Vehicular Visible Light Communication in a Two-Way-Two-Way Traffic Light Controlled Crossroad

Manuel Augusto Vieira, Manuela 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

Mirtes de Lima, 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: A43891@alunos.isel.pt, pvieira@deetc.isel.pt

***Abstract*—The concept of request/response and relative pose estimation for the management of the trajectory is used, in a two-way-two-way traffic lights controlled crossroad, using Vehicular Visible Light Communication (V-VLC). The connected vehicles receive information from the network and interact with each other and with the infrastructure. In parallel, an Intersection Manager (IM) coordinates the crossroad and interacts with the vehicles using the temporal/space relative pose concepts. V-VLC is performed using the street lamps, the traffic signaling and the headlamps to broadcast the information. Data is encoded, modulated and converted into light signals emitted by the transmitters. As receivers and decoders, optical sensors with light filtering properties are used. Cooperative localization is realized in a distributed way with the incorporation of the indirect vehicle-to-vehicle relative pose estimation method. A phasing traffic flow is developed, as Proof of Concept (PoC) and a generic model of cooperative transmission is analysed. Results expresses that the vehicle's behavior (successive poses) is mainly influenced by the manoeuvre permission and presence of other vehicles.**

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

I. INTRODUCTION

High-end models of last generation vehicles nowadays are equipped with hundreds of embedded computers and sensors which allow them to perceive their surroundings, and interact with it in semi-autonomous, and eventually, fully-autonomous fashion. Although at a slower pace, the road infrastructure has evolved as well, with adaptive traffic lights. Next step in the evolution course of transportation systems is to adopt the concept of communication and enable information exchange between vehicles and with infrastructure (V2I) shifting the paradigm from autonomous driving to cooperative driving by taking advantage of Vehicle-to-Everything (V2X) communications [1] [2]. The objective is to increase the safety and throughput of traffic intersections using cooperative driving [3] [4].

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 [5].Vehicular networking applications can take advantage of the LED-equipped lighting modules and transportation infrastructure to realize V-VLC. Here, the communication can be performed using the street lamps, the traffic signaling and the headlamps.

The goal is to develop a cooperative system that supports guidance services. An edge/fog based architecture is proposed. Here, the streetlights and traffic lights, through VLC, report its geographical positions and specific information to the drivers and its infrastructure is reused to embed the edge/fog nodes in them. Using this architecture, an Intersection Manager (IM) can increase the throughput of the intersection by exchanging information and directing the incoming Connected Autonomous Vehicles [6] [7] [8] [9]. Cooperative localization is realized in a distributed way with the incorporation of the indirect Vehicle-to-Vehicle (V2V) relative pose estimation method. The vehicle gathers relevant data from neighboring vehicles and estimates the relative pose of them. In this paper a V2X traffic scenario is stablished and bidirectional communication between the infrastructure and the vehicles is tested, using the VLC request/response concept. Tetra-chromatic white sources are used to broadcasting the geolocation and traffic information. The receiver modules include a light controlled filter [10] recovering the transmitted information.

This paper is organized as follows. After the introduction, in Section 2, the V-VLC system is described and the scenario, architecture, communication protocol, coding/decoding techniques analyzed. In Section 3, the experiential results are reported and the system evaluation performed. A phasing traffic flow diagram based on V-VLC is developed, as PoC, to control the arrival of vehicles to the

 ISBN: 978-1-61208-918-8

intersection. Finally, in Section 4, the main conclusions are presented.

II. VEHICULAR VISIBLE LIGHT COMMUNICATION SYSTEM

A. *Scenario and architecture*

The V-VLC make use of outdoor light sources (street lamps and traffic lights) as the access points, which can serve for both lighting and communication purposes, providing drivers with outdoor wireless communications. The system is composed by two modules: the transmitter and the receiver located at the infrastructures and at the driving cars. The block diagram of the V-VLC system is presented in Figure 1.

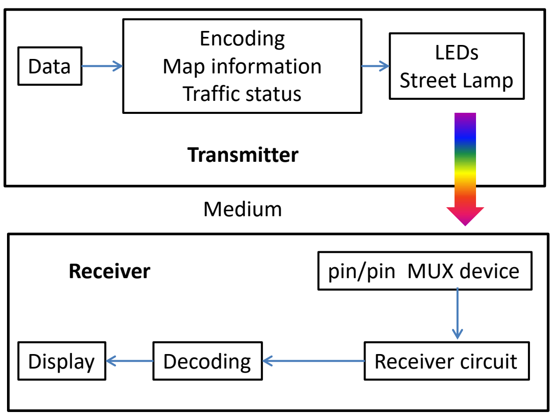

Figure 1. Block diagram of the VLC system.

To realize both the communication and the street illumination, white light tetra-chromatic sources are used providing a different data channel for each chip. At each node, only one chip of the LED is modulated for data transmission, the Red (R: 626 nm), the Green (G: 530 nm), the Blue (B: 470 nm) or the Violet (V) while the others provide constant current for white perception.

Data is encoded, modulated and converted into light signals emitted by the transmitters. Modulation and digital-to-analog conversion of the information bits is done using signal processing techniques. The signal is propagating through the optical channel and a VLC receiver, at the reception end of the communication link, is responsible to extract the data from the modulated light beam. It transforms the light signal into an electrical signal that is subsequently decoded to extract the transmitted information. The core element of a receiver is a Silicon-Carbon (SiC) photodetector. This component converts the optical power into electrical current. The VLC photosensitive receiver is a double pin/pin photodetector based on a tandem heterostructure, p-i'(a-SiC:H)-n/p-i(a-Si:H)-n sandwiched between two conductive transparent contacts [10]. Due to its tandem structure, the device is an optical controlled filter able to identify the wavelengths and intensities of the impinging optical signals. Its quick response enables the possibility of high speed communications. The generated photocurrent is processed using a transimpedance circuit obtaining a proportional voltage. The obtained voltage is then processed until the data signal is reconstructed at the data processing unit (digital conversion, decoding and decision [11, 12]).

A V2X communication link, in a traffic light controlled crossroad, was simulated.

In Figure 2a the lighting plan and generated joint footprints in the crossroad region (LED array=RGBV modulated color spots) is displayed. To build the I2V it is proposed a simplified cluster of unit square cells in an orthogonal topology that fills all the service area [12, 13]. 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 in the experimental results uses a smaller size square grid (2 cm), to improve its practicality. Each transmitter, $X_{i,j}$, carries its own color, X, (RGBV) as well as its horizontal and vertical ID position in the surrounding network (*i*,*j*). In the PoC, was assumed that the crossroad is located in the intersection of line 4 with column 3, and the emitters at the nodes along the roadside. To receive the I2V information from several transmitters, the receiver must be located at the overlap of the circles that set the transmission range (radial) of each transmitter. The nine possible overlaps, defined as fingerprint regions, are also displayed in Figure 2a for each unit cell. Thus, each LED sends a message that includes the synchronism, its physical ID and the traffic information. When a probe vehicle enters the streetlight´s capture range, the receiver replies to the light signal, and assigns an unique ID and the traffic message [13]. At each moment, *t*, the receiver identifies the footprint, finds it centroid and stores it as the reference point. All observations for a single section are jointly analyzed to produce an estimate of the occupied lane, direction and travel time along the considered section. The received message, acts twofold: as a positioning system and as a data receiver.

In Figure 2b we propose a draft of a mesh cellular hybrid structure to create a gateway-less system without any external gateways needed [14]. As illustrated the street lights, in this architecture, are equipped with one of two types of nodes: A “mesh” controller that connects with other nodes in its vicinity. These controllers can forward messages to the vehicles (I2V) in the mesh, effectively acting like routers nodes in the network. A “mesh/cellular” hybrid controller, that is also equipped with a modem provides IP base connectivity to the Intersection Manager (IM) services. These nodes acts as border-router and can be used for edge computing. The proposed short-range mesh network enables edge computing and device-to-cloud communication, by ensuring a secure communication from a street light controller to the edge computer or datacenter, through a neighbor traffic light controller with an active cellular connection.

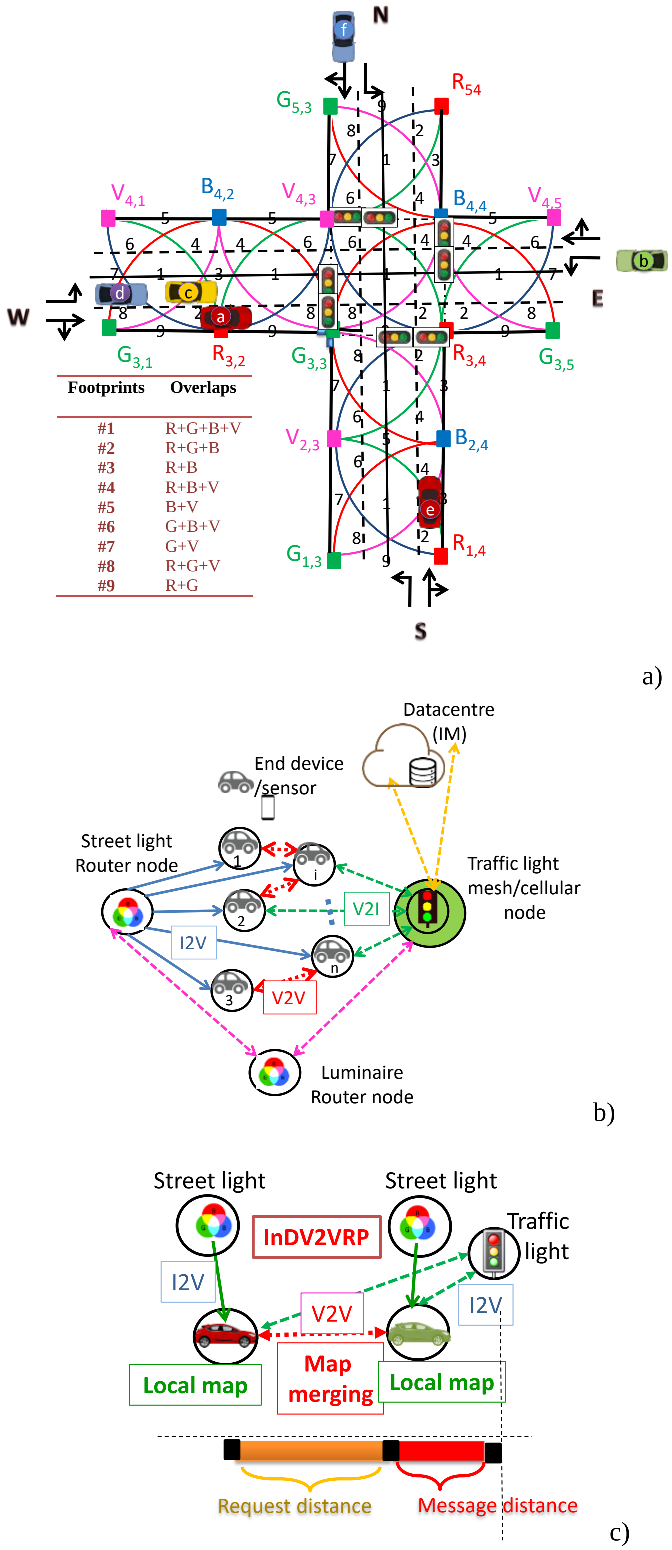

Figure 2. a) V2X optical infrastructure and generated joint footprints in a crossroad (LED array=RGBV color spots).b) Mesh and cellular hybrid architecture. c) Graphical representation of the simultaneous localization and mapping problem.

B. *Multi-vehicle cooperative localization*

The combined estimation of both position and orientation (pose estimation) of the vehicle is important to path definition. In a two-dimensional coordinate systems the pose, $q(t) = [x(t), y(t), \delta(t)]$, is defined by position (x,y) and orientation angle δ, with respect to the coordinate axes. Let's consider that $q_i(t,t')$ represents the pose of vehicle *i* at time *t´* relative to the pose of the same vehicle at time *t* and $q_{ij}(t)$ denotes the pose of vehicle *j* relative to the pose of vehicle *i* at time *t*. These three types of information $q_i(t)$, $q_i(t,t')$and $q_{ij}(t)$ compose the basic elements of a pose graph for multi-vehicle cooperative localization [15].

An Indirect V2V Relative Pose Estimation (InDV2VRPE) method is proposed and exemplified in Figure 2c. Here, when two vehicles are in neighborhood, the geometric relationship between them can be indirectly inferred via a chain of geometric relationships among both vehicles positions and local maps. Let´s consider two neighboring vehicles. Both vehicles, having self-localization ability based on I2V street lamps communication perform local Simultaneous Localization and Mapping (SLAM). The follower vehicle can be localized by itself, as in single vehicle localization, $q_i(t)$, and can also be localized by combining the localization result of vehicle leader and the relative localization estimate between the two vehicles, $q_{ij}(t)$. For a vehicle with several neighboring vehicles, it uses the indirect V2V relative pose estimation method to estimate the relative pose of each neighboring vehicle one by one and takes advantage of the data of each neighboring vehicle.

C. *Color phasing diagrams*

Four traffic flows were considered (Figure 2a): One from West (W) with three vehicles (*a*, *c*, *d*) approaching the crossroad, Vehicle *a* with straight movement and Vehicle *c* and Vehicle *d* with left turn only. In the second flow, Vehicle *b* from East (E), approaches the intersection with left turn only. In the third flow, Vehicle *e*, oncoming from South (S), has e right-turn approach. Finally, in the fourth flow, Vehicle *f*, coming from North, goes straight.

For the intersection manager crossing coordination, the vehicle and the IM exchange information through two specific types of messages, "request" (V2I) and "response" (I2V) as exemplified in Figure 2b. Inside the request distance, an approach "request" is sent, using as emitter the headlights. To receive the "requests", two different receivers are located at the same traffic light, facing the cross roads (local controller of the traffic light). Concretely, when one head vehicle enters in the infrastructure´s capture range of one of the receivers (request distance) the request message is received and decoded by the receiver facing the lane which is interconnected to the Intersection Manager. Those messages contain the assigned ID positions, speeds, and flow directions of the vehicles. The "request" contains all

 ISBN: 978-1-61208-918-8

the information that is necessary for a vehicle's space-time reservation for its intersection crossing. Intersection manager uses this information to convert it in a sequence of timed rectangular spaces that each assigned vehicle needs to occupy the intersection. An intersection manager's acknowledge is sent from the traffic signal over the facing receiver to the 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 (message distance in Figure 2c), the vehicle is required to follow the occupancy trajectories (footprint regions, Figure 2a) provided by the intersection manager. If a request has any potential risk of collision with all other vehicles that have already been approved to cross the intersection, the control manager only sends back to the vehicle (V2I) the "response" after the risk of conflict is exceeded. The use of both navigation and lane control signs to communicate lane restrictions is demanding. Downstream from that location (request distance), lane restrictions should be obeyed. Vehicles may receive their intentions (*e.g.*, whether they will turn left or continue straight and turn right) or specifically the need to interact with a trafic controler at a nearby crossroad (message distance). In the sequence, a traffic message coming from a transmitter nearby the crossroad will inform the drivers of the location of their destination (*i.e.*, the intended intersection exit leg).

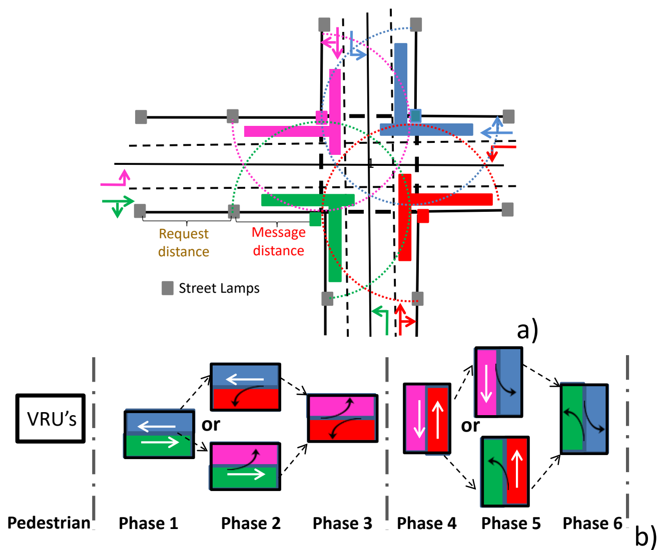

Figure 3: a) Physical area, color poses and channelization. b) Representation of a phasing diagram.

In the proposed architecture (Figure 2b), the major operational requirement of IM is the ability to register synchronized measurements in a common frame of reference. The effective solution is to maintain a buffer of time-stamped measurements and register them as a batch using a temporal sliding window. The vehicles can use such techniques to find their "color poses" at regular time intervals. We have assumed four "color poses" linked with the radial range of the modulated light in the crossroad nodes (dotted arcs in Figure 3a). As depicted in Figure 3a, where the physical area and channelization are shown, the West straight, South left turn and West right turn manoeuvres correspond to the "Green pose". "Red poses" are related with South straight, East left turn and South right turn manoeuvres, "Blue poses with East straight, North left turn and East right turn and finally "violet poses with North straight, West left turn and North right turn manoeuvres, In Figure 3b, a color phasing diagram is displayed. Here, since two movements can proceed simultaneously without conflict hence two of the timing functions will always have simultaneous control.

D. VLC Communication protocol and coding/decoding techniques

An on-off keying (OOK) modulation scheme was used to code the information. Synchronous transmissions based on a 64- bits data frame are analysed.

An example of the used codification to drive the headlamps LEDs of a vehicle, coming from N, located in in footprint #1 ($R_{3,4,}$ $G_{3,3,}$ $B_{4,4,}$ and V_{43}) moving to South is illustrated in Figure 4a.

Different control fields are used depending on the driver motivation. All messages, in a frame, start with the header labelled as Sync, a block of 5 bits. The same synchronization header [10101], in an ON-OFF pattern, is imposed simultaneously to all emitters. The next block (ID) gives the location (*x, y* coordinates) of the emitters inside the array ($X_{i,j,k}$). Cell's IDs are encoded using a 4 bits binary representation for the decimal number. So, the next 8 bits are assigned, respectively, to the *x* and *y* coordinates (*i, j*) of the emitter in the array. If the message is diffused by the IM transmitter, a pattern [0000]) follows this identification, if it is a request (R) a pattern [00] is used. The steering angle (δ) completes the pose in a frame time. Eight steering angles along the cardinal points and coded with the same number of the footprints in the unit cell (Figure 2a) are possible from a start point to the next goal. The last block is used to transmit the traffic message. A stop bit is used at the end of each frame.

The decimal numbers assigned to each ID block are pointed out in the Figure. Results show that, in network, $R_{3,4,S}$; $G_{3,3,S}$; $B_{4,4,S}$ and $V_{4,3,S}$ are the transmitted node packets, in a time slot, from the crossroad. In this location, the driver receives his request message [pose, and traffic needs] from the infrastructure. This allows it movement across the crossroad to South (violet code 9, δ=270º), directly from the current point (#1) to the goal point (#9).

The calibration of the receiver supplies an additional tool to enhance the decoding task. The calibration procedure is exemplified in Figure 4b. Here the MUX signal obtained at the receiver as well as the coded transmitted optical signals is displayed.

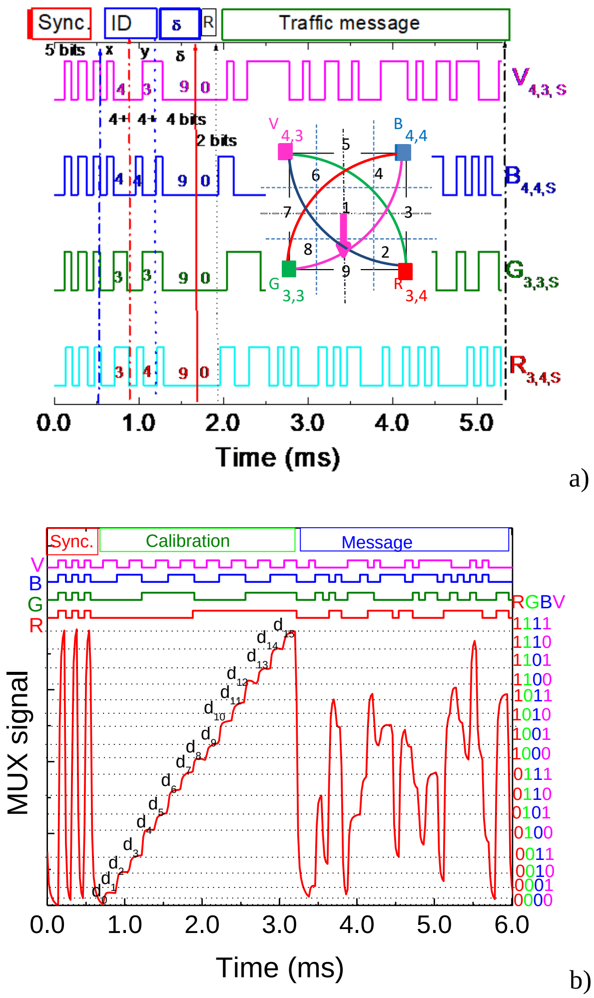

Figure 4 a) Frame structure representation of a request message. b) MUX/DEMUX signal of the calibrated cell. In the same frame of time a random signal is superimposed.

The message, in the frame, start with the header labelled as Sync, a block of 5 bits. In the second block, labelled as calibration, the joint transmission of four calibrated R, G, B and V optical signals is imposed. The bit sequence for this block was chosen to allow all the *on/off* sixteen possible combinations of the four RGBV input channels (2^4). Finally a random message was transmitted. All the ordered levels (d_0-d_{15}) are pointed out at the correspondent levels and are displayed as horizontal dotted lines. In the right hand side the match between MUX levels and the [RGBV] binary code assigned to each level is shown. Comparing the calibrated levels (d_0-d_{15}) with the different assigned 4-digit binary [RGBV] codes, ascribed to each level, the decoding is straightforward and the message decoded. The footprint position comes directly from the synchronism block, where all the received channels are, simultaneously, *on* or *off*. The pose of the mobile receiver (x,y, δ) in the network comes directly from the next 12 decoded bits. Finally, the received traffic message is decoded based on the last MUX levels.

III. V2X COOPERATIVE SYSTEM EVALUATION

Figure 5a displays the MUX signals assigned to a two IM response messages received by Vehicle *a*, driving the right lane, that enters Cell $C_{4,2}$ by the enter #2 ($t'_{1,a}$, Phase1, green pose), goes straight to E to position #8 ($t'_{2,a}$; Phase1, green pose).

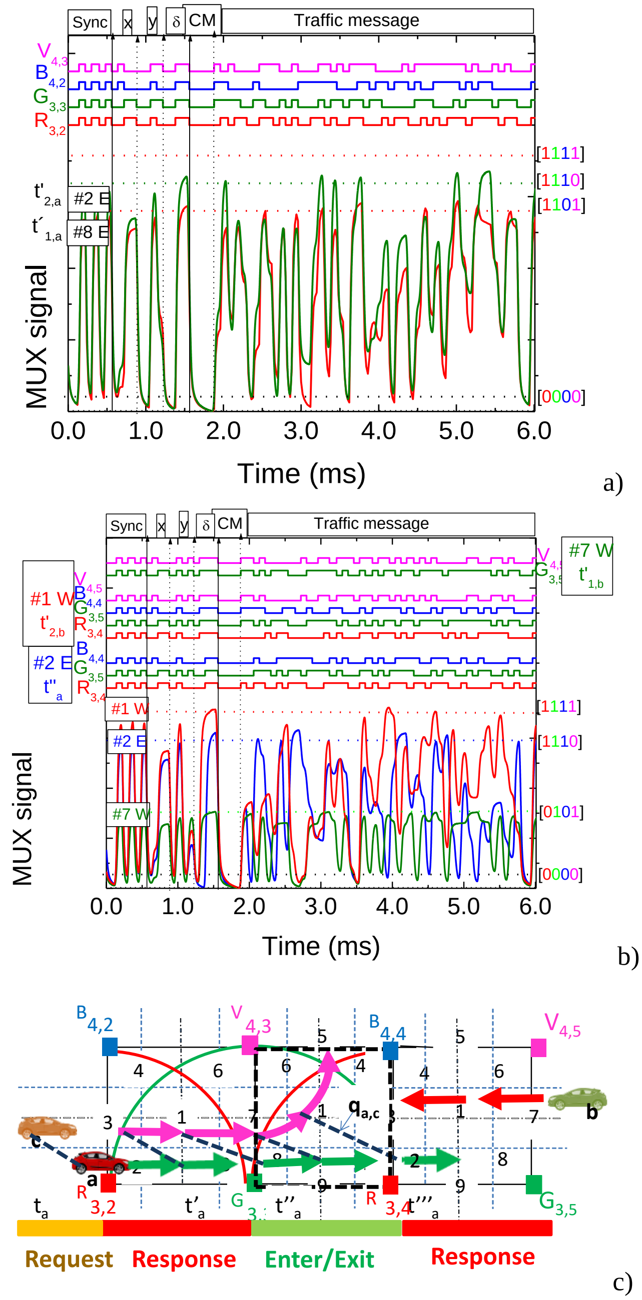

Figure 5. Normalized MUX signal responses and the assigned decoded messages acquired by vehicles *a*, *b*, *c* at different response times. On the top the transmitted channels packets [R, G, B, V] are decoded. a) Before the crossroad. b) After the cross road. c) Movement of the cars, in the successive moments, with their colorful poses (color arrows) and q_{ac} spatial relative poses (dot lines).

Then, this vehicle enters the crossroad through #8 (t''_a) and leaves it in the exit #2 at t'''_a , keeping always the same direction (E). In Figure 5b, vehicle *b* approaches the intersection after having asked permission to cross it and only receives authorization when the vehicle *a* has left the intersection (end of Phase 2). Then, Phase 3 begins with vehicle *b* heading to the intersection (W) (pose red) while vehicle *a* follows its destination towards E (pose green). In Figure 5c, the movement of the cars, in the successive moments, is shown through their colorful poses (color arrows) and q_{ac} spatial relative poses along the time (dot lines). Results show that, as the receiver moves between generated point regions, the received information pattern changes. The vehicle speed can be calculated by measuring the actual travelled distance overtime, using the ID´s transmitters tracking. Two measurements are required: distance and elapsed time. The distance is fixed while the elapsed time will be obtained through the instants where the number of received channels changes. The receivers compute the geographical position in the successive instants (path) and infer the vehicle's speed. In the following, this data will be transmitted to another leader vehicle through the V2V communication or to control manager (IM) at the traffic light through V2I. When two vehicles are in neighborhood and in different lanes, the geometric relationship between them can ($q_{i,j}$) (dotted lines in Figure 5c) can be inferred through local SLAM fusing their self-localizations via a chain of geometric relationships among the vehicles poses and the local maps.

For a vehicle with several neighboring vehicles, the mesh node uses the indirect V2V relative pose estimations method taking advantage of the data of each neighboring vehicle.

IV. CONCLUSIONS

This paper presents a new concept of request/response for the redesign and management of a trajectory in a two-way-two-way traffic lights controlled crossroad, using VLC between connected cars. A simulated traffic scenario was presented and a generic model of cooperative transmission for vehicular communication services was established. As a PoC, a phasing of traffic flows is suggested. The simulated/experimental results confirmed that the proposed cooperative VLC architecture is suitable for the intended applications. The introduction of VLC between connected vehicles and the surrounding infrastructure allows the direct monitoring of relative speed thresholds and inter-vehicle spacing increasing the safety.

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 UIDB/00066/2020. The project IPL/IDI&CA/2020/Geo-Loc/ISEL, is also acknowledge.

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