Adaptive Traffic Control Through Visible Light Communication

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Abstract— Monitoring the network traffic status of urban roads in real-time can provide rich and high-quality basic data and allow the assessment of traffic control effects. Our work focuses on the use of Visible Light Communication (VLC) as a support for transmission of information providing guidance to drivers, as well as specific information to them. Connected vehicles communicate with one another and with the infrastructure using street lights, street lamps, and traffic signals. As a result of joint transmission, optical mobile receivers collect data, calculate their location for positioning, and, correspondingly, read transmitted data from each transmitter. As receivers and decoders, optical sensors with light filtering properties, are used. To command the passage of vehicles safely queue/request/response mechanisms and temporal/space relative pose concepts are used. 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- Adaptative Traffic control; Queue distance; Vehicle Pose Connectivity; Vehicular-Visible Light Communication (V-VLC); White LEDs, SiC photodetectors.

I. INTRODUCTION

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 [1] [2] [3]. 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 [4].

The traffic data collected by the current traffic control system using induction loop detector and other existing sensors is limited. With the advancement of the wireless communication technologies and the development of the V2V and V2I systems, called Connected Vehicle, there is an opportunity to optimize the operation of urban traffic network by cooperation between traffic signal control and driving behaviors. In this area, Visible Light Communication (VLC) has a great potential for applications due to their relatively simple design for basic functioning, efficiency, and large geographical distribution. VLC is an emerging technology [5] 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, enabling the dual use of exterior automotive and infrastructure lighting for both illumination and communication purposes [6].

The adaptive traffic control strategy aims to respond to real-time traffic demand through current and predicted traffic flow data modeling. The adaptive traffic control system in a vehicle-to-everything (V2X) environment can collect more detailed information than the fixed coil detector, such as vehicle position, speed, queue length, and stopping time. 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 [7] [8].

Monitoring the network traffic status of urban roads in real-time can provide rich and high-quality basic data and allow the assessment of traffic control effects.

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. This paper is organized as follows. After the introduction, in Section 2, the V-VLC communication link 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). Finally, in Section 4, the main conclusions are presented.

II. V-VLC COMMUNICATION LINK

In this section, the transmitter and receiver of the proposed adaptive traffic control system are investigated concretely. The adaptive model is introduced specifically.

A. *System Design*

A V-VLC system consists of a transmitter to generate modulated light and a receiver to detect the received light variation located at the infrastructures and at the driving cars. Both the transmitter and the receiver are connected through the wireless channel.

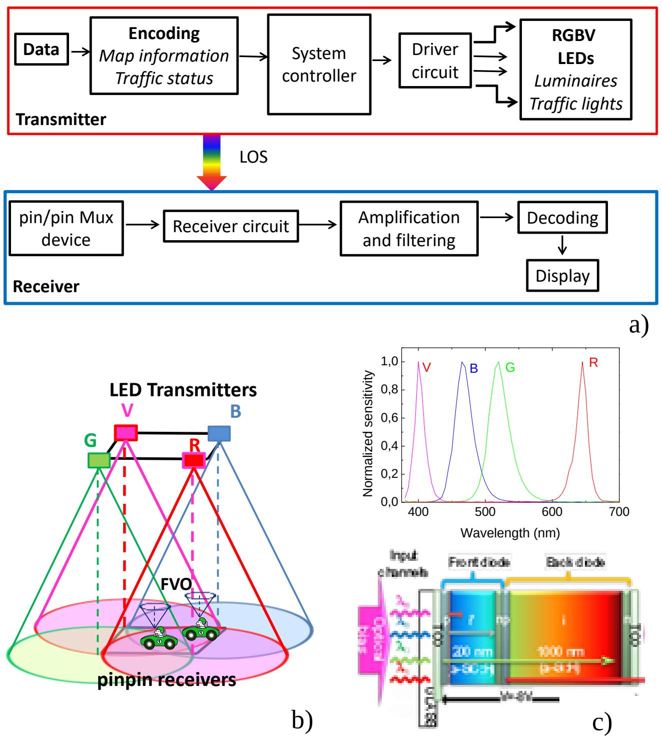

Figure 1. a) Block diagram of a VLC Communication link. b) Transmitters and receivers 3D relative positions. c) Spectra of the input channels and configuration and operation of the pin/pin Mux device

Figure 1 illustrates the basic architecture of a VLC system. Both communication modules are software defined, where modulation/ demodulation can be programed.The VLC emitter has a dual purpose, emits light, and transmits data instantaneously by using the same optical power without any noticeable flickering. The digital VLC emitter module converts the binary data to intensity modulated light waves for transmission. A driving circuit controls the switching of the LED according to the incoming binary data at the given data rate, generating an amplitude modulated light beam. Here, the light produced by the LED is modulated with ON–OFF-keying (OOK) amplitude modulation [9].

White light tetra-chromatic sources are used providing a different data channel for each chip. Each luminaire is composed of four white WLEDs framed at the corners of a square (see Figure 1b). They consist of red, green, blue and violet chips and combine the lights in correct proportion to generate white light. 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. Parasitic capacitance (traces and support circuitry) plays an important role in increasing the RC time constant and thus slowing transitions. However, the typical bit rates that can be supported by fast moving vehicles is usually limited by channel conditions, not by the switching speed of the LED.

The visible light emitted by the LEDs passes through the transmission medium and is received by the *MUX* photodetector that acts as an active filter for the visible region of the light spectrum [10]. The device operation is displayed in Figure 1c. Independent tuning of each channel is performed by steady state violet optical bias superimposed from the front side of the device. The generated photocurrent is measured at -8V. The MUX photodetector multiplexes the different optical channels, perform different filtering processes (amplification, switching, and wavelength conversion) and decode the encoded signals, recovering the transmitted information.

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 [11]. The coverage map for a square unit cell is displayed in Figure 2. All the values were converted to decibel (dB).The nine possible overlaps (#1-#9), defined as fingerprint regions, as well as the possible receiver orientations (steering angles; δ) are also pointed out for the unit square cell.

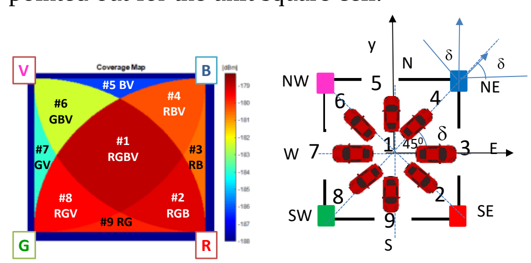

Figure 2. Illustration of the coverage map in the unit cell: footprint regions (#1-#9) and steering angle codes (2-9).

The received channel can be expresssed as $y=\mu hx+n$ where y represents the received signal, x the transmitted signal, μ is the photoelectric conversion factor which can be normalized as $\mu = 1$, h is the channel gain and n is the additive white Gaussian noise of which the mean is 0. The responsivity of the receiver depends on its physical structure and on the effective area collection. After receiving the signal, it is in turn filtered, amplified, and converted back to digital format for demodulation. The received signal power includes both the energy transmitted from the transmitter and from ambient light. 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 input of the guidance system is the coded signal sent by the transmitters to an identify vehicle (I2V), and includes its position in the network $P(x_i, y_j)$, inside the unit cell (#1-#9) and the steering angle, δ (2-9) that guides the driver orientation across his path.

B. 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. The simulated scenario is a traffic light controlled intersection as displayed in Figure 3.

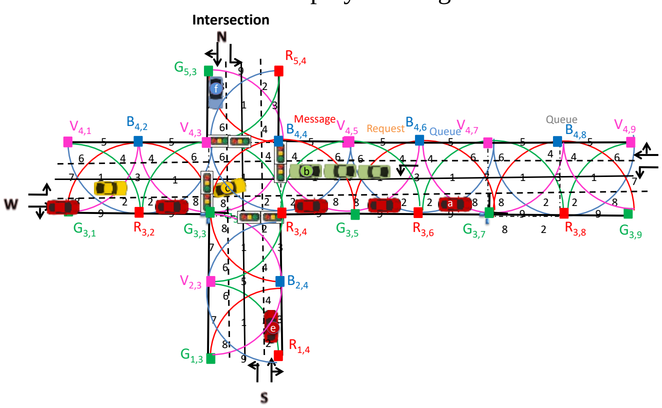

Figure 3. Simulated scenario. V2X optical infrastructure and generated joint footprints in a split crossroad (LED array=RGBV color spots).

Four traffic flows were considered. One is coming from West (W) with seven vehicles approaching the crossroad: five a_i Vehicles with straight movement and three c_i Vehicles with left turn only. In the second flow, three b_i Vehicles from East (E) approach the intersection with left turn only. In the third flow, *e* Vehicle, oncoming from South (S), has right-turn approach. Finally, in the fourth flow, *f* Vehicle coming from North, goes straight. Road request and response segments, offer a binary (turn left / straight or turn right) choice.

An orthogonal topology based on clusters of square unit cells was considered. 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 crossroad is located in the intersections of line 4 with column 3. The emitters (street lamps) 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.

Figure 4, presents a draft of a mesh cellular hybrid structure that can be used to create a gateway-free system.

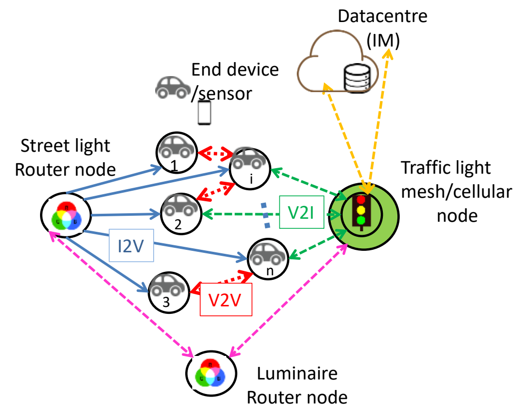

Figure 4. Mesh and cellular hybrid architecture.

The street lights 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, acting like routers nodes in the network. 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 [12]. This architecture enables edge computing and device-to-cloud communication (I2IM), 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.

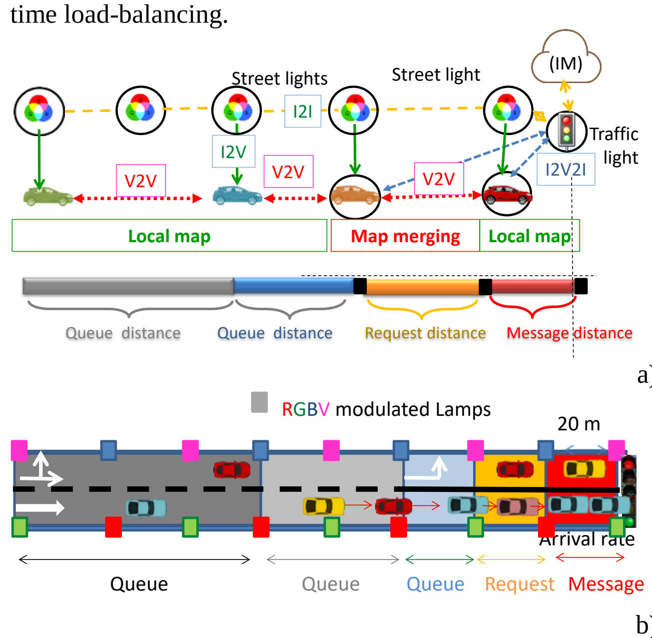

Figure 5. a) Graphical representation of the simultaneous localization as a function of node density, mobility and transmission range. b) Design of the state representation in the west arm of the intersection, with cells length.

As exemplified in Figure 5, the vehicle movement along the road can be thought as a queue, where the vehicles arrive at a lane, wait if the lane is congested and then move once the congestion reduces. For the intersection manager crossing coordination, the vehicle and the IM exchange information through two types of messages, "request" (V2I) and "response" (I2V). Inside the request distance, an approach "request" is sent, using as emitter the headlights. The "request" contains all the information that is necessary for a vehicle's space-time reservation for its intersection crossing (speeds, and flow directions). IM uses this information to convert it in a sequence of timed rectangular spaces that each assigned vehicle needs to occupy the intersection. The objective is to let the IM knows the position of vehicles inside the environment at each step *t*

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 5a. An IM acknowledge is sent, "response" 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 5, 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.

C. *Color Phasing diagram*

A color phasing diagram for a four-legged intersection is shown in Figure 6. We have assumed four "color poses" linked with the radial range of the modulated light in the RGBV crossroad nodes [13].

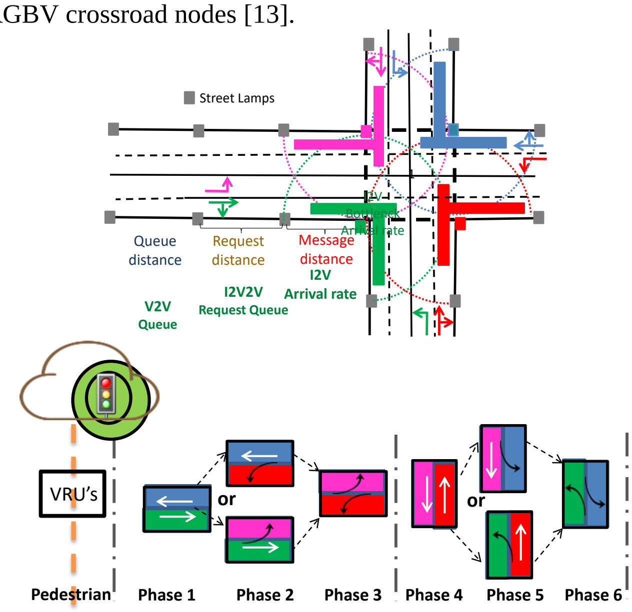

Figure 6. Phasing diagram in a four-legged intersection.

The West straight, South left turn and West right turn maneuvers correspond to the" Green poses". "Red poses" are related to South straight, East left turn, and South right turn maneuvers. "Blue poses" are related to East straight, North left turn, and East right turn maneuvers, and "violet poses" are related to North straight, West left turn, and North right turn maneuvers.

D. *Multi-Vehicle Cooperative Localization*

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. With V2I2V communication, the travel time that influences traffic channelization in different routes can be calculated and real-time data about speed, spacing, queues, and saturation can be collected across the queue, request and message distances. In Figure 7, the movement of the cars in successive moments is depicted with their colored poses (colored arrows) and $q_{i,j}$ spatial relative poses (dot line).

We denote *q(t), q(t´), q(t´´), q(t´´´)* as the vehicle pose estimation at the time *t, t´, t´´, t´´´* (request, response, enter and exit times), respectively. All the requests contain vehicle positions and approach speeds. If followers exist the request message from its leader includes the position and speed previously received by V2V. This information alerts the controller to a later request message (V2I), confirmed by the follow vehicle. In the PoC we have assumed that $t_{a1}<t_{b1}<t_{a2}<t_{b2}<t_{a3}<t_{c1}<t_{b3}<t_e<t_{a4}<t_{c2}<t_{a5}<t_f$.

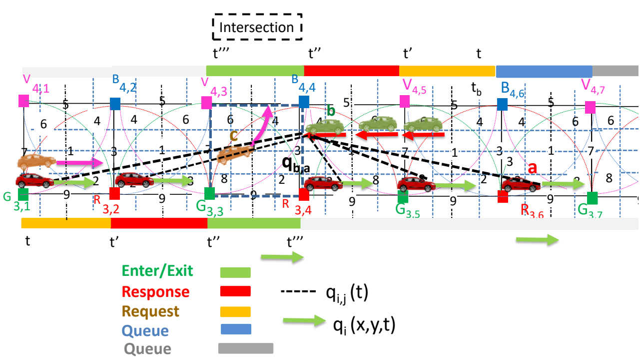

Figure 7 Movement of the cars, in the successive moments, with their colorful poses (color arrows) and $q_{i,j}$ spatial relative poses (dot lines).

The vehicle speed can be calculated by measuring the actual travelled distance overtime, using the ID´s transmitters tracking. The receivers compute the geographical position in the successive instants (path) and infer the vehicle's speed. When two vehicles are in neighborhood and in different lanes, the geometric relationship between them ($q_{i,j}$) can be inferred 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 [13].

III. EXPERIMENTAL EVALUATION

A. *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.

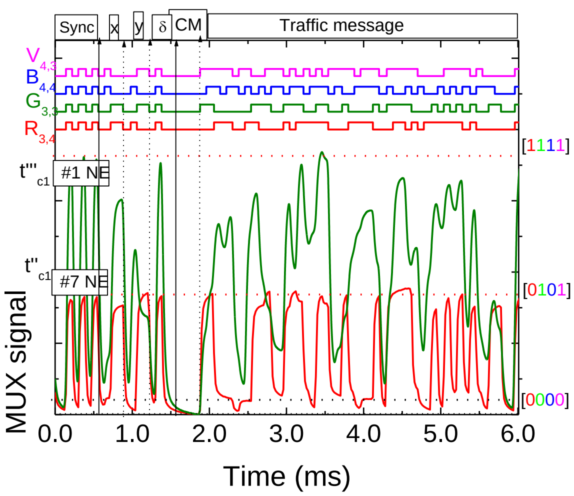

Figure 8 MUX signal responses and the assigned decoded inside the intersection; messages acquired by vehicle c_1, poses #7NE, #1NE. On the top the transmitted channels packets [R, G, B, V] are decoded.

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 8, two response MUX signals received by vehicle c_1 are displayed. This vehicle, driving on 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 (Phase2, violet pose). 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.

B. *Adaptive Traffic Control*

In Figure 9, the normalized MUX signals and the decoded messages assigned to IM received by Vehicle a_1, b_1 at different response times are shown. On the top the transmitted channels [R, G, B, V] are decoded.

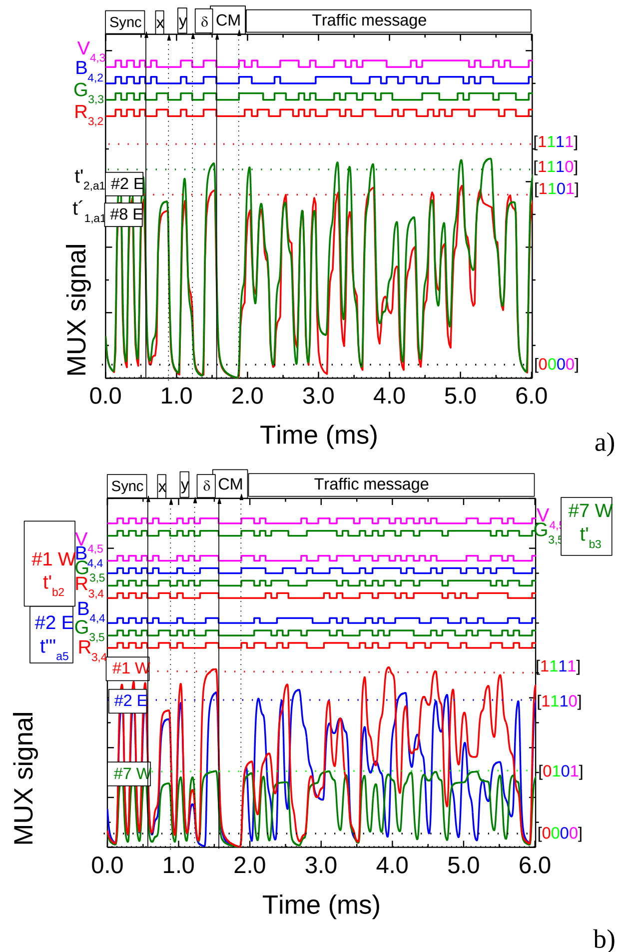

Figure 9 Normalized MUX signal responses and the assigned decoded messages acquired by vehicles a_5, b_2, b_3 at different response times. a) Vehicle a_1, poses #8E and #2E. b) Vehicle a_5, pose #2E, and Vehicle b_2 poses #7W and, b_3 at #1W.

Figuring out Figures 3 and 6, Figure 9a shows the MUX signals assigned to response messages received by Vehicle a_1, driving the right lane, that enters Cell $C_{4,2}$ in #2 (t'$_1$, Phase1, green pose), goes straight to E to position #8 (t'$_2$, Phase1, green pose). Then, this vehicle enters the crossroad through #8 and leaves it in the exit #2 keeping always the same direction (E). In Figure 9b, vehicles b_2 and b_3 approach the intersection after having asking permission to cross. Upon the last follower vehicle a_5 leaving the intersection

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(end of Phase 2), they receive authorization. Then, Phase 3 begins with vehicle b_1 heading to the intersection (W) (pose red) while vehicles a_i ($1<i<5$) follows its destination towards E (pose green).

C. *Traffic Signal Phasing*

The traffic controller uses queue, request and response messages, from the a_i, b_i, c_i, e_i and f_i vehicles, fusing the self-localizations $q_i(t)$ with theirs space relative poses $q_{ij}(t)$ (dotted lines in Figure 7) to generate phase durations appropriate to accommodate the demand on each cycle.

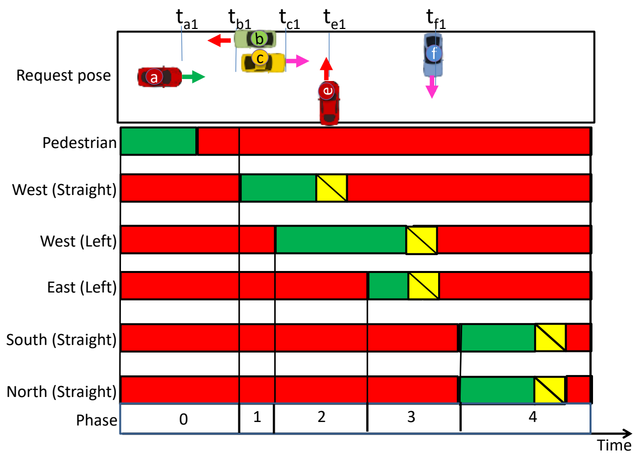

Figure 10 Requested phasing of traffic flows

Vehicle x is assigned a unique time to enter the intersection, $t[x]$. According to the phasing diagram (Figure 6), in Figure 10, the phasing flow for the intersection is visualized. From the capacity point of view it is more efficient, if Vehicle c_1 is given access before Vehicles b_i, and Vehicle c_2 is given access before Vehicle e, 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 8. The speed of Vehicle e was reduced, keeping a safe distance between Vehicle e and Vehicle d.

IV. CONCLUSIONS

Using V-VLC-ready connected cars, we propose a queue/request/response approach for managing four-legged 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. Delays between left-turns and forward movements are also allocated taking into account the pose analysis. 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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