A multi-hop relay based routing algorithm for vehicular visible light communication networks

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***Abstract*—The use of visible light communications (VLC) in intelligent transportation systems is becoming highly popular. In this paper, we present a prediction-based channel gain model and propose a multi-hop relay-based routing algorithm for vehicular VLC communication networks. Using the surrogate modeling lab platform SUMO and Matlab we show that, a stationary velocity of vehicles is better suited to form a good prediction, while the proposed routing algorithm offers improved signal-to-noise ratio.**

Keywords—vehicle-to-vehicle, visible light communication, multi-hop routing, prediction-based channel gain model

I. INTRODUCTION

Visible light communications (VLC) is a wireless communication technology that uses light emitting diodes (LEDs) and a photodiode (PD) or an image sensor (i.e., camera) as the transmitter (Tx) and receiver (Rx) respectively [1]. VLC offers higher security and improved transmission speeds compared with radio frequency communications. VLC-based intelligent transportation system (ITS) uses LED-based vehicle's headlights, taillights and road side lighting infrastructure at the Tx, which are operating frequency beyond the flickering range for the human eyes. VLC is a complementary communication technology for ITS, which allows the use of RF frequencies for other needed applications [2]. Furthermore, the increasing use of LEDs in vehicle and traffic lights offers excellent opportunities for the implementation of VLC technology as part of the ITS within smart environments [3].

In [4], C. Liu et al. proved that VLC can meet linear accessibility and delay requirements under dense traffic conditions. A data rate of 50 Mb/s over a transmission distance of 70 m for vehicle to vehicle (V2V) communications was reported in [5]. P.F. Luo et al. studied the performance of V2V VLC systems under different communication geometries during the daytime, and further confirmed that the V2V VLC link range can reach up to 70m [6]. Recently, E. Eso et al. experimentally demonstrated a long-distance feasibility of optical camera communications for a link span of up to 400 m [7]. However, simple point-to-point VLC systems with a limited transmit power cannot meet the communication requirements for long-distance transmission.

H. Ilhan et al. investigated the performance of amplify-and-forward for an inter-vehicular cooperative scheme assisted by a road-side access points which act as a relay [8]. Z.M. Cui et al. presented an improved V2V model considering the position and orientations of the Tx and the Rx, and then proposed a single-hop cooperative diversity scheme [9]. However, the extended distance of a single-hop relay is limited. To overcome this, M. Garai et al. proposed a tree-based architecture vehicular VLC networks (V2LCnet), which provided a rapid connection between several destination vehicles (DVs) and the source vehicle (SV) using multi-hop communications, thus notably increasing the overall coverage area [10]. However, in the proposed scenario, the SV was highly connected, thus resulting in increased communication latency and therefore network congestion. In addition, in order to control the size of the network tree, it was not possible to achieve a longer transmission range between any two vehicles in different groups. M.M. Luiz et al. presented the shortest path-based method dynamic routing protocol for VLC (DYRP-VLC). In this method, the SV broadcasts the routing request to the DVs in order to establish the shortest transmission paths with the minimum number of hops [11]. Although this method is suitable for transmission between any two vehicles, it does not guarantee the quality of transmission.

In this work, we present an improved channel gain model that uses the relative distance, relative velocity and time to predict future positions of vehicles. We further propose a new route metric for V2V VLC communication, which combines the received optical power and the number of corresponding communicable vehicles. Afterward, a multi-hop relay routing (MHRR) is achieved, which guarantees better routing in V2V to meet long-distance communication requirements. Our research work has provided the following contributions:

(*i*). Proposed a prediction-based channel gain model for VLC to overcome the problem of routing time lag.

(*ii*). Used the proposed route metric to select the next relay vehicle to ensure link quality and stability.

(*iii*). Proposed MHRR, which allows V2V communications with adequate signal to noise ratio (SNR) (i.e., lower bit error rates) compared with V2LCnet and DYRP-VLC.

The remainder of the paper is organized as follows: Section II analyzes the channel gain model for two scenarios of same and different lanes. In section III, the VLC-based V2V routing algorithm using multi-hop relay communications is proposed, while in section IV, the performance of the proposed routing algorithm is verified. Finally, the conclusion and future works are covered in section V.

II. Improved Channel Gain Model

When developing routing protocols in vehicular VLC, it is important to consider the real-time running status of each vehicle on the road. Currently, the global positioning system is widely used for navigation and therefore location identification of vehicles on the road. However, vehicles' position is time dependent while on the move. Therefore, the routing decision carried out may experience latency. Note that, the future positions of vehicles are influenced by their past locations, relative distances, velocities and times. In the proposed work, we use the vehicle's relative distance, velocity and time to predict its future position. We use the predicted position of the vehicle to develop an improved free space channel gain model for the vehicular VLC system.

As part of the system model, a generalized Lambertian radiation is used to simulate the light emission from the Tx (i.e., tail or head light in vehicles). The channel direct current (DC) gain model is given as [12]:

$$H(0)=\begin{cases}\dfrac{(m+1)A}{2\pi d^2}\dfrac{n^2}{\sin^2\psi_c}T_s\cos\psi\cos^m\phi, & 0\le\psi\le\psi_c\\ 0, & \psi\ge\psi_c\end{cases}, \tag{1}$$

where m is Lambertian emissivity of LED light source $m=-\dfrac{\ln 2}{\ln\cos\theta_{1/2}}$, $\theta_{1/2}$ is the half power angle of LED light, A is the PD receiving area, ψ is the incident angle between the axis of the Rx and the incident light, ϕ is the irradiation angle, n is internal refractive index of lens, ψ_c is the Rx's field of view, T_s is the Rx optical filter gain and d is the distance between the Tx and the Rx.

The channel gain between vehicles depends on the angle and the distance between the Tx and the Rx. In this work, we determine the angular displacement between the Tx and the Rx using the relative distance, relative velocity and predicted time of vehicles. Based on this, an improved channel gain model is obtained, which only depends on the distance. However, the time parameter can also be used to predict the future driving status. Note, using the predictive model the channel gain can be used to accurately select the relay vehicles based on the initial status of all vehicles. In this work, we used the taillights as the Tx and a PD as the Rx in trailing vehicle. Note that, we consider a three-lane road with the road and vehicle widths are denoted by w_L and w_v, respectively.

A. Same Lane

Here we assume that, vehicles v_s are driving in the same lane and are positioned at the center of the lane, see Fig. 1.

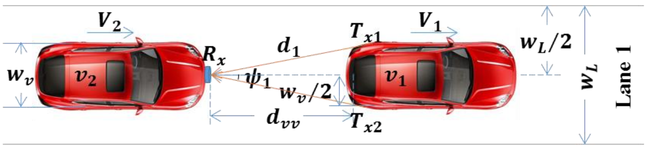


Fig. 1: Two vehicles travelling in the same lane. Front and back vehicles are the Tx and the Rx, respectively.

The horizontal distance between the taillight (e.g., the T_{x1} or the T_{x2}) of v_1 and the Rx of v_2 is $h_1\cong\frac{w_v}{2}$. The distance between vehicles traveling in the same lane and the incident angle between the taillights of v_1 and the Rx of v_2 can be expressed as:

$$\psi_1=\arctan\frac{h_1}{d_{vv}}. \tag{2}$$

Assume that, the relative velocity of vehicles is $V=V_1-V_2$. Take into account predicted time of vehicles t, after this period, the communications distance d_1' and the incident angle ψ_1' between the Tx and the Rx are given as:

$$d_1'^2=(d_{vv}+Vt)^2+h_1^2, \tag{3}$$

$$\psi_1'=\arcsin\frac{h_1}{d_1'}. \tag{4}$$

Note that, not all vehicles are of the same height, therefore the line of sight path between the taillight of v_1 and the Rx of v_2 might be at an elevation angle, which may need to be considered in scenarios where the distance between v_1 and v_2 is shorter (i.e., driving in urban area with the speed limit < 30 mph). Thus, the enhanced channel gain is as given:

$$H(0)=\begin{cases}\dfrac{(m+1)A}{2\pi d_1'^2}\dfrac{n^2}{\sin^2\psi_c}T_s\cos^{m+1}\psi_1', & 0\le\psi_1'\le\psi_c\\ 0, & \psi_1'\ge\psi_c\end{cases}. \tag{5}$$

Note, here we have assumed that the Tx and the Rx are on the same horizontal plane i.e., $\psi=\phi$.

B. Different Lanes

For vehicles in different lanes, we use the k parameter, i.e., for a three-lane road, k = 1 represent the vehicles driving in the 1st and 2nd lanes or the 2nd and 3rd lanes, and $k = 2$ represent the vehicles in the 1st and 3rd lanes. Fig. 2 shows vehicles on two different lanes with two transmission paths between the left and right taillight of v_1 and the Rx of v_2.

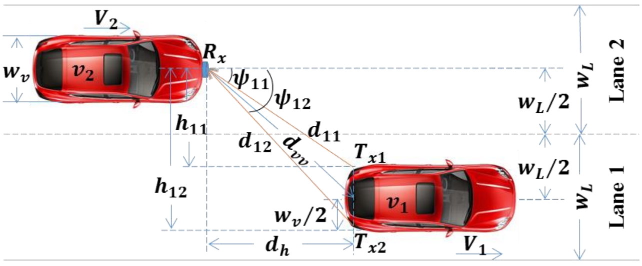


Fig. 2: Vehicles on two different lanes, i.e., k=1.

From the geometry in Fig. 2, the lateral distance between the Rx and the Txs are given by:

$$\begin{aligned} h_{11} &\cong w_L - \frac{w_v}{2} \\ h_{12} &\cong w_L + \frac{w_v}{2} \end{aligned} . \tag{6}$$

For vehicles driving in the 1st and 3rd lanes i.e., $k=2$, we have $h_{21} \cong 2w_L - \frac{w_v}{2}$ and $h_{22} \cong 2w_L + \frac{w_v}{2}$. Therefore, in general we have:

$$h_{ki} = \{h_{11}, h_{12}, h_{21}, h_{22}\}, k \in 1,2, i \in 1,2 . \tag{7}$$

Let's assume h_{ki} represents the lateral distance between the Tx and the Rx, which is perpendicular to the direction of the vehicles in the horizontal plane, in different scenarios (i.e., k=1 and k=2), where i represents different Tx (i.e., Tx1 and Tx2). Note, considering different h_{ki}, the incident angle between the taillight of v_1 and the Rx of v_2 is expressed as:

$$\psi_{ki} = \arctan\frac{h_{ki}}{d_h} = \arctan\frac{h_{ki}}{\sqrt{d_{vv}^2 - (k \cdot w_L)^2}} . \tag{8}$$

Considering the relative velocity of vehicles V and predicted time t, the corresponding distance and the incident angle between the Tx and the Rx are given as:

$$d_{ki}'^2 = h_{ki}^2 + \left(\sqrt{d_{vv}^2 - (k \cdot w_L)^2} + Vt\right)^2 , \tag{9}$$

$$\psi_{ki}' = \arcsin\frac{h_{ki}}{d_{ki}'} . \tag{10}$$

Thus, the improved channel gain for different lanes is given as:

$$H(0) = \begin{cases} \dfrac{(m+1)A}{2\pi d_{ki}'^2} \dfrac{n^2}{\sin^2 \psi_c} T_s \cos^{m+1} \psi_{ki}' , & 0 \le \psi_{ki}' \le \psi_c \\ 0, & \psi_{ki}' \ge \psi_c \end{cases} . \tag{11}$$

III. PROPOSED ROUTING ALGORITHM

This section presents the methodology adopted to design the proposed routing algorithm MHRR. We have considered three cases of (i) establishment of a candidate set; (ii) design of a new route metric; and (iii) description of the MHRR routing algorithm. The detailed description of each stage is outline in the followings:

A. Candidate Set

For the i^{th} vehicle v_i, the first layer candidate set FC_i consists of vehicles within the Tx's range of the v_i, which is given by

$$FC_i(v_j) = \{v_1, v_2, \cdots, v_j, \cdots, v_r\}, j = 1,2,\cdots, r , \tag{12}$$

where v_j represents the j^{th} vehicle within the transmission range of v_i, and r is the number of vehicles. Next, v_i checks the candidate vehicle, if it's Rx is blocked then no transmission and therefore discarded, and FC_i is updated. Based on the same selection principle for the candidate set, v_j's the first layer is set as the row vector of the second layer set matrix in v_i. The second layer candidate set matrix for v_i can be expressed as:

$$SC_i(v_{je}) = \begin{bmatrix} v_{11} & \cdots v_{1q_1} \cdots & v_{1l} \\ \vdots & \ddots & \vdots \\ v_{r1} & \cdots v_{rq_r} \cdots & v_{rl} \end{bmatrix}, j = 1,2,\cdots, r, e = 1,2,\cdots, q_j, \cdots, l \tag{13}$$

where v_{je} represents the candidate vehicle within the first layer candidate set of v_j, q_j represents the number of vehicles that v_j can transmit to and $l = \max\{q_1, q_2, \cdots, q_j, \cdots, q_r\}$. For different v_j, q_j is numerically different. Obviously, in the actual selection of the candidate set, if the traffic situation is relatively heavy, the same vehicle will be selected as the candidate vehicle a number of times, which will not affect the results of the routing decision process.

B. Routing Metric

We present a new metric, which determines how suitable a communication link L_{ij} will be to route information between two vehicles, v_i and v_j. The routing metric considers the quality of the communications link based on the received optical power p_r of v_j, which is expressed as [13]:

$$p_r = p_t H(0) , \tag{14}$$

where p_t is the transmit optical power of v_i. Furthermore, the quality of the communications link is also dependent on q_j .

Therefore, the routing metric is composed of p_r and q_j. The evaluation function is given as:

$$F_{ij} = \frac{q_j}{\sum_{j=1}^{r} q_j} p_r \qquad (15)$$
$$s.t. \quad t \le \frac{50 - d_{ij}}{V}$$

Using the above routing metric, for the i^{th} vehicle v_i, each candidate vehicle v_j in its first layer candidate set has a different F_{ij} value. Preferentially, the candidate vehicle with the largest F value is selected as the next relay vehicle, making up a communication route, from vehicle v_i to v_j. The proposed routing algorithm (to be described next) uses the routing metric in (15) to select multiple relay vehicles that form the route between the SV and the DV.

C. Routing Algorithm

In this work, when a vehicle is selected by the routing metric, the taillight is switched on to transmit information to the rear vehicle. The transmission between the SV and the DV could be via multiple relays, which is best illustrated in the flowchart of Fig. 3.

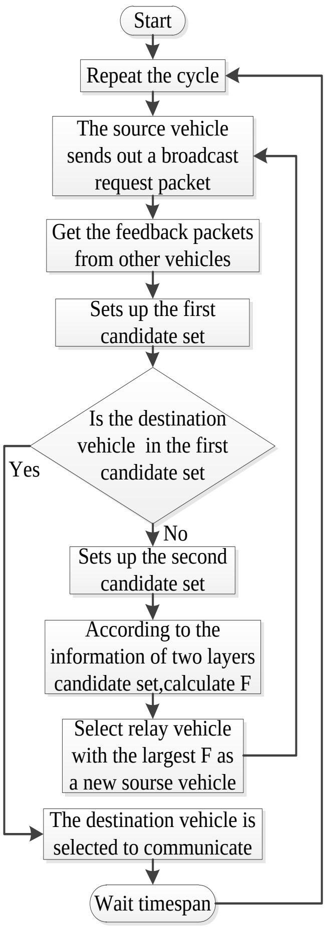


Fig. 3: MHRR algorithm.

The route construction starts with a SV broadcasting a route request packet (RP) in order to find a valid path to the DV, which propagates over two hops. On receiving the RP, the vehicles will send a route feedback packet (FP) to the SV, which contains the vehicle ID, velocity and position information. On receiving FP and based on the proposed routing metric, the vehicles are ranked and the one with highest ranking is selected as the relay, which is treated as a new SV. The above steps are then repeated until DV is found. However, if the SV fails to create a route to the DV, it will try again for a certain number of times.

MHRR works based on the proposed routing metric: the prediction-based channel gain and number of vehicles, which guarantees the timeliness and quality of transmission Moreover, MHRR operates an infinite number of cycles periodically, i.e., if a route is not discovered, the SV waits for one cycle and tries again, thus assuring that the route is always fresh and active.

IV. Performance Evaluations

In this paper, SUMO is used to simulate road conditions and vehicle/traffic states [14]. MATLAB is used to analyse the performance of V2V routing on the generated vehicle movement topology file. The proposed routing algorithm MHRR is evaluated and compared with the tree-based V2LCnet and the shortest path-based DYRP-VLC algorithms.

A. Simulation Scenario

A custom road model is used to simulate the vehicle's operating conditions. The road parameter settings are shown in Table 1. The running state of the simulated road and vehicles is presented in Fig. 4.

Table I. Simulation Parameters Set in SUMO

Symbol	Quantity	Value
n_v	Number of vehicles	300
n_L	Number of lanes	3
l_L	Total length of the lane	600 m
w_L	Lane width	3.2 m
n_{tr}	Number of traffic lights	3
t_T	Total driving time	1000 s
v_m	Maximum vehicle speed	40 km/h
l_v	Vehicle length	5 m
w_v	Vehicle width	2 m

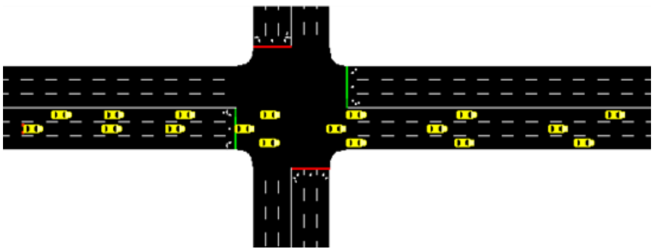


Fig. 4: Vehicle movement in SUMO.

A discrete number of vehicles is generated at each moment in SUMO. Therefore, in order to study the impact of the motion trajectory on the routing algorithm, the motion conditions of multiple continuous time periods in SUMO are intercepted for VLC performance simulation. i.e., a 100-600 s vehicle's movement segment is intercepted. Thereafter, the communication routes of vehicles are analyzed in MATLAB using the simulation parameters given in Table 2.

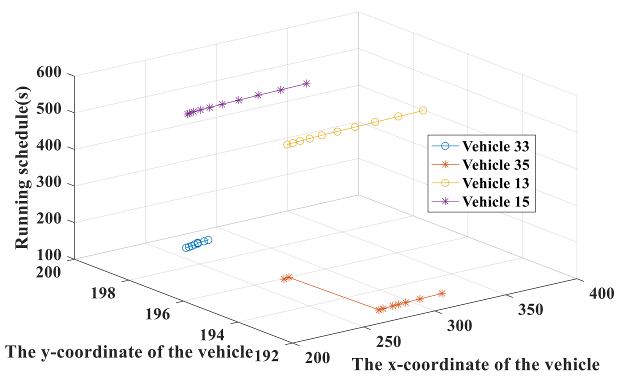
TABLE II. SIMULATION PARAMETERS SET IN MATLAB

Symbol	Quantity	Value
$\theta_{1/2}$	Half-power angle	30°
A	PD receiving area	1cm^2
n	Refractive index of lens	1.7
ψ_c	Receiver field angle	60°
T_s	Receiver optical filter gain	1
P_t	Transmit optical power	55 W
I_2	Background noise bandwidth factor	0.562
q	Electronic charge	1.6×10^{-19}C
B_{sky}	Natural light intensity	0.6 w/(m^2.nm)
R	Photoelectric conversion efficiency	0.35
Δf	Detector frequency response range	2MHz
$\Delta\lambda$	Wavelength range of received optical noise	220nm
g	Internal gain of detector current	10 KHz

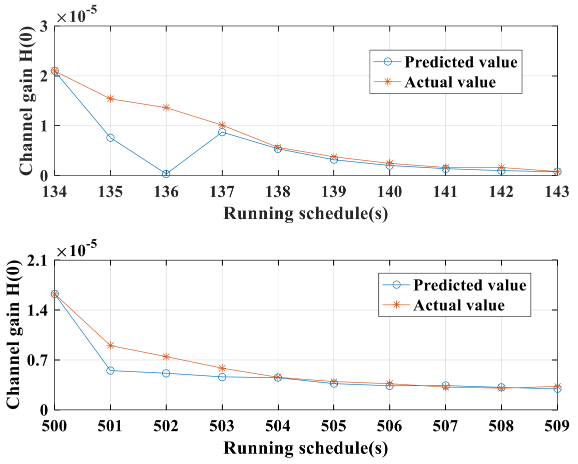
B. Analysis of simulation results

1) Accuracy of model

In the selected time segment, we analyse the channel gain between v_{33} and v_{35} during the time period of 134-143 s, and v_{13} and v_{15} over the time duration of 500-509 s, see Fig. 5. Fig. 5(a) presents the travel path of the two vehicles with v_{35} changing lane, and the two v_{13} and v_{15} travelling on the same line. In Fig. 5(b), the predicted channel gain obtained by the proposed model is compared with the actual channel gain according to the present position of vehicles. Where during the time interval of 134-143 s and 501-509 s, the predicted model uses the position of vehicles at time of 134 s and 500 s as the initial known position for prediction, respectively.



(a)



(b)

Fig. 5: The vehicle trajectory and channel gain for: (a) Travel path in 134-143s and 500-509s; and (b) Comparison of actual and predicted channel gain.

As can be seen from Fig. 5(b), the predicted result match the actual data for the running time ≥ 137 s and ≥ 504 s, whereas it is slightly worse for the running time in the range of 135-136 s and 501-503 s. This is because of the bearing of the vehicles 33 and 35, which are different when changing lanes and the sudden changes in the relative velocity between vehicles 13 and 15.

2) Validity of routing algorithm

The communications route between SV (number 1) and DV (number 17) using the V2LCnet, DYRP-VLC and MHRR in the selected time segment 500-509 s is shown in the Table 3.

TABLE III. COMMUNICATIONS ROUTE OF VEHICLES IN 500-509S

Name / Time	V2LCnet	DYRP-VLC	MHRR
500s	1-5-15-17	1-9-16-17	1-2-6-7-5-9-14-11-12-17
501s	1-4-8-17	1-9-16-17	1-2-6-7-5-9-17
502s	1-4-8-17	1-7-11-17	1-2-6-7-5-9-17
503s	1-7-11-17	1-7-11-17	1-2-4-7-10-9-8-17
504s	1-4-5-12-17	1-7-14-15-17	1-2-4-7-5-9-8-11-17
505s	1-4-5-11-17	1-7-8-12-17	1-2-4-7-10-9-8-11-17
506s	1-4-5-14-17	1-7-9-12-17	1-2-4-6-7-5-9-8-11-17
507s	1-2-7-8-13-17	1-6-9-12-16-17	1-2-4-6-7-5-9-8-11-12-17
508s	1-2-7-8-13-17	1-6-10-11-15-17	1-2-4-6-7-5-9-8-11-12-17
509s	1-2-6-5-8-12-15-17	1-4-7-9-11-13-16-17	1-2-4-6-7-5-9-8-11-12-13-17

As presented in Table 3, the SV can transmit information to the DV via the relay vehicles. Moreover, there are different optimization route at different time. Because of the highly dynamic nature of the vehicles, in determine the current routing based on the data from the previous actions, routing may not be suitable for the current situation. Thus, MHRR uses predicted information to improve the route performance in terms of timeliness.

Finally, to evaluate the VLC link quality using MHRR in comparison with V2LCnet and DYRP-VLC algorithms, we compare the SNR [15] at the receiver as is presented in Fig. 6. A shown, MHRR offers higher SNR. In the selected time segment, for MHRR the lowest SNR is obtained at the running time of 509 s, which is higher by 7.3 and 9.7 dB compared with the tree-based V2LCnet and the shortest path-based DYRP-VLC, respectively. Note, MHRR considers two layers candidate set vehicles when choosing the relay vehicle, which allows appropriate relay vehicle selection between the SV and the DV.

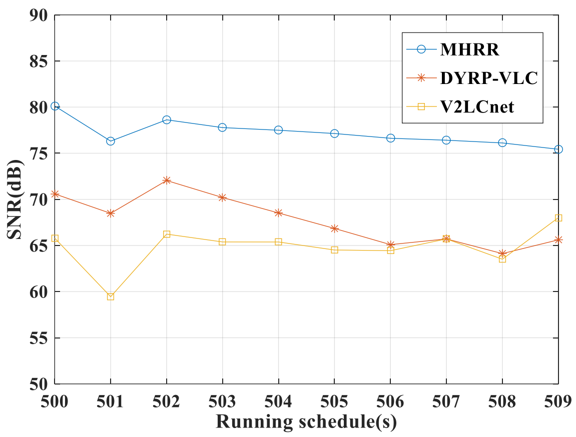


Fig. 6: SNR vs. the running time for V2LCnet, DYRP-VLC and MHRR.

V. Conclusion

In this paper, we presented an improved channel gain model and a multi-hop relay-based routing algorithm for a V2V VLC system to achieve long-distance transmission. We predicted the future position of vehicles and obtained a prediction-based channel gain model and used it as the part of the routing algorithm to select the next relay vehicle. The simulation results demonstrate that, the proposed algorithm offers higher SNR compared with the tree-based V2LCnet and the shortest path-based DYRP-VLC algorithms. We also observed that, the performance deterioration due to sudden changes in the driving direction and the relative velocity of vehicles, which needs further study in predicting the accuracy and finding the optimization route between the source and destination from a global perspective as part of our next work. And in future works, we will consider two way traffic scenario in order to improve both the channel gain model and the routing algorithm.

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