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Adaptive Traffic Control Using Cooperative Communication through Visible Light

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Abstract. The purpose of this study is to develop a Visible Light Communication (VLC) system that facilitates safe vehicle management through intersections using Vehicle-to-Vehicle, Vehicle-to-Infrastructure, and Infrastructure-to-Vehicle communications. By using the headlights, streetlights and traffic signaling to broadcast information, the connected vehicles interact with one another and with the infrastructure. Using joint transmission, mobile optical receivers collect data, calculate their location for positioning and, concomitantly, read the transmitted data from each transmitter. In parallel with this, an intersection manager coordinates traffic flow and interacts with the vehicles via Driver Agents embedded in them. A communication scenario is established, and a “mesh/cellular” hybrid network configuration proposed. Data is encoded, modulated and converted into light signals emitted by the transmitters. As receivers and decoders, optical sensors with light filtering properties, are used. Bidirectional communication between the infrastructure and the vehicles is tested. To command the passage of vehicles crossing the intersection safely queue/request/response mechanisms and temporal/space relative pose concepts are used. Data shows that the adaptive traffic control system in the Vehicle to Everything environment can collect detailed data, including vehicle position, speed, queue length, and stopping time. The short-range mesh network ensures a secure communication from streetlamp controllers to the edge computer through the neighbor traffic light controller and enables peer-to-peer communication.

Keywords: Vehicular communication, Traffic control, Light controlled intersection, Queue distance, Pose connectivity, White LEDs transmitters, SiC photodetectors, OOK modulation scheme, “mesh/cellular” hybrid network.

1 Introduction

The main objective of the Intelligent Transport System (ITS) technology is to optimize traffic safety and efficiency on public roads by increasing situation awareness and mitigating traffic accidents through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure

(V2I) communications [1] [2] [3]. The goal is to increase the safety and throughput of traffic intersections using cooperative driving [4][5]. For self-localization the precise knowledge of the own motion and position, is important. By knowing, in real time, the location, speed and direction of nearby vehicles, a considerable improvement in traffic management is expected.

This work focuses directly on the use of Visible Light Communication (VLC) as a support for the transmission of information providing guidance services and specific information to drivers. VLC is an emerging technology [6][7] 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. In the case of vehicular communications, the use of VLC is made easier because all vehicles, streetlights, and traffic lights are equipped with LEDs, using them for illumination. Here, the communication and localization are performed 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 [8][9]. VLC enables a more accurate measurement of the distance and position of vehicles with sub-meter resolution given the high directivity of visible light.

The paper is organized as follows. After the introduction, in Section 2, the V-VLC system is described and the scenario, architecture, communication protocol, coding/decoding techniques analyzed. In Section 3, the experimental results are reported, and the system evaluation performed. A phasing traffic flow diagram based on V-VLC is developed, as a Proof of Concept (PoC). Finally, in Section 4, the main conclusions are presented.

1.1 Background Theory on Adaptive Traffic Control

The traffic data collected by the current traffic control system using induction loop detector and other existing sensors is limited. With the advancement of the wireless communication technologies and the development of the V2V and V2I systems, called Connected Vehicle (CV) [10], there is an opportunity to optimize the operation of urban traffic network by cooperation between traffic signal control and driving behaviors. Besides, it will also provide a technical support for the development of Vehicle-to-X systems and autonomous driving industries. A real-time detection of the spatial and temporal data from the network traffic status of urban roads can provide rich and high-quality basic data and a fine-grained assessment of traffic control effects. A closed-loop feedback self-adaptive control system with better uncertainty response capability and higher intelligent decision-making level are inevitable results of the objective needs of the development and application of traffic control and advanced infrastructure technologies. The main difference between the existing self-adaptive traffic control systems is that it relies on traffic control data gathered via a data-driven approach. Also, it can provide support for the interaction between the traffic control system and the traffic flow.

Our adaptive traffic control strategy aims to respond to real-time traffic demand through current and predicted future traffic flow data modeling. Compared with the

traffic flow and occupancy information provided by the fixed coil detector in the traditional traffic environment, the adaptive traffic control system in V2X environment can collect more detailed data such as vehicle position, speed, queuing length, and stopping time. While V2V links are particularly important for safety functionalities such as pre-crash sensing and forward collision warning, I2V links provide the CV with a variety of useful information [11][12]. Since the information network of CVs affects driving behavior and the need for traffic stream control, more research is required on the theory of multimodal traffic control.

To conduct the research, the following questions are considered: Is it possible to implement a reliable VLC system using the proposed I2X vehicular visible communication model, in traffic controlled intersections? Using a network simulator, how can VLC be implemented in a traffic control intersection? By employing VLC at a traffic control intersection, what effects does it have on traffic performance parameters in an urban traffic scenario?

The proposed smart vehicle lighting system considers wireless communication, computer based algorithms, smart sensor and optical sources network, which stands out as a transdisciplinary approach framed in cyber-physical systems.

1.2 V-VLC Communication Link

A Vehicular VLC system (V-VLC) consists of a transmitter to generate modulated light and a receiver to detect the received light variation located at the infrastructures and at the driving cars. Both the transmitter and the receiver are connected through the wireless channel. Line of Sight (LoS) is mandatory.

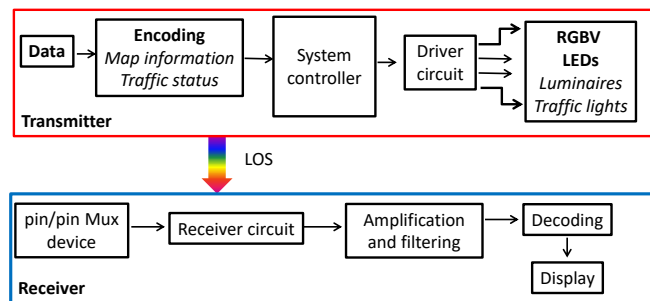


Fig. 1. Generic design of VLC system: data transmission and reception. Block diagram of the VLC link.

Fig. 1 illustrates the basic architecture of a V-VLC system. Both communication modules are software defined, where modulation/ demodulation can be programed.

The VLC emitter has a dual purpose, emits light, and transmits data instantaneously by using the same optical power without any noticeable flickering. The digital VLC emitter module converts the binary data to intensity modulated light waves for transmission. A driving circuit controls the switching of the LED according to the incoming binary data at the given data rate, generating an amplitude modulated light beam. Here,

the light produced by the LED is modulated with ON–OFF-keying (OOK) amplitude modulation [13].

White light tetra-chromatic (WLEDs) sources, framed at the corners of a square (see Fig. 2a) are used providing a different data channel for each chip. They consist of red, green, blue and violet chips and combine the lights in correct proportion to generate white light. At each node, only one chip of the LED is modulated for data transmission, the Red (R: 626 nm), the Green (G: 530 nm), the Blue (B: 470 nm) or the Violet (V: 390 nm). Modulation and digital-to-analog conversion of the information bits is done using signal processing techniques. Parasitic capacitance (traces and support circuitry) plays an important role in increasing the RC time constant and thus slowing transitions. However, the typical bit rates that can be supported by fast moving vehicles is usually limited by channel conditions, not by the switching speed of the LED.

Transmitters and receiver's 3D relative positions is displayed in Fig.2a. The LEDs are modeled as Lambertian sources where the luminance is distributed uniformly in all directions, whereas the luminous intensity is different in all directions [14]. The coverage map for a square unit cell is displayed in Fig. 2b. All the values were converted to decibel (dB). The nine possible overlaps (#1-#9), defined as fingerprint regions, as well as the possible receiver orientations (steering angles; δ) are also pointed out for the unit square cell.

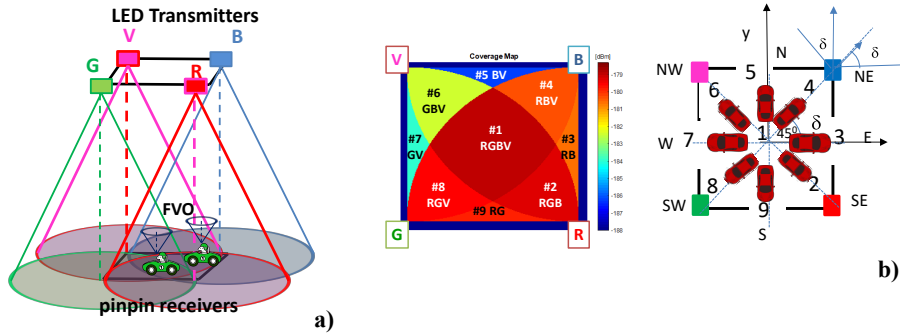


Fig. 2. a) Transmitters and receivers 3D relative positions. b) Illustration of the coverage map in the unit cell: footprint regions (#1-#9) and steering angle codes (2-9).

The visible light emitted by the LEDs passes through the transmission medium and is received by the MUX photodetector that acts as an active filter for the visible region of the light spectrum [15]. The MUX photodetector multiplexes the different optical channels, perform different filtering processes (amplification, switching, and wavelength conversion) and decode the encoded signals, recovering the transmitted information. The received channel can be expressed as $y = \mu hx + n$ where y represents the received signal, x the transmitted signal, μ is the photoelectric conversion factor which can be normalized as $\mu = 1$, h is the channel gain and n is the additive white Gaussian noise of which the mean is 0. The responsivity of the receiver depends on its physical structure and on the effective area collection. After receiving the signal, it is in turn filtered,

amplified, and converted back to digital format for demodulation. The received signal power includes both the energy transmitted from the transmitter and from ambient light. The device receives multiple signals, finds the centroid of the received coordinates, and stores it as the reference point position. Nine reference points, for each unit cell, are identified giving a fine-grained resolution in the localization of the mobile device across each cell (see Fig. 2b). The input of the guidance system is the coded signal sent by the transmitters to an identify vehicle (I2V), and includes its position in the network $P(x_i, y_j)$, inside the unit cell (#1-#9) and the steering angle, δ (2-9) that guides the driver orientation across his path.

2 Scenario, Environment and Architecture

2.1 Traffic Controlled Intersection

Four-legged intersections are usually two-way-two-way intersections (four-legged intersections), which are connected by eight incoming and eight exiting roads to North, West, South, and East. The simulated scenario is a four-legged traffic light-controlled intersection as displayed in Fig. 3.

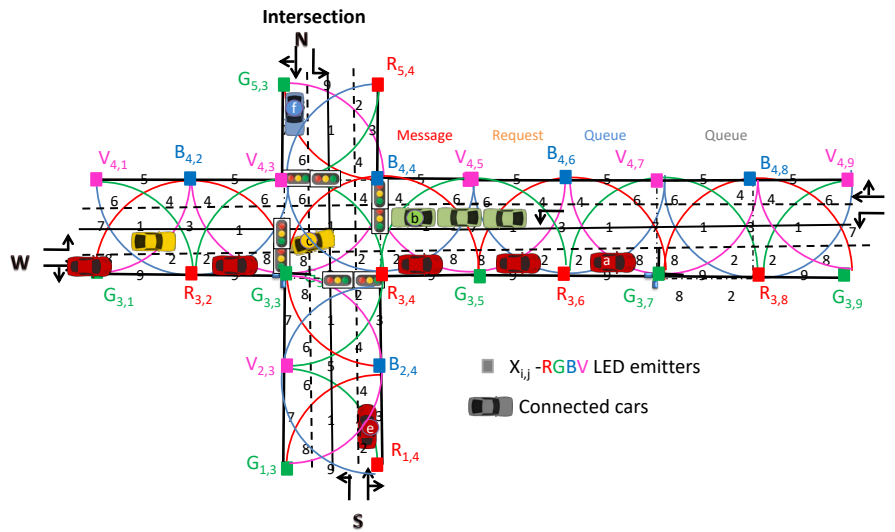


Fig. 3. Simulated scenario: Four-legged intersection and environment with the optical infrastructure (X_{ij}), the generated footprints (1-9) and the CV.

An orthogonal topology based on clusters of square unit cells was considered. The grid size was chosen to avoid an overlap in the receiver from the data in adjacent grid points. Each transmitter, $X_{i,j}$, carries its own color, X , (RGBV) as well as its horizontal and vertical ID position in the surrounding network (i,j). During the PoC, it was assumed that the crossroad is at the intersection of line 4 and column 3. Located along the roadside are the emitters (streetlamps). Thus, each LED sends an I2V message that includes the synchronism, its physical ID and the traffic information. When a probe vehicle

enters the streetlight's capture range, the receiver replies to the light signal, and assigns a unique ID and a traffic message [16].

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

2.2 Architecture

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 an ITS to the 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.

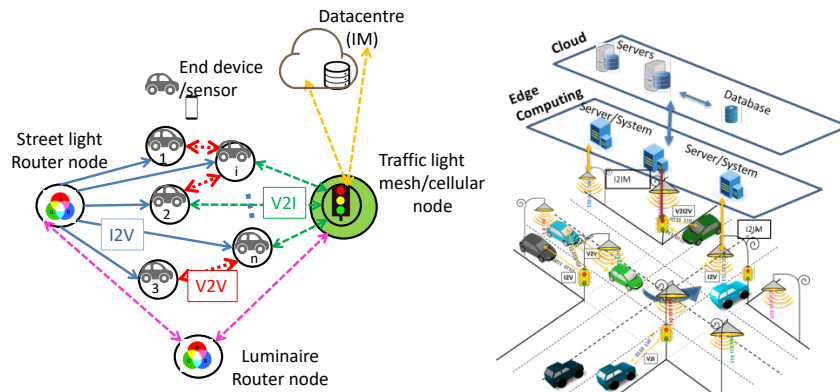


Fig. 4. Representation of the Edge Computing infrastructure. Mesh and cellular hybrid architecture.

Fig.4 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 like routers nodes in the network. The other one is the "mesh/cellular" hybrid controller that is also equipped with a modem provides IP base connectivity to the Intersection Manager (IM) services. These nodes act as border-router and can be used for edge computing [16].

This architecture enables edge computing and device-to-cloud communication (I2IM) and enables peer-to-peer communication (I2I), to exchange information. It performs much of the processing on embedded computing platforms, directly interfacing to sensors and controllers. It supports geo-distribution, local decision making, and real-time load-balancing.

As exemplified in Fig.5, the vehicle movement along the road can be thought as a queue, where the vehicles arrive at a lane, wait if the lane is congested and then move once the congestion reduces.

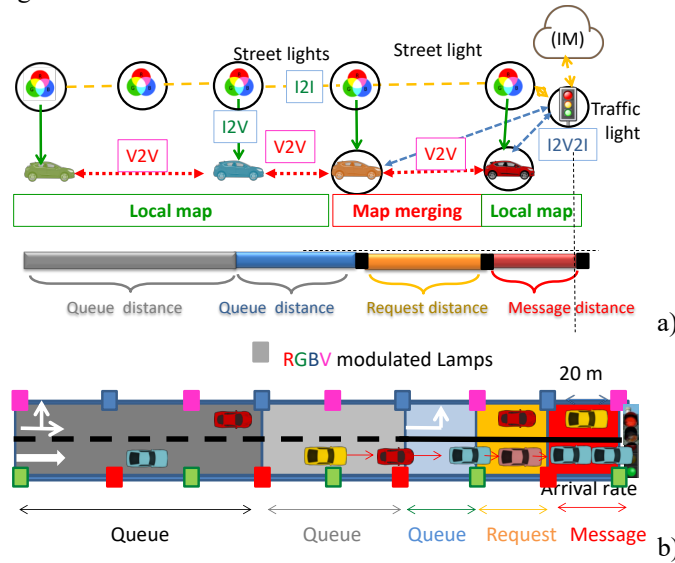


Fig. 5. a) Graphical representation of the simultaneous localization as a function of node density, mobility and transmission range. b) Design of the state representation in the west arm of the intersection, with cells length.

For the intersection manager crossing coordination, the vehicle, and the IM exchange information through two types of messages, “request” (V2I) and “response” (I2V). Inside the request distance, an approach “request” is sent, using as emitter the headlights. The “request” contains all the information that is necessary for a vehicle’s space-time reservation for its intersection crossing (flow’s direction and its own and followers’ speeds). IM uses this information to convert it in a sequence of timed rectangular spaces that each assigned vehicle needs to occupy the intersection. The objective is to let the IM knows the position of vehicles inside the environment at each step t . It includes only spatial information about the vehicles hosted inside the environment, and the cells used to discretize the continuous environment.

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 Fig. 5. The distance, d , between vehicles can be calculated based on a truncated exponential distribution [17]. An IM acknowledge is sent, “response” from the traffic signal over the facing receiver to

the in-car application of the head vehicle. Once the response is received (message distance in Fig.5), the vehicle is required to follow the provided occupancy trajectories (footprint regions, see Fig. 2 and Fig. 3). 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 Color Phasing diagram

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.

A color phasing diagram for a four-legged intersection is shown in Fig. 6. It was assumed four “color poses” linked with the radial range of the modulated light in the RGBV crossroad nodes [13]. The West straight, South left turn and West right turn maneuvers correspond to the “Green poses”. “Red poses” are related to South straight, East left turn, and South right turn maneuvers. “Blue poses” are related to East straight, North left turn, and East right turn maneuvers, and “violet poses” are related to North straight, West left turn, and North right turn maneuvers.

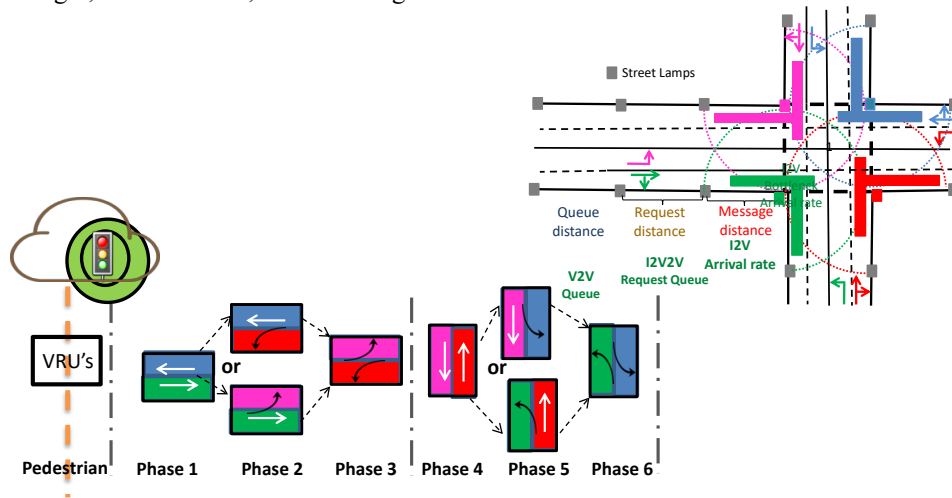


Fig. 6 Color phasing diagram in a four-legged intersection.

In the phasing diagram, 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, the phasing is referred to as “exclusive”. Functional barriers (dash dot lines) exist between exclusive pedestrian and Phase 1 and Phase 6.

The problem that the IM has to solve is, in fact, allocating 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 for pedestrians and to ensure that motorist expectancy is not violated.

2.4 Multi-Vehicle Cooperative Localization

There are critical points where traffic conditions change: the point at which a vehicle begins to decelerate when the traffic light turns red (message distance), the point at which it stops and joins the queue (queue distance), the point at which it starts to accelerate when the traffic light turns green (request distance) or the points at which the coming vehicle is slowed by the leaving vehicle (see Fig. 5). As a result, the road resistances can be calculated dynamically based on the relative pose positions of the vehicles and the traffic signal phase at intersections. With V2I2V communication, the travel time that influences traffic channelization in different routes can be calculated and real-time data about speed, spacing, queues, and saturation can be collected across the queue, request and message distances.

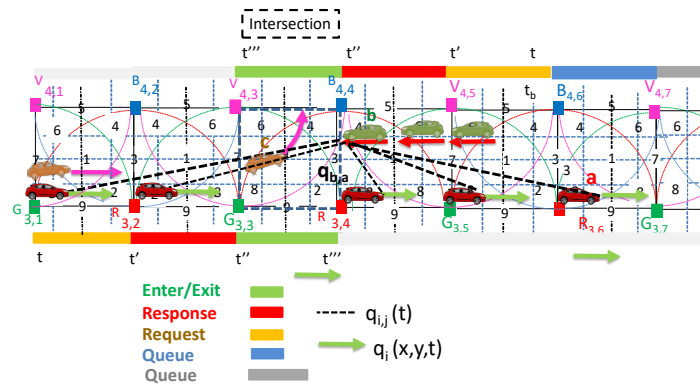


Fig. 7. Movement of the cars, in the successive moments, with their colorful poses (color arrows) and q_{ij} spatial relative poses (dot lines).

In Fig. 7, the movement of the cars in successive moments is depicted with their colored poses (colored arrows) and q_{ij} spatial relative poses (dot lines).

We denote $q(t)$, $q(t')$, $q(t'')$, $q(t''')$ as the vehicle pose estimation at the time t , t' , t'' , t''' (request, response, enter and exit times), respectively. All the requests contain vehicle positions and approach speeds. If followers exist, the request message from its leader includes the position and speed previously received by V2V. This information alerts the controller to a later request message (V2I), confirmed by the follow vehicle.

The vehicle speed can be calculated by measuring the actual travelled distance over-time, using the ID's transmitters tracking. Two measurements are required: distance and elapsed time. The distance is fixed while the elapsed time varies and depends on the vehicle's speed and is obtained through the instants where the footprint region

changes. The receivers compute the geographical position in the successive instants (path) and infer the vehicle's speed. When two vehicles are in neighborhood and in different lanes, the geometric relationship between them ($q_{i,j}$) can be inferred fusing their self-localizations via a chain of geometric relationships among the vehicles poses and the local maps. For a vehicle with several neighboring vehicles, the mesh node (Fig. 3 and Fig. 4) uses the indirect V2V relative pose estimations method taking advantage of the data of each neighboring vehicle [18].

3 VLC Evaluation

In the PoC (see Fig. 3) it is 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 fourth, fifth and sixth place, respectively. In seventh, eighth and ninth request places are b_3 , e and a_3 , respectively, followed in tenth place, by c_2 . In penultimate request is a_5 , and in the last one is f . So, $t_{a1} < t_{b1} < t_{a2} < t_{b2} < t_{a3} < t_{c1} < t_{b3} < t_e < t_{a4} < t_{c2} < t_{a5} < t_f$. According to our assumptions, 540 cars approach the intersection per hour, of which 80 percent come from east and 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.

3.1 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 a 64- bits data frame.

As exemplified in the top part of Fig. 8, the frame is divided into four, if the transmitter is a streetlamp or headlamp, or five blocks, if the transmitter is the traffic light. The first block is the synchronization block [10101], the last is the payload data (traffic message) and a stop bit ends the frame. The second block, the ID block gives the location (x , y coordinates) of the emitters inside the array ($X_{i,j}$). Cell's IDs are encoded using a 4 bits binary representation for the decimal number. The δ block (steering angle (δ)) completes the pose in a frame time $q(x,y, \delta, t)$. Eight steering angles along the cardinal points gives the car direction, and are coded with the same number of the footprints in the unit cell (Fig.2) are possible. If the message is diffused by the IM transmitter, a pattern [0000] follows this identification, if it is a request (R) a pattern [00] is used. The traffic message completes the frame.

Because the VLC has four independent emitters, the optical signal generated in the receiver can have one, two, three, or even four optical excitations, resulting in 2^4 different optical combinations and 16 different photocurrent levels at the photodetector.

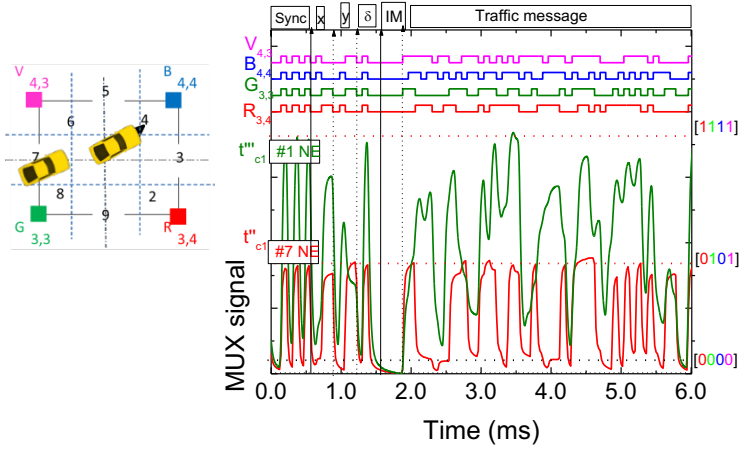


Fig. 8. MUX signal responses and the assigned decoded Inside the intersection; messages acquired by vehicle c_l , poses #7NE, #1NE. On the top the transmitted channels packets [R, G, B, V] are decoded.

As an example, in in Fig. 8 Vehicle c_l receives two response MUX signals as it crosses the intersection. This vehicle, driving on the left lane, receives order to enter the intersection in # 7, turning left (NE) and keeps moving in this direction across position #1 toward the North exit (Phase2, violet pose). In the right side, the received channels are identified by its 4-digit binary codes and associated positions in the unit cell. On the top the transmitted channels packets [R, G, B, V] are decoded.

3.2 Adaptive Traffic Control

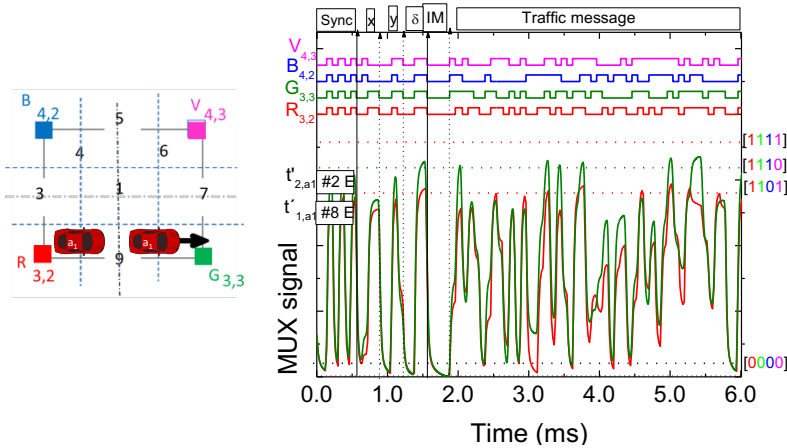


Fig. 9 Normalized MUX signal responses and the assigned decoded messages acquired by vehicles a_l at different response times. Message distance, Poses #8E and #2E.

In Fig. 9 and Fig.10 the normalized MUX signals and the decoded messages assigned to IM received by Vehicle a_1 , a_5 , b_2 , b_3 at different response times are shown. On the top the transmitted channels [R, G, B, V] are decoded. In the right side, the received channels for each vehicle are identified by its 4-digit binary codes and associated positions.

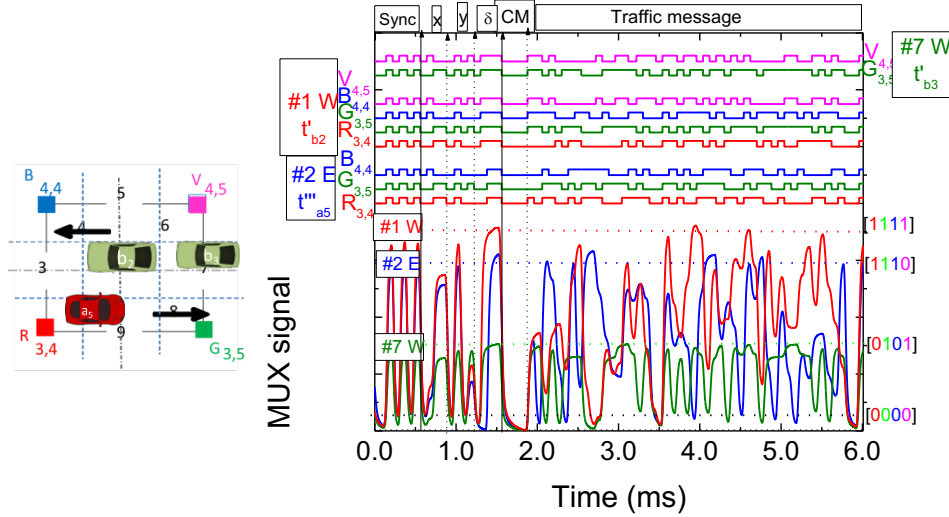


Fig. 10 Normalized MUX signal responses and the assigned decoded messages acquired by vehicles a_5 , b_2 , b_3 at different response times. Vehicle a_5 , pose #2E, and Vehicle b_2 poses #7W and, b_3 at #1W.

Figuring out Fig. 3 and Fig. 6, Fig.9 shows the MUX signals assigned to response messages received by Vehicle a_1 , driving the right lane, that enters Cell $C_{4,2}$ in #2 (t'_1 , Phase1, green pose), goes straight to E to position #8 (t'_2 , Phase1, green pose). Then, this vehicle enters the crossroad through #8 and leaves it in the exit #2 keeping always the same direction (E). In Fig. 10, vehicle b_2 and b_3 approaches the intersection after having asked permission to cross. It only receives authorization when the vehicle a_5 has left the intersection (end of Phase 2). Then, Phase 3 begins with vehicle b_1 heading to the intersection (W) (pose red) while vehicles a_i ($1 < i < 5$) follows its destination towards E (pose green).

3.3 Queuing System: Dynamic Traffic Signal Phasing

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

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 $q_i(x, y, \delta, t)$.

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 Fig.11 according to the phasing diagram, the cycle length is composed of 5 of the 7 phases contemplated (see Fig. 6) and divided in 16 time sequences. The exclusive pedestrian phase contains the "0", the "1" and the "16" sequences. The cycle's top synchronism starts with sequences "1". The first, second, third, and fourth phases contain sequences between "2" and "15" and control traffic flow.

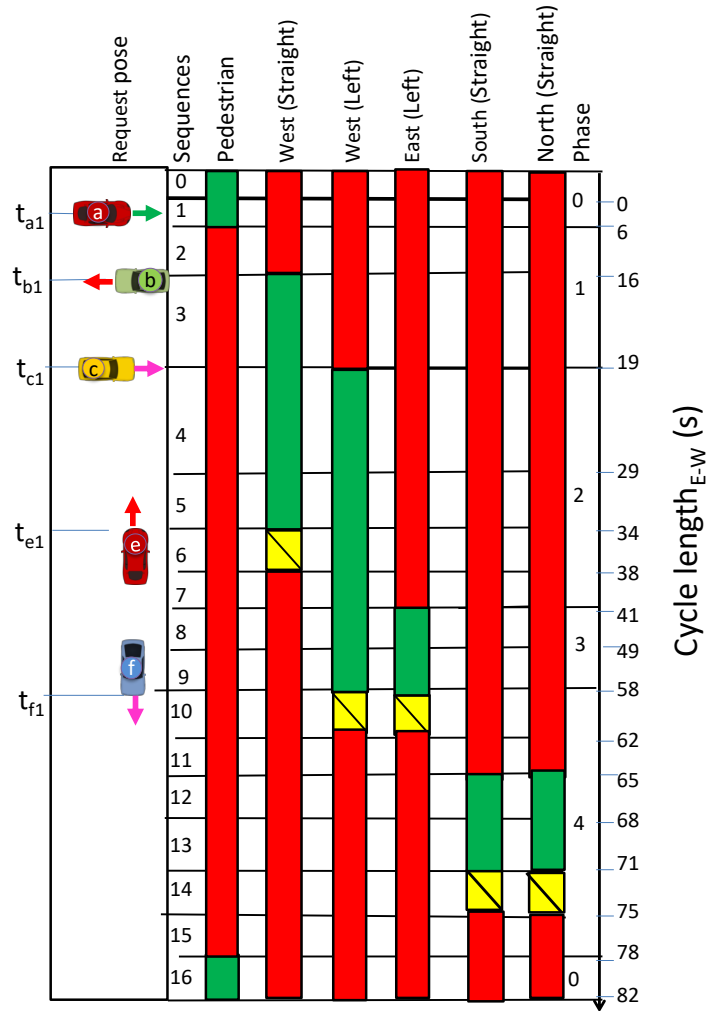


Fig. 11. Requested phasing of traffic flows.

The vehicle movement along the lane can be thought as a queue, where the vehicles arrive, wait if the lane is congested and then move once the congestion reduces. In Fig. 5, a graphical representation of the simultaneous localization and mapping problem using connectivity as a function of node density, mobility and transmission range was illustrated.

The matrix of states allows the user to view, enter, or modify the division of an intersection into states, as shown in Fig. 12. The matrix shows the durations of the states for a given cycle. In this matrix, each element represents the lighting state of the traffic light (if it is selected, the light is green) for the corresponding state. 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).

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

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

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. The following operations can be performed by the IM depending on the requests information: modify the durations of cycle; enter the fixed times; change the durations of states with the transportable from any state at a dynamic time or modify the intersection coordination offset.

The objective is to maximize the traffic flow through the intersection over time. For traffic coordination, in the scenario presented (Fig. 3), the IM receives requests for

access to the intersection from all the leading cars at different times. t_{x_l} (Fig.10). This type of information (V2I) enables the IM to know the precise location and the speed of all the leader vehicles, as well as the location and speed from their followers that was sent to the leaders through V2V. This data helps previewing the initial arrival times and speeds at the different sections. The IM has to minimize accumulated total waiting time $aTwt$ in each arm of the intersection defined as [19]:

$$aTwt_t = \sum_{xi=1}^n (awt)_{xi,t} \quad (1)$$

Where $awt(x_i, t)$ is the amount of time in seconds a vehicle x_i has a speed of less than 0.1 m/s at step t and n represents the total number of vehicles in the environment at step t . When the speed is less than 0.1 m/s a queue alert is generated. If:

$$r_t = aTwt_t - aTwt_{(t-1)} \quad (2)$$

$aTwt_t$ and $aTwt_{t-1}$ represent the accumulated total waiting time of all the cars in the intersection captured respectively at step t and $t-1$. If r_t is negative more vehicles in queues are added compared to the situation in the previous step $t-1$, resulting in higher waiting times compared to the previous step.

The PoC assumes that all the leaders approach the intersection with similar velocities at different times (Fig. 11). There is only one episode per scenario and the cars cycle in the same order every time. 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 (see Fig. 9). 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 (Fig. 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 (Fig. 8). From the capacity point of view, it is more efficient, if Vehicle c_1 is given access (Phase 2) before Vehicles b_i , and Vehicle c_2 is given access before Vehicle e , forming a west left turn of set of vehicles (platoon) before giving way to the fourth phase with north and south conflicting flows, as stated in Fig. 6. 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 (Fig.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-second cycle is recommended for this type of flow. The times associated with each sequence can be visualized in Fig. 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.

Safety and privacy are also the key requirements for the V-VLC. It is important to improve the coding techniques, in the future, in order to allow only the legitimate receivers to process secure request/response messages. Here, the security is embedded in the physical transmission. In the LoS channel no information can be made available by the eavesdropper, i.e., he is completely passive. Using the street lamp positions to determine vehicular flow eliminates the need for certificates or passwords from the network and replaces them with statistical secrecy.

4 Conclusions

With V-VLC-ready connected cars, we propose optimizing urban traffic network operation by integrating traffic signal control and driving behavior. For managing intersections, the adaptive traffic control system uses a queue/request/response approach. An architecture, scenario, environment, and hybrid mesh/cellular network configuration were developed and proposed. The V2I2V communications enable real-time monitoring of queues, requests, and messages, along with the travel times necessary to synchronize traffic routing in various routes. The vehicles are controlled in their arrival time and scheduled to cross intersections at predetermined times to reduce traffic delays. In order to demonstrate the concept, a phasing diagram and matrix of states are proposed based on the total accumulated time. Results show that the adaptive traffic control in a V2X environment can collect more detailed data, such as vehicle position, speed, queue length, and stopping time, than the traffic flow and occupancy information provided by fixed coil detectors. The traffic light phase is adjusted to the traffic scenario and the duration of the traffic light is changed dynamically which reduces travel times and unnecessary waiting for the green phase, leading to optimized traffic flow. The introduction of VLC between connected vehicles and the surrounding infrastructure allows the direct monitoring of critical points that are related to the queue formation and dissipation, relative speed thresholds and inter-vehicle spacing increasing the safety.

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References

1. Elliott, D., Keen W., and Miao L., “Recent advances in connected and automated vehicles” *Journal of Traffic and Transportation Engineering*, Vol. 6, Issue 2, pp.109-131(April 2019).
2. Jitendra, N., and Bajpai, “Emerging vehicle technologies & the search for urban mobility solutions, *Urban, Planning and Transport Research*, 4:1, pp.83-100, (2016).

3. Wang, N., Qiao, Y., Wang, W., Tang, S. and Shen, J. "Visible Light Communication based Intelligent Traffic Light System: Designing and Implementation," 2018 Asia Communications and Photonics Conference (ACP) DOI: 10.1109/ACP.2018.8595791(2018).
4. Cheng, N. et al. "Big data driven vehicular networks," *IEEE Network*, vol. 32, no. 6, pp.160–167, (Nov. 2018).
5. Singh, P., Singh, G., and Singh, A., "Implementing Visible Light Communication in intelligent traffic management to resolve traffic logjams" *Int. J. Comput. Eng. Res*, 5(9), pp.1-5 (2015).
6. O'Brien, D. et al. "Indoor Visible Light Communications: challenges and prospects," *Proc. SPIE 7091*, 709106, pp. 60-68 (2008).
7. Parth. H., Pathak, X., Pengfei, H. and Prasant, M., "Visible Light Communication, Networking and Sensing: Potential and Challenges," September 2015, *IEEE Communications Surveys & Tutorials* 17(4): Fourthquarter 2015, pp. 2047 – 2077 (2015).
8. Nawaz, T., Seminara, M., Caputo, S., Mucchi, L. and Catani, J. "Low-latency VLC system with Fresnel receiver for I2V ITS applications," *J. Sensor Actuator Netw.*, vol. 9, no. 3, p. 35 (Jul. 2020).
9. Caputo, S., et al. "Measurement-based VLC channel characterization for I2V communications in a real urban scenario," *Veh. Commun.*, vol. 28, Apr. 2021, Art. no. 100305.
10. Yousefi, S., Altman, E., El-Azouzi, R., and Fathy, M., "Analytical Model for Connectivity in Vehicular Ad Hoc Networks," *IEEE Transactions on Vehicular Technology*, 57, pp.3341-3356 (2008).
11. Pribyl, P., Pribyl, M., Lom, and Svitek, M., "Modeling of smart cities based on ITS architecture," *IEEE Intell. Transp. Syst. Mag.*, vol. 11, no. 4, pp. 28–36 (Nov. 2019).
12. Miucic, R. "Connected Vehicles: Intelligent Transportation Systems." Cham, Switzerland: Springer (2019).
13. Vieira, M. A., Vieira, M., Louro, P., Vieira, P., "Bi-directional communication between infrastructures and vehicles through visible light," *Proc. SPIE 11207*, Fourth International Conference on Applications of Optics and Photonics, 112070C (3 October 2019); doi: 10.1117/12.2526500 (2019).
14. Zhu, Y., Liang, W., Zhang, J., and Zhang, Y., "Space-Collaborative Constellation Designs for MIMO Indoor Visible Light Communications," *IEEE Photonics Technology Letters*, vol. 27, no. 15, pp. 1667–1670 (2015).
15. Vieira, M. A., Vieira, M., Vieira, P. and Louro, P., "Optical signal processing for a smart vehicle lighting system using a-SiCH technology," *Proc. SPIE 10231*, Optical Sensors 2017, 102311L (2017).
16. Yousefpour, A. et al., "All one needs to know about fog computing and related edge computing paradigms: A complete survey", *Journal of Systems Architecture*, Volume 98, pp. 289-330 (2019).
17. Momeni, S. and Wolfinger, B. E., "Availability evaluations for IPTV in VANETs with different types of access networks". *EURASIP Journal on Wireless Communications and Networking*, Springer Open Journal, 2014:117 (2014).
18. Vieira, M. A., Vieira, M., Louro, P., and Vieira, P., "Cooperative vehicular communication systems based on visible light communication" *Opt. Eng.* 57(7), 076101 (2018).
19. Vidali, A., Crociani, L., Vizzari, G., Bandini, S., "A Deep Reinforcement Learning Approach to Adaptive Traffic Lights Management" In *WOA 2019*, pp. 42-50, (Jun 26, 2019).