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Vehicular Visible Light Communication for Intersection Management †

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Abstract: An innovative treatment for congested urban road networks is the split intersection. Here, a congested two-way–two-way traffic light-controlled intersection is transformed into two lighter intersections. By reducing conflict points and improving travel time, it facilitates smoother flow with less driver delay. We propose a visible light communication system based on Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) and Infrastructure-to-Vehicle (I2V) communications able to safely manage vehicles crossing through an intersection, leveraging Edge of Things (EoT) facilities. Headlights, street lamps, and traffic signals are used by connected vehicles to communicate with one another and with infrastructure. Through internally installed Driver Agents, an Intersection Manager coordinates traffic flow and interacts with vehicles. For the safe passage of vehicles across intersections, request/response mechanisms and time and space relative pose concepts are used. A virtual scenario is proposed, and a "mesh/cellular" hybrid architecture used. Light signals are emitted by transmitters by encoding, modulating, and converting data. Optical sensors with light-filtering properties are used as receivers and decoders. The VLC request/response concept uplink and downlink communication between the infrastructure and the vehicles is tested. Based on the results, the short-range mesh network provides a secure communication path between street lamp controllers and edge computers through neighbor traffic light controllers that have active cellular connections, as well as peer-to-peer communication, allowing V-VLC ready cars to exchange information.

Keywords: vehicular communication; split intersection; vehicle pose connectivity; vehicular visible light communication (V-VLC); white LEDs; SiC photodetectors; OOK modulation scheme; traffic control

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1. Introduction

Current transportation systems are now more than ever likely to experience a major technological transformation. An anticipated next step in the evolution course of transportation systems is to adopt the concept of communication and enable information exchange between vehicles and with infrastructure (V2I). This will unleash the full potential of next-generation transportation systems while shifting the paradigm from autonomous driving to cooperative driving by taking advantage of Vehicle-to-Everything (V2X) communications [1,2]. Hence, the study of V2X communication is required in order to provide high reliability, low latency, and security in the exchange of driving and ambient data. Our goal in [3], as in others published works [4,5], was to increase the safety and throughput of traffic intersections using cooperative driving.

To increase the efficiency of traffic management and control, many efforts have been made. Real-time traffic planning and trajectory redesign are technical challenges. The first is accomplished through navigation, guidance and vehicle control methods. In the second case, analytical procedures and road traffic control expertise are needed. An

Intersection Manager (IM) can increase the throughput of the intersection by directing incoming Connected Autonomous Vehicles (CAVs) [6–9].

Intersections, by their nature, easily become traffic bottlenecks and conflict areas. Whenever there are two-way–two-way, four-legged, or split intersections on the road network, they are vital either from an operational perspective or from a safety perspective, because they cause considerable delays in traffic. Traffic volumes that arrive at the intersection, i.e., its demand, is the same. For the selection process to be effective, several other factors must be considered, such as road safety, performance, vehicle delay, and operational and functional requirements. The level of service at intersections can be improved by applying a split intersection. Here, the conventional four-legged intersection can be replaced by two separate intersections. Advantages of a split intersection are: improved safety, since it separates potential conflict points; increased efficiency, since it allows the intersection to handle a greater volume of traffic with less delay; a better synchronization, once corridor travel times are improved on both the major and side streets; and, finally, shorter wait times because fewer traffic signal phases means less time stopping at the intersections.

In Vehicular Communication Systems, the vehicles and roadside units are the communicating nodes, providing each other with information, such as safety warnings and traffic information [10]. The visible light communication (VLC) holds special importance when compared to existing forms of wireless communications [11,12]. VLC is an emerging technology that enables data communication by modulating information on the intensity of the light emitted by LEDs. VLC has a great potential for applications due to their relatively simple design for basic functioning, efficiency, and large geographical distribution. A V-VLC system is predominantly Line of Sight (LOS) due to physical properties of light waves and its propagation characteristics. Additionally, modern vehicles have front- and rear-light modules with optical components that focus light beams. Communications can benefit from this directionality because it reduces collisions and allows spatial reuse of modulation bandwidth. VLC is a precursor of optical communication for large scale-integration with other conventional communication technologies, and a strong candidate for next generation of indoor interconnection and networking, in parallel with radio communications.

In this paper, a virtual traffic scenario is proposed and bidirectional communication between the infrastructure and the vehicles is tested, using the VLC request/response concept. The proposed system involves wireless communication, smart sensoring and optical source networks, building up a transdisciplinary approach framed in cyber-physical systems. This paper is organized as follows. After the introduction, and the related work presented in Section 2, in Section 3, the V-VLC system is described and the scenario, architecture, communication protocol, coding/decoding techniques analyzed. In Section 4, the experiential results are reported and the system evaluation performed. A phasing traffic flow diagram based on V-VLC is developed, as PoC, to control the arrival of vehicles to the split intersection. Finally, in Section 5, the main conclusions are presented.

2. Related Works

Vehicular networking applications can take advantage of the LED-equipped lighting modules and transportation infrastructure to realize vehicular visible light communication (V-VLC). In this work, the communication and geolocation are performed exclusively by VLC using the streetlamps, 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. In [13], a VLC prototype suitable only for I2V communication is presented. The system consists of a regular traffic light as a transmitter (the red light is modulated with the information), and a photodetector with Fresnel lenses as a receiver. The traffic light transmits messages to the vehicle, which decodes them. Special emphasis is put on the optics of the photodetector. In [14], experimental measurement was carried out also by using a regular traffic light as source (red light) and a photoreceiver positioned at different distances along the road. Special emphasis was put on the model of the transmission pattern and propagation of the VLC signal. In [15], the problem of interference in a realistic urban scenario was analyzed, and a temporal and spatial hotspot for collisions in V-VLC is established. A heterogeneous crosslayer MAC protocol for V-VLC communication was also proposed. Realistic simulations of vehicles' mobility and V-VLC channel (V2V) are presented. Special emphasis was put on the design of the protocol and on the division of the radiation pattern of lighting modules into multiple sectors. GPS positions for the vehicles and RF transmissions to advertise them were used together with the VLC communication between the vehicles.

In [3,16,17], our goal was to present a cooperative I2V2V2I2V system that supports guidance services and uses an edge/fog-based architecture able to safely manage vehicles crossing through a split intersection. Only visible light communication is used to transmit and receive information. This makes our work different from the others. 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. Using an edge-fog based architecture, an Intersection Manager (IM) can increase the throughput of the intersection by exchanging information with and directing incoming CAVs. Using joint transmission from the white tetra chromatic streetlights, mobile optical receivers collect data, calculate their location for positioning and, concomitantly, read the transmitted data from each transmitter. As receivers and decoders, SiC pinpin optical sensors with light-filtering properties are used. Bidirectional communication between the infrastructure and the vehicles was tested. To command the passage of vehicles safely, queue/request/response mechanisms and temporal/space relative pose concepts are used. In [16] special emphasis was put color phasing diagram and, on the request/response mechanism to define the color pose. As PoC the movement of the cars with their colorful poses and spatial relative poses were experimentally evaluated. In [3,17] the main emphasis is put in the architecture and in the multi-vehicle localization. An indirect V2V relative pose estimation method was proposed and a phasing diagram for the split intersection presented.

In this paper, queue/request/response mechanisms and temporal/space relative pose concepts are extended, polished and dynamically adjusted. Vehicle movement along the road takes the form of a queue, where the vehicles arrive at a lane, wait if the lane is congested and then move once the congestion reduces. 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 [18,19]. To determine the delay, the number of vehicles queuing in each cell at the beginning and end of the green time is determined by VLC (V2V2I) observation. A standard four-legged intersection is compared with the split intersection and a dynamic phasing diagram flow is presented based on a matrix of states. The durations of movable states can be entered for any state at a dynamic time. It is possible for the IM to execute the following actions based on the request information: modify the durations of the cycle; enter the fixed times; change the durations of states with the transportable from any state at a dynamic time, and modify the intersection coordination offset, depending on the request information. The results indicate that the cooperative and dynamic 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.

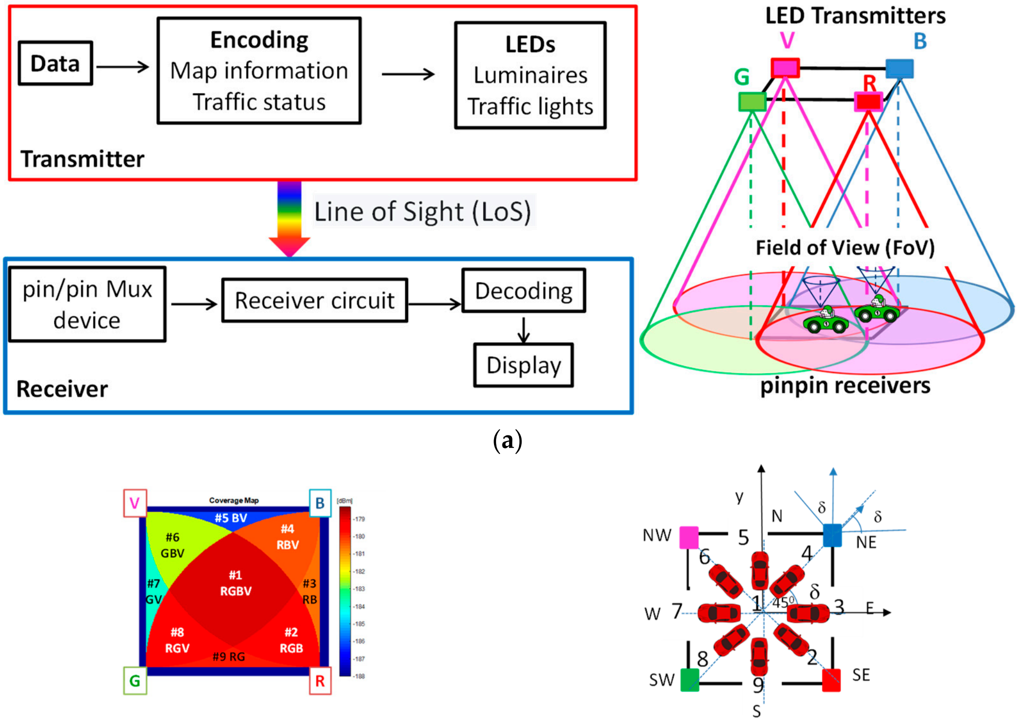
This paper focuses on the concept rather than on the practical implementations. Implementing the system in a real environment requires considering several constraints, including the dimensions, orientation, and motion of the target vehicles; the precise motion and position of the vehicle; the strategic locations of landmarks; and the unambiguously covered distances and speeds, as well as the field of view. The practical implementation of many tasks such as steering/velocity control, perception of the environment, and performance under all conditions of the roadway and environment will be challenging.

3. V-VLC Vehicular Communication

3.1. V2X Communication System

Vehicular communication is one of the key enabling technologies for future Intelligent Transportation Systems (ITSs) [20–22]. The V-VLC system makes use of outdoor light sources (street lamps and traffic lights) as the access points, which can serve for both lighting and communication purposes, providing drivers with outdoor wireless communications.

The system is composed of 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. Both communication modules (transmitter and receiver) are software defined, where modulation/demodulation can be programed.



(**a**)

(**b**)

Figure 1. (**a**) Block diagram and transmitters and receivers and 3D relative positions of the VLC system. (**b**) Illustration of the coverage map in the unit cell: footprint regions (#1–#9) and steering angle codes (2–9).

To realize both the communication and the street illumination, 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 1a). 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: 390 nm), while the others provide a constant current for white perception. The luminous intensity of each emitter is regulated by the driving current for white perception by the human eye and the divergence angle is approximately 120°. Data are encoded, modulated and converted into light signals emitted by the transmitters. Modulation and digital-to-analog conversion of the information bits are performed using signal processing techniques. This way, information is modulated onto the intensity of the light that is emitted by the transmitter and is transferred to receivers installed in the vehicles or infrastructures. The signal propagating through the optical channel and a VLC receiver, at the reception end of the communication link, is responsible for extracting the data from the modulated light beam. It transforms the light signal into an electrical signal that is subsequently decoded to extract the transmitted information.

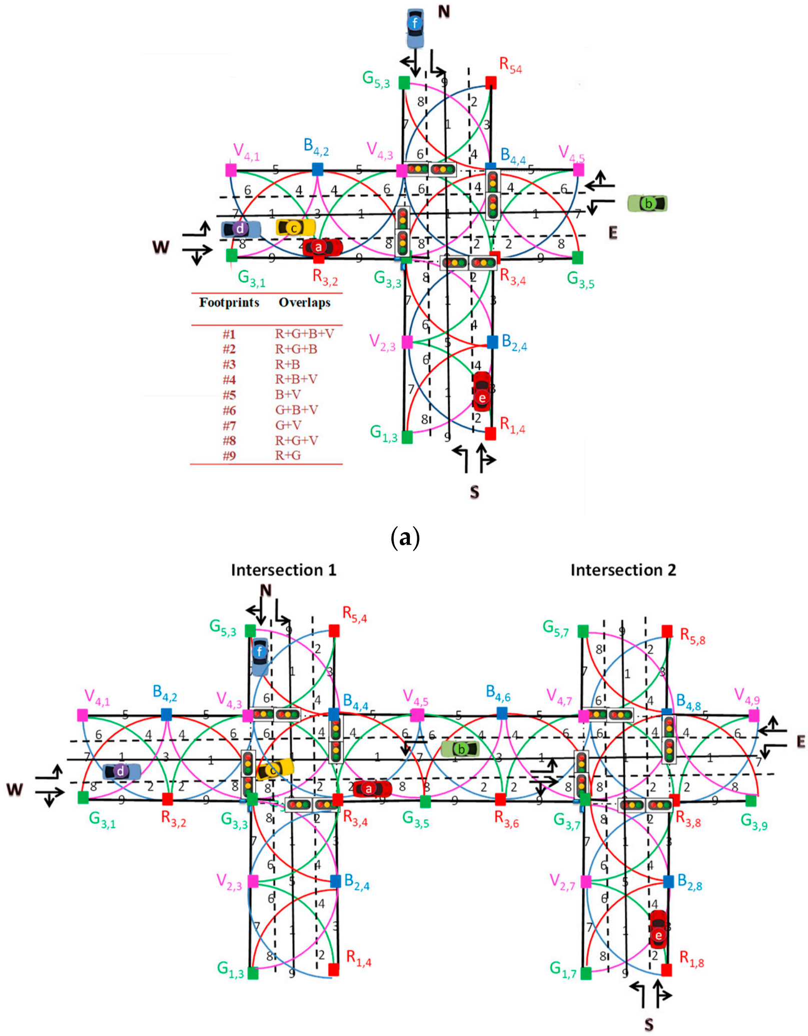
The core element of the receiver is a photodetector that converts the optical power into an electrical current. The VLC photosensitive receiver is a double pin/pin photodetector based on a tandem heterostructure, p-i′-n/p-i-n, sandwiched between two conductive transparent contacts. The front, thin pi′n structure made of a-SiC:H exhibits high absorption to short wavelengths (violet and blue light) and high transparency to the long wavelength (red light). In opposition, the back, thicker pin structure based on a-Si:H absorbs long wavelengths (red light), and the green light is absorbed in both structures. The device selectivity is tuned externally using reverse bias (−8 V) and optical steady-state illumination of short wavelength (400 nm). Due to its tandem structure, the device is an optical controlled filter able to identify the wavelengths and intensities of the impinging optical signals [23–25]. It offers high sensitivity and linear response, under irradiation. Its fast response enables high-speed communications. The generated photocurrent is processed using a transimpedance circuit, giving rise to a proportional voltage that is processed, by using signal conditioning techniques (adaptive bandpass filtering and amplification, triggering and demultiplexing). Finally, the data signal is reconstructed at the data processing unit (digital conversion, decoding and decision) [26,27]. This kind of receiver is useful for intensity-modulated signals, since the photodetector response is insensitive to the frequency, phase, or polarization of the carriers

To receive the I2V information from several transmitters, the receiver must be located at the overlap of the circles that set the transmission range (radial) of each transmitter. The nine possible overlaps (#1–#9), defined as fingerprint regions, as well as vehicle orientations (steering angle; δ), are also displayed for the unit square cell in Figure 1b.

3.2. Scenario and Architecture

A V2X communication link, in a two-way–two-way traffic light-controlled crossroad, was simulated. Typical four-legged intersections are linked to sixteen roads: eight roads incoming from and eight roads exiting to neighboring crossroads north, west, south, and east. In Figure 2a, the lighting plans of a standard intersection are shown, while in Figure 2b the corresponding plan for a split intersection is displayed. The generated joint footprints in both crossroad regions (LED array = RGBV-modulated color spots) are also inserted. The split intersection (Figure 2b) starts with only one main street that connects two crossroads (Intersection 1–Intersection 2). Road request and response segments, offer a binary (turn left/straight or turn right) choice. Moreover, vehicle's movement is known in each intersection and can be anticipated, considering the flow dependencies between two closely spaced signals. In coordinating traffic signals it is assumed that a vehicle's movement along a main street (W >> E) is known and can be anticipated. Knowing when a vehicle is going to pass intersection "1" allows for a green light to be pre-programmed for that vehicle's direction of travel. The two intersections are referred to as one entity, the interchange. Signal timing refers not only to the phasing patterns at the two intersections, but also to the cycle length and offset relationship between them. The two controllers provide high flexibility since they allow the use of all phasing patterns for both intersections [16].

To build the I2V, a simplified cluster of unit square cells in an orthogonal topology that fills the service area is proposed [28]. The grid size was chosen in order to avoid an overlap in the receiver from the data in adjacent grid points. The considered geometric scenario in the experimental results uses a smaller size square grid (2 cm), to improve its practicality. 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 Proof of Concept (PoC), it was assumed that the standard crossroad is located in the intersections of line 4 with column 3 (Figure 2a) and the split one in the intersection of line 4 with column 3 and 7 (Figure 2b). The emitters are located at the nodes along the roadside. Thus, each LED sends an I2V message that includes the synchronism, its physical ID and the traffic information. In response to the streetlight signal, the receiver assigns a unique ID and the traffic message to the probe vehicle when it enters the streetlight captures range.



(**a**)

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Figure 2. V2X optical infrastructure and generated joint footprints in a crossroad (LED array = RGBV color spots). (**a**) Standard intersection. (**b**) Split intersection.

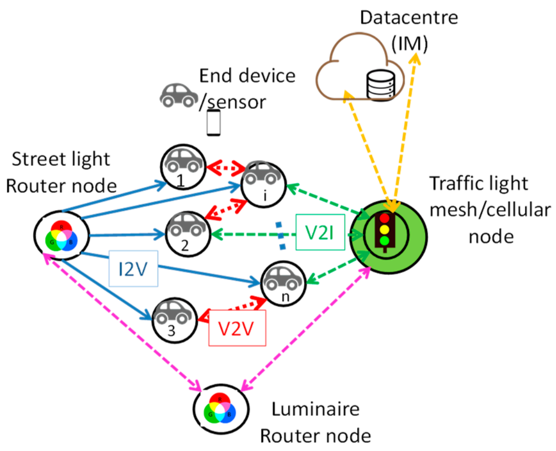
Figure 2a displays the imposed four traffic flows: From west (W), vehicles *a*, *c*, and *d* approach the crossroad, vehicle *a* with straight movement, vehicle c and vehicle *d* with left turns. From east (E), vehicle *b* approaches the intersection with left turn only. From south (S) vehicle *e*, oncoming, has a right-turn approach. In the fourth flow, vehicle *f*, coming from north, goes straight. In coordinating traffic signals vehicle's movement along a main street can be predictable as in Figure 2b. In the design of a coordinated system two-directional flows were considered. One from the west (W) with the same three vehicles (*a*, *c*, *d*) approaching Intersection 1. In the second flow, vehicle *b* from east (E) approaches Intersection 2 with straight movement and Intersection 1 with left turn only. The third traffic flow was shifted to Intersection 2. Vehicle *e*, oncoming from south (S) Intersection 2, has a right-turn approach while in the fourth flow, vehicle *f*, coming from north goes straight in Intersection 1.

3.3. Mesh Cellular Hybrid Structure and Multi-Vehicle Cooperative Localization

The term "Intelligent Control System" refers to any combination of hardware and software, which operates autonomously according to the information received and processed.

After processing, it is able to act towards the desired control through rational choices. In this case, it is intended to apply it to the Connected Vehicles (CV) systems. The computing and communication workload for CVs may also vary over time and locations, which poses challenges to capacity planning, resource management of computation nodes, and mobility management of the CVs. Thus, a well-designed computing architecture is very important for CV systems.

Figure 3a, presents a draft of a mesh cellular hybrid structure that can be used to create a gateway-free system. As illustrated the streetlights 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 similar to 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 [29]. This architecture enables edge computing and device-to-cloud communication (I2IM) and enables peer-to-peer communication (I2I), to exchange information, by ensuring a secure communication from a street light controller to the edge computer or datacenter, through a neighbor traffic light controller with an active cellular connection and enable peer-to-peer communication, to exchange information between V-VLC ready connected cars (Figure 3b). 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.



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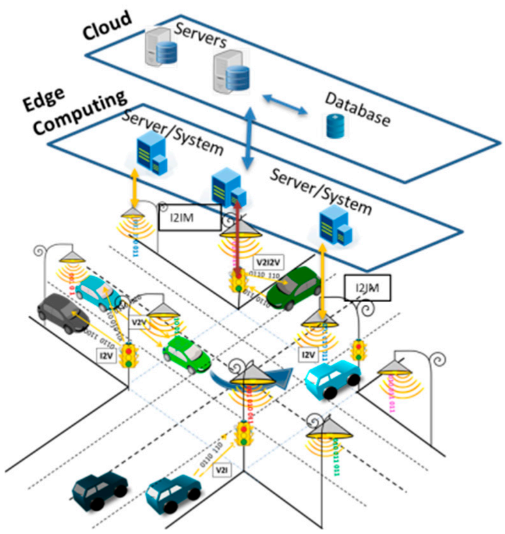


(**b**)

Figure 3. (**a**) Mesh and cellular hybrid architecture. (**b**) Communication links.

A highly congested traffic scenario will be strongly connected. As exemplified in Figure 4, 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. 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 4. The distance, *d*, between vehicles can be calculated based on a truncated exponential distribution [30].

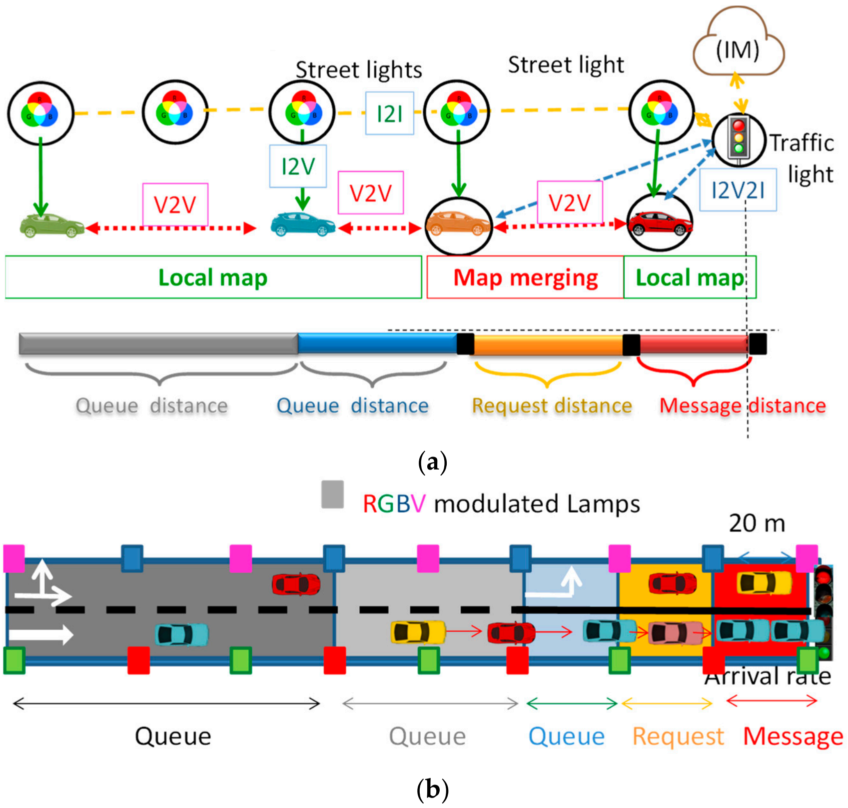


Figure 4. (**a**) Graphical representation of the simultaneous localization as a function of node density, mobility and transmission range. (**b**) Design of the state representation in the west arm of the intersection, with cells length.

For the Intersection Manager crossing coordination (Figure 4a), the vehicle and the IM exchange information through two types of messages, "request" (V2I) and "response" (I2V). Each driver, approaching the intersection area from each side has previously selected and stays in the appropriate lane for their destination (left turn only or shared by right-turn and through movements). Inside the request distance, an approach "request" is sent, using as emitter the headlights.

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). 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. An Intersection Manager's acknowledgement 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 4b), the vehicle is required to follow the provided occupancy trajectories (footprint regions, see Figure 2). If a request has any potential risk of collision with all other vehicles that have already been approved to cross the intersection, the control manager only sends back to the vehicle (V2I) the "response" after the risk of conflict is exceeded.

A route is a typical path that a vehicle follows as it approaches (request and message distances) and traverses the intersection. From a digital map (Figure 4), we automatically extract a set of attributes that characterize an intersection: the poses, q_i (x, y, t), the route and the traffic rules (stop, give way). 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 [29], t and t' are the request and cross times. An indirect V2V relative pose estimation method is proposed in Figure 4b. Here, when there are two neighboring vehicles, the geometric relationship between them can be indirectly inferred via a chain of geometric relationships among both vehicles' positions and local maps. For two neighboring vehicles, both having self-localization ability (streetlamps I2V), we can perform local Simultaneous Localization and Mapping. 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 the 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. Here, each streetlamp (I2V transmitter) sends a message, received and processed by a SiC receiver, at the vehicle's rooftop. By means of the headlights (transmitters), the information is resent to the leader vehicle (V2V) [25,31] or a "request" message to go forward or turn right or to turn left is sent directly to the receiver (V2I), at the traffic light. For crossroad coordination, a local controller located at the traffic light analyses the potential conflict points and sends a "response" to the approaching vehicles.

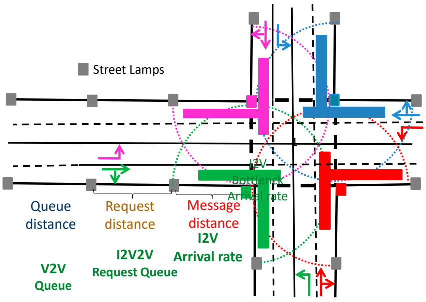
The use of both navigation and lane control signs to communicate lane restrictions is demanding. Downstream from the request distance, lane restrictions should be obeyed.

3.4. Color Phasing Diagrams

The specification of the phasing plan requires that each of the traffic movements to be accommodated be assigned to one of the timing functions to produce the desired sequence of displays. The choice of treatments used will determine which timing functions will be activated and which will be omitted from the phasing plan.

We have assumed four "color poses" linked with the radial range of the modulated light in the crossroad nodes. The assignment of the color phases to the active LED's at the crossroad is shown in Figure 5a. "Green poses" corresponds to west straight, south left and west right turn maneuvers, "Red poses" to south straight, east left and south right turn, "Blue poses" to east straight, north left and east right turn and "violet poses" to north straight, west left and north right turn maneuvers. In Figure 5b, a color phasing diagram in a four-legged intersection is shown; while in Figure 5c, the plan for a split intersection is displayed.

Here, Phase 2 and Phase 5 offer two alternatives, only one of which may be displayed on any cycle. Vehicles are stopped on all approaches to an intersection while pedestrians are given a WALK indication, and the phasing is referred to as "exclusive". Functional barriers (dash dot lines) exist between exclusive pedestrian and Phase 1 and Phase 6. A vulnerable road user-only phase and the separation of traffic flow on the north/south direction allows the introduction of bike lanes in Intersection 1 (south and east straight movements) and Intersection 2 (north straight movement), reducing vehicle and bicyclist potential conflict points. Taking into account Figure 2, two movements can proceed simultaneously without conflict; hence, two of the timing functions will always have simultaneous control. The IM has to allocate priority.



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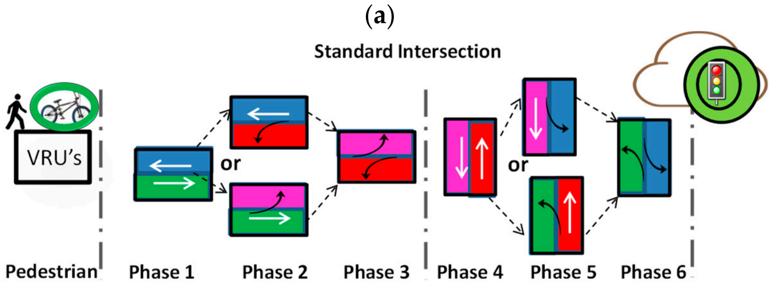

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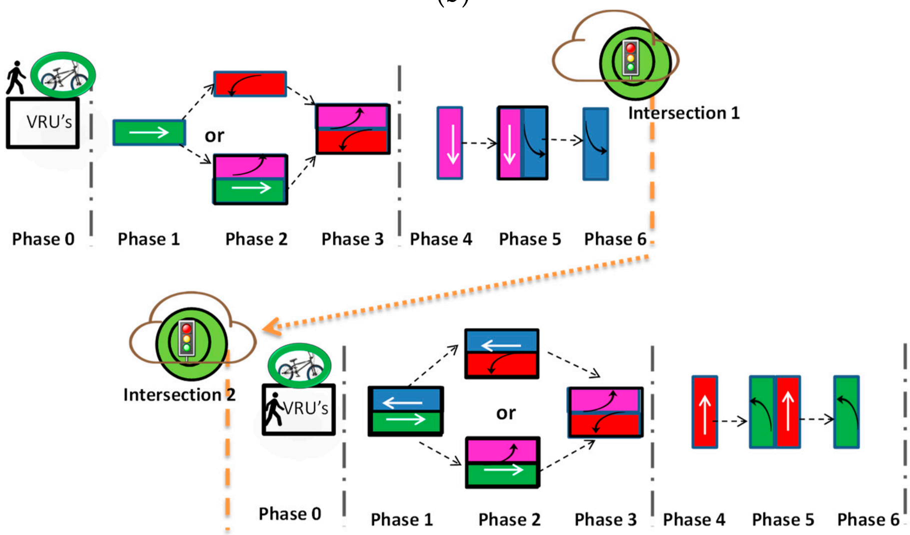


(**c**)

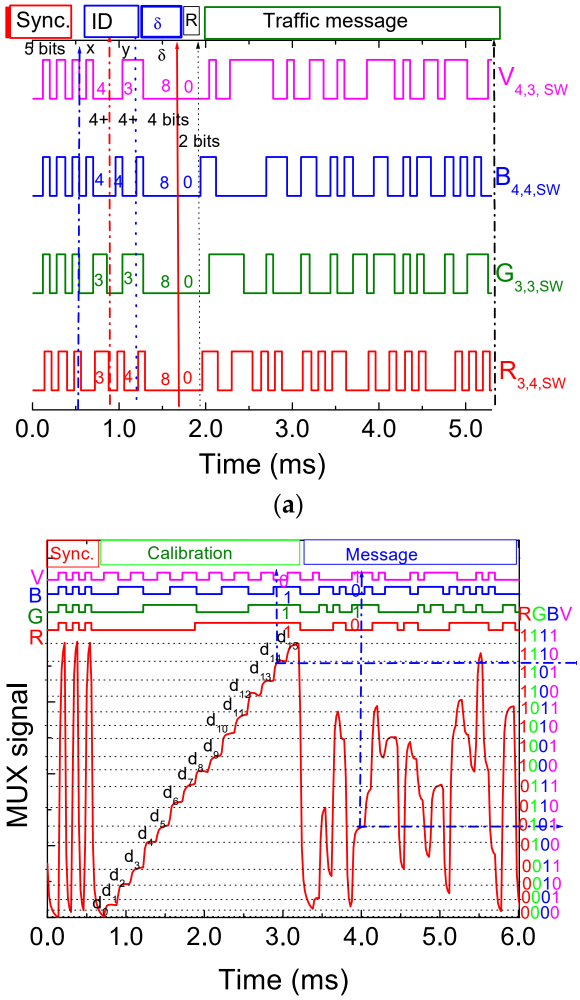
Figure 5. Phasing diagram: (**a**) Color poses. (**b**) Four-legged intersection. (**c**) Split intersection.

4. V2X Cooperative System Evaluation

4.1. 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 data frame of 64 bits. A data frame is exemplified in Figure 6.

If the transmitter is a streetlamp or headlamp, the frame is divided into four blocks; if the transmitter is the traffic light, five blocks are considered. The first block is the synchronization block [10101], the last is the payload data (traffic message) and a strop bit ends the frame. 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 bit binary representation for the decimal number. The δ block (steering angle (δ)) completes the pose in a frame time $q(x, y, \delta, t)$. Eight steering angles along the cardinal points and coded with the same number of the footprints in the unit cell (Figure 1b) 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 decimal numbers assigned to each ID block are pointed out in Figure 6a. So, in this time slot, $R_{3,4,Sw}$; $G_{3,3,Sw}$; $B_{4,4,Sw}$ and $V_{4,3,Sw}$ are the transmitted node packets, from the crossroad 1. Here, the driver receives his request message [pose, and traffic needs] from the infrastructure. This allows it movement across the crossroad to southwest (code 8), directly from the current point (#1) to the goal point (#8).



(**a**)

(**b**)

Figure 6. (**a**) Frame structure representation of a request message. (**b**) MUX/DEMUX signal of the calibrated cell. In the same frame of time, a random signal is superimposed.

Based on the measured photocurrent signal by the photodetector, it is necessary to decode the information received. For this purpose, a calibration curve is previously defined to establish this assignment. In Figure 6b, calibration curve that uses 16 distinct photocurrent thresholds resultant from the combination of the RGBV-modulated signals from the VLC emitter is plotted [29]. The correspondence between each footprint and the photocurrent level is highlighted on the right side of Figure 6b. Here, the MUX signal obtained at the receiver as well as the coded transmitted optical signals is displayed. The message, in the frame, start with the header labelled as Sync, a block of 5 bits [10101] imposed simultaneously to all the emitters. In the calibration block (second block), four calibrated R, G, B, and V optical signals are transmitted at the same time. Here, the bit sequence was chosen to allow all the *on/off* sixteen possible combinations of the four RGBV input channels (2^4). In the last block, a random message is transmitted. A periodic retransmission of the calibration curve is needed to ensure the correspondence to the output signal and an precise decoding of the transmitted information. Comparing the calibrated levels (d_0–d_{15}) with the assigned 4-digit binary [RGBV] codes, ascribed to each level (pointed out at the right side of Figure 6b), the decoding is straightforward, and the message decoded. Taking into account the frame structure (Figure 6a), after decoding the MUX signals, the pose (position and direction), the kind of transmitter (IM or Vehicle) and traffic message are revealed [30].

4.2. The Cooperative VLC System

In Figure 2, a traffic scenario was simulated using VLC cooperative communication. In the lab, as PoC, it was tested by moving the receiver along known paths. The worst-case scenario was modeled. Here, vehicles *a*, *b*, *c* and *d*, oncoming both intersections have a conflicting trajectory. When they reach the request distance (see Figure 4), they send a request to the traffic light controller (V2I) that faces the lane, asking permission to cross the intersection. If they receive permission (I2V), they go forward or turn left depending on the occupied lane, otherwise stop at the respective stop lines within the message distance. Four crossing different instants are considered: the request (t) and the response (t') times, and also the crossroad enter (t'') and the exit (t''') times. All the requests comprise vehicle positions and approach speeds. If a follower exists (vehicle *d*), the request message from its leader, *c*, 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. We have assumed that, in the four-legged intersection $t_a < t_b < t_c < t_e < t_d < t_f$. In the split, for Intersection 1: $t_a < t_c < t_d = t_b < t_f$; and for Intersection 2: $t_a = t_b < t_e$. In Figure 7, the movement of the cars, in the successive moments, with their colorful poses (color arrows) and $q_{i,j}$ spatial relative poses (dot lines), is displayed for a four-legged intersection (a) and for a split one (b).

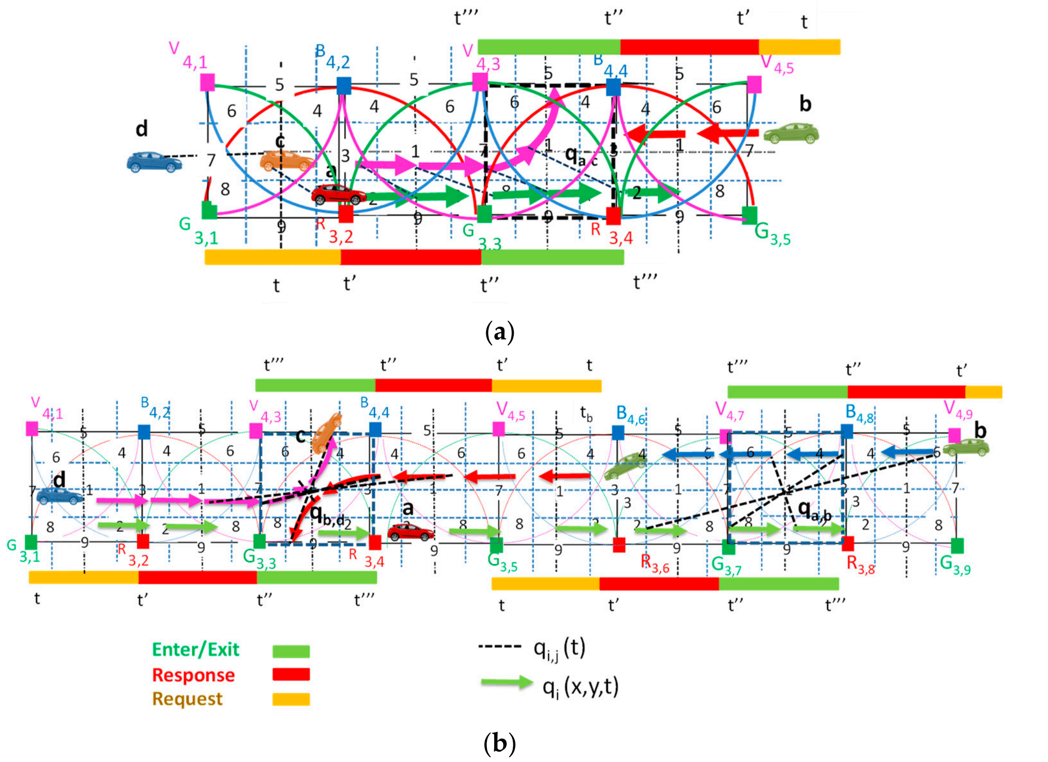


Figure 7. Movement of the cars, in the successive moments, with their colorful poses (color arrows) and $q_{i,j}$ spatial relative poses (dot lines). (**a**) Four-legged intersection. (**b**) Split intersection.

In coordinating traffic signals (Figure 7b), we assume that a vehicle's movement along a main street (W > E) can be predictable, and the two intersections referred to as one entity, the interchange. Thus, any reference to signal timing includes not only the joint set of phasing patterns at the two intersections, but also the cycle length and the offset relationship between the two intersections. The option of using two linked controllers provides the maximum flexibility because it allows the use of all phasing patterns for the pair of intersections.

We denote q, q', q'', q''' as the vehicle pose estimation at the time t, t', t'', t''' (request, response, enter and exit times), respectively. To estimate these variables, it is possible to take advantage of what is defined as control inputs, and which represent an estimation of the motion along the time. The vehicle speed can be calculated by measuring the actual travelled distance overtime, using the ID's transmitter tracking. Two measurements are required: distance and elapsed time. The distance is fixed while the lapsed time is obtained using the times where the footprint region changes. There is a fixed spacing between reference points (Figure 2), but the correspondent time integrated by the receiver varies depending on how fast the vehicle is going. The receivers compute the geographical position in the successive instants (path) and infer the vehicle's speed. When there are two neighboring vehicles in different lanes, the geometric relationship between them ($q_{i,j}$; dotted lines in Figure 7) can be inferred through local SLAM 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 (Figure 4) uses the indirect V2V relative pose estimations method taking advantage of the data of each neighboring vehicle. As an example, for vehicle d, two instants can be considered, t and t'. To help control the flow of vehicle b, the request the vehicle c leader, has to include its position and speed, earlier received by the V2V. This alerts the controller to a later request (V2I), set by the follow vehicle d, at t'_d.

Comparing the two types of intersections, in Figure 7a, vehicle b with a request at t_b only pass Phase 3 (see Figure 5) after waiting, at the stop line, for vehicle a to exit the intersection (t'''_a) and vehicle d to approach it. At the split intersection (Figure 7b), it will approach Intersection 1 simultaneously with vehicle d. For this to happen, the IM foresees the entry of vehicle b (t''_b) at Intersection 2, as well as the entry of vehicle a (t'_a) at Phase 1, using an appropriate *offset* between both intersections.

4.3. V-VLC Experimental Evaluation

As an example, the I2V MUX signals received and decoded (on top of the figures) by the receiver of each vehicle a, b, c, and d are shown in the figures, for the four-legged (Figure 8a,b) and for the split (Figure 8c,d) intersections, at different frame 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. On the top, the transmitted channels packets [R, G, B, V] are decoded.

The results show that the information pattern changes as the receiver moves between generated point regions. Figure 8a displays the MUX signals assigned to two IM messages received by Vehicles a and b. Assuming that vehicle a, driving in the right lane (Figure 8a) enters Cell $C_{4,2}$ by enter #2 (t'_a, Phase1, green pose), goes straight to E to position #8 (t''_a; Phase 1, green pose), 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, always keeping the same direction (E). Vehicle b approaches the intersection after having asked permission to cross (t_b) and only receives authorization when vehicle a has 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 its destination towards E (green pose). In Figure 8b, the normalized MUX signal responses and the assigned decoded messages from vehicle c inside the intersection are displayed at t''_c and t'''_c. The data show that vehicle c, driving in the left lane, receives an order to turn left (NE) at #7 and continues in this direction across position #1 toward the north exit (Phase 2, violet pose).

Figure 8c shows two requests made by vehicles a (green pose; #2E; ${t_2}'_a$) and b (blue poses; #6; ${t_2}'_b$) to the cross Intersection 2, Phase 1. In Figure 8d, the correspondent messages to cross Intersection 1, Phase 3, from vehicle b (red pose; #7W; ${t_1}'_b$), vehicle d (violet pose; #1E; ${t_1}'_d$) and vehicle b (red pose; #1SW; ${t_1}''_b$) are displayed.

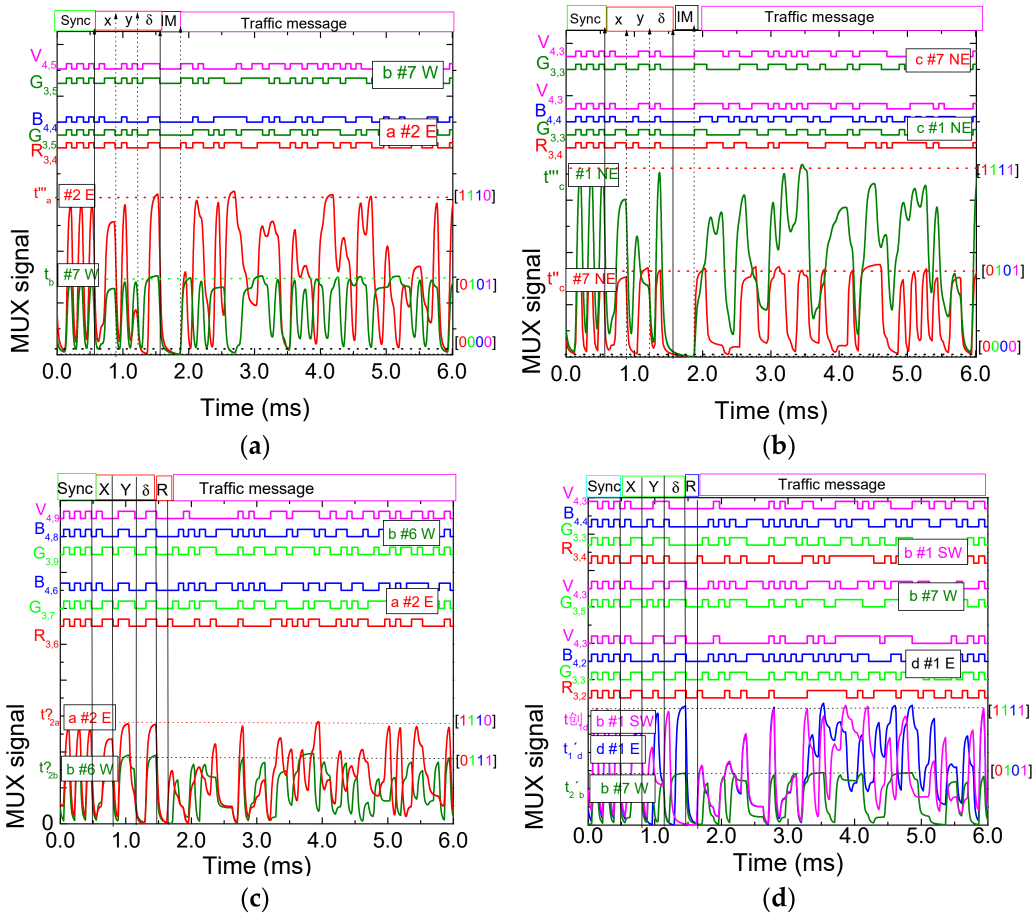


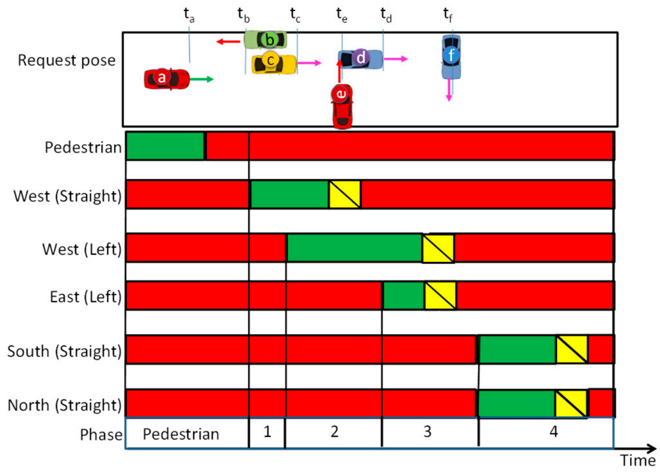
Figure 8. Vehicle *a*, *b*, *c*, and *d*′s normalized MUX signal responses and assigned decoded messages. On the top the transmitted channels packets [R, G, B, V] are decoded. (**a**) Four-legged intersection (out of the crossroad; vehicle *a*, pose #2E, and vehicle *b*, pose #7W). (**b**) Four-legged intersection; (inside the crossroad; vehicle *c*, poses #7NE, #1NE). (**c**) Split intersection (out of the crossroads; vehicle *a*, pose #2E, and vehicle *b*, poses #6W). (**d**) Split intersection (crossroad 1; vehicle *b*, pose #7W and #1SW, and vehicle *d*, before crossroad 1, poses #1E).

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*). In the four-legged intersection, vehicle *b* must wait for the vehicle *d* to cross, while three actions must be taken in the split intersection to promote smooth movement avoiding congestions and delays: changing the synchronism of Intersection 2, delaying the simultaneous passage of vehicles *b* and *a* at Intersection 2 (Phase 1) and finally, allowing the joint passage of vehicles *b* and *d* at Intersection 1 in the same phase of vehicle 1 (Phase 3).

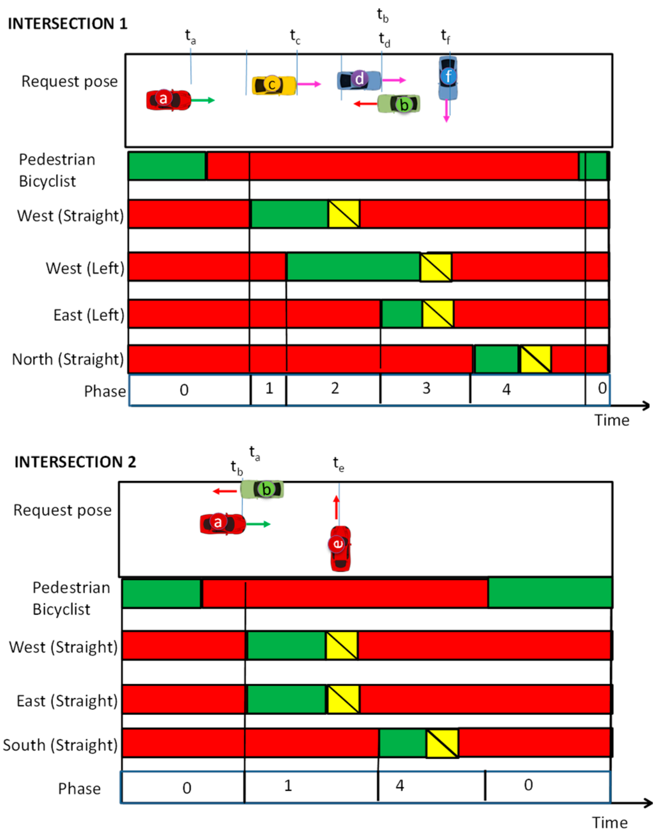
4.4. Traffic Signal Phasing: V2X Communication

Based on the simulated traffic scenario (Figure 2) and utilizing V-VLC request/response messages, a phasing diagram was drawn, for functional areas with two-way–two-way four-legged (Figure 9a) and split (Figure 9b) intersections.

Traffic volumes that arrive at the intersection are the same in both. Here, the traffic controller uses request and response messages, from vehicles *a*, *b*, *c*, *d*, *e* and *f*, fusing the self-localizations q_i (t) with their space relative poses q_{ij} (t) to generate phase durations appropriate to accommodate the demand on each cycle. Each driving vehicle is assigned an individualized time to the request (t) to enter the intersection, and $t[x]$ is the request time of vehicle x with their pose representations.



(**a**)



(**b**)

Figure 9. Requested phasing of traffic flows: (**a**) Standard intersection; the pedestrian phase, Phase 1 (W straight flow), Phase 2 (W straight and left flows), Phase 3 (W and E left flows), and Phase 4 (N and S straight flows). (**b**) Split intersection: Intersection 1: Phase 0, pedestrian/bicyclist phase, Phase 1 (W straight flow), Phase 2 (W straight and left flows), Phase 3 (W and E left flows), and Phase 4 (N straight flow); Intersection 2: Phases 0, pedestrian/bicyclist phase, Phase 1 (W and east straight flows), and Phase 4 (S and right-turn approach flow). $t[x]$ is the request time of vehicle x.

Results show five different phases for the four-legged intersection: the pedestrian phase, Phase 1 (W straight flow), Phase 2 (W straight and left flows), Phase 3 (W and E left flows), and Phase 4 (N and S straight flows) as shown in Figure 9a. In Figure 9b, for the split intersection, the phasing flow for both crossroads are 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), and Phase 4 (N straight flow); Intersection 2: Phases 0, pedestrian/bicyclist phase, Phase 1 (W and east straight flows), and Phase 4 (S and right-turn approach flow). The exclusive pedestrian and bicyclist stage, "Walk" interval begins in both at the end of Phase 5.

From a capacity point of view, in a four-legged intersection, 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 9a. The speed of vehicle e was reduced, keeping a safe distance between vehicle e and vehicle d. So, vehicle b approaches the intersection after having asked permission to cross it and only receives authorization when the vehicle a has left the intersection (end of Phase 2). Then, Phase 3 begins with vehicle b heading to the intersection (W) (pose red) while vehicle a follows its destination towards E (pose green). In the split intersection, the conventional four-legged intersection was replaced by two separate intersections (Figure 9b). The main benefit was to improved safety, since it separates potential conflict points where vehicles, pedestrians, and bicyclists may cross paths. The separation of traffic flow on the north/south street allows Intersection 1 to handle a greater volume of traffic and operate with less delay. The pedestrian Phase will begin early and the number of phases in Intersection 2 was reduced. The wait times are shorter because fewer vehicle traffic signal phases means less time stopping at the intersections.

Additionally, through synchronization of the two signalized intersections, the corridor travel times is improved on both the major and side streets. Results show that the vehicles' arrival is controlled and scheduled to cross the intersections in order to reduce traffic delay. The pose analysis is also used to allocate delays between left turns and forward movements. As a final remark, traffic light split coordination using the V-VLC request-response concept facilitates traffic circulation, promoting smooth movement along the network, forming platoons with efficient speeds, preventing the formation of queues, avoiding congestion and delays. This is also an effective way to reduce excessive fuel consumption and preserve the environment through minimal air pollution. To evolve towards real implementation, the performance of the V-VLC system still needs improvement, namely the distance between conflicting vehicles along with the trajectories of other opposing vehicles should also be monitored and optimized.

4.5. Queuing System: Dynamic Traffic Signal Phasing

A highly congested traffic scenario will be strongly connected. 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 10.

The same four traffic flows were considered. One is coming from west (W) but 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. According to the simulated scenario, each car represents a percentage of traffic flow. We have assumed that the intersection is approached by 540 cars per hour, of which 80 percent are coming from the east or west. Then, 50% of cars will turn left or right at the intersection and the other 50% will continue straight. There is only one episode per scenario and the cars cycle in the same order every time.

In the PoC, we have assumed that a_1, b_1, and a_2, make up the top three requests, followed by b_2, a_3, and c_1 in the fourth, fifth and sixth places, respectively. In the seventh, eighth and ninth request places are b_3, e and $a_{3,}$ respectively, followed in tenth place by c_2. The penultimate request is a_5, and the last one is f. So, $t_{a1} < t_{b1} < t_{a2} < t_{b2} < t_{a3} < t_{c1} < t_{b3} < t_e < t_{a4} < t_{c2} < t_{a5} < t_f$.

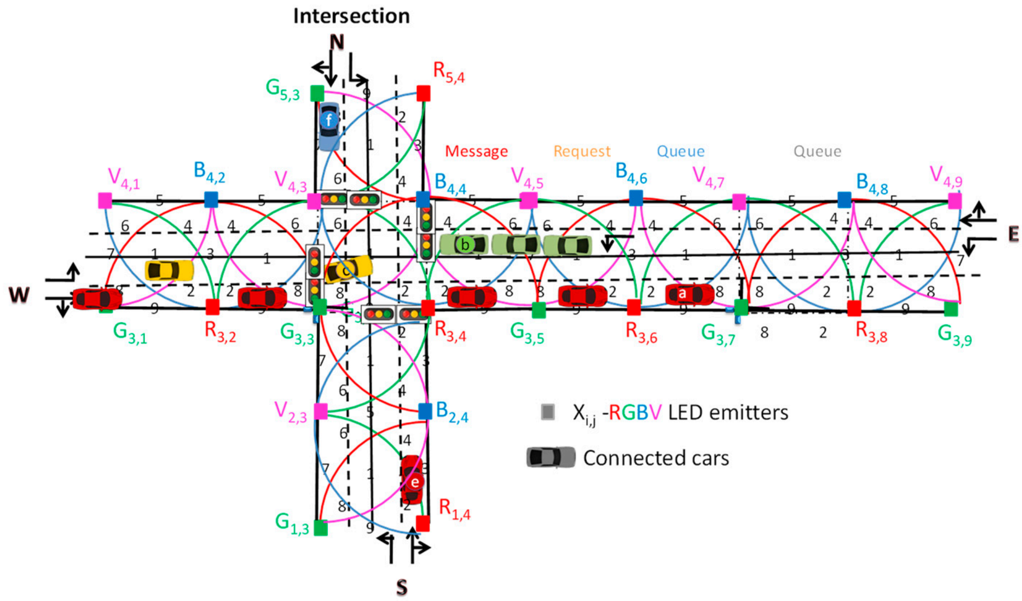


Figure 10. Simulated scenario: Four-legged intersection and environment with the optical infrastructure (X_{ij}), the generated footprints (1–9) and the CV.

The following parameters are therefore needed to model the queuing system: The initial arrival time (t_0) and velocity (v) in each the occupied section. The initial time is defined as the time when the vehicles leave the previous section (queue, request or message distances) and move along the next section, q_i (t, t'). The service time is calculated using vehicle speed and distance of the section. The number of service units or resources is determined by the capacity of the section, $n(q_i\ (x, y, \delta, t))$ and vehicle speed which depends on the number of request services, and on the direction of movement along the lane q_i (x, y, δ, t). To each driving Vehicle, x_i, is assigned the unique time at which it must enter the intersection, $t''[x_i]$.

The phase flow of the PoC intersection is shown in Figure 11 according to the phasing diagram. In this diagram, the cycle length is composed of 5 of the 7 phases contemplated (see Figure 5a) and divided in 16 time sequences. The exclusive pedestrian phase contains the "*0*", "*1*" and "*16*" sequences. The cycle's top synchronism starts with sequence "*1*". The first, second, third, and fourth phases contain sequences between "2" and "*15*" and control traffic flow.

The matrix of states allows the user to view, enter, or modify the division of an intersection into states, as shown in Figure 12.

The matrix shows the durations of the states for a given cycle. It is important to note that each element in this matrix represents how the light is lit for each state of the traffic light (if it is selected, then the light is green). Columns represent the duration of the states in the different arms of the intersection, from cycle minimum [fluid traffic] to cycle maximum [dense traffic]. For a medium traffic scenario, three distinct cycles are considered based on the higher volume traffic in the request directions (N-S, W-E straight or left). The column on the right of the matrix is called the column of fixed times. A fixed time is filled in when a state has the same duration for all the cycles of the lighting plan. The durations of movable states can be entered for any state at a dynamic time. It is possible for the IM to execute the following operations based on the information in the request: modifies the durations of the cycle; enters the fixed times; changes the durations of states with the transportable from any state at a dynamic time; and modifies the intersection coordination offset, depending on the request information.

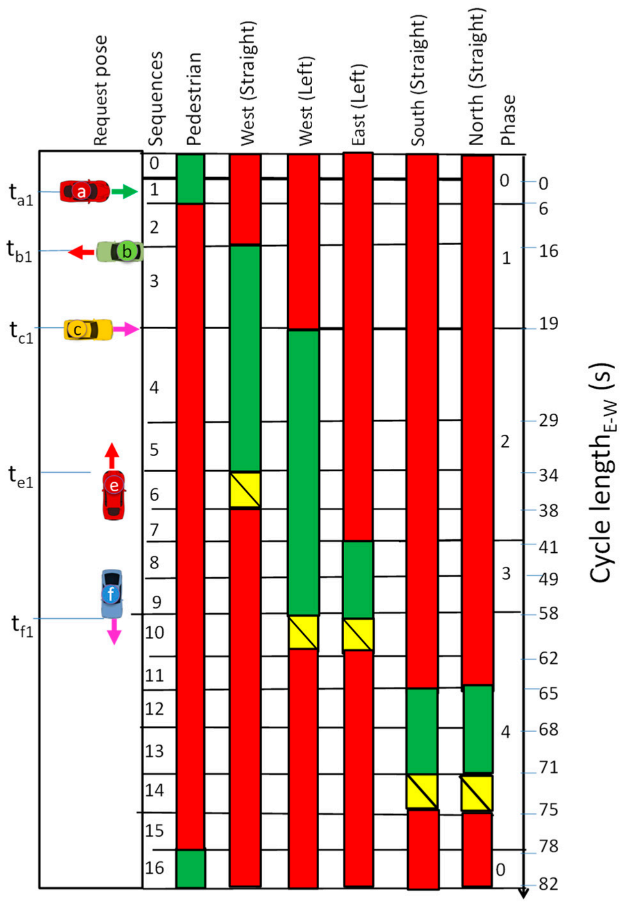


Figure 11. Requested phasing of traffic flows.

Sequences	Low-traffic scenario (s)	N-S medium traffic scenario (s)	E-W medium traffic scenario (Left) (s)	E-W medium traffic scenario (Straight) (s)	High traffic scenario (s)	Fixed time (s)
0	9	3	3	3	3	
1	0	6	6	6	6	
2						10
3						3
4	0	8	7	10	12	
5						5
6						4
7						3
8	3	3	8	8	10	
9	3	3	9	9	8	
10						4
11						3
12	3	6	3	3	7	
13	3	8	3	3	9	
14						4
15						3
16	0	4	4	4	6	
Cycle lenght	**60**	**80**	**82**	**85**	**100**	**39**

Figure 12. Matrix of states at a four-legged intersection.

The PoC assumes that all the leaders approach the intersection with similar velocities at different times (Figure 11). Vehicle a_1 was the first to request to cross the intersection and informed IM about its position and also that four others follow it at their positions with their speeds. Phase 1, sequence 3, therefore, begins at $t'a_1$. Vehicle b_1 requests access later and includes the mappings of its two followers in its request. As the order to cross conflicts with a_i movement, he and his followers will pile up on the stop line increasing the total waiting time of the b_i cars. The fourth sequence is an adaptive sequence (Figure 12). Due to the presence of a medium E-W traffic scenario, the IM extends the green time in order to accommodate the passage of all the a_i followers as well as the simultaneous passage of the arriving c_i (Figure 8). From a capacity point of view, it is more efficient if vehicle c_1 is given access (Phase 2) before vehicle 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 with north and south conflicting flows, as stated in Figure 5. Meanwhile, the speed of vehicle e was reduced, increasing the total accumulated time in the S-N arm.

Adaptive sequences 8 and 9 kick off Phase 3 (Figure 11) and the sequence times will be adjusted according to the variation of r_t for the left turn of the b_i cars. A new phase, Phase 4, begins and includes two adaptive sequences, sequence 12 and 13. Their time intervals will be as short as possible, which will free up capacity in the cycle for the E-W flows that are heavily loaded. Taking into account the accumulated total waiting time in each arm, an 85 s cycle is recommended for this type of flow. The times associated with each sequence can be visualized in Figure 11.

So, the real-time detection of the spatiotemporal data based on urban road network traffic status can provide rich and high-quality basic data and fine-grained assessment of control effects for traffic control.

5. Conclusions and Future Trends

We propose a way to optimize urban traffic network operations by integrating traffic signal control and driving behavior with V-VLC-ready connected cars. To command the passage of vehicles crossing the intersection, request/response mechanisms and temporal/space relative pose concepts were used. A communication scenario is established and a "mesh/cellular" hybrid network configuration proposed. The comparison between a four-legged intersection and a split intersection is presented. A phasing of traffic flows is proposed as a proof of concept. According to results, vehicles are controlled and scheduled to cross intersections in order to minimize traffic delays. Taking into account the pose analysis, the delays between left turns and forward movements are also allocated. Split intersections reduce the number of phases and increase the pedestrian phase, resulting in fewer stops at intersections. Additionally, through synchronization of the two signalized intersections, the corridor travel times is improved on both the major and side streets. The simulated/experimental results confirmed that the proposed cooperative VLC architecture is suitable for the intended applications. By using VLC between connected vehicles and their environment, critical points such as queue formation and dissipation, relative speed thresholds, and inter-vehicle spacing can be directly monitored.

For further development, the research team plans to finalize the embedded application, which will be used to experiment with either static or moving vehicles on several road configurations. This paper focuses on the concept rather than on the practical implementations. Implementing the system in a real environment requires considering several constraints, including the dimensions, orientation, and motion of the target vehicles; the precise motion and position of the vehicle; the strategic locations of landmarks; and the unambiguously covered distances and speeds, as well as the field of view. The practical implementation of many tasks such as steering/velocity control, perception of the environment, and performance under all conditions of the roadway and environment will be challenging.

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