Vehicle Visible Light Communication at a Four-Legged Traffic Light Controlled Crossroad

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***Abstract*— A four-legged traffic lights controlled crossroad with Vehicular Visible Light Communication (V-VLC) is used for trajectory management, using request/response concept and relative pose estimation. The connected vehicles receive information from the network and interact with each other and with the infrastructure. An Intersection Manager (IM) coordinates traffic crossings and interacts with vehicles through 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. The results express that the vehicle's behavior (successive poses) is mainly influenced by the maneuver 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

This paper is an extended version from the one presented in SENSORDEVICES 2021 [1].

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 [2] [3]. The objective is to increase the safety and throughput of traffic intersections using cooperative driving [4] [5].

Intersections, by their nature, easily become traffic bottlenecks and conflict areas. Two-way-two-way four-legged and split intersections are critical points of the road network either in terms of road safety, or at the level of operational conditions, because they usually cause considerable delays due to congestion problems. This specificity of intersections compels their careful study in order to achieve optimal road network operational conditions. They are distinguishable from each other by their geometric configuration, control conditions and technological requirements. Hence, it is necessary the existence of consistent selection criteria enabling one's choice for the best solution. The volume of traffic arriving at the intersection, i.e., its demand, remains the same. So, in the selection process it is fundamental to consider many other aspects such as road safety, performance, average delay per vehicle and functional and operational conditions in order to arrive at a best solution. The level of service at intersections can be improved by applying a split intersection. Here the conventional four-legged intersection can be replaced by two separate intersections. The main benefits of a split intersection are: improved safety, increased efficiency, a better synchronization and shorter wait times. Improved safety since it separates potential conflict points where vehicles, pedestrians, and bicyclists may cross paths. Increased efficiency since the separation of traffic flow on the major street allows the intersection to handle a greater volume of traffic and operate with less delay. A better synchronization, once corridor travel times are improved on both the major and side streets through synchronization of the two signalized intersections. Finally, shorter wait times because fewer vehicle traffic signal phases means less time stopping at the intersections.

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 [6]. The Visible Light Communication (VLC) holds special importance when compared to existing forms of wireless communications [7] [8]. VLC is an emerging technology that enables data communication by modulating information on the intensity of the light emitted by LEDs. VLC is a precursor of optical communication for large scale-integration with other conventional communication technologies, and a strong candidate for next generation of indoor interconnection and networking, in parallel with radio communications. VLC finds application in many fields, namely: indoor navigation and localization services, safe communication at RF hazardous/undesirable places and V2X communications. Moving forward, an effort should be carried out to keep researching this topic, building synergies between the solid research work under VLC and RF technical areas. In fact, the self-configuration, self-optimization and self-healing (RF) use cases are progressing into VLC, and should be considered in future.

One of the main issues in a VLC system is the limited bandwidth of a few MHz for white light LEDs. There are several schemes for increasing the bandwidth of VLC, including equalization, multilevel modulation, parallel transmission, and Multiple Input Multiple Output (MIMO). MIMO is considered as a simple and effective technique, which divides a serial input data stream into multiple streams and concurrently transmits them to the multiple receivers. By doing so, the system capacity and the power efficiency are improved, compared to a conventional VLC system [9] [10] [11]. At the receiver, the original data can be recovered, if a full knowledge of the channel state information is available, which can be obtained by transmission of the pilot signals periodically.

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 [12] [13] [14] [15]. 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 [16] 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 presented. The communication protocol, coding/decoding techniques are analyzed in Section 3. In Section 4, the experiential results are reported and the system evaluation performed. In Section 5, a phasing traffic flow diagram was developed, as a proof of concept, based on V-VLC, in order to control the arrival of vehicles at the intersection. Finally, in Section 6, the main conclusions are presented.

II. VEHICULAR VISIBLE LIGHT COMMUNICATION SYSTEM

A. Navigation Concepts

Navigation consists of vehicles laterally organized within lanes and needing to strictly drive within them. Two vehicles cannot occupy the same position in the same lane.

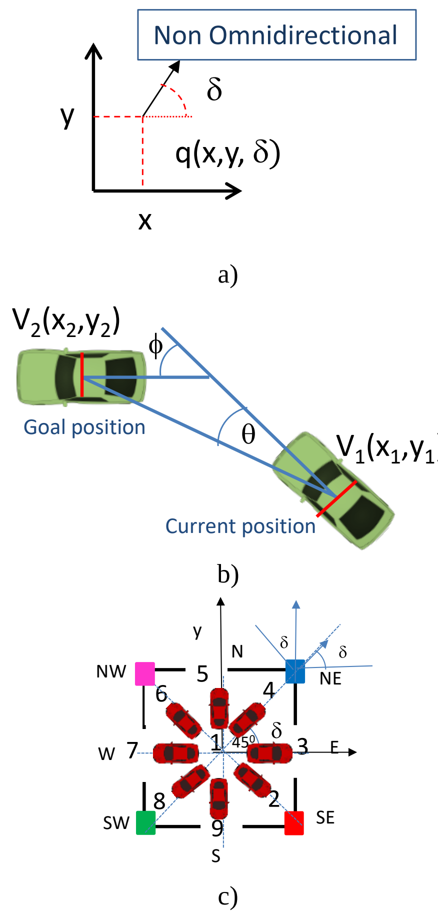


Figure 1. a) Pose: q=(x,y,δ). b) Ackermann steering principle. c) Pose orientations (N, S, E, W, NE, SE,SW, NW).

Self-localization is a fundamental issue since the vehicle must be able to estimate its position and orientation within a map of the environment it is navigating. The combined estimation of both position and orientation (pose estimation) are important to path definition. Consider a vehicle driving in a lane. Its non-omnidirectional configuration, in a two-dimensional coordinate systems is defined by position (x,y) and orientation angle δ, with respect to the coordinate axes. $q(t) = [x(t), y(t), \delta(t)]$ denotes its pose at time t, in a global reference frame. The triple $q=(x,y,\delta)$ is the mobile user pose, as displayed in Figure 1a.

The trajectory is a specification of both the path to take and the time information associated with the path, to be followed by the vehicle path consists of a set of points representing the positional coordinates of a particular route. Navigation to a goal location from a known starting location follows a basic principle. The vehicle decides which direction of travel to take at an intersection (e.g., turn right, turn left, or continue straight) by minimizing the difference in angle between the vehicle's heading and the direction to the goal, θ, as exemplified in Figure 1b. The concept of Ackermann steering principle [17] is summarized in Figure 1b. The principle took into account the angle, ϕ, required for the mobile receiver to steer from its current position to its intended position ($\theta = \phi/2$) [18] [19] [20]. Here, the pose of vehicle is grouped into eight orientations of viewpoint according to the cardinal points. The eight orientations are pointed out in Figure 1c (N, S, E, W, NE, SW, NW, SE). The pose of the vehicle in the same orientation will be varied to cover every angle. In this example, the vehicle navigates through a two-way-two-way intersection. The vehicle can detect the type of intersection that it is approaching (*e.g.* in Figure 1b.The principle, two-way-two-way intersection with the option to turn right, continue straight or left) using receivers measurements in real time. With this information, the angle between the vehicle's heading and the direction to the goal is determined for each possible route.

We denote q, q´, q´´ and q´´´ the vehicle pose estimation at the time t, t´, t´´ and t´´´(request, response, enter and exit times). To estimate these variables, it is possible to take advantage of what we call control inputs and which represent an estimation of the motion along the time. They come from receivers able to give the idea of the displacement. They help to build and improve the map and indirectly, to estimate the vehicle poses.

B. *Communication modules*

The Vehicular VLC (V-VLC) system makes 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 and the transmitter and receiver relative positions of the V-VLC system are presented in Figure 2a. Both communication modules (transmitter and receiver) are software defined, where modulation/ demodulation can be programed.

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.

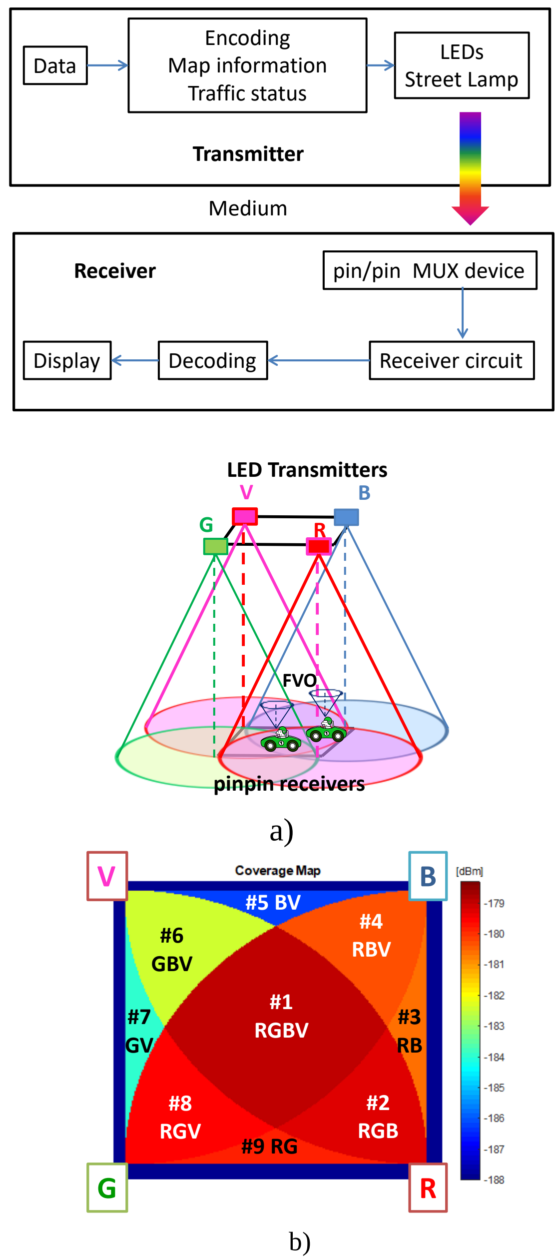


Figure 2. a) Block diagram of the VLC system.b) Illustration of the coverage map in a square unit cell.

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 [16]. 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 [21] [22]).

To receive the information from several transmitters, the receiver must be positioned where the circles from each transmitter overlap, producing at the receiver, a multiplexed (MUX) signal that, after demultiplexing, acts twofold as a positioning system and a data transmitter. The grid size were chosen to avoid overlap in the receiver from adjacent grid points. The coverage map for a square unit cell is displayed in Figure 2b. Friis' transmission equation is frequently used to calculate the maximum range by which a wireless link can operate. The coverage map is obtained by calculating the link budget from the Friis Transmission Equation [23]. The Friis transmission equation relates the received power (P_R) to the transmitted power (P_E), path loss distance (L_R), and gains from the emitter (G_E) and receiver (G_R) in a free-space communication link:

$$P_{R\,[dBm]} = P_{E\,[dBm]} + G_{E\,[dB]} + G_{R\,[dB]} - L_{R\,[dB]} \qquad (1)$$

Taking into account Figure 3, the path loss distance and the emitter gain will be given by:

$$L_{R\,[dB]} = 22 + 20\ln\frac{d}{\lambda} \qquad (2)$$

$$G_{E\,[dB]} = \frac{(m+1)A}{2\pi d_{E-R}^2} I(\emptyset)\cos(\theta) \qquad (3)$$

With A the area of the photodetector and d_{E_R} the distance between each transmitter and every point on the receiver plane.

The receptors act as active filters [16]. Due to their filtering properties the gains are strongly dependent on the wavelength of the pulsed LEDs. Gains of 5, 4, 1.7 and 0.8 were used, respectively, for the R, G, B and V LEDs.

The coverage map, Figure 2b, was obtained by calculating the link budget using the Equation (3). The input parameters are displayed in Table 1. All the values were converted to decibel.

TABLE 1. LINK BUDGET INPUT.

Variable	Value			
	Red LED	**Green LED**	**Blue LED**	**Violet LED**
I_N(mcd)	730	650	800	900
G_E(dB)	Equation (5)			
G_R	5	4	1.7	0.8
L_R(dB)	Eq. (4)			

Users in different locations are served simultaneously by the same transmitter leading to a fine grained implementation. Due to the overlapping coverage area of adjacent nodes, joint transmission exists. In Table II the overlap regions (footprints) below each Access Point (AP) are displayed. Results show that the received power in each cell depends on the receiver position. Nine separated levels were found, in the square topology, and correspond to the nine possible combinations of the pulsed LEDs framed at corners of the unit cell (Figure 2b).

TABLE 2. FINE-GRAINED TOPOLOGIES: FOOTPRINT REGIONS.

Footprint regions	Square topology	Hexagonal topology
#1	RGBV	RGV
#2	RGB	GBV
#3	RB	RBV
#4	RBV	RGB
#5	BV	RGBV
#6	GBV	-
#7	GV	-
#8	RGV	-
#9	RG	-

Each node, $X_{i,j}$, carries its own color, X, (RGBV) as well as its ID position in the network (i,j). The overlap regions (footprints) are pointed out in Figure 2b and reported in Table 2. The device receives multiple signals, finds the centroid of the received coordinates and stores it as the reference point position (# in Figure 2b).

III. COOPERATIVE DRIVING

A. V2X Scenario and Architecture

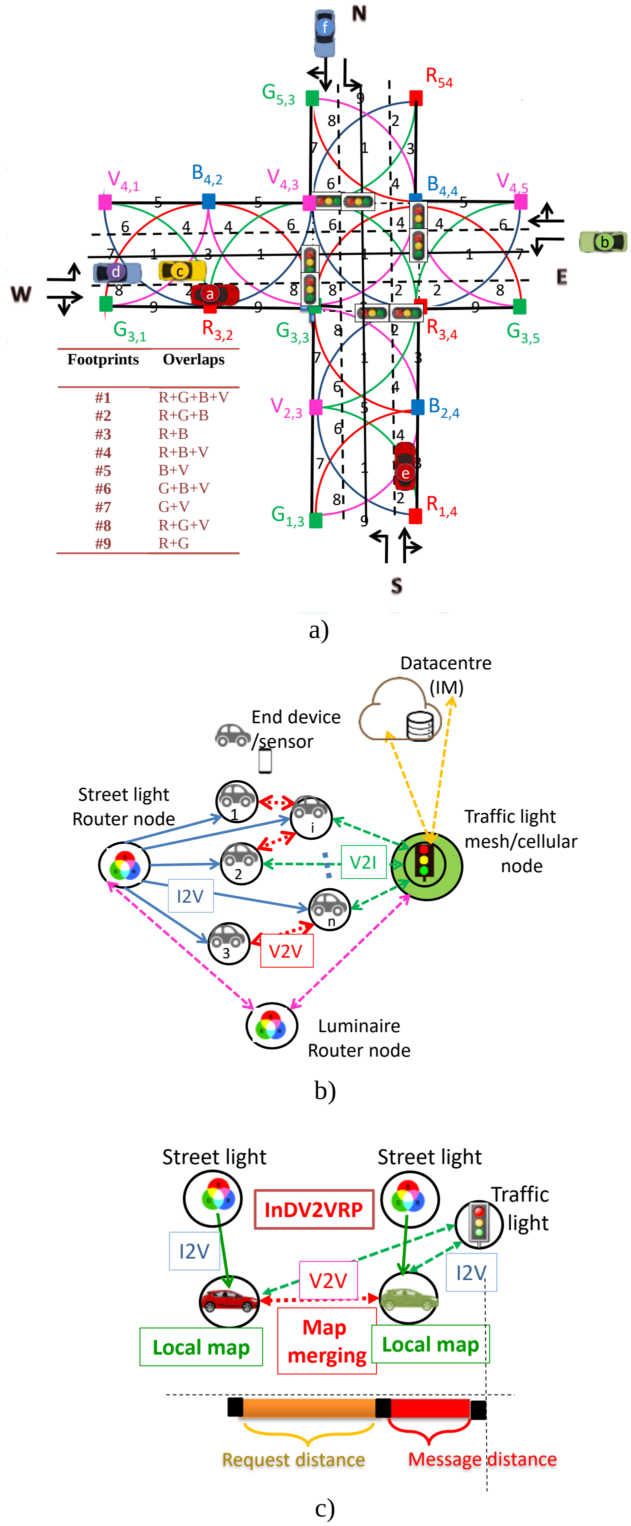
The typical single intersection (four-legged intersection) is attached to sixteen roads, eight incoming from and eight outgoing to North, West, South, and East neighbor crossroads' roads. A V2X communication link, in a traffic light controlled crossroad, was simulated. In Figure 3a the lighting plan and generated joint footprints in the crossroad region (LED array=RGBV modulated color spots) is displayed. An orthogonal topology was assumed.

Four traffic flows were considered (Figure 3a): 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.

It is proposed to build the I2V with a simplified cluster of unit square cells, in an orthogonal topology, that fills the entire service area [21] [24]. 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**,** to improve its practicality. In the PoC, was assumed that the four-legged crossroad is located in the intersection of line 4 with column 3, and the emitters at the nodes (street lamps) 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 3a 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 [22]. The received message, acts twofold: as a positioning system and as a data receiver. 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.

In Figure 3b we propose a draft of a mesh cellular hybrid structure to create a gateway-less system without any external gateways needed [25].

As shown, in this architecture, streetlights are equipped with one of two kinds of nodes: A "mesh" controller that connects with other nodes in its vicinity. Essentially, they are acting as routers in the network by forwarding messages to vehicles (I2V) in the mesh.



Footprints	Overlaps
#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

Figure 3. 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.

The other one is the “mesh/cellular” hybrid controller that is also equipped with a modem provides IP base connectivity to the Intersection Manager (IM) services. These nodes act 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 and enable peer-to-peer communication, to exchange information between V-VLC ready connected cars.

B. *Multi-vehicle cooperative localization*

A concept of request/response for multi-vehicle cooperative localization is used.

For the intersection manager crossing coordination the vehicle and the IM exchange information through two types of messages, “request” (V2I) and “response” (I2V). Each driver, approaching the intersection area from each side has previously selected and stays in the appropriate lane for their destination (left turn only or shared by right-turn and through movements). Inside the request distance, an approach “request” is sent, using as emitter the headlights as illustrated in Figure 3c.

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 (V2I). The “request” contains all the information that is necessary for a vehicle’s space-time reservation for its intersection crossing (speeds, and flow directions). 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 3c), the vehicle is required to follow the provided occupancy trajectories (footprint regions, see Figure 2). 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. A course is a typical path that is followed by a vehicle while approaching (request and message distances) and traversing the intersection.

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 [26].

From a digital map we automatically extract a set of attributes that characterize an intersection: the poses, $q_i(x, y, t)$, the courses and traffic rules (stop, give way).

The Indirect V2V Relative Pose Estimation (InDV2VRPE) method is exemplified in Figure 3c. 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*

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.

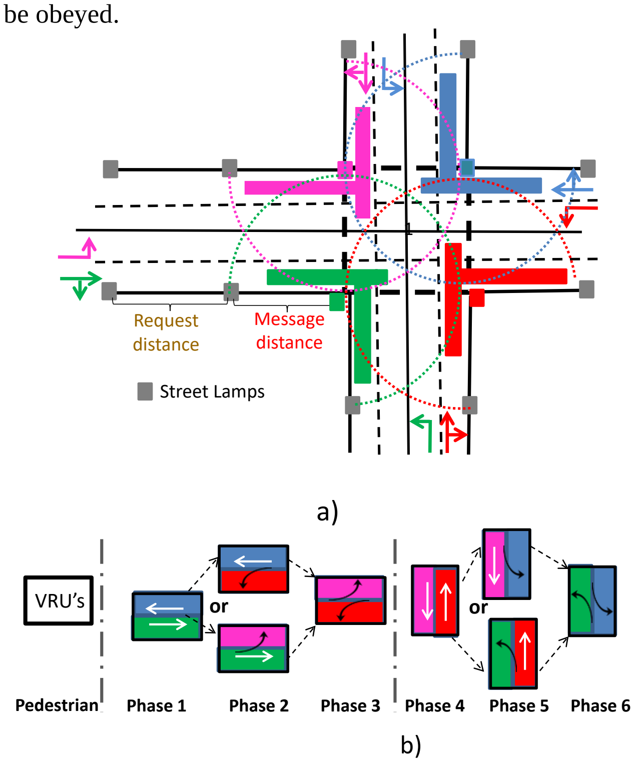


Figure 4. a) Physical area, color poses and channelization. b) Representation of a phasing diagram.

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).

In the proposed architecture (Figure 3b), 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. Based on Figure 4a, 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" have to do with manoeuvres like turning south straight, turning east left and turning south right. "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 4b, a color phasing diagram is displayed. Since two movements can occur simultaneously without conflict, two of the timing functions are always controlled simultaneously.

IV. VLC Communication protocol and coding/decoding techniques

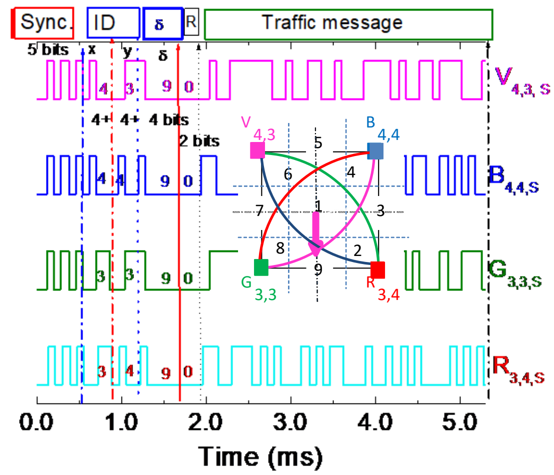
An on-off keying (OOK) modulation scheme was used to code the information. Synchronous transmissions based on a 64- bits data frame are analysed.

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 5a.

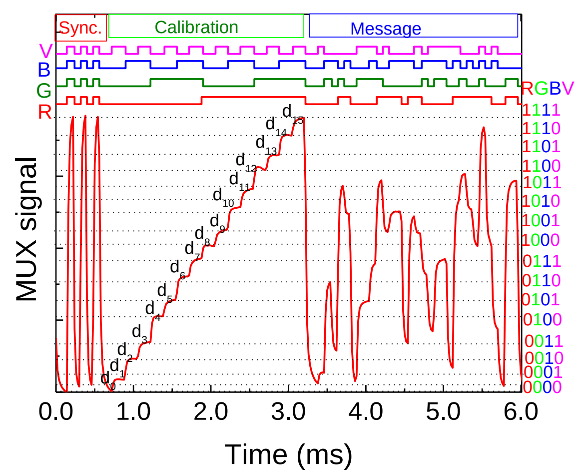
Different control fields are used depending on the driver motivation. All messages, in a frame, start with the header labelled as Sync, a block of 5 bits. The same synchronization header [10101], in an ON-OFF pattern, is imposed simultaneously to all emitters. The next block (ID) gives the location (*x, 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 1c) 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 5a. 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 its 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 5b. Here the MUX signal obtained at the receiver as well as the coded transmitted optical signals are displayed.



a)



b)

Figure 5. 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, starts 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.

V. SYSTEM EVALUATION

A. *V2X Communication*

Figure 6a displays the MUX signal associated with two IM response messages. The messages were 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). 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 6b, 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 6c, the movement of the cars is illustrated by their colorful poses (color arrows) and their spatial relative poses, q_{ac} (dot lines), as time develops.

According to the results, the received information patterns change as the receiver moves between generated point regions. 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 6c) can be inferred through local SLAM fusing their self-localizations via a chain of geometric relationships among the vehicles poses and the local maps.

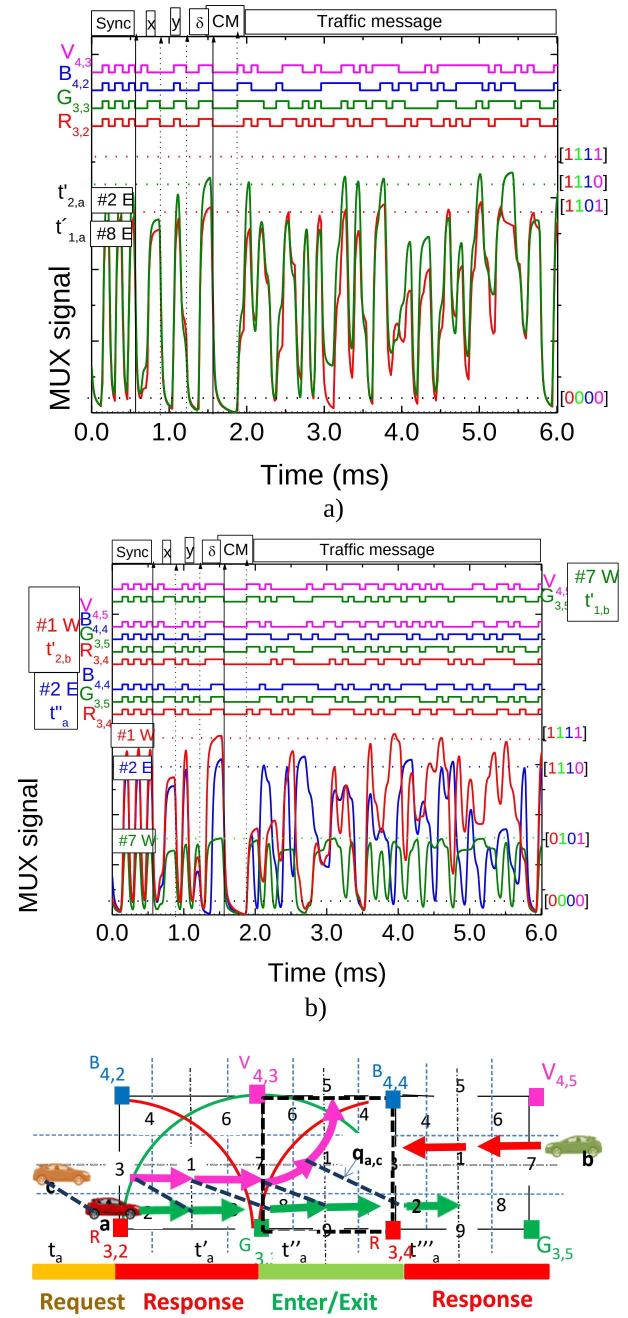


Figure 6. Normalized MUX signal responses and the assigned decoded messages at different response times. On the top the transmitted channels packets [R, G, B, V] are decoded. a) Before the crossroad. b) After the cross road. c) Movement of the cars, in the successive moments, with their colorful poses (color arrows) and q_{ac} spatial relative poses (dot lines).

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.

B. *Traffic Signal Phasing: V2X Communication*

A phasing diagram was presented in Figure 4, for functional areas with two-way-two-way intersection. A traffic scenario was simulated (Figure 3a) using the new concept of VLC request/response messages. A brief look into the process of timing traffic signals is given in Figure 7.

To design traffic-actuated controls, we consider *a*, *b*, *c*, *d*, *e*, and *f* vehicles requesting and responding message information to determine phase durations appropriate to meet demand. Each driving vehicle is assigned an individualised time to request (*t*) and access (*t´*) the intersection. The exclusive pedestrian stage, "Walk" interval begins at the end of Phase 5 (Figure 4b).

A first-come-first-served approach could be accomplished by accelerating or decelerating the vehicles so that they arrive at intersections when gaps have been created between conflicting traffic flows and pedestrians. However, a one-by-one service policy at high vehicle arrival rates is inefficient. From the capacity point of view it is more efficient, if Vehicle *c* is given access at t'_c before Vehicle *b*, at t'_b to the intersection and Vehicle *d* is given access at t'_d before Vehicle *e*, at t'_e then, forming a west left turn of set of vehicles (platoon) before giving way to the fourth phase (north and south conflicting flows), as stated in Figure 7. The speed of Vehicle *e* was reduced, keeping a safe distance between Vehicle *e* and Vehicle *d*.

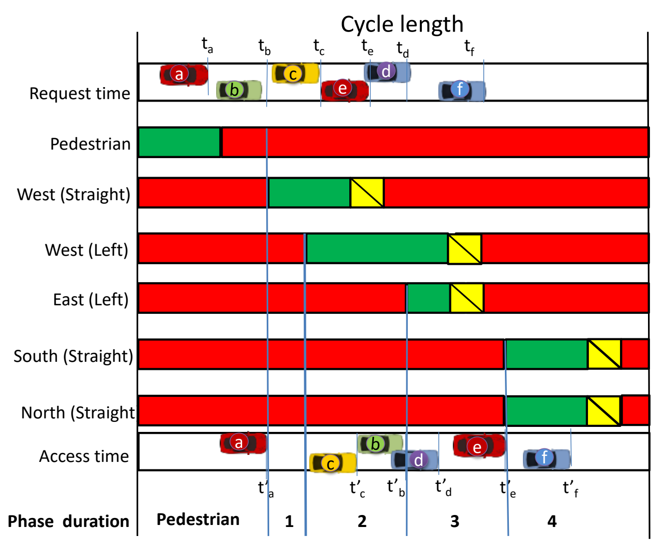


Figure 7. Requested phasing of traffic flows: pedestrian phase, Phase 1 (W straight flow), Phase 2 (W straight and left flows), Phase 3(W and E left flows), Phase 4 (N and S straight flows). $t_{[x]}$ is the request time from the Vehicle *x* and $t'_{[X]}$ the correspondent response time from the manage controller.

As a final remark, traffic light coordination using the V-VLC request-response concept facilitates traffic circulation, promoting smooth movement along the network, forming platoons with efficient speeds, preventing the formation of queues, avoiding congestion and delays. This is also an effective way to reduce excessive fuel consumption and preserve the environment through minimal air pollution.

To evolve towards real implementation, the performance of V-VLC system still needs improvement, namely the distance between conflicting vehicles along with the trajectories of other opposing vehicles should also be monitored and optimized.

VI. 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. The connected vehicles receive information from the network (I2V), interact with each other (V2V) and also with the infrastructure (V2I), using the request redesign distance concept. In parallel, a control manager coordinates the crossroad and interacts with the vehicles (I2V) using the response redesign distance concept. 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.

In order to evolve towards real implementation, the performance of such systems still needs improvement, namely the distance between conflicting vehicles along with the trajectories of other opposing vehicles should also be monitored and optimized. 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 UIDB/00066/2020. The project IPL/IDI&CA/2020/Geo-Loc/ISEL, was also acknowledge.

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