Visible Light Communication in Vehicular Communication Applications

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Abstract— This paper addresses the issues related to the Visible Light Communication (VLC) usage in vehicular communication applications. We propose a Visible Light Communication system based on Vehicle-to-Vehicle, Vehicle-to-Infrastructure and Infrastructure-to-Vehicle communications able to safely manage vehicles crossing through an intersection. By using the streetlamps, street lights and traffic signaling to broadcast information, the connected vehicles interact with one another and with the infrastructure. Using joint transmission, mobile optical receivers collect data, calculate their location for positioning and, concomitantly, read the transmitted data from each transmitter. As receivers and decoders, optical sensors with light filtering properties, are used. Bidirectional communication between the infrastructure and the vehicles is tested. To command the passage of vehicles safely queue/request/response mechanisms and temporal/space relative pose concepts are used. The results show that the innovative solutions for congested intersections are related to the introduction of split intersections. The results indicate that the V-VLC system increases safety by directly monitoring critical points such as queue formation and dissipation, relative speed thresholds, as well as inter-vehicle spacing.

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Keywords- Vehicular Communication; Split Intersection; Queue distance; Vehicle Pose Connectivity; Vehicular-Visible Light Communication (V-VLC); White LEDs, SiC photodetectors; Traffic control.

I. INTRODUCTION

Vehicles can connect to others, or to the infrastructure, providing an Internet connection [1]. In this area, VLC have a great potential for applications due to their relatively simple design for basic functioning, efficiency, and large geographical distribution.

The main objective of the Intelligent Transport System (ITS) technology is to optimize traffic safety and efficiency on public roads by increasing situation awareness and mitigating traffic accidents through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [2] [3] [4]. By knowing, in real time, the location, speed and direction of nearby vehicles, a considerable improvement in traffic management is expected. The goal is to increase the safety and throughput of traffic intersections using cooperative driving. Intersections, by their nature, easily become traffic bottlenecks and conflict areas because they usually cause considerable delays due to congestion problems. In the split intersection, the conventional four-legged intersection is replaced by two separate lighter intersections which facilitate a smoother flow with less driver delay [5][6].

VLC is an emerging technology [7][8] that enables data communication by modulating information on the intensity of the light emitted by LEDs. In the case of vehicular communications, the use of VLC is made easier because all vehicles, street lights, and traffic lights are equipped with LEDs, using them for illumination. Here, the communication and localization is performed using the street lamps, the traffic signaling and the head and tail lamps, enabling the dual use of exterior automotive and infrastructure lighting for both illumination and communication purposes [9][10].

Our work focuses directly on the use of VLC as a support for the transmission of information providing guidance services and specific information to drivers. A Vehicle-to-Everything (V2X) traffic scenario is simulated and bidirectional communication between the infrastructure and the vehicles is tested, using the VLC request/response concept. Every vehicle is equipped with a receiver module for receiving the mapped information generated from the street lamps. The receiver modules include a photodetector based on a tandem a-SiC:H/a-Si:H pin/pin light controlled filter [11][12] that multiplex the different optical channels, perform different filtering processes (amplification, switching, and wavelength conversion) and decode the encoded signals, recovering the transmitted information. Here, the streetlights and traffic lights, through VLC, report its geographical positions and specific information to the drivers since its infrastructure can also be reused to embed the edge/fog nodes in them. Cooperative localization is realized in a distributed way with the incorporation of the indirect V2V relative pose estimation method. The vehicle gathers relevant data from neighboring vehicles and estimates the relative pose of them using the indirect V2V relative pose.

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 experimental results are reported and the system evaluation performed. A phasing traffic flow diagram based on V-VLC is developed, as a Proof of Concept (PoC), to control the arrival of vehicles to the split intersection. Finally, in Section 4, the main conclusions are presented.

II. V-VLC VEHICULAR COMMUNICATION

While V2V links are particularly important for safety functionalities such as pre-crash sensing and forward collision warning, I2V links provide the connected vehicles with a variety of useful information [13] [14].

A. *System Design*

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 1.

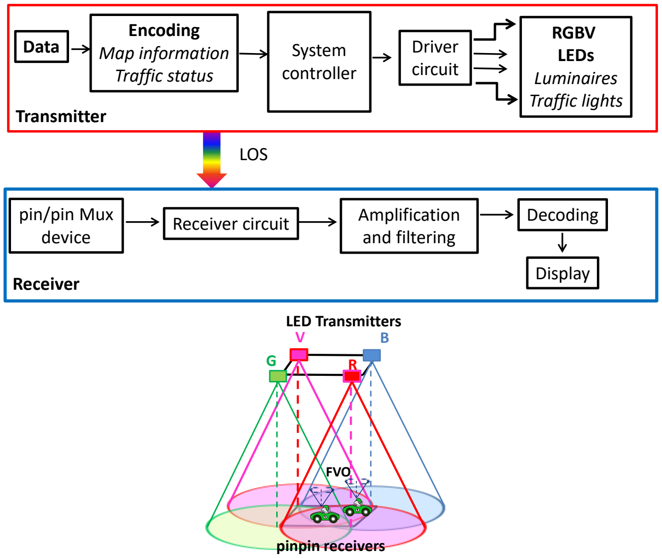

Figure 1. Block diagram and transmitters and receivers 3D relative positions.

Both communication modules are software defined, where modulation/ demodulation can be programed. In the transmission side, a modulation and conversion from digital to analog data is done. An On-Off Keying (OOK) modulation scheme was used to code the information [15] [16].The visible light emitted by the LEDs passes through the transmission medium and is received by the MUX device. White light tetra-chromatic sources are used providing a different data channel for each chip. Each luminaire is composed of four white LEDs framed at the corners of a square (see Figure 1). 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). Modulation and digital-to-analog conversion of the information bits is done using signal processing techniques.

The coverage map for a square unit cell is displayed in Figure 2. The LEDs are modeled as Lambertian sources where the luminance is distributed uniformly in all directions, whereas the luminous intensity is different in all directions [17].

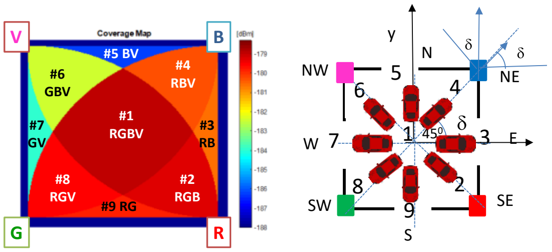

Figure 2. Illustration of the coverage map in the unit cell: footprint regions (#1-#9) and steering angle codes (2-9).

The input of the aided guidance system is the coded signal sent by the transmitters to an identify vehicle, and includes its position in the network *P(x, y)*, inside the unit cell and the steering angle, δ, that guides the driver across his path. The device receives multiple signals, finds the centroid of the received coordinates, and stores it as the reference point position. Nine reference points, for each unit cell, are identified giving a fine-grained resolution in the localization of the mobile device across each cell (see Figure 2). The VLC photosensitive receiver is a double pin/pin photodetector based on a tandem heterostructure, p-i'-n/p-i-n sandwiched between two conductive transparent contacts. Exposed to light, the device offers high sensitivity and linear response, generating a proportional electrical current.

B. *Architecture, Scenario and Multi-Vehicle Cooperative Localization*

In Figure 3a, the proposed architecture is illustrated. Under this architecture, the short-range mesh network purpose is twofold: enable edge computing and device-to-cloud communication, by ensuring a secure communication from a luminaire controller to the edge computer or datacenter (I2IM), through a neighbor traffic light controller with an active cellular connection; and enable peer-to-peer communication (I2I), to exchange information. It performs much of the processing on embedded computing platforms, directly interfacing to sensors and controllers. It supports geo-distribution, local decision making, and real-time load-balancing.

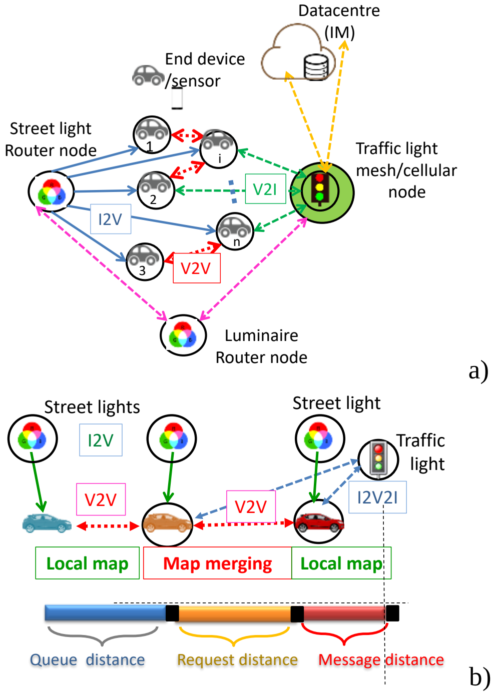

Figure 3. a) Mesh and cellular hybrid architecture. b) Graphical representation of the simultaneous localization and mapping problem using connectivity as a function of node density, mobility and transmission range.

A highly congested traffic scenario will be strongly connected. In order to determine the delay, the number of vehicles queuing in each cell at the beginning and end of the green time is determined by V2V2I observation, as illustrated in Figure 3b. Based on a truncated exponential distribution the distance, *d* between vehicles is calculated [18].

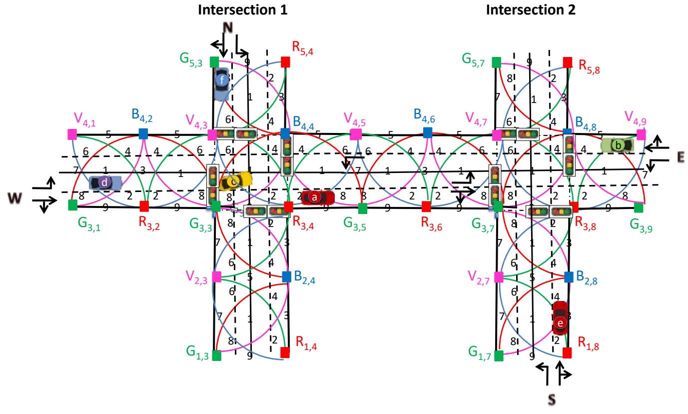

Figure 4. Simulated scenario. V2X optical infrastructure and generated joint footprints in a split crossroad (LED array=RGBV color spots).

The simulated scenario is a traffic light controlled split intersection as displayed in Figure 4. The grid size was chosen in order to avoid an overlap in the receiver from the data in adjacent grid points. 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 split crossroad is located in the intersections of line 4 with column 3 and 7 (see Figure 4). The emitters are located at the nodes along the roadside. Thus, each LED sends a I2V 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 a unique ID and the traffic message [16].

Figure 4 illustrates the split intersection, which has only one main street connecting two crossroads (Intersection 1-Intersection 2). Four traffic flows were considered. One is coming 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 types of messages, “request” (V2I) and “response” (I2V). Each driver, approaching the intersection area from each queue 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.

The request message is received and decoded by the receiver in the traffic light facing the lane (local controller) 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. Once the response is received (message distance in Figure 3b), 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.

There are critical points where traffic conditions change: the point at which a vehicle begins to decelerate when the traffic light turns red (message distance), the point at which it stops and joins the queue (queue distance), the point at which it starts to accelerate when the traffic light turns green (request distance) or the points at which the coming vehicle is slowed by the leaving vehicle. As a result, the road resistances can be calculated dynamically based on the relative pose positions of the vehicles and the traffic signal phase at intersections. With V2I2V communication, the travel time that influences traffic channelization in different

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routes can be calculated and real-time data about speed, spacing, queues, and saturation can be collected across the queue, request and message distances.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, *t* and *t'* are the request and cross times 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) [19, 20]. An Indirect V2V Relative Pose Estimation method is proposed in Figure 3b. 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. 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.

In Figure 5, a color phasing diagram in split intersection is shown. We have assumed four "color poses" linked with the radial range of the modulated light in the RGBV crossroad nodes [20].

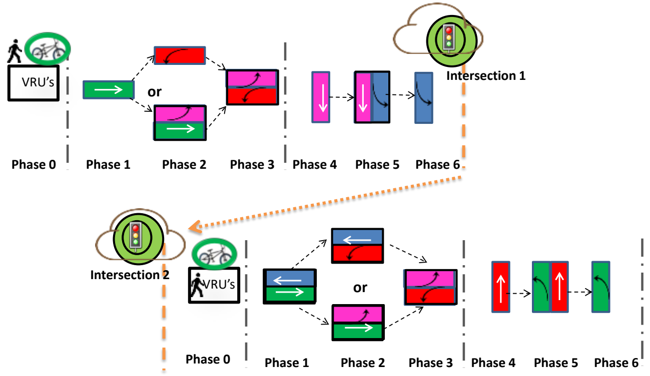

Figure 5 Phasing diagram in a split intersection

On the basis of the proposed phasing diagram, a phase for vulnerable road users (VRU's) only, as well as the separation of traffic flow in the North / South direction, allows the introduction of bike lanes at Intersection 1 (South and East straight movements) and Intersection 2 (North straight movements), reducing conflicts between vehicles and cyclists. The West straight, South left turn and West right turn maneuvers correspond to the "Green poses". "Red poses" are related with South straight, East left turn and South right turn maneuvers, "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 maneuvers.

C. Communication Protocol and Coding/Decoding Techniques

To code the information, an On-Off keying (OOK) modulation scheme was used and it was considered a synchronous transmission based on a 64- bits data frame. The frame is divided into four, if the transmitter is a streetlamp or headlamp, or five blocks, if the transmitter is the traffic light. The first block is the synchronization block [10101], the last is the payload data (traffic message) and a stop bit ends the frame. The second block, the ID block gives the location (*x*, *y* coordinates) of the emitters inside the array ($X_{i,j,}$). Cell's IDs are encoded using a 4 bits binary representation for the decimal number. The δ block (steering angle (δ)) completes the pose in a frame time *q(x,y, δ, t)*. Eight steering angles along the cardinal points and coded with the same number of the footprints in the unit cell (Figure 2) are possible from a start point to the next goal. 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 traffic message completes the frame.

Because the VLC has four independent emitters, the optical signal generated in the receiver can have one, two, three, or even four optical excitations, resulting in 2^4 different optical combinations and 16 different photocurrent levels at the photodetector. As an example, in Figure 6, the V2I MUX signals received and decode (on the top of the figures) is displayed for the split intersection. In the right side, the received channels are identified by its 4-digit binary codes and associated positions in the unit cell. On the top the transmitted channels packets [R, G, B, V] are decoded. In accordance with Figures 2 and 3, results show a request from vehicle *a*, when crossing Intersection 2 (Green pose; #2E: $R_{3,6}$ $G_{3,7}$, B $_{4,6}$ δ (3)) under Phase 1.

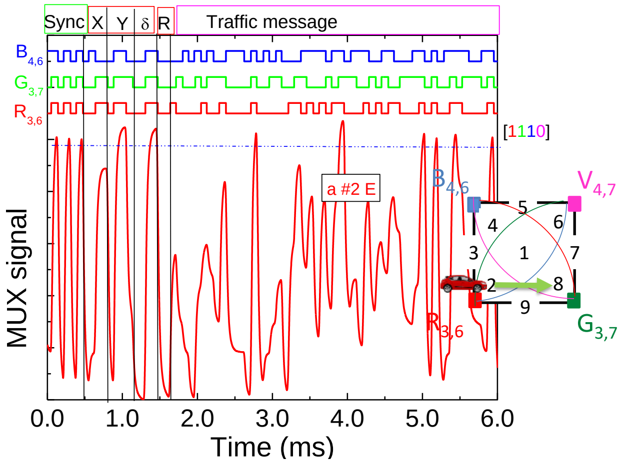

Figure 6 MUX signal and frame structure representation of a request message. On the top the transmitted channels packets are decoded [R, G, B, V].

III. EXPERIMENTAL EVALUATION

In Figure 7, it is displayed the normalized MUX signals and the decoded messages assigned to IM received by Vehicle *a*, *b* (Figure 7a) and *c* (Figure 7b) at different response times. On the top the transmitted channels packets [R, G, B, V] are decoded. In the right side, the received channels for each vehicle are identified by its 4-digit binary codes and associated positions in the unit cell.

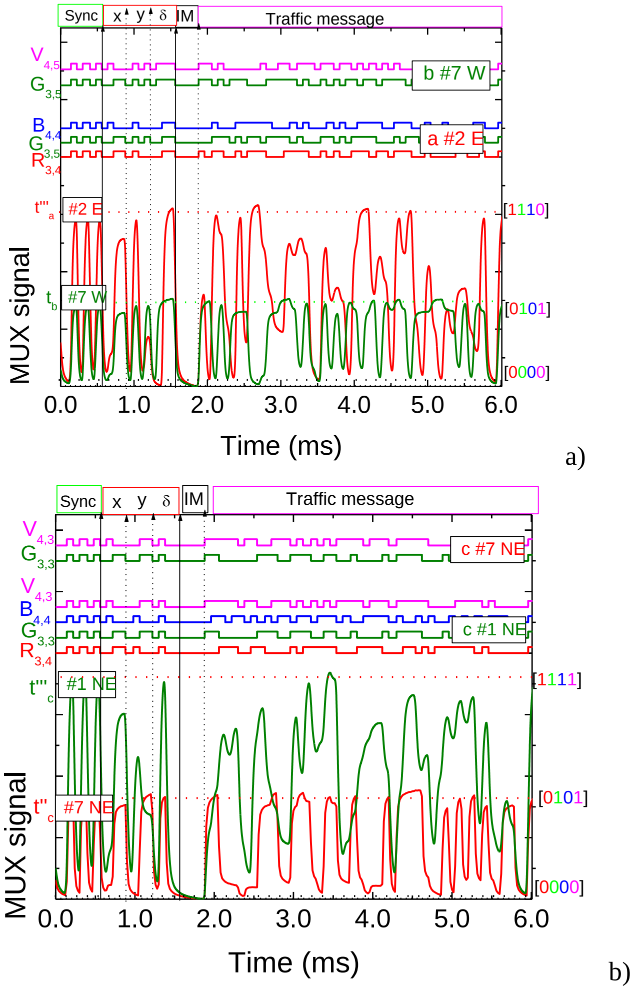

Figure 7 Normalized MUX signal responses and the assigned decoded messages acquired by vehicles *a*, *b* and *c* at different response times. On the top the transmitted channels packets [R, G, B, V] are decoded. a) Vehicle *a*, pose #2E, and vehicle *b*, pose #7W). b) Vehicle c, poses #7NE, #1NE.

Results show that, as the receiver moves between generated point regions, the received information pattern changes. Taking into account Figure 4 and Figure 6, Vehicle *a*, driving the right lane enters the response distance by #2 (t'_a, Phase1, green pose), goes straight to E. Then, this vehicle enters the crossroad through #8 (t''_a) and leaves it in the exit #2 at t'''_a , as displayed in the figure, keeping always the same direction (E). Vehicle *b* after crossing Intersection 2, approaches the Intersection 1, asked permission to cross it (t_b) and receives authorization when the vehicle *a* left the intersection (end of Phase 2, t'''_a). Then, Phase 3 begins with vehicle *b* heading to the intersection (W) (pose red) while vehicle *a* follows it destination towards E (green pose). In Figure 7b, signal responses and the assigned decoded messages from vehicle *c* inside the intersection are displayed at t''_c and t'''_c. Data shows that vehicle *c*, driving in the in the left lane, receives order to enter the intersection in # 7, turning left (NE) and keeps moving in this direction across position #1 toward the North exit (Phase 2, violet pose).

In both intersections, before the request of vehicle *d* to cross Intersection 1, the IM is aware through the request made by its leader *c* that a follower is approaching (*d*). Three actions must be taken to promote smooth movement avoiding congestions and delays: changing the synchronism of intersection 2, delaying the passage of vehicles *b* and finally, allowing the joint passage of vehicles *b* and *d* at Intersection 1 in the same phase (Phase 3).

Based on the simulated traffic scenario (Figure 4) and using the concept of V-VLC queue/request/response messages (Figure 3) a phasing diagram was drawn and reported in Figure 8.

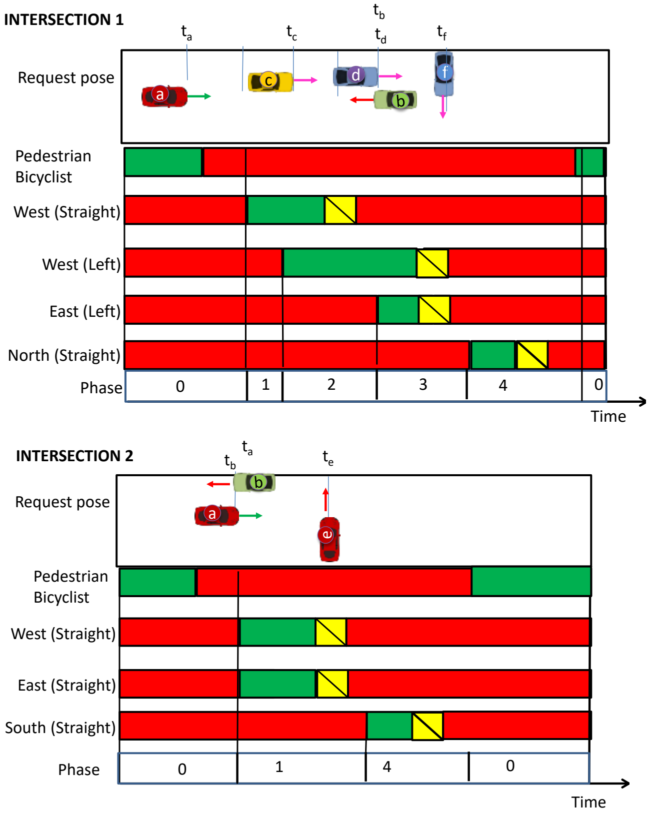

Figure 8 Requested phasing of traffic flows

The traffic controller uses queue, request and response messages, from the *a*, *b*, *c*, *d*, *e* and *f* vehicles, fusing the self-localizations $q_i(t)$ with theirs space relative poses $q_{ij}(t)$ to generate phase durations appropriate to accommodate the demand on each cycle. The driving Vehicle *x* with its pose representation is assigned a unique time to enter the intersection, *t[x]*. According to the phasing diagram (Figure 3), in Figure 8, the phasing flow for the split intersection is visualized: Intersection 1: Phases 0, pedestrian/bicyclist phase, Phase 1 (W straight flow), Phase 2 (W straight and left flows), Phase 3 (W and E left flows), Phase 4 (N straight flow); Intersection 2: Phases 0, pedestrian/bicyclist phase, Phase 1 (W and East straight flows), Phase 4 (S and right-turn approach flow. The exclusive pedestrian and bicyclist stage, "Walk" interval begins in both at the end of Phase 4.

IV. CONCLUSIONS

Using V-VLC-ready connected cars, we propose a queue/request/response approach for managing split intersections. A communication scenario is stablished and a "mesh/cellular" hybrid network configuration proposed. As a PoC, a phasing of traffic flows is suggested. In this study, the vehicles' arrival is controlled and they are scheduled to cross intersections at predetermined times to minimize traffic delays. V2I2V communication provides real-time data on queues, requests, and messages distances, including queue, request, and message travel times that influence traffic channeling in various routes. Compared with radio transceivers and directional antennas used in connected cars, visible light provides more accurate distance and position measurement thanks to its high directivity. Based on the simulated/experimental results, the proposed VLC cooperative architecture appears to be appropriate for the intended applications. The introduction of VLC between connected vehicles and the surrounding infrastructure allows the direct monitoring of critical points that are related to the queue formation and dissipation, relative speed thresholds and inter-vehicle spacing increasing the safety.

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