Smarter Intersections with Cooperative Vehicular Visible Light Communication

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***Abstract*— Our proposed system utilizes Vehicle-to-Vehicle, Vehicle-to-Infrastructure, and Infrastructure-to-Vehicle communications to create a Visible Light Communication system for managing vehicles crossing light-controlled intersections in a safe manner. The system leverages connected vehicles and infrastructure to exchange information through the use of headlights, streetlights, and traffic signals. In this system, transmitters emit light signals that are encoded, modulated, and converted from data. Optical sensors with light filtering properties serve as receivers and decoders, allowing them to capture and interpret the transmitted signals. To facilitate effective communication, a specific communication scenario is established. Concurrently, an intersection manager takes charge of coordinating traffic flow and interacts with vehicles using embedded Driver Agents. The system incorporates a dynamic phasing diagram based on the total accumulated time to illustrate the concept. The collected data demonstrates that the adaptive traffic control system in the V2X environment can gather detailed information, including vehicle position, speed, queue length, and stopping time. By dynamically controlling traffic flows at intersections, the system adjusts the durations of cycles based on traffic demands. This improved temporal management of phases results in smoother traffic flow and higher average speeds.**

Index Terms*— *Traffic control; Reinforcement Learning; Vehicular Visible Light Communication; Cooperative Driving.

I. INTRODUCTION

The primary objective of Intelligent Transport System (ITS) technology is to enhance traffic safety and efficiency on public roads by increasing situational awareness and mitigating traffic accidents through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications[1] [2] [3]. Inefficiencies in existing traffic light cycle control systems lead to problems such as long delays and energy wastage. To address these issues and improve efficiency, it is crucial to utilize real-time traffic information as input and dynamically adjust the duration of traffic lights accordingly. The ultimate goal is to enhance safety and increase the throughput of traffic intersections through cooperative driving [4][5].

This research specifically focuses on utilizing Visible Light Communication (VLC) as a means of transmitting information to provide guidance services and specific information to drivers. The objective is to decide the duration of traffic signals based on the data collected from VLC data transmission. VLC is an emerging technology [6][7] that enables data communication by modulating information on the intensity of light emitted by LEDs. In the context of vehicular communications, VLC becomes more accessible as all vehicles, streetlights, and traffic lights are equipped with LEDs, which are primarily used for illumination. By utilizing streetlamps, traffic signals, and the headlights and taillights of vehicles, communication and localization can be facilitated, allowing for the dual use of exterior automotive and infrastructure lighting for both illumination and communication purposes[8][9]. After the introduction, Section II introduces the scenario, environment, and architecture for cooperative guidance systems. In Section III, a proposal for Dynamic Traffic Phasing is presented, followed by an analysis of the Adaptive V-VLC in Section IV. Sections V and VI establish a correlation between experimental and simulated results. Finally, Section VII encapsulates the main conclusions drawn from the study.

A. Background Theory on Adaptive Traffic Control

As wireless communication technologies advance and V2V and V2I systems, known as Connected Vehicles (CV), are developed, there arises an opportunity to optimize the operation of urban traffic networks through cooperation between traffic signal control and driving behaviors. The adaptive traffic control strategy we propose aims to effectively respond to real-time traffic demand by utilizing current and predicted future traffic flow data modeling.

In comparison to the fixed coil detectors used in traditional traffic environments, the adaptive traffic control system in a V2X environment can collect more detailed

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data. This includes not only traffic flow and occupancy information but also specific details such as vehicle position, speed, queuing length, and stopping time. By leveraging the capabilities of the V2X system, the adaptive traffic control system can gather comprehensive and granular data, providing a more accurate representation of the traffic situation [10][11]. This increased level of data granularity allows for more precise analysis and decision-making in traffic control. It enables the adaptive traffic control system to dynamically adjust signal timings, optimize signal phasing, and coordinate traffic flow based on real-time conditions and predicted future demand. By incorporating the detailed data provided by the V2X environment, the adaptive traffic control system can improve traffic efficiency, reduce delays, and enhance overall urban traffic network performance.

B. V-VLC Communication Link

A Vehicular VLC system (V-VLC) comprises a transmitter that generates modulated light and a receiver located in infrastructures and driving cars to detect the received light variation. Both the transmitter and receiver are connected through the wireless channel. In this system, the light produced by the LED is modulated using ON-OFF-keying (OOK) amplitude modulation [12]. The environment is defined by a cluster of square unit cells arranged in an orthogonal geometry. Different data channels are provided by tetra-chromatic white light (WLEDs) sources positioned at the corners of the square unit cells[13][14].

The input of the V-VLC system consists of coded signals sent by transmitters such as streetlights and headlights. These signals are intended to communicate with identified vehicles (I2V), traffic lights (V2I), or other vehicles (V2V). The input also includes the position of transmitters in the network and the steering angle (δ) to guide the driver's orientation along their path. To manage the passage of vehicles crossing the intersection, queue/request/response mechanisms and temporal/space relative pose concepts are employed. The coded signals are received and decoded by a PINPIN photodetector with light filtering properties.

C. Intelligent control system

In order to develop an intelligent control system model that facilitates safe vehicle management through intersections using V2V, V2I, and I2V communications, Reinforcement Learning (RL) concepts are utilized. RL is a training method that involves rewarding desired behaviors and/or punishing undesired ones [15] [16]. The simulations are agent-based and are conducted using a tool for Simulation of Urban MObility (SUMO) [17]. As the agent gains experience, it learns to avoid negative situations and focus on positive ones. The traffic lights in SUMO are controlled by the learning agent based on its decisions, and the overall flow of traffic is described while rewarding the actions of the traffic lights control agent. The agent's goal is to explore new states while maximizing its total reward to develop the best possible policy. A dynamic phasing diagram and a matrix of states based on the total accumulated time are presented to illustrate the concept.

II. SCENARIO, ENVIRONMENT AND ARCHITECTURE

In Figure 1, the scenario with two traffic signals controlled intersections is displayed.

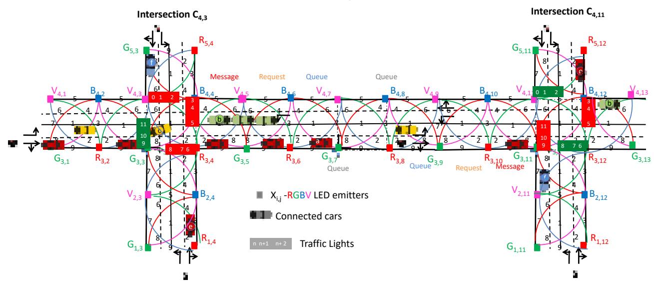

Fig. 1. Simulated scenario with the optical infrastructure (X_{ij}), the generated footprints (1-9), the CV and the environment.

Based on clusters of square unit cells, an orthogonal topology was considered. Each transmitter, $X_{i,j}$, carries its own color, X, (Red, Green, Blue, Violet) as well as its horizontal and vertical ID position in the surrounding network (*i*,*j*). During the Proof of Concept (PoC), it was assumed that the crossroads are located at the intersections of line 4 with column 3 and column 11, respectively. In Figure 1, four traffic flows were considered. Twenty-four vehicles arriving from West (W): twenty red a_i Vehicles with straight movement and four yellow c_i Vehicles with left turn only. In the second flow green Vehicles from East (E) b_i approach the intersection with left turn only (thirteen straight and two left turn). In the third flow, six orange e_i Vehicles, oncoming from South (S), two have left-turn approach and four straight movement. Finally, in the fourth flow, thirteen blue f_i Vehicles coming from North, nine go straight and four have left turn in both intersections. 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. 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 nineth request places are b_3, e_1 and a_3, respectively, followed in tenth place, by c_2. In penultimate request is a_5, and in the last one is f_1. 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.

In the proposed system, a mesh cellular hybrid structure is utilized, as depicted in Figure 2. The "mesh" controller, situated at the streetlights, plays the role of forwarding messages to vehicles (I2V) within the mesh. It functions similar to router nodes in a network, facilitating communication between vehicles. On the other hand, the "mesh/cellular" hybrid controller acts as a border-router and

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can also be employed for edge computing. This hybrid architecture allows for edge computing and device-to-cloud communication (I2IM), enabling the exchange of information. It leverages embedded computing platforms to perform a significant portion of processing tasks, while directly interfacing with sensors and controllers. This approach supports geo-distribution, local decision making, and real-time load balancing. By utilizing the mesh cellular hybrid structure, the system can effectively process and analyze data at the edge, enabling quicker response times and reducing the burden on central cloud infrastructure. Furthermore, this architecture promotes peer-to-peer communication (I2I), enabling direct information exchange between vehicles. This peer-to-peer communication enhances the efficiency of data sharing and collaboration among vehicles in the network.

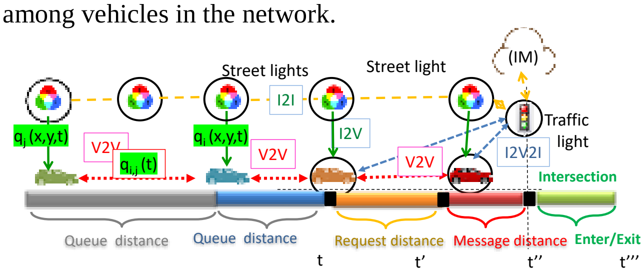

Fig. 2. Representation of the Edge Computing infrastructure. Mesh and cellular hybrid architecture.

Emitters (street lights) are located along the roadside (Figure 1). 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 [15]. When approaching the intersection, it asks permission "request" to cross. 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), the vehicle is required to follow the provided occupancy trajectories (footprint regions, see Figure 1). 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. The vehicle speed can be calculated by measuring the actual travelled distance overtime, using the ID´s transmitters tracking, $q_i(x,y,t)$. For a vehicle with several neighboring vehicles, the mesh node uses the indirect V2V relative pose estimations, $q_{ij}(t)$ method taking advantage of the data of each neighboring vehicle [18].

III. DYNAMIC TRAFFIC SIGNAL PHASING

Existing inefficient traffic light cycle control causes numerous problems, such as long delay and waste of energy. The traffic signal duration will be based on the collected data from V2V, V2I and I2V VLC communication. 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_0) 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 $q_i(x, y, \delta, t)$. The maximum number of possible vehicles in the message distance is 4 by lane and 8 by route. So, a maximum of 32 vehicles are expected at the message distances (20 m) based on the stipulated average vehicle length (4.5 m). It was assumed that $t_{a1}<t_{b1}<t_{a2}<t_{b2}<t_{a3}<t_{c1}<t_{b3}<t_e<t_{a4}<t_{c2}<t_{a5}<t_f$. To each driving Vehicle, x_i, is assigned the unique time at which it must enter the intersection, $t''[x_i]$.

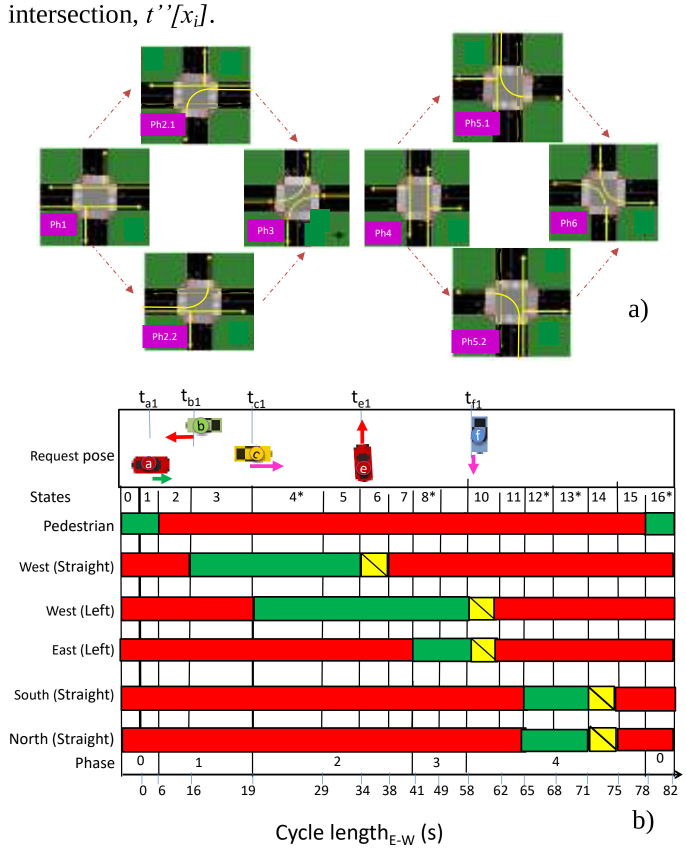

Fig. 3. a) Diagram of phases. b) Requested phasing of traffic flows ($t_{a1}<t_{b1}<t_{a2}<t_{b2}<t_{a3}<t_{c1}<t_{b3}<t_e<t_{a4}<t_{c2}<t_{a5}<t_f$). * Adaptive sequences.

The phase flow of the PoC intersection is shown in Figure 3b according to the phasing diagram assumed in Figure 3a. In this diagram, the cycle length is composed of 5 of the 7 phases contemplated and divided in 16 time

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sequences (states). The states marked with * are dynamic movable states that depends on the traffic demand during the cycle. 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. The PoC assumes that all the leaders approach the intersection with similar velocities at different times (Figure 3b). 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. 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.

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. Meanwhile, the speed of Vehicle *e* was reduced, increasing the total accumulated time, r_t, in the S-N arm. Adaptive sequences 8 and 9 kick off Phase 3 and the sequence times will be adjusted according to the variation of waiting accumulated times for the left turn of the b_i cars. A new phase, Phase 4, begins and includes two adaptive sequences, sequence 12 and 13 also dependent on the accumulated waiting times of the N-S arms. 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 Figure 3.

IV. V-VLC Adaptive Traffic Control

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. Each infrastructure is equipped with white tetrachromatic LEDs, making it possible to transmit four signals simultaneously. So, all that is needed is a receiver that actively filters each of the channels, and a four-fold increase in bandwidth is possible. Each of the RGBV signals sent has calibrated amplitude that defines it. Because each VLC infrastructure 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 [15]. Filtering is achieved by the PINPIN demultiplexer, which receives the combined OOK signal and through prior knowledge of the calibrated amplitudes is able to decode the sent message. As an example, in in Figure 4 Vehicle c_1 (Figure 1), receives three MUX signals as it crosses the intersection during Phase2.This vehicle, driving on the left lane (#8 E), was the sixth to ask permission to cross the intersection it receives order to enter the intersection in pose # 8E, turns left (#1NE) and keeps moving in this direction across position #1 toward the North exit (#4N). 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. The environment is also inserted to guide the eyes.

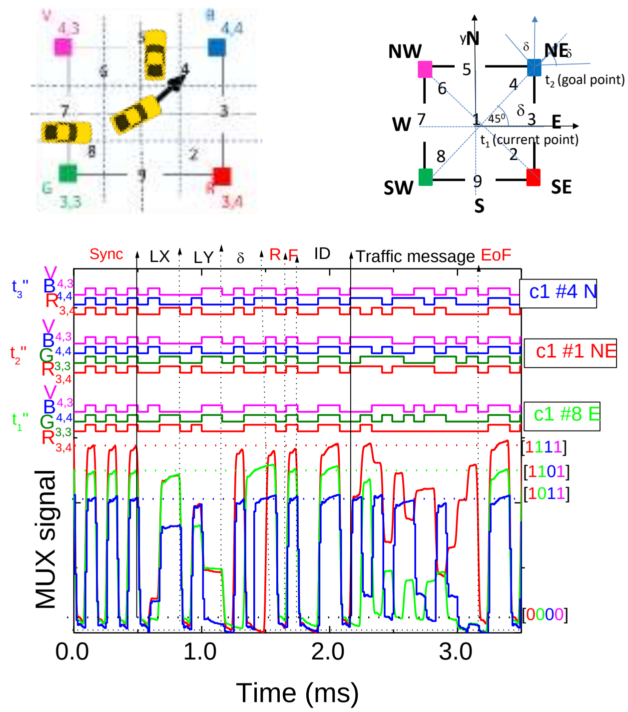

Fig. 4. MUX signals and assigned decoded poses inside intersection 1 acquired by vehicle c_1, entering (t_1''), crossing (t_2'') and exit (t_3''). On the top the transmitted channels packets [R, G, B, V] are decoded. The insert visualizes the environment.

As exemplified in the top part of Figure 4, the frame is divided into several blocks. The first block is the synchronization block. The synchronism always considers the same sequence of bits for all transmitters in a pattern [10101], having as a second purpose the identification of the maximum possible amplitude at reception. By knowing the maximum amplitude received it is possible to identify the footprint region [15]. With this information and with the help of the calibration signal, the location of the vehicle in its cell is defined. The next two blocks, 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 coded steering angles along the cardinal points gives the car direction. The next block (R) identifies the message type, which can be a “request” [00], a “response” [01] or another message type. The Flag (F) is a bit indicating whether there is vehicle identification in the following bits or not. Its purpose is to alert the decoder that the following bit sequence corresponds to the vehicle identification rather than the payload. ID block is the temporary identification of the vehicle, decided and provided by the infrastructure on the “response” message and order the request message at the intersection. Here, 5 bits are considered because a maximum of 32 vehicles per lane (8 routes, 4 lanes) are expected at message distance (20 m). The last is the traffic message. It is the body of the message, and may include other information such as the road condition, average-waiting time, and weather conditions, among others. EoF Bit or sequence of bits defines the end of the frame. In this case, the sequence [0110] was considered.

V. DYNAMIC TRAFFIC FLOW CONTROL SIMULATION

The considered environment for SUMO simulation (Figure 1), is a 4-way intersection, 2 lanes on each arm approach the intersection from compass directions, leaving 2 lanes on each arm. Each arm is 100 meters long. On every arm, each lane defines the directions that a vehicle can follow. In both intersections, a traffic light system, controlled by the IM (also known as agent), manages the approaching traffic.

Figure 5, illustrates the state representation for the west arm of the intersections at specific time points. Each lane has a dedicated traffic light labeled TL/0-15. The state representation segregates the arm into discrete "response", "request", and "queue" cells. In total, there are 4 cells (0/message, 1/request, 2,3/queues) per lane (L/0-7), resulting in a total of 32 state cells during the simulation.

During the simulation, an array contains information about all vehicles present at a given time, with states assigned to them. The state of a vehicle, denoted as *"v_i,"* where *i* represent the order of the crossing request, consists of a two-digit string. The first digit represents the lane the vehicle is in, while the second digit represents its position within that lane. For example, the state of the leader vehicle a1 in lane L0 would be represented as v_1*="00"*, and the state of the leader vehicle b_1 in lane L4 would be represented as v_2*="50"*.

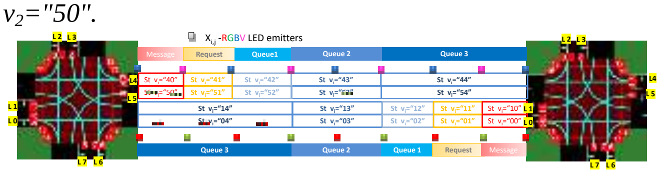

Fig. 5. State representation for the west arm of the intersections. Traffic Lights’ (TL; 0-15), Lanes (L ;1-7.) Agent states (s_t) representation.

The training process is divided into multiple episodes, typically exceeding 100 episodes. Actions (Figure 3a) are performed when the traffic light system activates a set of lanes for a predetermined time during green phases. The yellow phase lasts four seconds, while the green phase lasts eight seconds. If the current action matches the previous action, there is no yellow phase, and the current green phase continues. However, if the current action differs from the previous one, a 4-second yellow phase occurs between the two actions. The reward, denoted as *r*, represents the environment's response to the agent's decision. The reward is based on a traffic efficiency metric, allowing the agent to assess whether the action taken improves or hampers intersection efficiency. In the presented scenario (Figure 1), the IM receives access requests to the intersection from leading vehicles at different times (t_{x1}, Figure 3). This V2I information provides the IM with precise location and speed data of all leading vehicles, as well as the location and speed of their followers obtained through V2V communication. This data helps the IM anticipate the initial arrival times and speeds at various sections, facilitating traffic coordination.

VI. ADAPTIVE V-VLC TRAFFIC CONTROL EVALUATION

To exemplify the process, in Figure 6 it is displayed a response to leader vehicle b_1 at t_{b1}.

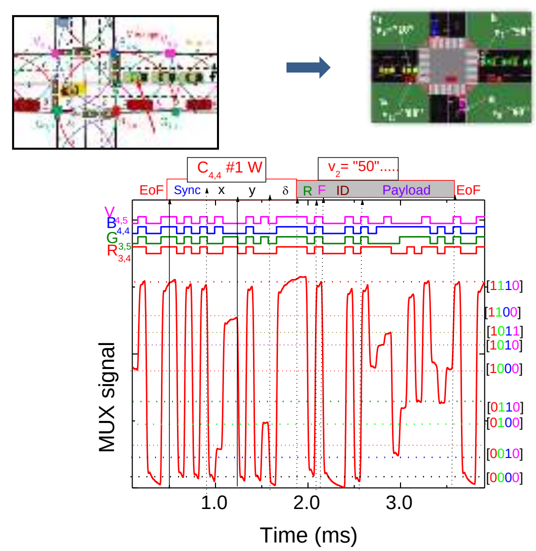

Fig. 6. Normalized MUX signal and the assigned and decoded messages acquired by vehicles b_1. Pose C_{44}, #1W.

As far as circulation is concerned, the vehicles are all moving at an average of 10 m/s, dropping the speed to 5 m/s when reaching the traffic light at the beginning of the cycle, during pedestrian eviction. Considering this speed, approximately three seconds of green light are estimated to be required for each vehicle to drive through the traffic light. Taking into account Figure 1 a state diagram resulting from the SUMO simulation was generated and presented in Figure 7. Essentially, the result demonstrates the feasibility and benefit of creating a dynamic system that adapts to specific traffic scenarios. It is important to improve the coding techniques, in the future, in order to allow only the legitimate receivers to process secure request/response

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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.

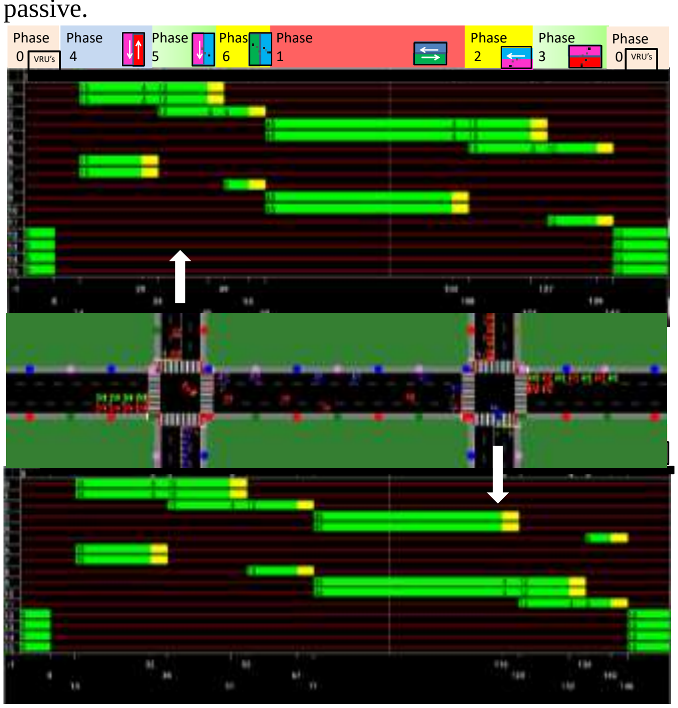

Fig. 7. State diagram resulting in two coordinated intersections. On the top an insert of environment and the color phasing is inserted.

VII. CONCLUSIONS

The integration of V-VLC technology with connected cars has optimized the operation of urban traffic networks by combining traffic signal control with driving behavior. A queue/request/response approach is employed for managing intersections, facilitated by V-VLC communications. This system enables real-time monitoring of queues, requests, and messages, along with the synchronization of traffic routing in different routes based on travel times.

To demonstrate the concept, architecture, scenario, and environment were developed. A phasing diagram is proposed to illustrate the traffic control process. A simulation using an urban mobility simulator was conducted, showcasing the benefits of adaptive traffic control. For future work, expanding upon this study could involve refining the developed architecture, scenario, and environment, further validating the proposed phasing diagram's efficacy in real-world traffic control, and exploring advanced simulation techniques to delve deeper into the advantages of adaptive traffic control.

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