Cooperative Communication between Vehicles and Road Infrastructures through Visible Light

Manuela Vieira, Manuel Augusto Vieira, Paula Louro,
ADETC/ISEL/IPL,
R. Conselheiro Emídio Navarro, 1959-007
Lisboa, Portugal
CTS-UNINOVA
Quinta da Torre, Monte da Caparica, 2829-516,
Caparica, Portugal

e-mail: mv@isel.ipl.pt, mv@isel.pt, plouro@deetc.isel.pt

Pedro Vieira
ADETC/ISEL/IPL,
R. Conselheiro Emídio Navarro, 1959-007
Lisboa, Portugal
Instituto das Telecomunicações
Instituto Superior Técnico, 1049-001,
Lisboa, Portugal
e-mail: pvieira@isel.pt

***Abstract*—A vehicular communication system that combines illumination, signaling, communications, and positioning functions is presented. The bidirectional communication between the infrastructures (I) and the vehicles (V) is performed through Visible Light Communication using the street lamps, the traffic signals and the headlights to broadcast the information. Wavelength Division Multiplex photodetectors receive and decode the information. White polychromatic-LEDs (Light Emitting Diodes) are used for lighting and also to implement the decoding operation. This allows modulating separate data streams into four wavelengths which together multiplex to white light. A traffic scenario is proposed, along with the transmitter to receiver setup. The performance of a cooperative driving system (I2V2V2I2V) is evaluated. Streams of messages containing the physical address ID of the emitters are used, transmitting a codeword that is received and decoded by the receivers. As a proof of concept, a cooperative vehicular traffic scenario is presented and bidirectional communication established and tested. A traffic signal phasing in a light controlled crossroad is presented. The experimental results confirm that the cooperative vehicular architecture is a promising approach concerning communications between road infrastructures and cars, fulfilling data privacy.**

Keywords- Vehicular Communication; Light Fidelity; Visible Light Communication; white LEDs; SiC photodetectors; OOK modulation scheme; Traffic control.

I. INTRODUCTION

Visible Light Communication (VLC) holds special importance when compared to existing forms of wireless communications [1]. Only Light-Emitting Diodes (LED) lamps can be used for the transmission of visible light [2]. 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 (street lighting and traffic signals) and in the vehicle lighting systems. Compared to Radio Frequency based communications, VLC offers robustness against jamming attacks, a smaller interference domain, and a large license-free spectrum [3].

Vehicular Communication Systems are a 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][5]. Communication between fixed locations and vehicles (infrastructure-to-vehicle, I2V) between vehicles (vehicle-to-vehicle, V2V), and between vehicles and fixed locations (vehicle-to-infrastructure, V2I) is essential to transfer information in real time. The I2V applications focus on utilizing the traffic related infrastructure, such as traffic lights or streetlights, to communicate useful information. Hence, VLC can be realized as a secondary application in LED arrays that are placed for lighting [6].

A problematic in vehicular VLC is the design of a proper sensor. In the past, we have developed a receiver based on amorphous SiC technology that enhances the transmission capacity of the optical communications in the visible range and allows reaching outdoor high speed communication. The core of the device is a tandem a-SiC:H/a-Si:H pin/pin light controlled filter. When different visible signals are encoded in the same transmission path [7], the device multiplexes the different optical channels, performs different filtering processes (amplification, switching, and wavelength conversion) and decodes the encoded signals, recovering the transmitted information [8].

In this paper, a traffic scenario for a light controlled crossroad is proposed, along with the transmitter to receiver setup. The paper is organized as follows. After the introduction (Section I), in Section II, the performance of a cooperative driving system is analyzed. To achieve cooperative vehicular communications (I2V2V2I2V), in

 ISBN: 978-1-61208-745-0

Section III, streams of messages containing the physical address ID of the emitters are used, transmitting a codeword that is received and decoded by the SiC pin/pin devices. As a Proof of Concept (PoC), a traffic scenario with bidirectional cooperative communication between the infrastructures and the vehicles is presented and tested in Section IV. Finally, in Section V, conclusions are addressed.

The proposed vehicular communication system involves wireless communication, smart sensing and optical sources network, building up a transdisciplinary approach framed in cyber-physical systems.

II. Vehicular Communication

A. Traffic Scenario

A I2V2V2I2V communication link in a light traffic controlled crossroad was simulated. The illustration of the proposed scenario is displayed in Figure 1a. Using the I2V communication, each street lamp (transmitter) sends a message, which is received and processed by a SiC receiver, located at the vehicle's rooftop. Using the headlights as transmitters, the information is resent to a leader vehicle (V2V) or a "request" message to go forward is sent directly to a crossroad receiver (V2I), at the traffic light, interconnected to a local manager that feeds one or more signal heads. For crossroad coordination, a local controller emitter, sends a "response" message to the vehicles approaching the intersection.

To build the vehicular I2V communication system, it is proposed a simplified cluster of unit square cells in an orthogonal topology that fill all the service area. We have assumed that the crossroad is located in the interception of line 2 with column 3 of the network, and the emitters at the nodes along the roadside. Two traffic flows are considered, one in the horizontal direction (W: West) with two vehicles approaching the crossroad (Vehicle 1) and the other (Vehicle 3) with a third vehicle (Vehicle 2) oncoming on the vertical direction (S: South). The lighting plan and generated joint footprints are illustrated in Figure 1b. The luminaries, placed at the nodes of the network, are based on commercially available white polychromatic LEDs made of Violet (V: 400 nm) and polychromatic Red, Green and Blue (RGB) LEDs. while the others provide constant current Only one chip of each LED is modulated for data transmission, the Red (R: 626 nm), the Green (G: 530 nm) or the Blue (B: 470 nm) while the others provided constant current for white illumination. Each transmitter, $X_{i,j}$, carries its own colour, X, (RGBV), as well as its horizontal and vertical ID position in the surrounding network (i,j) and sends a message that includes the synchronism, its physical ID and the traffic information. The geometric scenario used for calculation uses a smaller size square grid (2 cm), to improve its practicality. To receive the information from several transmitters, the receiver has to be positioned where the circles from each transmitter overlap, producing, at the receiver, a Multiplex (MUX) signal that, after demultiplexing, acts twofold as a positioning system and a data transmitter. The nine possible allowed overlaps (footprint regions) are pointed out in Figure 1b.

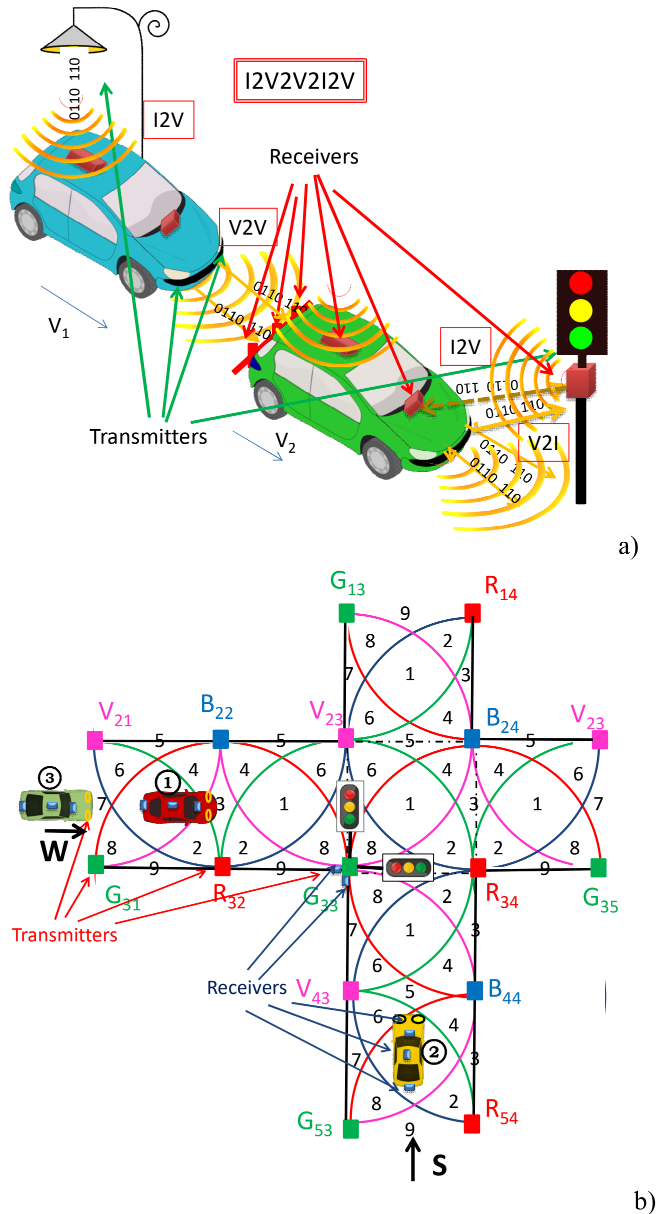

Figure 1. a) Traffic scenario. Illustration of the proposed vehicular I2V2V2I2V communication link. b) Lighting plan and generated joint footprints in a crossroad. Footprints: #1 (R+G+B+V); #2 (R+G+B); #3(R+B); #4 (R+ B+V), #5 (B+V) ; #6 (G+B+V); #7(G+V), #8 (R+G+V), #9 (R+G),

Each LED transmits its own data depending on the area it locates. The device receives different signals, identifies the footprint, finds its centroid and stores it as the reference point [9]. To build the V2V system between a leader vehicle and a follower, the follower sends the message that is received by the leader and can be retransmitted to the next car [10][11] or to the infrastructure. The leader vehicle infers the driving distance and the relative speed between

 ISBN: 978-1-61208-745-0

both [12]. Therefore, each vehicle receives two different messages: one transmitted by the streetlight (I2V) and one coming from the follower vehicle (V2V), and a comparison can be performed.

For the manager's intersection crossing coordination, the connected vehicle and the intersection manager exchange information through two specific types of messages, "request" (V2I) and "response" (I2V). Two receivers are located at the same traffic light, facing the crossroads. When one head vehicle enters in the infrastructure´s capture range of one of the receivers, a request message is received and decoded by the corresponding receiver interconnected to the intersection manager (local controller of the traffic light). Each driver approaching the intersection area from S, W (or both) sends an approach "request". Those messages contain the assigned ID positions, speeds, and flow (W, S) direction of the vehicles. So, the "request" contains all the information that is necessary for a vehicle's space-time reservation for its intersection crossing. The intersection manager uses the "request" information to convert a it in a sequence of timed rectangular spaces that each vehicle needs to occupy in the intersection. Using a white LED, the intersection manager's acknowledgment is sent to an in-car application of the head vehicle. The response includes both the infrastructure and the vehicle identifications and the "confirmed vehicle" message. Once the response is received, the vehicle is required to follow the occupancy trajectories (footprint regions, see Figure 1b) provided by the intersection manager. If a "request" has any potential risk of collision, the control manager only sends back to the vehicle (V2I) the "response" after the risk of conflict disappears.

B. Coding Techniques

To encode the messages, an On-Off keying (OOK) modulation scheme was used. The OOK is considered suitable for applications in which the communication distance is more important than data rate. The advantages of OOK include its simplicity and ease of implementation. The codification of the optical signals is synchronized and includes the information related to the position ID of the transmitters and the message to broadcast. We have considered a 32 bits codification. Each frame is divided into three or four blocks, depending on the kind of transmitter: street lamps (Figure 2a) or traffic light (Figure 2b). We assigned the first block the synchronization (SYNC) in a [10101] pattern and the last one to the message to transmit (Payload Data). A stop bit is used at the end of each frame. In Figure 2a, an example of the codification used to drive the street lamps LEDs in the crossroad is illustrated. Here, the second block (6 bits) is assigned to ID-BIT [rrr;ccc] of the emitter, the first three bits give the ID binary code of the line and the next three the ID binary code of the column.

$R_{3,4}$, $G_{3,3}$, $B_{2,4}$ and V_{23} are the transmitted node packets, in a time slot, inside the crossroad. In Figure 2b, a response message of the traffic controller emitter located at the traffic light is displayed. The second block (INFO) in a pattern [000000] means that a response message is being sent by the controller manager. The third block (6 bits) identifies the vehicle position (ID) for which the message is intended. Here, the signal controller [000000] responds to a request of a vehicle located in the crossroad at position # 1 ($R_{3,4}$, $G_{3,3}$, $B_{2,4}$ and V_{23}).

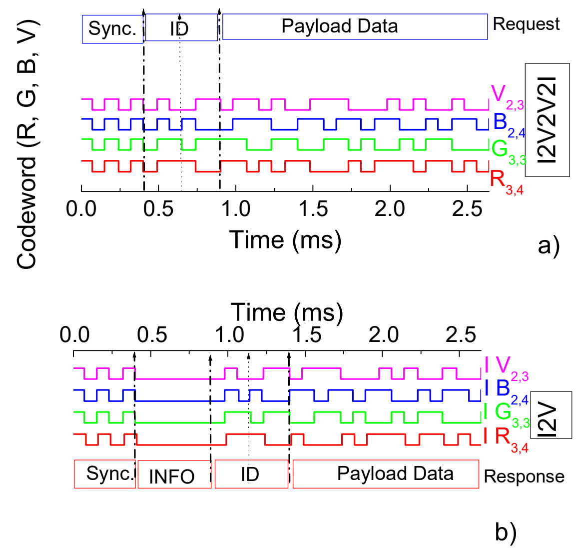

Figure 2. Frame structure representation. a) Codification used to drive the street lamps LEDs in the crossroad. $R_{3,4}$, $G_{3,3}$, $B_{2,4}$ and $V_{2,3}$ are the transmitted node packet, in a time slot, from the crossroad in the network. b) Encoded message response of the controller to a vehicle located in the crossroad (#1, $R_{3,4}$, $G_{3,3}$, $B_{2,4}$ and $V_{2,3}$).

C. Signal Decoding, Positioning and Driving Distance

In a stamp time, Figure 3a displays a MUX signal acquired by the a-SiC:H/a-Si:H pin/pin light controlled filter [8]. On top, the signals used to drive LEDs are shown to track the *on/off* states of each input. The bit sequence was chosen to allow all the *on/off* sixteen possible combinations of the four input channels. Results show that the MUX signal presents as many off separated levels as the *on/off* possible combinations of the input channels, allowing decoding the transmitted information [13]. All the sixteen ordered levels (d_0-d_{15}) are pointed out at the correspondent levels, and displayed as horizontal dotted lines. On the right-hand side of Figure 3, the match between MUX levels and the 4 bits binary code ascribed to each level is shown. Hence, the signal can be 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*.

In Figure 3b, the normalized MUX signals acquired by a receiver at the crossroad, in positions #1, #3 and #5 (see Figure 1b), are displayed. The MUX signal presented in Figure 3a was used for calibration purposes. On the right-hand side of the figure, the match between MUX levels and the 4 bits binary code ascribed to each level is shown. The decoded packet of transmitted information when all the four transmitters are received simultaneously (#1) is presented in the top of the figure. Comparing the calibrated levels (dotted lines in Figure 3a) with the different generation levels (dotted lines in Figure 3b), in the same time frame, a straightforward algorithm [10] was used to build a 1-to-32 demultiplexer function.

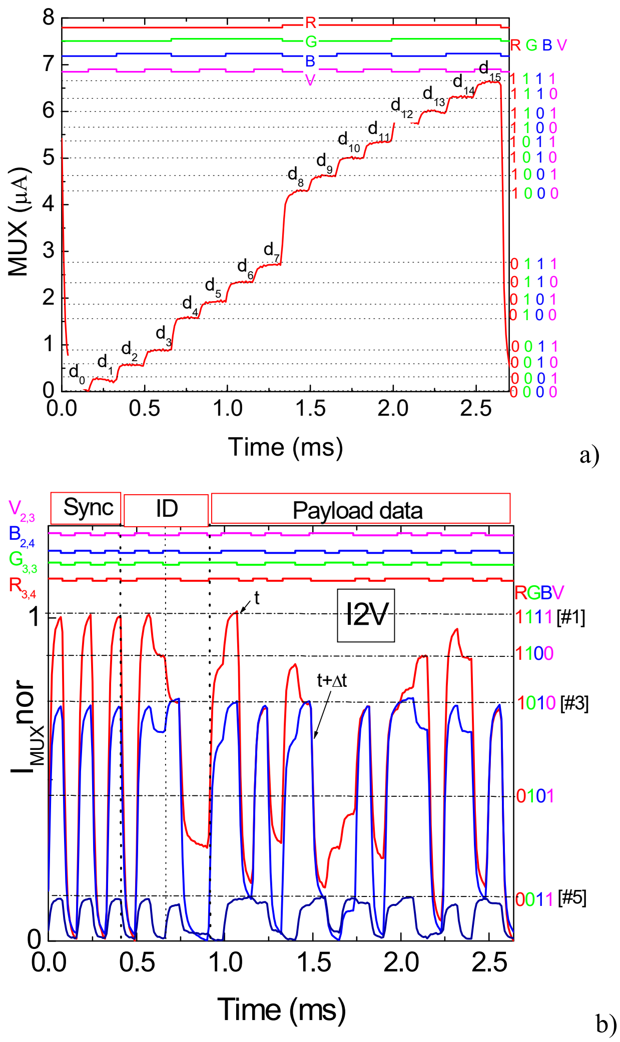

Figure 3. a) MUX signal of the calibrated cell. On the top the transmitted channels packets [R, G, B, V] are depicted. b) MUX/DEMUX signal inside the crossroad for a vehicle in positions #1, #3, #5, #7 and #9. On the top the transmitted channels packets [$R_{2,3}$, $G_{3,3}$, $B_{2,4}$, $V_{2,3}$] are decoded.

After decoding the MUX signals, the localization of the mobile target is direct. Taking into account the frame structure (Figure 2), the position of the receiver inside the navigation cell and its ID in the network is revealed. The 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 and is displayed in the right side of the Figure 3a. For instance, the level [1010] corresponds to the level d_{10} where the red and the blue channels are simultaneously *on,* so, position #3 is assigned to the receiver. Each decoded message carries, also, the transmitter's node address. So, the next block of six bits gives the ID of the received node. In #3, the location of the transmitters are $R_{3,4}$ and $B_{2,4}$ while in #1 the assigned transmitters are $R_{3,4}$, $G_{3,3}$ $B_{2,4}$ and $V_{2,3.}$ The last block is a 20 bit word and is reserved for the transmission of the traffic message (payload data). The vehicle speed can be calculated by measuring the traveled distance overtime, using the ID´s transmitters tracking. In order to obtain the receiver's speed, two measures are required: distance and elapsed time (assuming uniform motion). The distance is fixed while the elapsed time, Δt, will be obtained through the instants where the number of received channels changes. At the initial instant, t, the receiver moves West from #1 to #3 (Figure 3b). The decoded MUX message changes from four ($R_{3,4}$ $G_{3,3}$ $B_{24}V_{2,3}$) to two ($R_{3,4}$ $B_{2,4}$) transmitted channels at t+Δt. The spacing between reference points is fixed (Figure 1b) while the correspondent time integrated by the receiver varies and depends on the vehicle's speed crossing the crossroad. The receivers compute the geographical position in the successive instants (path) and infer the vehicle speed. In the following, this data will be transmitted to another leader vehicle through the V2V communication or to the control manager at the traffic light through V2I [14].

III. BIDIRECTIONAL COMMUNICATION

A. Cooperative Communication

In the proposed scenario, when a vehicle coming from W reaches position # 3 or one from S position #5 it sends a message to the controller requesting permission to cross the intersection (Figure 1b). If there is permission, it goes forward; otherwise, it stops at the respective stop lines (W # 7; S # 9). Three instants are considered, t_1, t_2 and t_3. At t_1 and t_2, Vehicle 1 and Vehicle 2 approach, respectively, the intersection and contact optically the intersection manager (controller) by sending a request message to the receiver (V2I) at the traffic light that faces the road. All the requests must contain the vehicle positions and the approach velocities. As a follower exists (Vehicle 3), the request message from Vehicle 1 includes its position and speed received previously by V2V. This information alerts the controller to a later request message (V2I), at $t_{3,}$ confirmed later by the following vehicle. Therefore, three subsequent instants have to be predictable, t'_1, t'_2 and t'_3, as the correspondent access times of the Vehicles 1, 2 and 3 to the crossroad.

An example of messages exchange executed by the control manager is shown in Figure 4. Here, the MUX signal at each receiver and the assigned decoded messages (at the top of the figures) are displayed at the request times, t_1 and t_2 (Figure 4a) and at the response times, t'_1 and t'_2 (Figure 4b) for Vehicles 1 and 2, respectively.

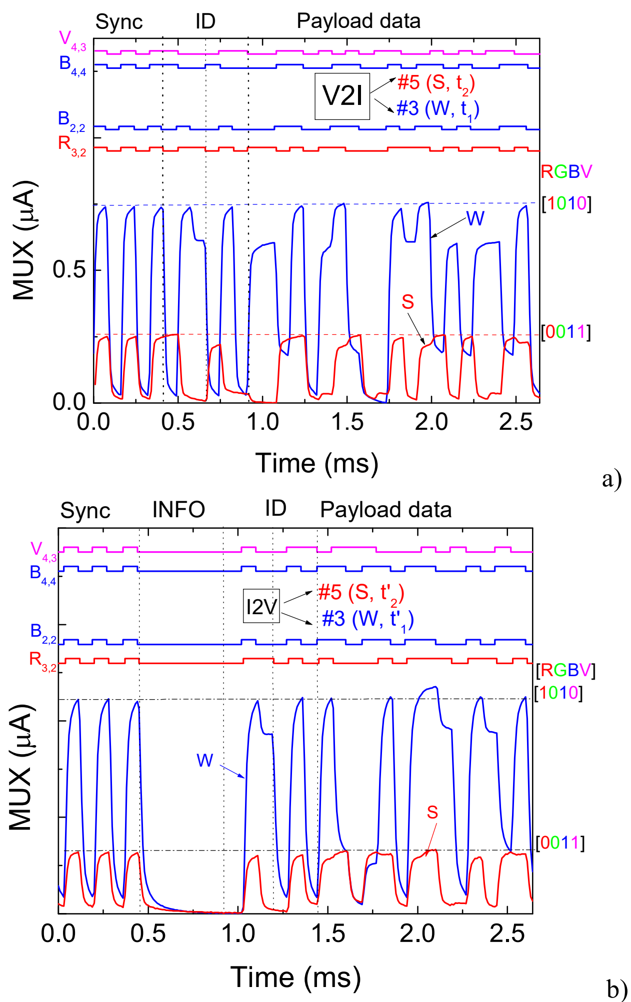

Figure 4. V2I2V MUX/DEMUX signals. On the top the transmitted channels packets [R, G, B, V] are decoded. a) Request message: V2I communication from Vehicles 1 and 2 and the infrastructure at t_1 and t_2. b) Response message: I2V communication between the control manager and the Vehicle 1 and Vehicle 2 at t'_1 and t'_2.

At the request times, the positions of both vehicles are identified: W #3 ($R_{3,2}$ and $B_{2,2}$) for Vehicle 1 and S #5 ($B_{4,4}$ and $V_{4,3}$) for Vehicle 2. At the access times, t'_1 and t'_2 (Figure 4b), the connected vehicles receive their own responses (ID: W #3 or S #5) from the control manager (INFO: 000000). At these times, each connected vehicle is required to follow the occupancy trajectories (footprint regions) provided by the intersection manager (payload data).

B. *Traffic Signal Phasing*

Signal phasing is the sequence of individual signal phases within a cycle that define the order in which pedestrians and vehicular movements are assigned the right-of-way. 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.

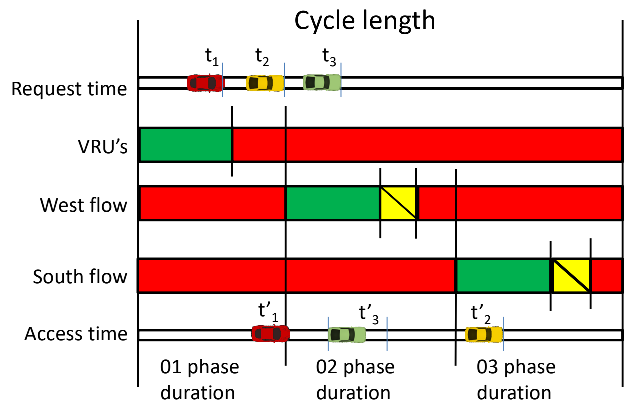

Figure 5. Phasing of traffic flows: phase number 01(pedestrian phase), phase number 02 (W flow), phase number 03(S flow).

A traffic scenario was simulated (Figure 1). A brief look into the basic anatomy and the process of timing traffic signals is given in Figure 5. The sequential diagram describes the phasing of the traffic flows composed of two single-lane road phases crossing at the square intersection area: the W flow stage (02 phase) and the S flow stage (03 phase). Green splits are calculated by dividing the cycle length in proportion to the critical lane volumes. Each driving vehicle is then assigned an individualised time to request ($t_{1,2,3}$) and access ($t'_{1,2,3}$) the intersection. During the course of phases 02 and 03 the pedestrians, through a pushbutton, request to pass the crossroad and are acknowledged. The phase 01 stage, "Walk" interval begins at the end of phase 03 and the controller sends a response message to nomadic road user´s devices (e.g., smartphone, tablets). Sufficient time must be provided to cross the entire travelled width of the street. In phase 01 the "don't walk" interval is calculated based on the length of the crosswalk.

A first-come-first-served 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 5.

IV. CONCLUSIONS AND FUTURE TRENDS

This paper presents a distributed mechanism for the performance management of a traffic light controlled crossroad network, where connected vehicles receive information from the network (I2V), interact with each other

 ISBN: 978-1-61208-745-0

(V2V) and with the infrastructure (V2I). A control manager coordinates the crossroad and interacts with the vehicles (I2V). VLC is the transmission technology. A simulated traffic scenario was presented and a generic model of cooperative transmissions for vehicular communications services was established. The experimental results confirmed that the proposed cooperative VLC architecture is suitable for the intended applications. The introduction of VLC between connected vehicles and the infrastructures, I2V2V2I2V communication allows the direct monitoring of relative speed thresholds and inter-vehicle spacing. The distance between conflicting vehicles and the trajectories of other opposing vehicles should also be monitored and optimized.

In order to move towards real implementation, the performance of such systems still needs improvement. As further work, the research team plans to finalize the embedded application, for experimenting in several road configurations with either static or moving vehicles.

ACKNOWLEDGEMENTS

This work was sponsored by FCT – Fundação para a Ciência e a Tecnologia, within the Research Unit CTS – Center of Technology and systems, reference UID/EEA/00066/2019 and projects reference IPL/2018/II&D_CTS/UNINOVA_ISEL and by: IPL/IDI&CA/2018/LAN4CC/ISEL.

REFEEENCES

[1] S. Schmid, G. Corbellini, S. Mangold, and T. R. Gross, “An LED-to-LED Visible Light Communication system with software-based synchronization,” in 2012 IEEE Globecom Workshops, pp.1264–1268, 2012.

[2] I. L. Azevedo, M. G. Morgan, and F. Morgan, "The Transition to Solid-State of the IEEE , vol.97, no.3, pp. 481-510, March 2009.

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

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

[6] 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.

[7] M. A. Vieira, P. Louro, M. Vieira, A. Fantoni, and A. Steiger-Garção, “Light-activated amplification in Si-C tandem devices: A capacitive active filter model,” IEEE sensor journal, 12(6), pp. 1755-1762, 2012.

[8] 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, 102311L, 2017.

[9] M. A. Vieira, M. Vieira, P. Vieira, and P. Louro, “Vehicle-to-Vehicle and Infrastructure-to-Vehicle Communication in the Visible Range,” Sensors & Transducers, 218 (12), pp. 40-48, 2017.

[10] 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. Copyright (c) IARIA ISBN: 978-1-61208-581-4, pp. 57-62, 2017.

[11] 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, 102311L., 2017.

[12] M. A. Vieira, M. Vieira, P. Vieira, and P. Louro, "Cooperative vehicular communication systems based on visible light communication," Opt. Eng. 57(7), 076101, 2018.

[13] M. A. Vieira, M Vieira, J. Costa, P. Louro, M Fernandes, and A. Fantoni, “Double pin Photodiodes with two Optical Gate Connections for Light Triggering: A capacitive two-phototransistor model,” in Sensors & Transducers Journal, 10 Special Issue, pp. 96-120, 2011.

[14] M. A. Vieira, M. Vieira, P. Louro, and P. Vieira, “Vehicular Visible Light Communication I2V2V2I Connected Cars,” The Ninth International Conference on Sensor Device Technologies and Applications, SENSORDEVICES 2018. Copyright (c) IARIA, 2018. ISBN: 978-1-61208-660-6, pp. 175-180, 2018.