VehicularVisible Light Communication

I2V2V2I connected cars

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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; Visible Light Communication; 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 Radio Frequency (RF)-based mobile communication systems. 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 [1]. 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 to improve safety and reduce congestion [2]. 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 Light Emiting Diodes (LEDs). In the case of an ITS based on Visible Light Communication (VLC), it will be possible to make use of the conventional automotive and traffic LEDs. 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. Compared to RF-based communications, VLC offers robustness against jamming attacks, a smaller interference domain, and a large license-free spectrum [3].

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 [4]. 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 the recent past, we have developed a Wavelength Division Multiplexing (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

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[5], 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' [6].

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. 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.

II. CONNECTED VEHICLES MODEL

An infrastructure-to-vehicle followed by vehicle-to-vehicle and by vehicle-to-infrastructure communication was simulated. The illustration of the proposed scenario is displayed in Figure 1, for a light traffic controlled crossroad.

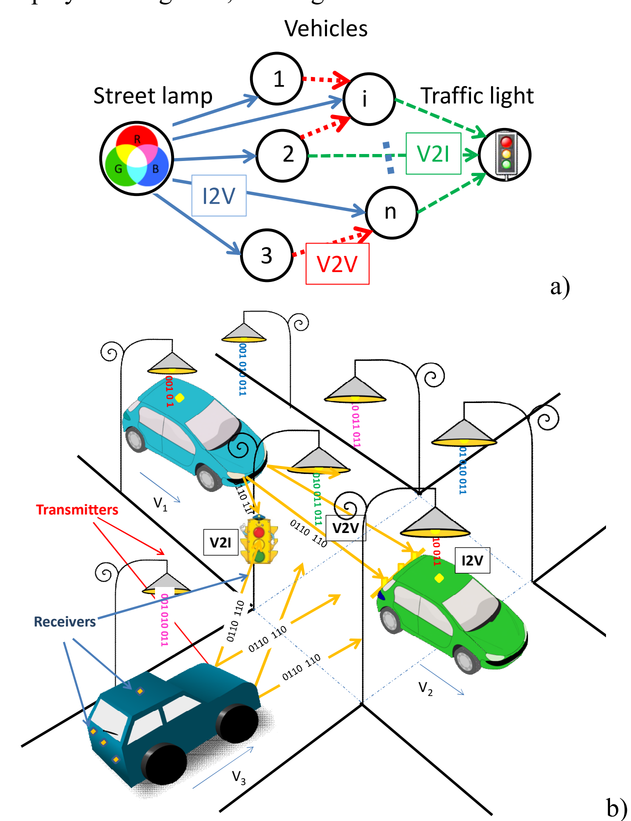

Figure 1. Illustration of the proposed V2V, V2I and I2V communication scenario: a) Generic model for cooperative vehicular communications. b) Connected vehicles communication in a crossroad.

In Figure 1a, the generic cooperative vehicular model is shown and in Figure 1b, 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.

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.

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 2. 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. The nine generated regions, defined onwards as footprints, are presented in Figure 2 [6].

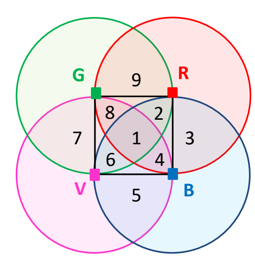

Figure 2. Unit cell (LED array = RGBV color spots).

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. The lighting plan and generated joint footprints are illustrated in Figure 3. 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

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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*).

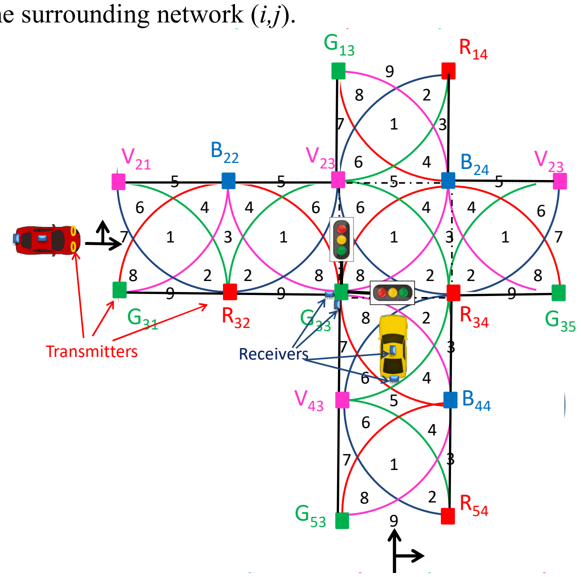

Figure 3. Lighting plan and generated joint footprints in a crossroad.

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 [7] or to the infrastructure. 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. 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.

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. 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

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.

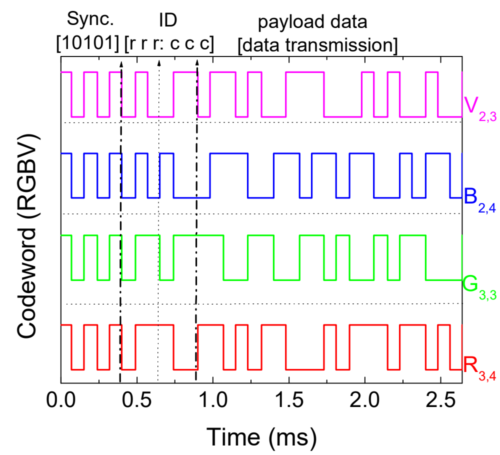

Figure 4. Frame structure. Representation of one original encoded message [10101: rrr ccc: XY….]. $R_{3,4}$, $G_{3,3}$, $B_{2,4}$ and $V_{2,3}$ are the transmitted node packet, in a time slot, from the crossroad in the network.

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.

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B. The pi´npin receiver

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 5. The deposition conditions and optoelectronic characterization of the single layers and device, as well as their optimization were described previously [5] [8].

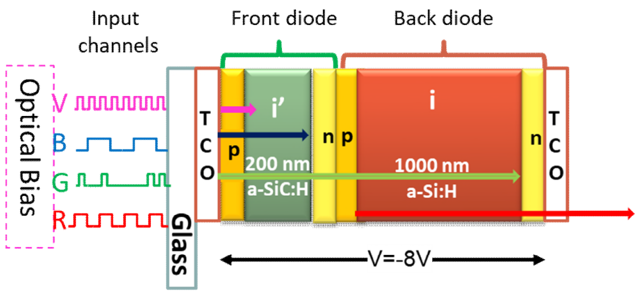

Figure 5. Double pin configuration and device operation.

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 mixture 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. Previous results have shown that the device acts as a Multiplexer/demultiplexer device [5] [9].

C. Signal decoding and positioning

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

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 [10]. 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*.

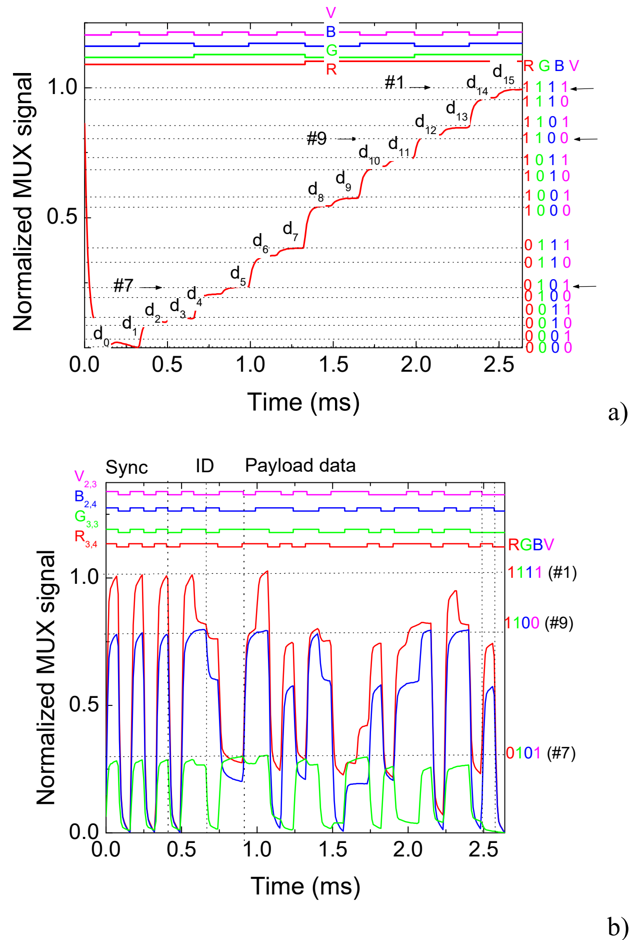

Figure 6. a) MUX/DEMUX signals under 390 nm front irradiation. On the top the transmitted channels packets [R, G, B, V] are decoded. a) Calibration cell. b) MUX signal at positions #1, #7 and #9.

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

A. *I2V communication*

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 their 4 digit binary code.

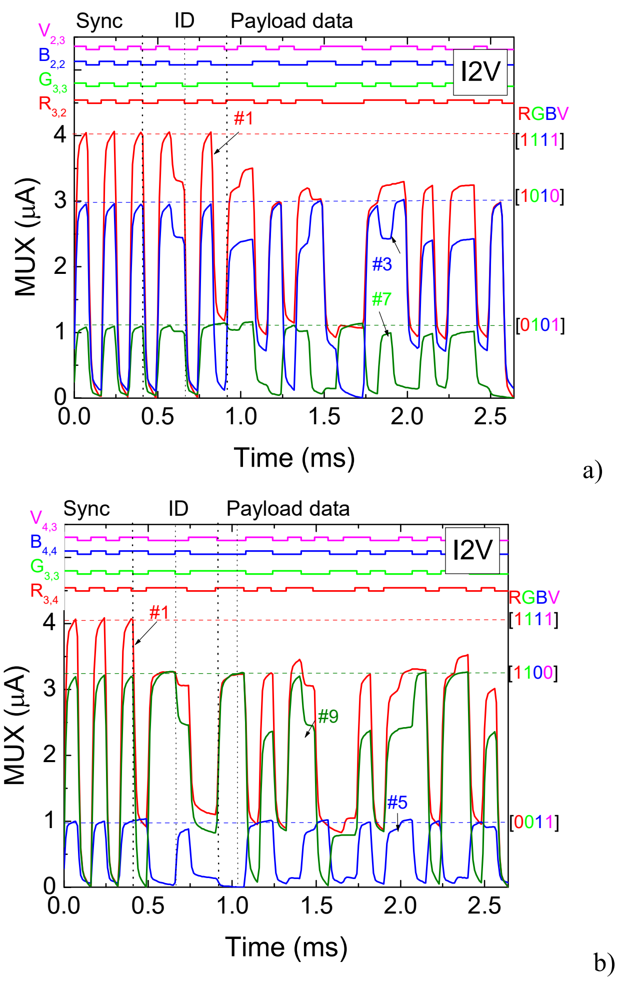

Figure 7. a) Three MUX/DEMUX signals under 390 nm front irradiation. On the top the transmitted channels packets [R, G, B, V] are decoded. a) West flow (#3>#1>#7). b) South flow (#5>#1>#9).

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 3b, 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. A brief look is given in Figure 8.

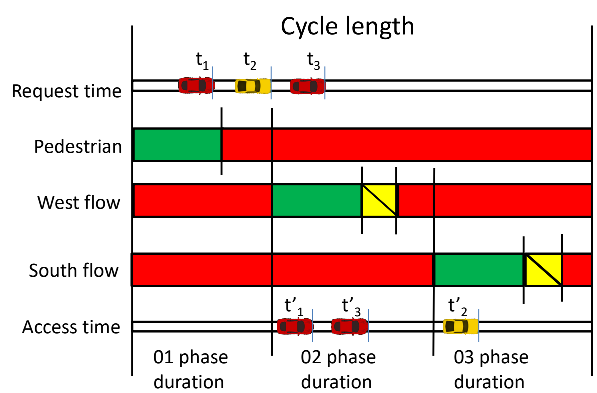

Figure 8. Phasing of traffic flows: phase number 01 (pedestrian phase), phase number 02 (W flow), phase number 03 (S flow).

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

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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.

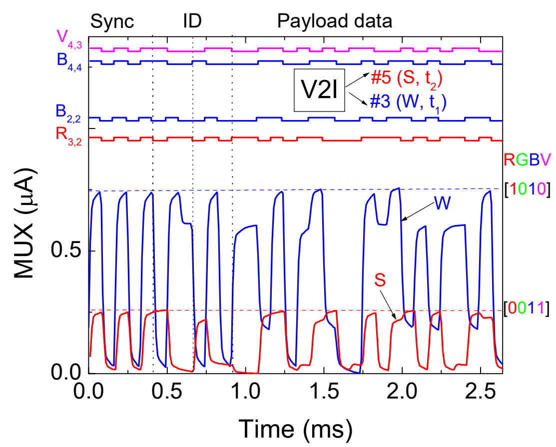

Figure 9. Proof of concept. MUX/DEMUX signals. V2I communication from Vehicles 1 and 2 and the infrastructure. On the top the transmitted channels packets [R, G, B, V] are decoded.

In Figure 9, the V2I 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. 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.

To model a worst-case situation, vehicles approaching the intersection from different flows are assumed to have a conflicting trajectory. 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). 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.

V. Conclusions

A distributed mechanism for the control and management of a traffic light controlled crossroad network, where connected vehicles receive information from the network (I2V), interact each other (V2V) and with the infrastructure (V2I) was analyzed. 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.

Acknowledgements

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References

[1] N. Kumar, N. Lourenço, D. Terra, L. N. Alves, and R. L. Aguiar, "Visible Light Communications in Intelligent Transportation Systems", IEEE Intelligent Vehicles Symposium, pp. 748-753, 2012.

[2] C. Liu, B. Sadeghi, and E. W. Knightly, "Enabling Vehicular Visible Light Communication (V2LC) networks," Proceedings of the Eighth ACM International Workshop on Vehicular Inter-Networking (VANET '11), ACM, New York, NY, USA, pp. 41-50, 2011.

[3] H. Parth, Pathak, F. Xiaotao, H. Pengfei, and M. Prasant,"Visible Light Communication, Networking and Sensing: Potential and Challenges" September 2015, IEEE Communications Surveys & Tutorials 17(4): Fourthquarter 2015, pp. 2047 – 2077, 2015.

[4] S. Yousefi, E. Altman, R. El-Azouzi, and M. Fathy, "Analytical Model for Connectivity in Vehicular Ad Hoc Networks", IEEE Transactions on Vehicular Technology, vol. 57, pp. 3341-3356 ,2008.

[5] M. Vieira, P. Louro, M. Fernandes, M. A. Vieira, A. Fantoni and J. Costa, "Three Transducers Embedded into One Single SiC Photodetector: LSP Direct Image Sensor, Optical Amplifier and Demux Device" Advances in Photodiodes InTech, Chap.19, pp. 403-425, 2011.

[6] M. A. Vieira, M. Vieira, P. Vieira, and P. Louro, "Optical Signal Processing for a Smart Vehicle Lighting System using a-SiCH technology" Proc. SPIE 10231, Optical Sensors 2017, pp. 102311L , May 16, 2017;

[7] M. A. Vieira, M. Vieira, P. Louro, and P. Vieira, "Smart Vehicle Lighting System in the Visible Range: Vehicle-to-Vehicle Communication" The Eighth International Conference on Sensor Device Technologies and Applications. SENSORDEVICES 2017. - Rome, Italy. pp. 57-62.

[8] M. A. Vieira,, P. Louro, M. Vieira, A. Fantoni, and Steiger-Garção, A., "Light-activated Amplification in Si-C Tandem Devices: A Capacitive Active Filter Model" IEEE Sensor Journal, 12, no. 6, pp. 1755-1762, 2012.

[9] M. A. Vieira, M. Vieira, V. Silva, P. Louro, and J. Costa, "Optical signal processing for data error detection and correction using a-SiCH technology" Phys. Status Solidi C 12, No. 12, pp. 1393–1400 , 2015.

[10] M. A. Vieira, M. Vieira, M., V. Silva, P. Louro, and M. Barata, "Optoelectronic Logic Functions Using Optical Bias Controlled SiC Multilayer Devices". MRS Proceedings, 1536, pp. 91-96, 2013.

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