# VLC Connected Cooperative Driving

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

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

***Abstract*—Using a new concept of request/response in a two-way-to-way traffic light controlled crossroad, the redesign of the trajectories can be accomplished by the application of methods for navigation, guidance and combination of expert knowledge of vehicle road traffic control. In this work, the bi-directional communication between the Vehicles (V2V), between vehicles and Infrastructures (V2I)) is performed through Visible Light Communication (VLC), using the street lamps and the traffic signaling to broadcast the information. Data is encoded, modulated and converted into light signals emitted by the transmitters. Tetra-chromatic white sources are used, providing a different data channel for each chip. As receivers and decoders, SiC Wavelength Division Multiplexer (WDM) devices, with light filtering properties, are considered. A Vehicle-to-Everything (V2X) traffic scenario is proposed, and bidirectional communication between the infrastructure and the vehicles is tested, using the VLC request/response concept. A phasing traffic flow is developed as a proof of concept. The experimental results confirm the cooperative VLC architecture. A significant increase in traffic throughput with the least dependency on infrastructure is achieved.**

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

## I. INTRODUCTION

Connected Autonomous Vehicles (CAVs) [1][2][3]. To increase the efficiency of traffic management and control, many efforts have been made. Two technical challenges were considered: trajectory redesign and real-time traffic planning. Our goal is to increase the safety and throughput of traffic intersections using VLC connected cooperative driving.

For vehicular communications, two emerging technological trends in the vehicular industry are reshaping the physical world, which are corresponding to the self-driving and remote driving technologies [4][5]. To enable both driving technologies, massive Vehicle-to-Everything (V2X) communications will be studied and incorporated in 6G [ 6 ]. V2X communication technologies give new possibilities to autonomous cars, since they create the opportunity for constant cooperation among different vehicles and between vehicles and intelligent road infrastructure, thus making tasks like route planning and accident avoidance much easier. Communication between fixed locations and vehicles is essential to transfer information in real time. Here, the communication is performed through VLC [7][8] using the street lamps and the traffic signaling to broadcast the information.

The proposed system is composed of several transmitters, the street lights and the traffic signals, which transmit map information and traffic messages required to the moving vehicles. Data is encoded, modulated and converted into light signals emitted by the transmitters. Then, this information is transferred to receivers installed in the vehicles. Tetra-chromatic white sources are used providing a different data channel for each chip. The receiver modules include a photodetector based on a tandem a-SiC:H/a-Si:H pin/pin light controlled filter [9][10][11].

In this work, a two-way communication between vehicles and the traffic lights is implemented, using VLC. The redesign of the trajectory, inside a complex intersection, is presented. Street lamps and traffic lights broadcast the information. The On-vehicle VLC receivers decode the messages and perform V2V distance measurements. An I2X traffic scenario is proposed and characterized. A phasing traffic flow is developed as a Proof-of-Concept (PoC). The arrival of vehicles is controlled and scheduled to cross the intersection at times that minimize delays. Delays between left-turns and forward movements are also allocated. The simulated results confirm that the redesign of the intersection and its management through the cooperative request/response VLC architecture allows to increase the safety and to decrease the trip delay.

In this paper, a traffic scenario for a light controlled crossroad is proposed, along with the transmitter to receiver setup. The paper is organized as follow. After the introduction (Section I), in Section II, the performance of a cooperative driving system is analyzed. To achieve cooperative vehicular communications (I2X), streams of messages containing the ID physical address of the emitters are used, transmitting a codeword that is received and decoded by the SiC pin/pin devices. As a PoC, in Section

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III, a traffic scenario with bidirectional cooperative communication between the infrastructures and the vehicles is presented and tested. Finally, in Section IV, conclusions are addressed.

## II. VEHICULAR COMMUNICATION

Vehicular communication using visible light is analysed using redesign concepts were the request/response idea between the vehicles and the infrastructures is implemented.

### *A. Redesign Concepts*

The redesign of the traffic-actuated controller uses a vehicle request/respond message information.

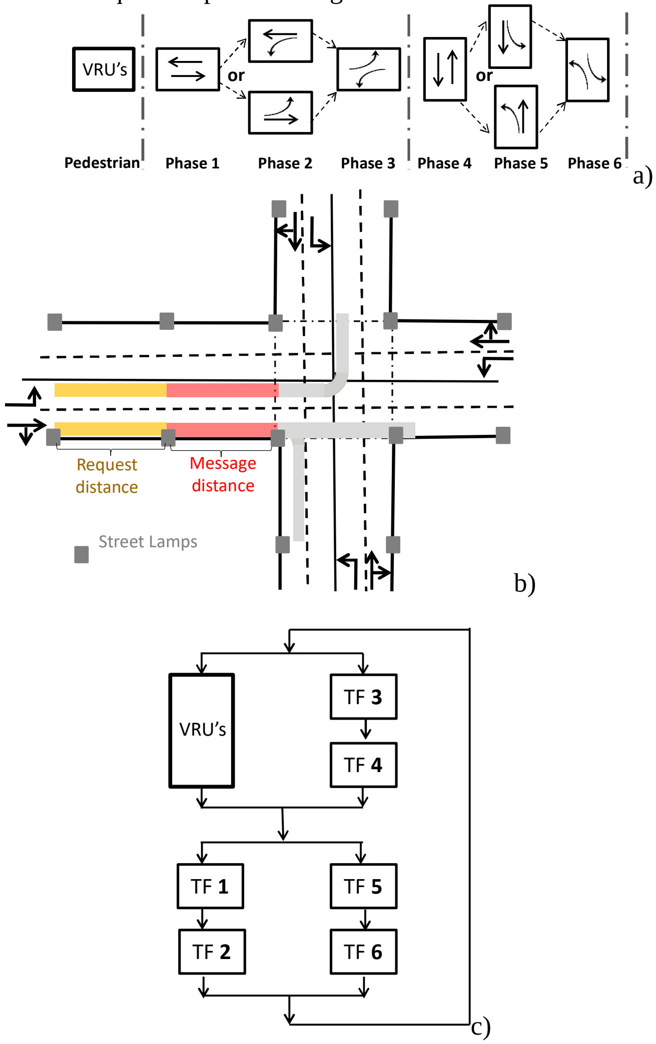


Figure 1. a) Representation of phasing diagram. b) Physical area and channelization. c) Timing function configuration.

This information generates phase durations appropriate to accommodate the demand on each cycle. Examples of the representation of a redesigned phasing diagram, a functional area with two-way-two-way intersection and a timing function configuration are presented in Figure 1. In Figure 1a, a phasing diagram is displayed. Each Timing Function (TF) controls only one movement. Since two movements can proceed simultaneously without conflict as shown in Figure 1b, hence two of the timing functions will always have simultaneous control, as exemplified in Figure 1c. The problem that the traffic-actuated intersection manager has to solve is to allocate the reservations among a set of drivers in a way that a specific objective is maximized. Signal timing involves the determination of the appropriate cycle length and apportionment of time among competing movements and phases. The timing apportionment is constrained by minimum "green" times that must be imposed to provide pedestrians to cross and to ensure that motorist expectancy is not violated.

The use of both navigation and lane control signs to communicate lane restrictions is demanding. Downstream from that location (request distance in Figure 1b), 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 Figure 1b). 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).

### *B. Virtual V2X scenario .*

To build the I2V, it is proposed a simplified cluster of unit square cells in an orthogonal topology that fills all the service area. 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. Thus, 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 interception of line 2 with column 3, and the emitters at the nodes along the roadside (Figure 2).

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. [ 12 ][ 13 ]. To receive the I2V information from several transmitters, the receiver must be located at the overlap of the circles that set the transmission range of each transmitter. The nine possible overlaps are displayed in Figure 2 for each unit square cell. 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 [14].

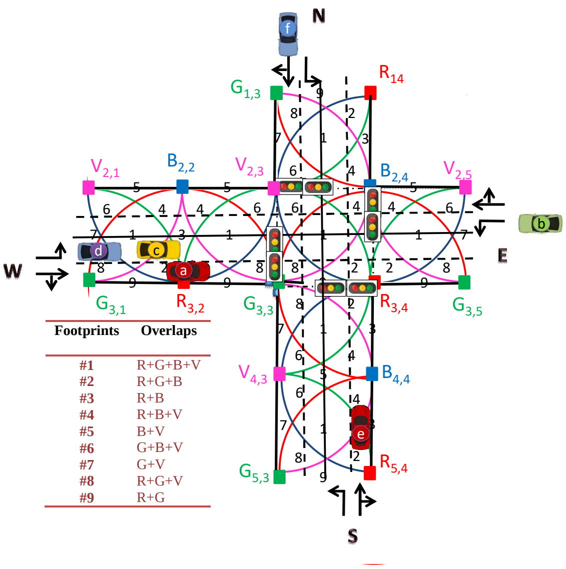


Figure 2 .V2X lighting plan model and generated joint footprints in a crossroad (LED array=RGBV color spots).

Four traffic flows were considered: 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 interception 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. Using the I2V communication, each street lamp (transmitter) sends a message, which is received and processed by a SiC receiver, located at the vehicle's rooftop. Using the headlights as transmitters, the information is resent to a leader vehicle (V2V) or, depending on the predefined occupied lane, a "request" message to go forward or turn right (right lane) or to turn left (left lane) is sent directly to a crossroad receiver (V2I), at the traffic light, interconnected to a local manager that feeds one or more signal heads. For crossroad coordination, a emitting local controller located at the light signal, sends a "response" message to the intersection approaching vehicles. In the following, bidirectional communication is stablished (V2I2V).

To build the V2V system, the follower sends the message that is received by the leader and can be retransmitted to the next car or to the infrastructure [15]. The leader vehicle infers the drive distance and the relative speed between them [16]. This information can be directed to the next car (V2V) or to an infrastructure (V2I).

For the intersection manager crossing coordination, the vehicle and the intersection manager exchange information through two specific types of messages, "request" (V2I) and "response" (I2V). 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). The "request" contains all 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 1b), the vehicle is required to follow the occupancy trajectories (footprint regions, Figure 2) 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.

### *C. Coding/decoding Techniques*

To encode the messages, an on-off keying (OOK) modulation scheme was used. The codification of the optical signals is synchronized and includes the information related to the ID position of the transmitters and the message to broadcast. We have considered a 32 bits codification as described in Figure 3.

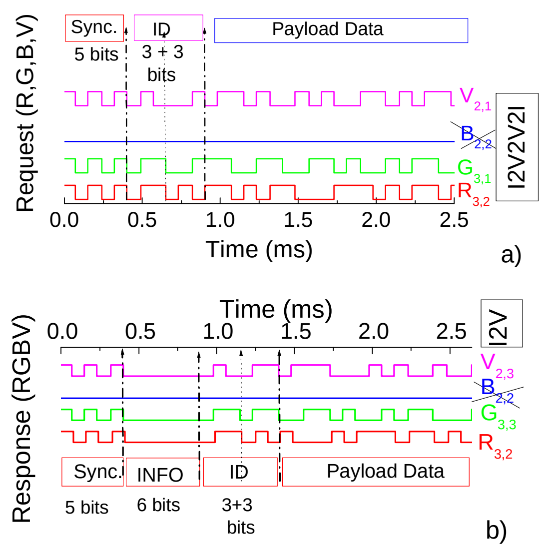


Figure 3 Frame structure representations. a) Codification used to drive the headlights of a vehicle in a request message from footprint #8. $R_{3,2}$, $G_{3,1}$, and $V_{2,1}$ are the transmitted node packet, in a time slot .b) Encoded message response of the controller to the request message of the vehicle in positio #8 ($R_{3,2}$, $G_{3,1}$, and $V_{2,1}$).

Each frame is divided into three or four blocks depending on the kind of transmitter: street lamps, headlamps (Figure 3a) or traffic light (Figure 3b). We assigned the first block to the synchronization (SYNC) in a [10101] pattern and the last one to the message to transmit (Payload Data). A stop bit is used at the end of each frame. Thus, $R_{3,2}$, $G_{3,1}$, and $V_{21}$ are the transmitted node packets, in a time slot by the headlamps. In Figure 3b, the second block (INFO) in a pattern [000000] means that a response message is being sent by the controller manager. Here, the signal controller responds to the request of the vehicle located in position # 8 ($R_{3,2}$, $G_{3,3}$, and $V_{23}$) at the request time. This response is received in the unit cell adjacent to the crossroad (message distance, Figure 1b) that shares a common node ($R_{3,2}$) with the request distance (see Figure 2).

In Figure 4, a MUX signal due to the joint transmission of four R, G, B and V optical signals, in a data frame, is displayed. The bit sequence (on the top of the figure) was chosen to allow all the *on/off* sixteen possible combinations of the four input channels ($2^4$).

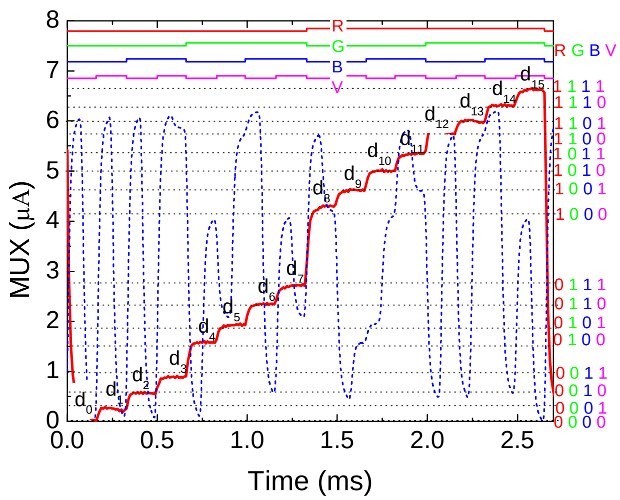


Figure 4. MUX signal of the calibrated cell. On the top the transmitted channels packets [R, G, B, V] are depicted. A received MUX signal is also superimposed to exemplify the decoding algorithm.

Results show that the code signal presents as much separated levels as the *on/off* possible combinations of the input channels, allowing decoding the transmitted information [9]. All the levels ($d_0$-$d_{15}$) are pointed out at the correspondent levels, and displayed as horizontal dotted lines. In the right hand side, the match between MUX levels and the 4 bits binary code assigned to each level is shown. For demonstration of the decoding technique, the signal transmitted in Figure 3a and received, in the same frame of time, is also added (dotted curve). Hence, the signal can be decoded by assigning each output level ($d_0$-$d_{15}$) to a 4- digit binary code [$X_R$, $X_G$, $X_B$, $X_V$], with X=1 if the channel is *on* and X=0 if it is *off*.

## III. Vehicular Communication

Vehicular communication based on LED assisted navigation is analyzed and the proof of concept presented.

### A. *Led assisted navigation, position and travel direction*

In Figure 5, for a I2V communication, the normalized MUX signals acquired by a receiver at the crossroad, in positions #1, #2, #4, #6 or #8, confirms the decoding process.

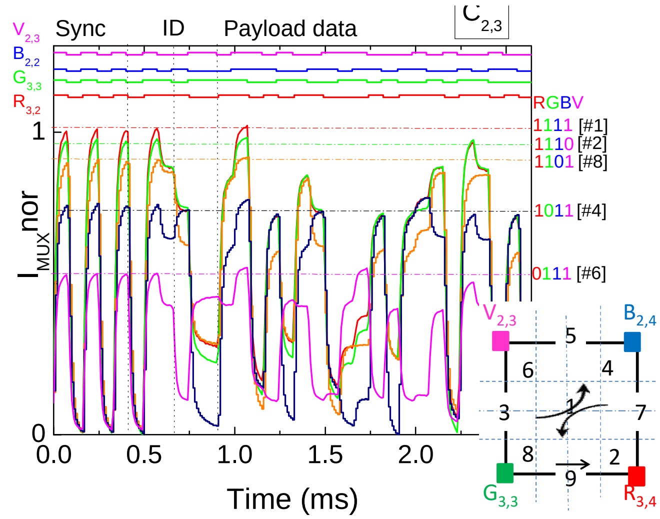


Figure 5. Normalized MUX signals acquired by a receiver at the crossroad, in positions #1, #2, #4, #6 or #8 On the top the transmitted channels packets [R, G, B, V] are decoded.

On the right hand side of the figure, the match between MUX levels and the 4 bits binary code ascribed to each higher level is shown. Decoding, when the four channels overlap (#1), is set on the top of the figure to direct into the packet sent by each node. After decoding the MUX signals, and taking into account, the frame structure (Figure 3), the position of the receiver in the unit cell and its ID in the network is revealed [17]. The footprint position comes directly from the synchronism block, where all the received channels are, simultaneously, *on* or *off* and is pointed out in the right hand of Figure 5. For instance, in #4 the maximum amplitude detected corresponds to the binary word [1011], meaning that it has received the joint transmission from the red, blue and violet channels. Each decoded message carries, also, the transmitter's node address. So, the next block of six bits gives it ID. In position #4 the network location of the transmitters are $R_{3,4}$ [011;100], $B_{2,4}$ [010;100] and $V_{2,3}$ [010;011 ]. The last block is reserved for the traffic message (Payload data). The stop bit (0) is used always at the end of each frame.

To compute the point-to-point along a path, we need the data along the path. Taking into account Figure 1 and Figure 5, in this example, Vehicle ***a*** enters the crossroad in position #8 and it goes straight to position #2 (Phase1, TF1), while vehicle *c* turn left, moving across position 1 (Phase2, TF2). In Phase3, TF3, Vehicle *b*, coming from East and Vehicle *d* coming from West, both turn left. The speed of Vehicle *b* was reduced, maintaining a safe distance between Vehicle *b* and Vehicle *a*. 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. Between two consecutive data sets, there is a navigation data bit transition (channel is missing or added). It was observed that when the receiver moves from #8 to # 2 (Figure 7) one ID channels was lost ($B_{2,4}$) and one are added ($V_{2,3}$). Here, the 4-bynary bit code has changed from [1101] to [1110] while Vehicle *c* and *d* change theirs from [1111] to [0011] and Vehicle *b* to [1100]. The spacing between reference points is fixed while the correspondent time integrated by the receiver varies and depends on the vehicle's speed. 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 at the traffic light through V2I.

## B. *Cooperative system and phasing diagram*

To model the worst-case scenario, vehicles approaching the intersection from different flows are assumed to have a conflicting trajectory (Figure 2). Two instants are considered for each vehicle, the request time (t) and the response time (t'). All the requests contain vehicle positions and approach speeds. If a follower exists (Vehicle *d*), 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 $t_a<t_c<t_d$, and $t_a<t_b<t_c$.

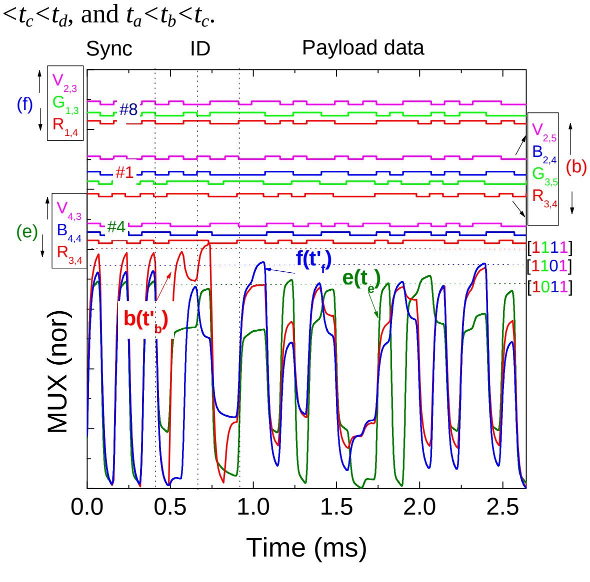


Figure 6. MUX signals and the assigned decoded messages (at the top of the figure) from vehicles *b*, *e* and *f* at different request and response times (I2V).

As an example, in Figure 6, the I2V MUX signals received and decode (on the top of the figure) by the receivers of the vehicles *b*, *e* and *f* are also displayed at request ($t_e$) and ($t'_b$ and $t'_f$) response times. 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 After decoding we have assigned position #4 ($R_{3,4}\,G_{4,4}\,V_{4,3}$) for Vehicle *e*, position #1 ($R_{3,4}\,G_{3,5}\,B_{2,4}\,V_{2,5}$) for Vehicle *b* and position #8 ($R_{1,4}\,G_{1,3}\,V_{2,3}$) to Vehicle *f* , respectively at theirs request and response times $t_e$ , $t'_b$ and $t'_f$ . Here, $t'_e<t'_f$.

## C. *Traffic Signal Phasing in a V2X Communication*

A phasing diagram and a timing function configuration were presented in Figure 1, for functional areas with two-way-two-way intersection. A traffic scenario was simulated (Figure 2) using the new concept of VLC request/response messages. A brief look into the process of timing traffic signals is given in Figure 7.

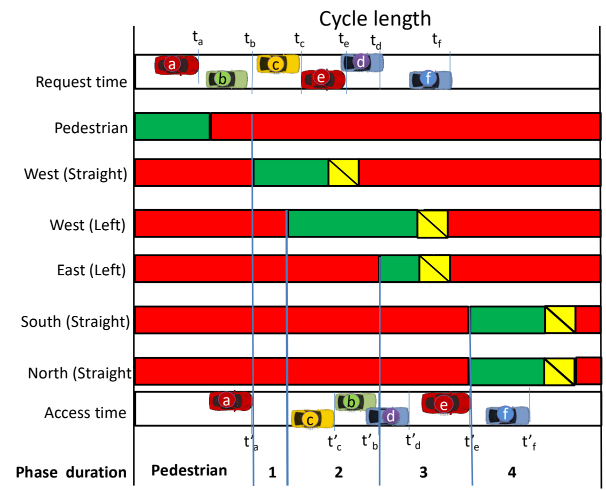


Figure 7 Requested phasing of traffic flows: pedestrian phase, Phase 1 (W straight flow), Phase 2 (W straight and left flows), Phase 3(W and E left flows), Phase 4 (N and S straight flows). $t_{[x]}$ is the request time from the Vehicle *x* and $t'_{[X]}$ the correspondent response time from the manage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

Redesign traffic-actuated controller uses *a*, *b*, *c*, *d*, *e* and *f* vehicles requesting and responding message information to generate phase durations appropriate to accommodate the demand on each cycle. Each driving vehicle is assigned an individualized time to request (*t*) and access (*t´*) the intersection. The exclusive pedestrian stage, "Walk" interval begins at the end of Phase 5 (see Figure 1).

A first-come-first-serve approach could be realized by accelerating or decelerating the vehicles such that they arrive at the intersection when gaps in the conflicting traffic flows and pedestrians have been created. However, a one-by-one service policy at high vehicle arrival rates is not efficient. 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.

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The speed of Vehicle *e* was reduced, keeping a safe distance between Vehicle *e* and Vehicle *d*.

## 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. 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.

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