VLC ready connected cars: trajectory redesign inside an intersection

Vieira, M. A., Vieira, M., Louro, P., Vieira, P.
VLC Ready Connected Cars: Trajectory Redesign Inside an Intersection

M. A. Vieira\textsuperscript{a,b}, M. Vieira\textsuperscript{a,b,c}, P. Louro\textsuperscript{a,b}, P. Vieira\textsuperscript{a,d}

\textsuperscript{a}Electronics Telecommunications and Computer Dept. ISEL/IPL, R. Conselheiro Emídio Navarro, 1949-014 Lisboa, Portugal
\textsuperscript{b}CTS-UNINOVA, Quinta da Torre, Monte da Caparica, 2829-516, Caparica, Portugal;
\textsuperscript{c}DEE-FCT-UNL, Quinta da Torre, Monte da Caparica, 2829-516, Caparica, Portugal;
\textsuperscript{d}Instituto de Telecomunicações, Instituto Superior Técnico, 1049-001, Lisboa, Portugal.

ABSTRACT

The redesign of the trajectories though complex, can be accomplished by the application of methods for navigation, guidance and combination of knowledge of road traffic control of vehicles. In this work the communication between the infrastructures and the vehicles, between vehicles and from the vehicles to the infrastructures is performed through Visible Light Communication (VLC) using the street lamps and the traffic signaling to broadcast the information. Vehicle headlamps and taillights are used to transmit data to other vehicles or infrastructures allowing digital safety and data privacy. 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 used. The primary objective is to control the arrival of vehicles to an intersection and schedule them to cross at times that minimize delays. A further objective is to allocate delays between left-turns and forward movements, moderating the speed and slot between vehicles travelling in these directions, maintaining a safe distance from one to another. Pedestrians and bicycles are incorporated. A Vehicle-to-Everything (V2X) traffic scenario is established 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 showing that communication between connected cars is optimized using a request/response concept. An increase in the traffic throughput with least dependency on infrastructure is achieved.

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

1. INTRODUCTION

Communication is a core function of interactive systems. Information has to be transmitted between sensors, control systems, user interface and network information. The Visible Light Communication (VLC) holds special importance when compared to existing forms of wireless communications \cite{1,2,3}. VLC seems to be appropriate for providing wireless data exchange for automotive applications in the context in which the LED lighting began to be widespread in transportation, being integrated in traffic infrastructures (street lighting and traffic signals) and in the vehicle lighting systems. In order to serve the changing needs of road traffic control, the road space and road structure surrounding an intersection have evolved into complex forms. Visible light represents a new communication opportunity for vehicular networking applications. The communication is performed through VLC using the street lamps and the traffic signaling to broadcast the information.

An Intersection Manager (IM) can increase the throughput of the intersection by exchanging information with and directing incoming Connected Autonomous Vehicles \cite{4,5,6,7}. 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. The first, although technically complex, can be accomplished by applying navigation, guidance and vehicle control methods. The second requires a combination of road traffic control expertise and analytical procedures.
Our goal is to increase the safety and throughput of traffic intersections using VLC connected cooperative driving. Two emerging technological trends are redesigning the physical world: the self-driving and the remote driving [8, 9]. To enable both, massive Vehicle-to-Everything (V2X) communications will be studied and incorporated in 6G, which will cover the way for high-reliability and low-latency, as well as secure exchange of massive driving and ambient data. 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 [10]. 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 (Infrastructure-to-Vehicle, I2V) between vehicles (Vehicle-to-Vehicle, V2V), and between vehicles and fixed locations (Vehicle-to-Infrastructure, V2I) is essential to transfer information in real time. The I2V applications focus on utilizing the traffic related infrastructure, such as traffic light or streetlight to communicate useful 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. Every street light is having their differentiable unique Identifications (IDs) for the generation of the visible light signal that transmits the map information through Visible Light Transmitter module. Tetra-chromatic white sources are used providing a different data channel for each chip. Every vehicle mounted mobile terminal, is equipped with a receiver module for receiving the mapped information generated from the street light and after displaying this generated information in the mobile terminal. The receiver modules include a photodetector based on a tandem a-SiC:H/a-Si:H pin/pin light controlled filter [11, 12, 13] that multiplex the different optical channels, perform different filtering processes (amplification, switching, and wavelength conversion) and decode the encoded signals, recovering the transmitted information.

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. A V2X 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.

2. VLC VEHICULAR COMMUNICATION

2.1 Redesign Concepts

Intersections are defined by both their physical and functional areas. The functional area consists of two basic elements: lane changing and requesting distance to cross or distance responding and queue storage and extends both upstream and downstream from the physical area and associated channelization. Usually, pre-timed controllers display fixed phase durations that repeat from cycle to cycle. “Redesign phasing” is generally more efficient than traditional pre-timed sequential phasing. The redesign of the traffic-actuated controller uses vehicle request/respond message information to generate 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 specification of the phasing plan requires that each of the traffic movements has to be accommodated and assigned to one of the timing functions, in order to produce the desired sequence of displays (Figure 1c). The choice of used treatments will determine which timing functions will be activated, and which will be omitted from the phasing plan. In the phasing diagram, Phase 2 and Phase 5 offer two alternatives. Only one of which may be displayed on any cycle. If the phasing is referred as “exclusive” the vehicles are stopped on all ways to an intersection, while pedestrians and bicycles are given a WALK indication. Functional barriers (dash dot lines in Figure 1a) exist between exclusive pedestrian and Phase 1and Phase 6. The separation between vehicles traveling in opposing simultaneous directions (Phase 3) should be adequate. Minimum separation may be acceptable where turning paths are highly visible and speeds are low.
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 (i.e., the time required to execute a complete sequence of phases) 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 traffic 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).

### 2.2 V2X communication scenario

The block diagram of the VLC system is presented in Figure 2. The system is composed by two modules: the transmitter and the receiver located at the infrastructures and at the driving cars.

![Block diagram](https://ebooks.spiedigitallibrary.org/conference-proceedings-of-spie)

A V2X (I2V2V2I2V) communication link, in a light traffic controlled crossroad, was simulated. 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
For crossroad coordination, an emitting local controller located at the light signal, send a “response” message to the intersection approaching vehicles. In the following, bidirectional communication is established (V2I2V). The crossroad link is displayed in Figure 3.

To build the I2V vehicular communication system, it is proposed a simplified cluster of unit square cells in an orthogonal topology that fills all the service area [15]. The luminaires are placed at the nodes of the network. To realize both the communication and the street illumination, white light tetra-chromatic sources are used providing a different data channel for each chip. A four-code assignment for the modulated LEDs was used. 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, $X_{ij}$, carries its own color, $X$, (RGBV) as well as its horizontal and vertical ID position in the surrounding network $(i,j)$. In Figure 3 the lighting plan and generated joint footprints in the crossroad region (LED array=RGBV modulated color spots) is displayed. In the PoC, was assumed that the crossroad is located in the interception of line 2 with column 3 of the network, and the emitters at the nodes along the roadside. The grid size was chosen in order to avoid an overlap in the receiver from the data from adjacent grid points. The geometric scenario used in the experimental results, uses a smaller size square grid (2 cm), to improve its practicality.

The VLC receiver transforms the light signal into an electrical signal that is subsequently decoded to extract the transmitted information. The VLC photosensitive receiver is a double pin/pin photodetector based on a tandem heterostructure, $p-i'(a$-$Si:H)-n/p-i'(a$-$Si:H)-n$ [11, 12]. Exposed to the visible light, the device offers high sensitivity and linear response, generating a proportional electrical current. Its quick response enables the possibility of high-speed communications. The obtained voltage is then processed, by using signal conditioning techniques (adaptive bandpass filtering and amplification, triggering and demultiplexing), until the data signal is reconstructed at the data processing unit (digital conversion, decoding and decision [14, 15]). 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, defined as fingerprint regions, are displayed in Figure 3 for each unit square 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 [16].

Figure 3. V2X lighting plan model and generated joint footprints in a crossroad (LED array=RGBV color spots).
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 and travel time along the considered section. Thus, the received message, acts twofold: as a positioning system and as a data receiver. Instead of estimating exact vehicle position, speed, and queues from point detector actuations, V2X communication allows the direct measurement of these values.

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 established (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 [17, 18] or to the infrastructure [15]. The follower vehicle is equipped with two headlamps transmitters. The leader vehicle is assumed to be equipped with three SiC pi’npi receivers, symmetrically distributed at the tails. The leader receives three signals, compares them and, based on their intensities, infers the drive distance and the relative speed between them [19]. This information can be directed to the next car (V2V) or to an infrastructure (V2I). Each vehicle can receive two messages; the streetlight (I2V) message and the follow vehicle message(V2V), and a comparison is performed.

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). Each driver, approaching the intersection area from each side (S, W, E or N), 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. To receive the “requests”, two different receivers are located at the same traffic light, facing the cross roads (local controller of the traffic light). Concretely, when one head vehicle enters in the infrastructure’s capture range of one of the receivers (request distance) the request message is received and decoded by the receiver facing the lane which is interconnected to the intersection manager. Those messages contain the assigned ID positions, speeds, and flow directions of the vehicles. The “request” contains all 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 3) 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.

2.3 Coding 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. Each frame is divided into three or four blocks depending on the kind of transmitter: street lamps, headlamps (Figure 4a) or traffic light (Figure 4b). 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. An example of the used codification to drive the headlamps LEDs of a vehicle, coming from W, located in the right lane in footprint #8 (\( R_{3,2} \), \( G_{3,1} \), and \( V_{21} \)) is illustrated in Figure 4a. Here, the second block (3+3 bits) is assigned to ID-BIT of the emitter; the first three bits give the ID binary code of the line and the next three the ID binary code of the column. Thus, \( R_{3,2} \), \( G_{3,1} \), and \( V_{21} \) are the transmitted node packets, in a time slot by the headlamps. In Figure 4b, a response message of the traffic controller emitter located at the traffic light is displayed. The second block (INFO) in a pattern [000000] means that a response message is being sent by the controller manager. The third block (6 bits) identifies the vehicle position (ID) for which the message is intended. Here, the signal controller
[000000] responds to the request of the vehicle located in position # 8 (R3,2, G3,3, and V23) at the request time (request distance). This response is received in the unit cell adjacent to the crossroad (message distance, Figure 1b) that shares a common node (R3,2) with the request distance (see Figure 3).

2.4 Decoding Techniques and Bit Error Control

In Figure 5a, a MUX signal (data) due to the joint transmission of four R, G, B and V optical signals, in a data frame, is displayed. The data bit sequence (R G B V; on the top of the figure) was chosen to allow all the on/off sixteen possible combinations of the four input channels (2^4). 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 [13]. All the levels (d0-d15) 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. Hence, the signal can be decoded by assigning each output level (d0-d15) 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.

The proximity of the magnitude of consecutive levels can leads to errors in the decoded information that should be checked and corrected using the parity bit control [20]. Error detection codes (parity bits, P_R, P_G, P_B) are generated as a function of the bits (R, G, B, V) being transmitted. Such codes are appended to the data bits and transmitted. The receiver calculates the code based on the incoming bits and compares it with the incoming code to check for errors. For a 4 input channel transmission, 3 parity channels are needed to define the parity bits generating channel redundancy. Thus, the encoder takes four input data bits [R G B V] and generates three additional parity bits to which corresponds one of
the eight \(2^3\) allowed levels generated by the parity MUX signal (parity in Figure 5a). The parity bits \([P_R, P_G, P_B]\) are defined as [21]:
\[
P_R = V \oplus R \oplus B \\
P_G = V \oplus R \oplus G \\
P_B = V \oplus G \oplus B
\] (1) (2) (3)

For parity check three red, green and blue channels were read in simultaneous with the data code \([P_R, P_G, P_B]\). The 7-bit word \([R G B V; P_R, P_G, P_B]\) at the output of the encoder will be read in a format with the data and the parity bits separated. In Figure 5a the received codeword that corresponds to"0001:111" (see arrow in figure) are in the same time slot. Since \(d_1\) is too near \(d_2\) the message (0010:111) could be measured instead, which is impossible since the \(d_2\) (0010) correspondent parity level is"101", is too far way). So, an error can be detected in the transmission and has to be corrected. In order to automate the process of decoding the original transmitted data an algorithm was developed and tested. The transmitted information is recovered by comparing, for the same time slot, both signals from the word and parity MUX levels as shown in Figure 5b. Here, for a I2V communication, the normalized MUX signal and its parity confirms the decoding process. On the right hand side of the figure, the match between higher MUX level and its 4 bits binary is shown. After decoding the MUX signals, and taking into account, the frame structure (Figure 4), the position of the receiver in the unit cell and its ID in the network is revealed [21]. 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. Results show that the receiver is in position \#1 since the maximum amplitude corresponds to the binary word [1111: 111], meaning that it has received the joint transmission from the red, green, blue and violet channels without error as confirm by the parity bits. Each decoded message carries, also, the transmitter’s node address. So, the next block of six bits gives it ID. In position \#1 the network location of the transmitters are: \(R_{12} [011:010], G_{13} [011:011], B_{22} [010:010]\) and \(V_{23} [010:011]\). Those addresses are also confirmed through the parity check error. The last block is reserved for the traffic message (Payload data). The stop bit (0) is used always at the end of each frame.

3. I2X COOPERATIVE SYSTEM EVALUATION

3.1 Led assisted navigation

The input of the aided navigation system is the coded MUX signal, and the output is the system state decoded at each time step \(\Delta t\). As a PoC, performed in the lab, a navigation data bit transition was tested by moving the receiver along known pattern path.

![Normalized MUX signals acquired by a receiver at the crossroad, in positions \#1, \#2, \#4, \#6 or \#8](image_url)

On the top the transmitted channels packets \([R, G, B, V]\) are decoded.

In Figure 6 displays the MUX signals received when Vehicle \(a\) enters the crossroad in position \#8 \(t_1\) and it goes straight to position \#2 \(t_2\) (Phase1, TF1), while vehicle \(c\) turn left, moving across position \#1 (Phase2, TF2). 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 one ID channels was lost (B_2,4) and one are added (V_2,3). Here, the 4-binary 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 (Figure 4) 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.

3.2 V2X cooperative system

A traffic scenario was established for a cooperative V2X communication. The PoC was simulated using the laboratory experimental conditions (see section 2). To model the worst-case scenario, vehicles approaching the intersection from different flows are assumed to have a conflicting trajectory (Figure 4). When a vehicle approaches the intersection, either in the right or in the left lane and reaches the request distance (Figure 1b) sends a light signal to the controller (V2I), at the traffic light that faces the lane (see Figure 3), requesting permission to cross the intersection. If there is permission, (I2V) it goes forward or turns left depending on the occupied lane, otherwise it will stop at the respective stop lines within the response distance. 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 V2I. This information alerts the controller to a later request message (V2I), confirmed by the follow vehicle. In the PoC we have assumed that t_e<t_f, t_e<t_b and t_e<t_c.

As an example, in Figure 7, 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_e’) 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.

![Figure 7](image)

Figure 7. 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).

After decoding we have assigned position #4 (R_3,4 G_4,2 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_e’, t_f and t_f’. Here, t_e’<t_f’.

An example of message exchange received and sent by the control manager is shown in Figure 8.
The MUX signal at each receiver and the assigned decoded messages (at the top of the figure) are displayed at the request times, $t_a$ and $t_b$ (Figure 8a) and at the response times, $t'_b$ and $t'_c$ (Figure 8b) for Vehicles $a$ and $e$, respectively. At the request times, the position of both vehicles are identified: W #2 ($R_{3,2}$, $G_{3,1}$ and $B_{2,2}$) for Vehicle $a$ and S #2 ($R_{3,4}$, $G_{5,3}$ and $B_{4,4}$) for Vehicle $e$. As soon as ($t'_b$ and $t'_c$) the connected vehicle receives its own response (ID: W #2 or S #2) from the control manager (INFO: 000000), the connected vehicle is required to follow the occupancy trajectories (footprint regions) provided by intersection manager (Payload data).

### 3.3 Traffic Signal Phasing: 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 3) using the new concept of VLC request/response messages. A brief look into the process of timing traffic signals is given in Figure 9.

![Phasing Diagram](image.png)

**Figure 9** 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). $t_{r,x}$ is the request time from the Vehicle $x$ and $t'_{r,x}$ 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 (Figure 7 an Figure 8) to generate phase durations appropriate to accommodate the demand on each cycle. 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 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 \( e \) is given access at \( t'_e \) 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 9. The speed of Vehicle \( e \) was reduced, keeping a safe distance between Vehicle \( e \) and Vehicle \( d \).

### 4. CONCLUSIONS AND FUTURE TRENDS

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 UID/EEA/00066/2019 and by FLAD, Fundação Luso-Americana para o Desenvolvimento. The projects: IPL/2018/II&D_CTS/UNINOVA_ISEL and: IPL/IDI&CA/2019/Bid-VLC/ISEL, are also acknowledge.

### REFERENCES


