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Enhancing Traffic Management through Visible Light Communication-Driven Signaling and Cooperative Trajectories

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Abstract: Visible Light Communication (VLC) is a promising solution proposed for optimizing traffic signals and vehicle trajectories at urban intersections. This approach utilizes light communication between connected vehicles (CVs) and infrastructure to enable coordinated traffic interactions. By leveraging streetlamps, intersection signals, and headlights, VLC facilitates the transmission of information between CVs and the infrastructure. The system is designed to be flexible and adaptive, accommodating diverse traffic movements across multiple signal phases. To evaluate the effectiveness of VLC, simulations are conducted using the SUMO urban mobility simulator. These simulations generate traffic flows and incorporate VLC mechanisms and relative pose concepts for queueing, requesting, and responding to interactions. To dynamically control traffic flows and alleviate congestion during peak hours, a deep reinforcement learning algorithm is employed. This algorithm optimizes traffic by utilizing both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. Comparisons are made between the traditional trajectory and signal optimization techniques. The results demonstrate the benefits of VLC in terms of throughput, delay, and the reduction of vehicle stops. In conclusion, VLC presents an integrated approach that harnesses light communication to optimize traffic signals and vehicle trajectories at urban intersections. Through simulations and comparisons, VLC proves its effectiveness in enhancing traffic efficiency and reducing congestion, offering promising insights for future urban traffic management systems.

Keywords: Visible light communication, Optical sensors, Cooperative traffic control, Connected vehicles, Deep Reinforcement learning; SUMO simulation.

1. Introduction

In today's world, communication technology has become a subject of controversy due to the increasing overload of radio frequencies and the need for stable and consistent systems. As a potential solution to this challenge, Visible Light Communication (VLC) emerges by utilizing light-emitting diodes (LEDs) as light sources and photodiodes as photodetectors. By modulating visible light in time and frequency, VLC offers a promising alternative for communication technology [1]. Only light emitting diodes (LED) lamps can be used for the transmission of visible light [2]. This functionality has given rise to a novel communication technology, VLC, where LED luminaires can be used for high-speed data transfer [3]. VLC is an emerging technology [4] that enables data communication by modulating information on the intensity of the light emitted by LEDs. Increasingly, smart cities can become comfortable, quick, and safe places to travel. Technology has advanced to the point where even non-autonomous vehicles are equipped with sophisticated sensors and computers. That was the first step on the road to improve road safety.

The application of VLC goes beyond traditional communication methods and extends to intelligent traffic control systems. By implementing a real-time traffic control system, traffic flow can be significantly improved through effective resource management and information exchange. This study specifically focuses on utilizing Visible Light Communication as a means of transmitting information, providing guidance services, and delivering specific information to drivers. 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. In this context, communication and localization are facilitated through the utilization of streetlamps, traffic signaling, and the headlights and taillights of vehicles. This approach allows for the simultaneous use of outdoor automotive lighting and infrastructure lighting to serve both illumination and communication purposes [5, 6].

We propose a cooperative I2V2V2I2V system that supports guidance services. This system employs an edge/fog-based architecture, which effectively manages the safe passage of vehicles through connected intersections. Vehicular Communication Systems are a type of network in which vehicles and roadside units are the communicating nodes, providing each other with information [7]. The main objective is to optimize traffic safety and efficiency on public roads through V2V and V2I communications [8-10]. Real-time traffic information is essential for optimizing traffic light duration. By monitoring the location, speed, and direction of nearby vehicles, significant improvements in traffic management can be achieved.

2. Connected Vehicles and VLC

The central aim is to enhance both safety and efficiency on public roads through the implementation of Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. This endeavor revolves around elevating situational awareness and curtailing traffic accidents. A key strategy involves utilizing real-time traffic information to inform dynamic adjustments in traffic light durations, ultimately optimizing traffic flow and minimizing potential hazards.

At the heart of this effort lies the integration of V2V and V2I communications. By harnessing the real-time data regarding the location, speed, and direction of nearby vehicles, a comprehensive and accurate understanding of the road environment is achieved. This real-time awareness enables informed decision-making, leading to substantial enhancements in traffic management. The envisioned outcome is a marked improvement in both the safety and efficiency of road usage, offering a promising path towards a smarter and more secure transportation landscape.

2.1. Intelligent Control System

To develop the intelligent control system model that facilitates safe vehicle management through intersections using V2V, V2I, and I2V communications, Reinforcement Learning (RL) concepts were used. RL is a training method based on rewarding desired behaviors and/or punishing undesired ones [11-13].

The simulations were agent-based and they have been carried out in a tool for Simulation of Urban MObility (SUMO) [14].

Fig. 1 illustrates the reinforcement learning loop, where the agent receives the current state of the environment (St) and learns from the feedback of the action taken (At) on the overall traffic flow. The agent's action directly affects the traffic light, which serves as the controller of the intersection. This iterative process allows the agent to learn from its actions and improve over time, avoiding negative situations and focusing on positive outcomes. The agent's experiences and actions are stored to train a model and enhance its decision-making capabilities [15]. The traffic lights in SUMO are controlled by the learning agent following its decisions, the overall flow of traffic is described, and the actions of the traffic lights control agent are rewarded. The reward (R_t), represent the accumulated total waiting time of all the cars in the intersection captured respectively at agentsteps $t-1$ and t. The objective of the IM is to minimize the total waiting time at each arm of the intersection. When a vehicle's speed drops below 0.1 m/s, a queue alert is triggered. The IM agent must explore new states while simultaneously maximizing its overall reward. To illustrate this concept, a dynamic phasing diagram and a state matrix based on the total accumulated time are provided.

2.2. Scenario, Environment and Architecture

In Fig. 2a, a scenario with two traffic signal-controlled intersections is depicted. In Fig. 2b illustration of the coverage map in the unit cell, footprint regions (#1-#9) and steering angle codes (2-9) are exemplified.

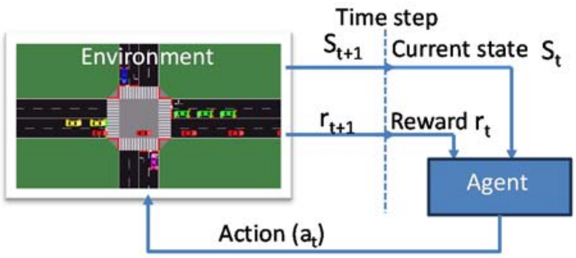
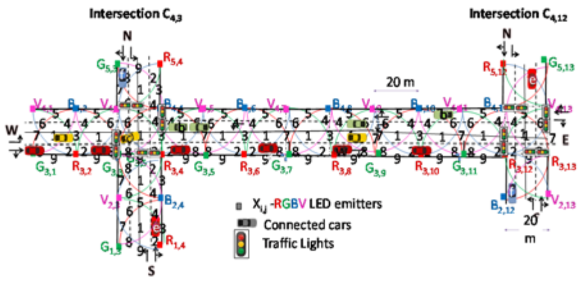
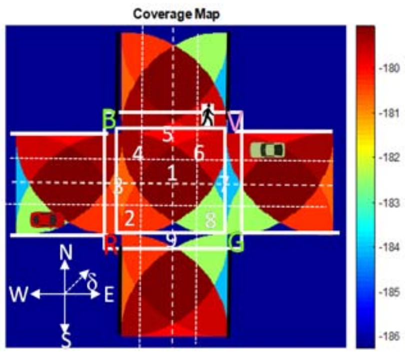


Fig. 1. Illustration of the reinforcement learning's loop of action-reward feedback.



a)



b)

Fig. 2. a) Simulated scenario with the optical infrastructure. b) Illustration of the coverage map in the unit cell: footprint regions (#1-#9) and steering angle codes (2-9).

The environment is defined by a cluster of square unit cells arranged in an orthogonal geometry (Fig. 2a). Different data channels are provided by tetra-chromatic white light (WLEDs) sources positioned at the corners of the square unit cells (Fig. 2b) distributed along the road and at the crossroads. Tetra-chromatic white light (WLEDs) sources, framed at the corners of a square unit cell, provide different data channels. 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. The coverage map in a four-legged intersection is displayed in Fig. 2b. The coded nine possible overlaps (#1-#9), defined as fingerprint regions, as well as the possible receiver directions (Cardinal points;δ) are also pointed out for the intersection.

This layout helps define the structure and arrangement of the intersections within the scenario. Each transmitter, $X_{i,j}$, carries its own color, X, (Red, Green, Blue, Violet) as well as its horizontal and vertical ID position within the surrounding network (*i,j*) [16]. In the Proof of Concept (PoC), it was assumed that the crossroads are situated at the intersections of line 4 with column 3 and column 11.

In Fig. 2, there are two traffic signal-controlled intersections with four traffic flows. From the West, there are twenty red a_i vehicles with straight movement and four yellow c_i vehicles with left turn only. From the East, there are green *bi* vehicles with left turn only (thirteen straight and two left turn). From the South, there are six orange e_i vehicles, with two having a left-turn approach and four with straight movement. From the North direction, there are thirteen blue f_i vehicles, with nine going straight and four having a left turn at both intersections. The road request and response segments offer a binary choice between turning left/straight or turning right. The vehicles represent a percentage of the traffic flow, and their ordering in terms of priority is determined. The top three requests are a_1, b_1, and a_2, followed by b_2, a_3, and c_1. In the seventh, eighth, and ninth places are b_3, e_1, and a_4, respectively, followed by c_2 in the tenth place. The penultimate request is a_5, and the last one is f_1. Based on the assumptions, there are 540 cars approaching the intersection per hour, with 80 % of them coming from the east and west directions. Among these cars, it is assumed that 50 % of them will make a left or right turn at the intersection, while the remaining 50 % will continue straight.

2.3. Visible Light Communication Link

A Vehicular Visible Light Communication system (V-VLC) is structured around a transmitter and a receiver connected via a wireless channel. The transmitter's role involves generating modulated light, often utilizing the ON-OFF-keying (OOK) amplitude modulation technique. Concurrently, the receiver detects fluctuations in the received light signal [17]. This dynamic system finds implementation in the road infrastructure, manifesting as streetlights, and within the vehicles themselves, taking shape as headlights.

Within this ecosystem, the environment is meticulously defined, characterized by a cluster of square unit cells arranged in an orthogonal configuration. The cornerstone of this setup is the deployment of tetra-chromatic white light sources (WLEDs) positioned strategically at the corners of each unit cell. These light sources offer distinct data channels [18].

Functionally, the V-VLC system processes coded signals as inputs. These signals are transmitted by transmitters, which can take the form of streetlights or headlights. Their purpose ranges from vehicle identification (I2V), communication with traffic lights

(V2I), to facilitating communication between vehicles (V2V). The encoded signals encapsulate not only the essential information about the transmitter's position within the network but also the steering angle (δ) imperative for guiding the driver's orientation along their trajectory.

To manage the seamless passage of vehicles through intersections, a sophisticated interplay of queue/request/response mechanisms and temporal/space-relative pose concepts are employed [19]. These mechanisms ensure efficient traffic management and orderly vehicular movement at crossroads.

The coded signals transmitted by the transmitters are subsequently received and decoded by a PIN-PIN photodetector. This photodetector boasts light filtering properties, ensuring the precision and accuracy of data reception, a pivotal aspect in maintaining the integrity of the communication process.

2.4. Architecture

Illustrated in Fig. 3 is the implementation of a hybrid structure seamlessly fusing mesh networking with cellular technology. At the crux of this configuration is the "mesh" controller, strategically positioned at streetlight installations. This controller assumes the critical role of a message-forwarding entity, orchestrating the efficient flow of information among vehicles operating within the mesh network. Its functionality closely resembles that of router nodes within a network framework.

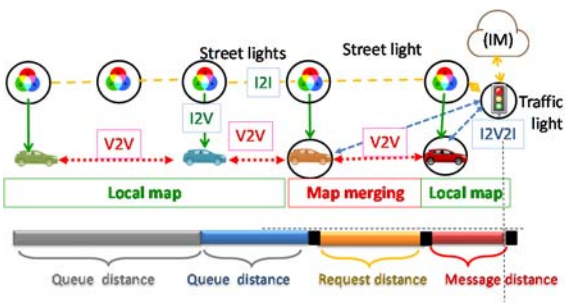


Fig. 3. VLC Edge Computing infrastructure.

Complementing the mesh controller is the hybrid controller, an innovative convergence of mesh and cellular capabilities. This hybrid entity performs a dual role: firstly, it functions as a border-router, skillfully bridging the mesh and cellular domains. Additionally, this hybrid controller serves as a catalyst for edge computing functionalities, effectively extending the computational capacity of the network [20].

This architectural paradigm yields a host of functionalities. On one hand, it seamlessly supports edge computing capabilities, empowering the execution of computations closer to the data source. On the other hand, it accommodates device-to-cloud communication (I2IM), ushering in the potential for real-time data exchange between devices and cloud-based resources. Simultaneously, the architecture fosters peer-to-peer communication (I2I), facilitating direct information exchange among devices.

Embedded within this framework are computing platforms that hold a pivotal position. These platforms undertake the essential tasks of processing and interfacing with sensors and controllers. In essence, they form the dynamic hub where data is processed, transformed, and made available for further analysis or dissemination.

3. Intelligent Traffic Signal Control

3.1. Dynamic Traffic Phasing

In Fig. 4, a visual representation unfolds, elucidating the sequential progression of phases within the intersection. On the top the phases are exemplified.

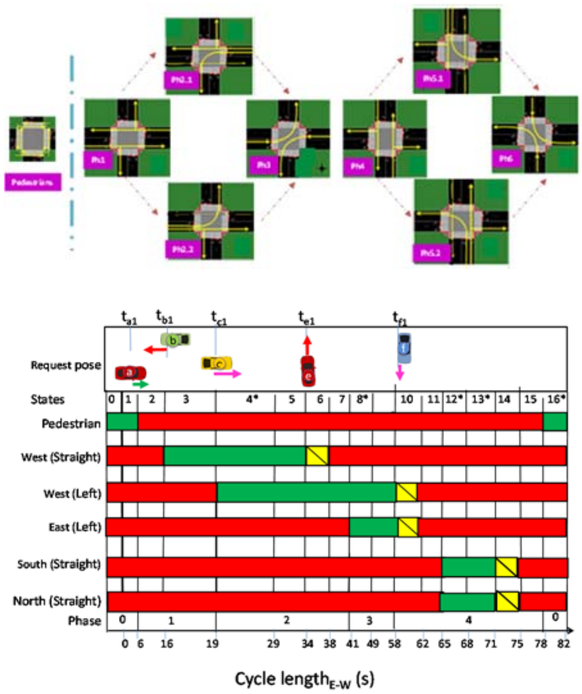


Fig. 4. Requested phasing of traffic flows.
* Adaptive sequences.

This orchestrated flow adheres to a structured cycle length comprising six distinct phases. Each of these phases is further intricately subdivided into 16 discrete time sequences or states, delineating a comprehensive temporal framework for the intersection's operation.

An essential observation to highlight is that states designated with an asterisk (*) hold a dynamic quality, representing movable states that adapt in response to varying traffic demands within the cycle. Specifically, sequences marked with the numbers *"0"*, *"1"*, and *"16"* denote the exclusive pedestrian phase, signaling a dedicated time interval for pedestrian movement.

Furthermore, the synchronization of the cycle initiates with sequence *"1"*, marking the commencement of the orchestrated flow of phases. Within this cycle, phases one through four are each allocated sequence spanning from *"2"* to *"15"*. These sequences within these phases play a pivotal role in meticulously regulating the traffic flow, ensuring a structured and efficient movement of vehicles through the intersection.

3.2. 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 (Fig. 2b). 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 [18]. 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 Fig. 5 Vehicle c_1 (Fig. 2), 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.

As exemplified in the top part of Fig. 5, 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 [18]. 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.

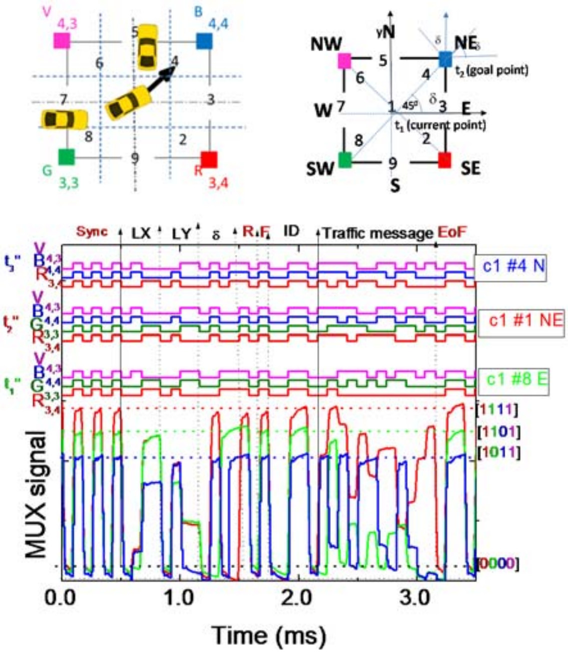


Fig. 5. MUX signals and assigned decoded poses inside intersection 1 acquired by vehicle c_1, entering (t_1''), crossing (t_2'') and exit (t_3''). On the top the transmitted channels packets [R, G, B, V] are decoded. The insert visualizes the environment.

3.3. Dynamic Traffic Flow Control Simulation

The simulated environment for the SUMO simulation, illustrated in Fig. 2, models a 4-way intersection with two lanes on each arm. The arms converge on the intersection from the cardinal directions, creating a total of eight lanes. Each arm has a length of 100 meters. On every arm, each lane specifies the allowable directions for vehicles. The right lane permits vehicles to turn right or proceed straight, while the left lane confines vehicles to left turns only.

To manage traffic flow, a traffic light system is in place at both intersections. The Intersection Manager (IM), also known as the agent, controls this system. The IM oversees approaching traffic by coordinating the timing of traffic signals, ensuring efficient and safe movement within the intersection. Fig. 6a labels the Traffic Lights (TL), Lanes (L), and possible trajectories of vehicles. In Fig. 6b, the state representation for the west arm of the intersection is demonstrated for a simulated timeframe.

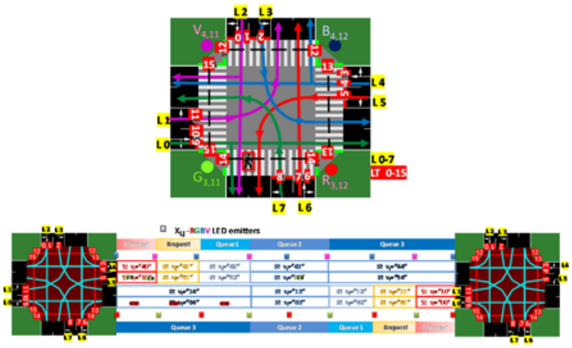


Fig. 6. a) Traffic Lights' (TL) and Lanes(L) identification and vehicles' possible trajectories. b) State representation for the west arm of the intersections. Traffic Lights' (TL; 0-15), Lanes (L;1-7.).

Each arm of the intersection is partitioned into discrete cells representing "response," "request," and "queue" zones to detect vehicle entry into incoming lanes. Before reaching the intersection's stop line, there are four cells (0/message, 1/request, 2, 3/queues) per lane. Each lane (L/0-7) is associated with a dedicated traffic light (TL/0-15), resulting in a total of 32 state cells during simulation.

In the simulation, an array is employed to store the state of all vehicles at a specific time, with unique states assigned to each vehicle. The state of a vehicle, labeled as "v_i" where "i" corresponds to the crossing request order, is expressed as a two-digit string. The initial digit designates the lane in which the vehicle is located, while the second digit indicates its position within that lane. For instance, the states of leaders a_1 (in lane L0) and b_1 (in lane L5) would be denoted as v_1 = "00" and v_2 = "50," respectively.

The training process is structured into multiple episodes, with the user typically specifying a total number of episodes exceeding 100. Each episode represents a training iteration, during which actions are executed based on the activation of specific lanes by the traffic light system, following predetermined timings during the green phases (refer to Fig. 4). The yellow phase is set at four seconds, and the green phase lasts for eight seconds. If the action taken in the current agent step (*t*) mirrors the action taken in the previous agent step (*t-1*), there is no yellow phase, and the current green phase is extended. However, if the action selected in the current agent step differs from the previous action, a 4-second yellow phase occurs between the two actions. This mechanism facilitates smoother transitions between different actions and provides time for vehicles to respond to changing traffic signals. In the SUMO simulation, one simulation step corresponds to one second, resulting in eight simulation steps between two identical actions.

The reward (*r*) serves as the environment's response to the agent's decision, quantifying how favourable or unfavourable the agent's action was in terms of achieving desired objectives or optimizing performance metrics. This reward signal is essential for guiding reinforcement learning algorithms, helping the agent improve its decision-making abilities over time.

To incentivize the agent effectively and enhance intersection efficiency, it's crucial to base the incentive on a traffic efficiency performance metric. This metric enables the agent to assess whether its actions have led to a reduction or improvement in intersection efficiency. In the presented scenario (Fig. 2), the Intersection Manager (IM) receives requests for intersection access from leading vehicles at different times (t_{x1} in Fig. 4). Vehicle-to-Infrastructure (V2I) information provides the IM with precise location and speed data of leader and follower vehicles through V2V communication. This data allows the IM to anticipate the initial arrival times and speeds of vehicles at various sections of the intersection.

For vehicle circulation, it's assumed that all vehicles are moving at an average speed of 10 m/s. However, when vehicles approach the traffic light at the cycle's beginning, during pedestrian evacuation, their speed decreases to 5 m/s. Considering this speed change, it's estimated that approximately three seconds of green light are needed for each vehicle to pass through the traffic light. By incorporating this information into the incentive system, the agent can be motivated to make decisions that optimize traffic flow, minimize delays, and ensure efficient utilization of green light time, ultimately improving overall intersection efficiency.

3.4. Adaptive V-VLC Traffic Control Evaluation

Using the application programming interface (API) provided by SUMO, it is possible to interface with external programs and interact with the simulation environment. SUMO provides various statistics related to the overall traffic flow and provides various outputs, such as diagrams illustrating the duration of each state or color of the traffic lights throughout the simulation. Based on the simulation scenario depicted in Fig. 2, a state diagram was generated using SUMO simulation. Fig. 7a and Fig. 7c show the phase diagrams for the two connected intersections, TL1 and TL2. The SUMO environment is illustrated in Fig. 7b.

The simulation scenario was adapted from a real-world environment in Lisbon [21, 22], and it considers the presence of roads that impact the traffic flow at both intersections. These roads, referred to as the target road, have a dynamic influence on the traffic flow, and the impact of the historical traffic state from other roads on the target road is limited in time. Here, the E-W arm was considered as a target road. The transmission of traffic flow and traffic waves measures the time duration for which the traffic state of other roads affects the target road within the same period. As traffic continuously enters the system, the composition of the traffic flow on the target road undergoes changes over time. To improve the traffic flow conditions, a modification was made to the initially proposed phases (as shown in Fig. 4).

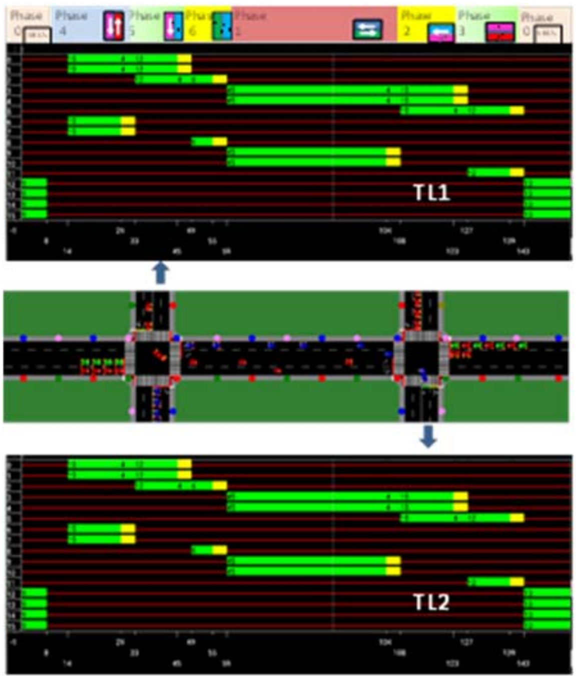


Fig. 7. State diagram resulting in two coordinated intersections (TL1 and TL2). On the top an insert of environment and the color phasing is inserted. At the middle the environment is draft.

The modification involved an immediate transition from the pedestrian phase (Ph0) to the N>S phase (Ph4), followed by the remaining phases in both intersections. This change in phase order was found to enhance the traffic flow conditions in the simulation. By adjusting the phase sequence and optimizing the traffic light control strategy based on the simulation results, it is possible to achieve improvements in traffic flow, reduce congestion, and enhance overall intersection performance.

In Fig. 8, a comparison is presented between the queue (halting) and average speed observed every second in SUMO/VLC (Simulation of Urban MObility with Visible Light Communication) for a 130-second cycle. The simulation assumes a saturation flow of 2500 vehicles per hour.

The results demonstrate that on the regulated roads, there are typically no congested conditions occurring in each new cycle. The queue of vehicles in the first section of the demand acts as an integrator, meaning it accumulates vehicles and its length increases as vehicles enter the section. This becomes critical when the queue approaches the capacity of the link road. In the unsaturated regime, which assumes that all vehicles in the queue leave the target road by the end of the sampling time, the queue of vehicles is always zero. However, when the red light is activated, a maximum queue of vehicles is generated since all vehicles in the queue are held back. This analysis provides insights into the behavior of traffic flow and queue dynamics within the simulated environment. It demonstrates the impact of traffic lights and their timing on the accumulation and dispersal of vehicles at different sections of the road network. Fig. 9 represents the reward obtained, after the training, when the network was tested. The test was performed for the two intersections scenario with independent crossings. The results obtained from the experiment indicate that as the number of action steps increases, the cumulative rewards become more positive. This demonstrates that the agent learns to make better decisions over time during the test. The feasibility and benefits of creating a dynamic system that can adapt to specific traffic scenarios are evident in the results. Safety and privacy are crucial requirements for the V-VLC system.

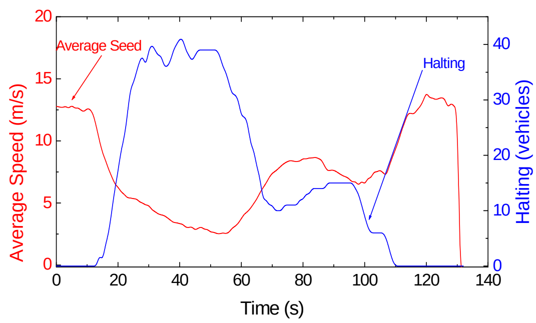


Fig. 8. Average speed and halting along a cycle.

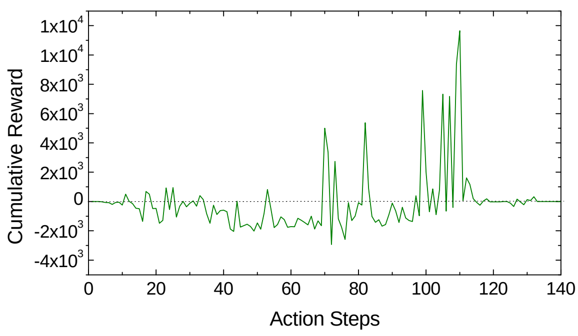


Fig. 9. Cumulative reward.

To bolster security, upcoming advancements should prioritize the enhancement of coding techniques to guarantee that exclusively authorized receivers can decipher secure request/response messages. These security measures extend deep into the fabric of the physical transmission process, particularly within the Line of Sight (LoS) channel. In this context, potential eavesdroppers are rendered passive observers, devoid of any access to transmitted information.

One promising avenue for augmenting security entails harnessing the positional data of streetlamps to deduce the flow of vehicular traffic. This innovative approach holds the potential to obviate the necessity for traditional certificates or passwords within the network. Instead, it paves the way for a paradigm shift toward statistical secrecy. By weaving this statistical approach into the security framework, the reliance on explicit authentication measures can be alleviated, while concurrently fortifying the layers of protection against unauthorized access.

In essence, the trajectory for fortifying security within the system rests upon refined coding techniques, the intrinsic security attributes of the LoS channel, and the intelligent utilization of positional information for traffic flow analysis. This approach promises to yield enhanced security measures, ushering in a future where secure communication flourishes within the framework of advanced vehicular systems.

4. Conclusions

V-VLC technology integration in connected cars offers significant improvements to urban traffic networks by integrating traffic signal control with driving behavior. This innovative system utilizes a queue/request/response approach for efficient intersection management while providing real-time monitoring of queues and messages. Through detailed data collection, V-VLC technology enables dynamic adjustments to traffic light phases and durations, leading to reduced travel times and minimized waiting for drivers. Furthermore, V-VLC enhances safety by directly monitoring crucial areas such as queue formation, ensuring a safer and more efficient traffic flow.

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