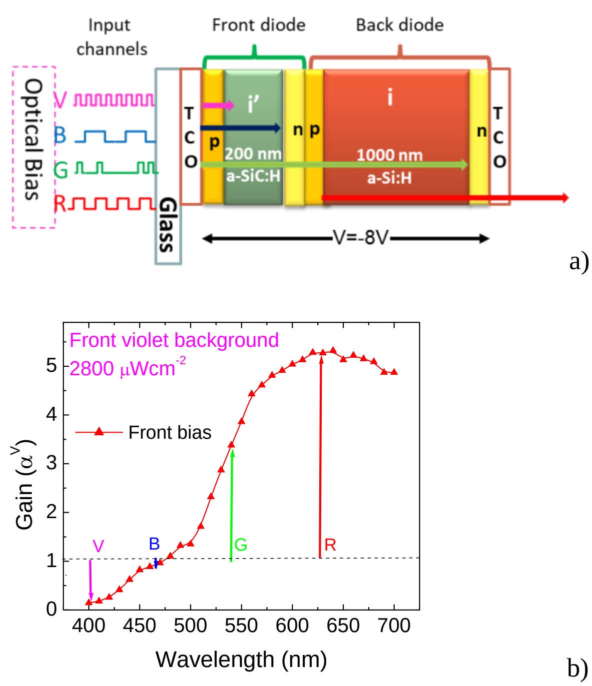


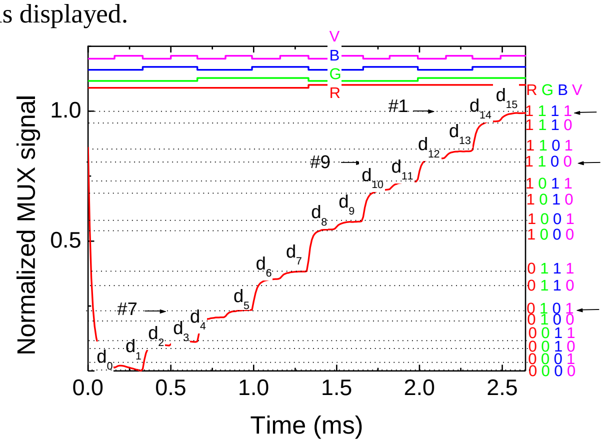
Figure 5. a) Double pin configuration and device operation. b) Spectral gain under violet front optical bias (α^V). The arrows point towards the optical gain at the analyzed R, G, B and V input channels.

The device operates within the visible range using for data transmission the modulated light supplied by the violet (V) and by the trichromatic red (R), green (G), blue (B) LED transmitters. The combination of the modulated optical signal (transmitted data) impinging on the receiver are absorbed accordingly to their wavelengths. The combined optical signal (MUX signal; received data) is analysed by reading out the generated photocurrent under negative applied voltage (-8V), with a 390 nm background lighting, applied from the front side of the receiver [8, 20].

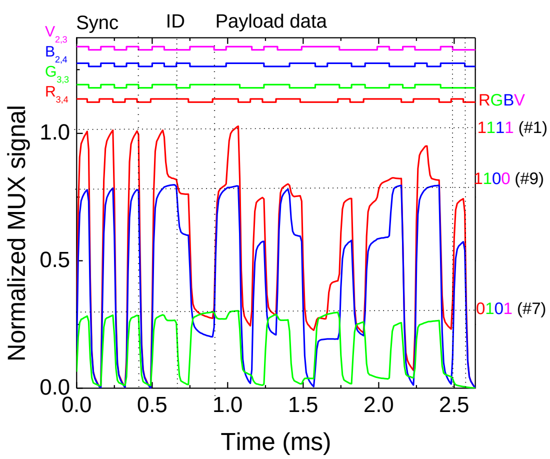
In Figure 5b, the spectral gain defined as the ratio between the photocurrent with and without applied optical bias, is displayed. The arrows point towards the gain at the analysed R, G, B and V input wavelength. Results show that the device acts as an active filter under irradiation. Under front irradiation, the long wavelength channels are enhanced and the short wavelength channels quenched. It is interesting to notice that as the wavelength increases the signal strongly increases. This nonlinearity is the main idea for the decoding of the MUX signal at the receiver.

C. *Signal decoding and positioning*

In Figure 6, the normalized MUX signal, in a stamp time, is displayed.



a)



b)

Figure 6. a) MUX/DEMUX signals under 390 nm front irradiation. On the top the transmitted channels packets [R, G, B, V] are decoded. a) Calibration cell. b) MUX signal at positions #1, #7 and #9.

In Figure 6a, the bit sequence was chosen to allow all the *on/off* sixteen possible combinations of the four channels. On top, the signals used to drive LEDs are shown to guide the eyes into the *on/off* states of each input.

In Figure 6b, the MUX signals acquired by the receiver, located at the crossroad, position #1, #9 and #7 (see Figure 3), are displayed. The decoded packet of transmitted information when all the channels are received is presented in the top of the figure.

The results from Figure 6a show that the MUX signal presents as much separated levels as the *on/off* possible combinations of the input channels, allowing decoding the transmitted information [21]. On the right hand side, the match between MUX levels and the 4 bits binary code ascribed to each level is shown. The MUX signal presented in Figure 6a, is used for calibration purposes.

The signal is decoded by assigning each output level to a 4- digit binary code, [X_R, X_G, X_B, X_V], with X=1 if the channel is *on* and X=0 if it is *off*.

After decoding the MUX signals, the localisation of the mobile target is direct. Taking into account the frame structure (Figure 4), the position of the receiver inside the navigation cell and its ID in the network is revealed. The ID position comes directly from the synchronism block, where all the received channels are, simultaneously, *on* or *off*. The 4-bit binary code ascribed to the higher level identifies the receiver position in the unit cell. Those binary codes are displayed in the right hand of the figure. For instance, the level [1100] corresponds to the level d_5 where the green and the violet channels are simultaneously *on* (see arrow in Figure 6a). The same happens to the other footprints (#1 and #9). Each decoded message carries, also, the node address of the transmitter. So, the next block of six bits gives de ID of the received node. In #7 the location of the transmitters, in the network, are $G_{3,2}$ and $V_{2,3}$ while in #1 the assigned transmitters are $R_{3,4}$, $G_{3,2}$ $B_{2,4}$ and $V_{2,3}$. The last block is reserved for the transmission of the traffic message (payload data). A stop bit (0) is used at the end of the frame.

IV. Cooperative VLC System evaluation

The system topology for positioning is a self-positioning system in which the measuring unit is mobile. This unit receives the signals of several transmitters in known locations (corners of the square grid), and has the capability to compute its location based on the measured signals. In Figure 3, a traffic scenario was established for the cooperative I2V, V2V and V2I communications. The proof of concept was simulated using the laboratory experimental conditions (see Section II).

A. *I2V communication*

To compute the point-to-point exposure along a path, we need the data along the path in successive instants. Street lamps work as transmitters, sending information together with different IDs related to their physical locations. The optical receiver inside the mobile terminal extracts the location information to perform positioning and, concomitantly, the transmitted data from each transmitter [22].

Figure 7a displays the I2V MUX signal received, in three times slots, by a rooftop receiver, moving in the W direction, when the vehicle is located in #3, moves to #1 and arrives to the stop line (#7). In Figure 7b, it moves from south from #5 to #1 and arrives to the cross line (# 9). In the top of both figures, the decoded packet of data sent by the addressed R, G, B and V transmitters are pointed out. On the right sides of the figures, the received channel, and so the footprint position in the navigation cell, are identified by its 4 digit binary code.

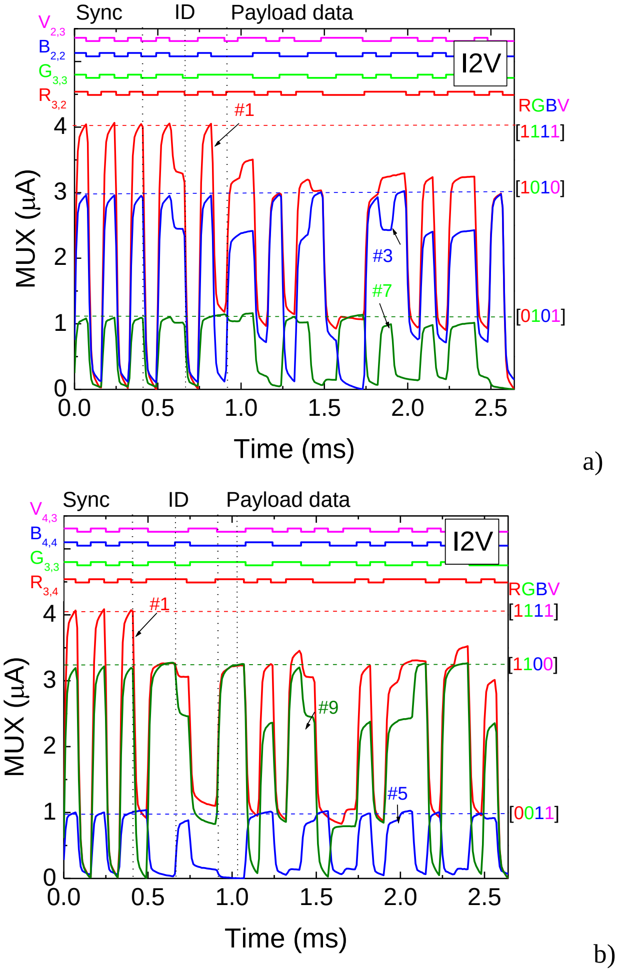


Figure 7 a) Three MUX/DEMUX signals under 390 nm front irradiation. On the top the transmitted channels packets [R, G, B, V] are decoded. 1) West flow (#3>#1>#7). b) South flow (#5>#1>#9).

In Figure 7a, the nodes $R_{3,2}$ […011 010…], $G_{3,3}$ […011 011…], $B_{2,2}$ […010 010…] and $V_{2,3}$ […010 011…] are recognized while in Figure 7b the $R_{3,4}$ […011 100…], $G_{3,3}$ […011 011…], $B_{4,4}$ […100 100…], and $V_{4,3}$ […100 111…] nodes are identified. In the others positions, only two messages arrive to the receiver. The assigned reference nodes in Figure 7a are: $R_{3,2}$; $B_{2,2}$ (#3) and $G_{3,3}$;$V_{2,3}$ (#7), while in Figure 7b the assigned reference point are: #5 ($B_{4,4}$; $V_{4,3}$) and #9 ($R_{3,4}$; $G_{3,3}$). The vehicle speed can be calculated by measuring the actual distance travelled overtime using ID´s transmitters tracking. The distance is fixed while the elapsed time will be obtained through the instants where the number of received channels changes. As in Figure 3c, at the instant initial, t_0, the receiver moves west from footprint 3 to footprint 1 (Figure 7a). The decoded MUX message changes from two ($R_{3,2}$ $B_{2,2}$) to four ($R_{3,2}$ $G_{3,3}$ $B_{2,2}V_{2,3}$) transmitted channels. After an elapsed time, Δt, footprint 7 is reached and the number of received transmitters changes again to two ($G_{3,3}$ $V_{2,3}$). In the following, this data will be transmitted to another leader vehicle through the V2V communication or to the traffic light through V2I.

B. Traffic Signal phasing: I2V, V2V and V2I communication

Signal phasing is the sequence of individual signal phases within a cycle that define the order in which pedestrian and vehicular movements are assigned the right-of-way. The cycle repeats itself continuously over time but the timing of the light switches is made according to the phasing of the traffic light.

The phasing duration is variable and dependent on factors such as the traffic situation, rush hours, etc. Safety requirements dictate that two vehicles consecutively accessing the intersection and belonging to the same flow must be separated by tailgate distance. If the two consecutive vehicles belong to different flows, they must be separated by vehicle stopping distance, which is larger than tailgate distance for practical values of the system parameters. A brief look into the basic anatomy and the process of timing traffic signals is given in Figure 8.

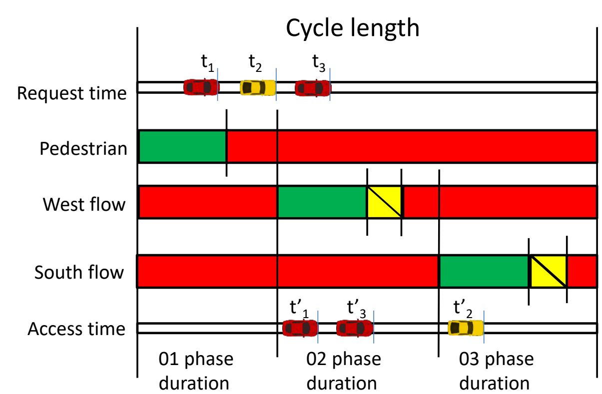
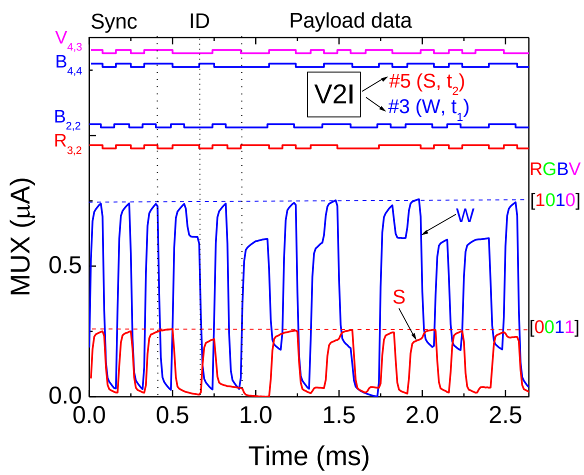
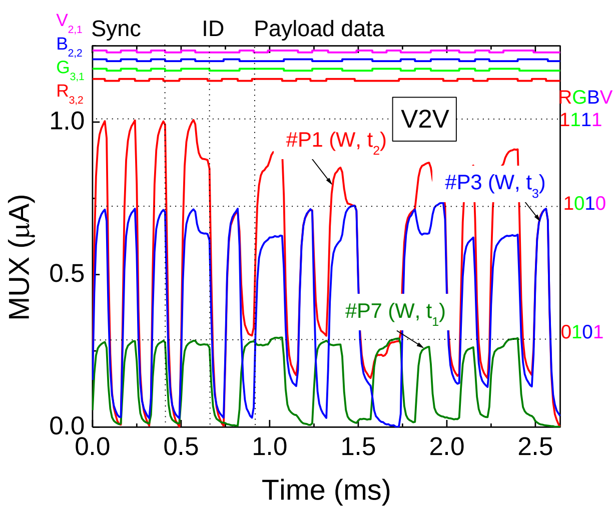


Figure 8 Phasing of traffic flows: phase number 01(pedestrian phase), phase number 02 (W flow), phase number 03(S flow).

A traffic scenario was simulated. We consider two flows of vehicles entering the system at the beginning of their respective roads, one from West (W flow), and one from South (S flow). Three vehicles are considered. Vehicle 1 and Vehicle 3 belong to the same flow (W) and Vehicle 2 belongs to the S flow. The phasing of the traffic flows is composed of a pedestrian-only stage (01 phase), and two single-lane road phases crossing at a square intersection area: the W flow stage (02 phase) and the S flow stage (03 phase). Each phase exists as an electrical circuit from the controller to the traffic light and feeds one or more signal heads. A phase can apply to a two aspect head (pedestrians; red or green) or to a three aspect head (vehicles; red or yellow or green). The green and yellow represent the time where it is allowed to pass the traffic light and the red the time not allowed. The traffic pedestrian lights are passively green as long as no vehicle is approaching.



a)



b)

Figure 9 Proof of concept. MUX/DEMUX signals. On the top the transmitted channels packets [R, G, B, V] are decoded. a) V2I communication from Vehicles 1 and 2 and the infrastructure. b) V2V communication between vehicle 3 and Vehicle 1.

To model a worst-case situation, vehicles approaching the intersection from different flows are assumed to have a conflicting trajectory. A vehicle's intersection access time is defined as the time at which the head of the vehicle enters the intersection area. Therefore, three subsequent instants have to be predictable, t'_1, t'_2 and t'_3, as the correspondent access times of the Vehicle 1, Vehicle 2 and Vehicle 3 (Figure 8).

A first-come-first-serve approach could be realized by accelerating or decelerating the vehicles such that they arrive at the intersection when gaps in the conflicting traffic flows and pedestrians have been created for them. However, a one-by-one service policy is not efficient at high vehicle arrival rates. From a capacity point of view it is more efficient, if Vehicle 3 is given access at t'_3 before Vehicle 2, t'_2 to the intersection, then, forming a west platoon of vehicles before (t'_2) giving way to the south conflicting flow as stated in Figure 8.

In Figure 9a, the V2I and in Figure 9b, the V2V communications, in successive moments, are displayed. Three instants are considered to define the phase's duration, t_1, t_2 and t_3 (Figure 8). At t_1 and t_2, Vehicle 1 and Vehicle 2 approaches, respectively, the intersection and contact optically the intersection manager (controller) by sending a request message to the receiver (V2I) located at the traffic light that faces the road (Figure 3b). Vehicle 3, contacts the infrastructure (V2I) at t_3. Those messages contain their positions and approach velocities. As a follower exists (Vehicle 3), the request message may also include it position and speed. This information alerts the controller to a later request message (V2I), at t_3, confirmed later by the follow vehicle. In Figure 9a, the MUX signal at each receiver and the assigned decoded messages (at the top of the figure) are displayed at t_1 and t_2. The position of both vehicles are: $R_{3,2}$ and $B_{2,2}$ (#3, W) for Vehicle 1 and $B_{4,4}$ and $V_{4,3}$ (#5, S) for Vehicle 2. Data in Figure 9b, shows that Vehicle 3, contacts at t_1, the leader (V2V), from #7, W ($G_{3,1}$ V_{21}). At t_2 moves to #1 ($R_{3,2}$ $G_{3,1}$ $B_{2,2}$ V_{21}) and finally sends the request message, at t_3, from #3,W ($R_{3,2}$ $B_{2,2}$) to the leader (V2V) and to the infrastructure (V2I).

V. CONCLUSIONS

A distributed mechanism for the control and management of a traffic light controlled crossroad network, where convehicles receive information from the network (I2V), interact each other (V2V) and with the infrastructure (V2I) was analyzed. VLC is the transmission technology. A simulated traffic scenario was presented and a generic model of cooperative transmissions for vehicular communications services was established.

As a proof of concept, a phasing of traffic flows is suggested. The system is composed by VLC transmitters that modulate the light produced by white LEDs, and by VLC receivers, based on photosensitive elements (a-SiC:H pinpin photodiodes), that code and decode the emitted modulated signals. The experimental results confirmed that the proposed cooperative VLC architecture is suitable for the intended applications. Considering the experimental results obtained in the prototype and reported in this paper, and the potential for further improvements, it seems reasonable to anticipate the increasing usage of this approach in the near future.

In order to move towards real implementation, the performance of such systems still needs improvement. As a future goal, we plan to finalize the embedded application, for experimenting in several road configurations with either static or moving vehicles.

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