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Data Delivery Delay Reduction for VANETs on Bi-Directional Roadway

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ABSTRACT In this paper, we investigate the data delivery delay from source to destination for VANETs on bi-directional roadways. The topology includes bi-directional roadways, left-turn lane, straight through lane, right-turn lane with traffic lights deployed at the intersections. Due to the multi-hop feature of data delivery and the limited range of radio transmission, the roadways' topology and the switch operations of traffic lights will jointly affect the data delivery delay. By employing the queuing theory and analyzing the traffic lights operations, we propose the formulae of data delivery delay for different scenarios and extend the analysis to a more general scenario. We find that in the scenario of single intersection, the data delivery delay can be reduced by appropriately selecting the relay nodes. Specifically, in the case of green traffic light at the intersection, opposite lane vehicles can be used to reduce the delay, while for red traffic light, left-turn lane vehicles are used to reduce the delay in a similar approach, i.e., by using multi-hop transmission. The proposed algorithm is verified on single lane roadway, opposite-only, and left-turn-only lane for different simulation time slots, the number of mobile nodes and the value of R/W (R is the wireless communication range and W is the length of the road intersection) through VanetMobiSim and NS-2. Numerical results show that for single intersection, the data delivery delay can be reduced by choosing appropriate relay nodes. Besides, the successful packet delivery rate of bi-directional roadway is better than that of single line roadway scenario.

INDEX TERMS Bidirectional roadway, data delivery delay, intersection, traffic lights, VANET.

I. INTRODUCTION

With the rapid development of wireless technologies, Vehicular Ad Hoc Networks (VANETs) has attracted great attention recently due to its potential application in vehicles broadband service such as multimedia transmission, emerging communication, etc [1]. Data delivery delay is an important factor to judge the performance of VANETs, especially in road safety (e.g., incident warning, traffic alerts, et al.) and high QoS requirement such as voice communication and multimedia services [2]. And many research activities in both academic and industry have been carried out to study it. [9] indicated that the directional propagation including forward propagation and reverse propagation could be used for sending data packet for different scenarios and by mixing two types of directional propagations, the data delivery delay could be decreased.

The road intersection plays an important role in the whole traffic network [4] and has drawn much attention as it is the junctions between different road segments and can control the traffic flow [5] by adjusting the traffic lights. However, the real-time traffic information, which includes the traffic light status [6], the congestion or emergency [7] on the road segments etc., and should be shared among vehicles, may be delayed or even discarded at the road intersection [8]. Thus it's very necessary to analyze the process of data delivery at road intersections.

It is very challenging to investigate the data delivery delay at road intersections. Firstly, by considering the road intersection as a dot in the grid topology and ignoring the data delay for the red light at intersection which may be long, it is very difficult to analyze the data delivery process for road intersections with traffic lights. Secondly, long range communication is used to solve the data delivery problem in [18]. However, the problems of higher interference, high packet loss, and high power consumption will make it for more difficult for real applications. An alternative choice to deal with the data delivery is to deploy road-side units at the intersections, but the infrastructure install fee is very expensive [19].

The contributions of this paper are as follows:

- We analyze the traffic flow of a single intersection and use the queue theory to calculate the length of waiting queue at the road intersection.
- We find that the bidirectional roadway topology can decrease the data delivery delay at the intersection. We use the opposite lane and left-turn lane vehicles as relay nodes, and design appropriate transmitting ways to reduce the data delivery delay.
- By investigating different scenarios of intersections, we propose the corresponding formula to calculate the delivery delay at road intersection and analysis the possible routing in the $n \times n$ grid-road scenario. Note that here the processes of data delivery delay in analyzed in two-dimension square.
- We simulate the delay and the packet fraction at R/W (R is the wireless communication range and W is the length of road intersection.) for different slots and number of mobile nodes. Simulation results show that the two-dimension topology has better performance.

The remainder of this paper is organized as follows. In Section II, we introduce the related works in this field. We present the system model in Section III and, the detailed results and discussion in the Section IV. Section V gives some simulations via VanetMobiSim [15] and NS-2 [3]. Finally, some conclusions and idea of future work are drawn in Section VI.

II. RELATED WORK

The mobile status of vehicles and traffic density is influenced by traffic lights, i.e. red lights and green lights. To analyse the data delivery at intersections and choose the best routing, researchers have proposed many methods, which can be divided into two major types, one is using the flexible traffic lights scheduling and intelligent traffic system to reduce the waiting time for moving vehicles, and the other is improving the routing protocol and optimizing system parameters to minimize the delivery delay in a centralized or distributed way. This kind of method aims to choose the best routing of data delivery at the intersection.

References [6] and [11] proposed adaptive and intelligent traffic lights scheduling to deal with the traffic congestion problem at the intersections. They used the information of the traffic light sensors as feedback to decrease the red light time when the vehicles enter the intersections. According to the vehicular density, position and speed, a feasible red light time can be obtained so as to decrease the red light period. Tian D et al. focused on finding the most suitable nodes for the next hop and proposed a tunable probabilistic infection and limited-time forwarding nature of VANETs to achieve a balance between reachability and efficiency of message dissemination [16]. To decrease the resource utilizaiton, [17] presented a decentralized approach for information dissemination in VANETs with various threshold parameters to help nodes to decide whether to rebroadcast or discard received messages. However, there is little work focused on the performance of average delay at road intersections.

The paper [10] analysed the influence of traffic lights at the road intersections on data delivery. When the traffic light is red, the data delivery delay will be increased because the cars stop for waiting. However, when a vehicle goes into the waiting queue, it may have the probability to put forward the packet and then decrease the delay. On the other hand, when the traffic light is green, it is obvious that the nodes' mobility is unconstrained. However, the next hop might have no node to transmit the data packet, which will lead to a larger carry delay. That is to say, the red light will limit the nodes' mobility, but also have the possibility to reduce the data delivery delay at the same time. Although the green light makes the vehicle keep going, there is a small probability for putting packet forward. Reference [10] provided qualitative results, which is a good solution for the delay problems. Durga et al. proposed an intersection based connectivity-aware geocast routing. It also studied the impact of traffic signal through the simulation [21]. The paper [21] enhanced the packet delivery ratio and reduced the packet loss. In [14], a detailed data delivery delay formed by the straight road to the intersection is presented. But it only focused on a single moving line for one-dimension topology, which only contains one lane on the straight road, two dimension case and the delay of passing the center of the intersection is not considered. In [13], the authors investigated both the negative and positive influence of traffic lights on the data delivery in VANETs. It calculated the data delivery delay along the road with multiple traffic lights, but did not consider the delay at road intersection which is a dot. Reference [12] proposed a mobility model at road intersections and presented mathematical analysis by using Markov process method. It described the scenario model at road intersection including traffic lights and other obstacles in urban environment and provided related validation and simulations. Besides, it also proposed a mobility model at intersection and classified according to the direction of vehicles. Reference [20] proposed the road-side units placement algorithm to provide vehicles with multi-hop data delivery at road intersections.

III. SYSTEM MODEL

In this section, we describe the details of the system scenario, the traffic flow at a single road intersection and the details of the process of the data delivery.

A. THE SYSTEM SCENARIO

In our system, we suppose that the vehicles' arrival and departure at the road intersections allow the Poisson distribution. All the vehicles on the road have equal size so that we can analysis the length of waiting queue and moving queue according to the number of vehicles. The On-board Units (OBU) deployed on the vehicles can receive and sent the beacon messages of traffic information about the neighbor vehicular nodes and the traffic lights' signal, periodically. The vehicular speeds on the road segment in free traffic flow are changing. The average velocity at the road intersection can be estimated based on the density. The traffic lights in the grid topology are synchronized. We first discuss the signal operation of traffic lights and the traffic flow at a single road intersection and then extend the topology from one intersection to a grid road.

B. ROAD INTERSECTION

As illustrated in Fig. 1, a road intersection has four crossings for the vehicles' floating, including east, south, west and north, which can satisfy the entering and leaving of different directions' nodes. Every arrival and departure has three directions, including straight lane, left turn and right turn. We can know that the data packet must pass the center of the intersection if it uses the straight lane or left turn to help transmission. However, the right lane, whose turn arc is much smaller, do not pass the center of the road intersection. The traffic lights' influence on the right-turn lane is slight. In other words, we analyze the straight lane and the left turn when we study the intersection's influence on data delivery.

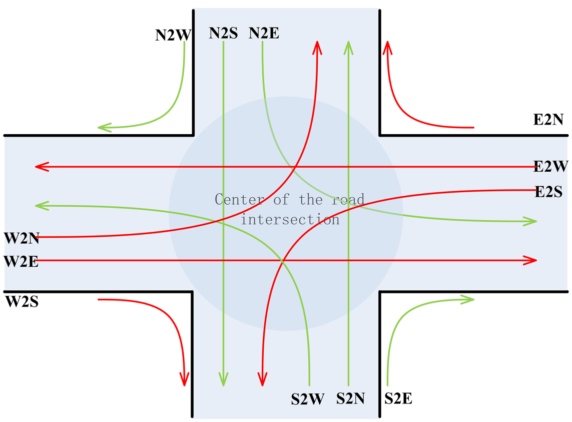

FIGURE 1. Illustration of a single road intersection.

In the grid topology formed by multiple intersections, the choice of routing bases on the performance of data delivery delay. We consider two methods to solve the problem of data delivery at the intersection. One method is using the bi-directional roadway topology to delivery the packets at the intersection. The data packets pass the center of the intersection in this case. The other method is choosing other routes which are using the right turn to avoid the intersection. The choice of the routing bases on the total data delivery delay from source to destination. We choose the routing whose total data delivery delay is the least.

C. DATA DELIVERY DELAY

In this part, we discuss the process of data delivery delay, including the straight road, the waiting queue and the road intersection. We analyze the delay of these three steps and propose the method to decrease the intersection's data delivery delay in the detailed cases.

Step 1: Data delivery on the straight road.

Data delivery on the straight road uses the carry-and-forward mechanism. When there is no nodes in the range of the wireless communication, the source nodes will carry the data packet and keep moving. As shown in Fig. 2, the carry delay is related to the nodes' speed and position. The time of entering the waiting queue at the intersection is less when the vehicular node moves with high speed. The source node forward the data packets to the vehicular node within the communication range by hop to decrease the carry delay. The value of carry delay and forward delay depend on the vehicular density on the straight road. In our system model, we suppose that the carry delay and the forward delay have the same order of magnitude.

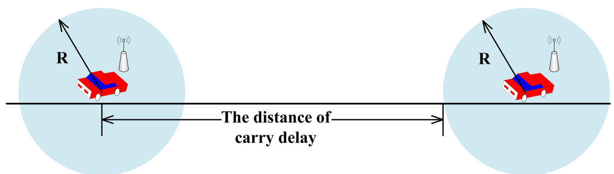

FIGURE 2. Illustration of the carry delay.

Step 2: Data delivery in the waiting queue

When the last vehicular node of waiting queue is in the communication range of source node, the source node transmits the data packet to the last node of the waiting queue. As shown in Fig. 3, the data packet is transmitted along the waiting queue by the multi-hops. The packets can be transmitted along the waiting queue by multi-hop until to the head of the waiting queue. The head node of waiting queue becomes the new node to carry the packets.

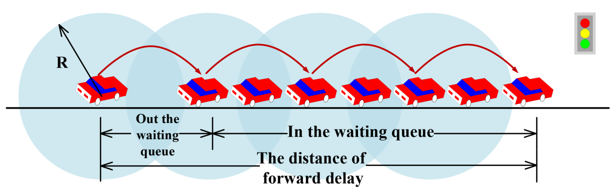

FIGURE 3. Illustration of the multi-hop in the waiting queue.

Step 3: Data delivery at the road intersection

Case 1: The length of road intersection is smaller than the transmission range ($W \leq R$)

The delay of passing the center of the intersection is related to the length of the intersection and the range of the wireless of communication. If the communication range is longer than the size of intersection, the time-consuming of pass the intersection is just the time of one hop.

Case 2: The length of road intersection is longer than the transmission range ($W > R$)

In the case 2, we will analyse the impact of traffic lights' statuses to data delivery delay at the road intersection. The bidirectional roadways topology can decrease the data delivery delay based on the status of traffic lights.

Case 2.1: The traffic light is green.

When the traffic light is green, the first node of the waiting queue will become the new moving node and carry the data packet to pass the center of the intersection. The opposite-lane nodes in bidirectional roadways can become the relay nodes and reduce the duration of carry process, aiming to decrease the delay at road intersection.

Case 2.2: The traffic light is red.

When the traffic light is red, the head node of the straight lane stops at the road intersection and waits for the signal operation of red light. The carry delay will be long in this case. The bidirectional roadways topology by adding the left-turn lanes can decrease the data delivery delay at the road intersection. When the straight lane is red light, the left-turn lane should be green light. The data packet change the propagation direction and is transmitted by the left-turn lanes rather than waiting in the straight lane. In next section, we can give more evidence and investigate the delivery delay of bidirectional roadways quantitatively.

TABLE 1. Parameters cited in the main results.

Notation	Description
P	the probability of the vehicle arriving the waiting queue
λ	average arrival rate at the intersection
μ	average output rate at the intersection
$\overline{n}$	average number of waiting vehicles
l_q	the length of the waiting queue
Δd	the length per vehicle
D_{ij}	the data delivery delay from intersection i to intersection j
L_{ij}	the length of road ij
R	average range of wireless communication
v	the vehicular speed on the straight lane
t_{hop}	the average wireless transmission delay per hop
W	the range of the intersection
t_r	the time of red light
t_g	the time of green light
B	the length of the left turn at the intersection

IV. MAIN RESULTS

In this section, we analyze the data delivery delay in two-dimension topology. The parameters cited in the main results are listed in TABLE 1.

A. THE WAITING QUEUE BACKLOG

The length of the waiting queue and the nodes' positions in the traffic flow are changing all the time. We consider the problem of waiting queue by using Queuing Theory. A Queuing system constitutes with three parts, called inputting, queuing and outputting. Inputting describes the law of the vehicles' arrival into the intersection. The real arrival of the intersections follows Poisson distribution. The probability of the nodes' arrival at the intersection is

$$P(X = k) = \frac{e^{-\lambda}\lambda^k}{k!}. \tag{1}$$

Here, λ is the average arrival rate at the intersection. Regarding the time of passing the intersection as the service time, the average output rate is μ. Let's

$$\eta = \frac{\mu}{\lambda}. \tag{2}$$

There are three mechanisms of queue in the queuing system, including Losing system, Waiting system, and Mixing system. The condition of the intersection is the Waiting system, that means once entering the waiting queue, the vehicle will not leave until the traffic lights turn green. So there is only one lane for the vehicles' service once it enters the waiting queue. The service process (output) of the intersection condition is Poisson distribution. So we use the model of $M/M/N$, which means Poisson Input, Poisson Output, and has the N lanes to service. In the $M/M/N$ mode, there are N roadways to support the service. In this paper, we suppose the waiting vehicle does not change the lane during the red light. So the value of the N is 1. In the system of $M/M/1$, the average of number of vehicles $\overline{n}$ is

$$\overline{n} = \frac{\eta}{1-\eta} = \frac{\mu}{\lambda - \mu}. \tag{3}$$

Thus, the length of the waiting queue at the intersection is

$$l_q = \overline{n}\Delta d. \tag{4}$$

Here, Δd is the average length of the vehicles.

In [14], it has proposed the case of one-dimension and single direction.

Lemma [14]: The total data delivery delay of the whole process D_{ij} and the expectation of data delivery delay is

$$D_{ij} = d_c + d_f = \frac{L_{ij} - R - l_q}{v} + \lceil \frac{R + l_q}{R} \rceil t_{hop}. \tag{5}$$

Here, d_c is the carry delay, d_f is the forward delay, and L_{ij} is the length of the road. The duration per hop is the t_{hop} and the range of wireless communication is R. In this paper, we propose the bidirectional roadway to make the data packet pass the center of the intersection.

Theorem 1: When the length of intersection is smaller than the range of wireless communication ($W < R$), the delay at the road intersection is t_{hop}.

It is easy to prove that the traffic lights' signal operation do not influence the data delivery on the case that the length of road intersection is smaller than the range of wireless communication. In this case, the data packet can pass the center of the road intersection by using one hop. Therefore, the delay of the data packet passing the center of the intersection is

$$D_{ij} = t_{hop}. \tag{6}$$

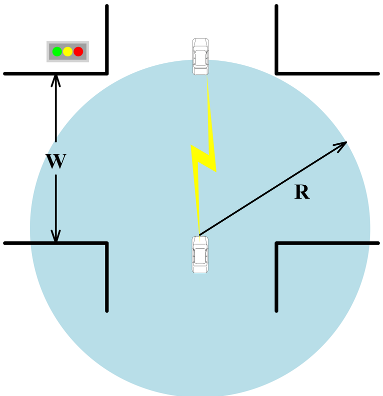

FIGURE 4. Illustration of packet delivery when $W < R$.

B. INTERSECTION DATA DELIVERY USING OPPOSITE LANE

Theorem 2: When the length of intersection is longer than the range of wireless communication ($W > R$), the delay of passing the center of the intersection is

$$D_{\mathrm{ij}}^{\mathrm{o}} = \frac{W-R}{v_1+v_2} + t_{\mathrm{hop}} + \lceil \frac{(\frac{W-R}{v_1+v_2} + t_{\mathrm{hop}})v_2}{R} \rceil t_{\mathrm{hop}}. \quad (7)$$

The equation (7) is the data packet's total delay of passing the center of the intersection. The queue's average speed from south to north is v_1. The queue's speed from north to south is v_2. v_1 and v_2 can be the same. t_{hop} is the delay time per hop in the VANET. $\frac{W-R}{v_1+v_2}$ is the duration that the head vehicle of single line carries the data packets at the road intersection. And then the head node forwards the packets by one hop to the head node vehicle in the opposite lane which is in the range of wireless communication. The last part of equation (7) is the duration when the packets forward by multi-hop among the opposite lane to pass the center of intersection. The data packet's transmitting process is shown in Fig. 5.

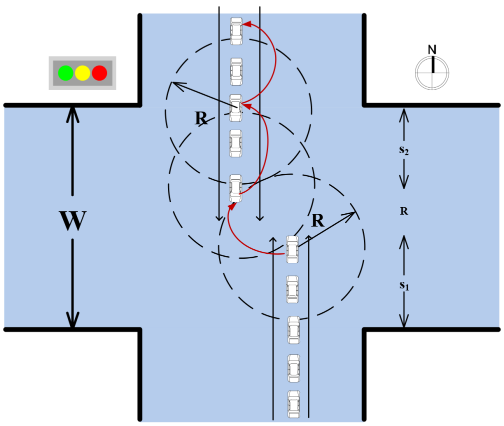

FIGURE 5. Illustration of packet delivery by opposite lane.

Proof: The whole process that the data packet passes the center of the intersection includes three steps. In the first step, as shown in Fig. 5, when the traffic light turns red to green, the two waiting queues of both directions begin passing the intersection. The data packet is carried by the head vehicle of the queue which moves from south to north. According to the encounter problem in the math,

$$\begin{cases} s_1 + s_2 + R = W \\ s_1 + s_2 = v_1 t + v_2 t \end{cases}$$

uniting the two equations, and the carry delay will be $\frac{W-R}{v_1+v_2}$. The second step occurs at the time that the two heads of the opposite traveling queues' distance equals the range of the wireless communication R. The bidirectional roadways use this period to change the propagation direction and decrease the data delivery delay. So this step's delay is the average wireless transmission delay per hop (t_{hop}). And then, the queue traveling from north to south sends the data packet to pass the center of the intersection. The data packet's sending direction is opposite from the vehicles' mobile direction. During data packet's multi-hop, the queue from north to south is still moving. Therefore, the distance between data packet and the next straight road become $(\frac{W-R}{v_1+v_2} + t_{\mathrm{hop}})v_2$. The data packet is relayed on opposite lane by the multi-hop. Therefore, the number of multi-hop is $\lceil \frac{(\frac{W-R}{v_1+v_2}+t_{\mathrm{hop}})v_2}{R} \rceil$. Summing three steps' data delivery delay, the data delivery delay is

$$\frac{W-R}{v_1+v_2} + t_{\mathrm{hop}} + \lceil \frac{(\frac{W-R}{v_1+v_2} + t_{\mathrm{hop}})v_2}{R} \rceil t_{\mathrm{hop}}.$$

□

Furthermore, we suppose that the south queue and the north queue start going at the same time in equation (7). When the two phases' traffic lights is asynchronism, we should consider an additional parameter Δt. In this case, the data delivery delay at road intersection is

$$\frac{W-R-\Delta t v_{\mathrm{i}}}{v_1+v_2} + \Delta t + t_{\mathrm{hop}} + \lceil \frac{(\frac{W-R-\Delta t v_{\mathrm{i}}}{v_1+v_2} + \Delta t + t_{\mathrm{hop}})v_2}{R} \rceil t_{\mathrm{hop}}, \quad (8)$$

where v_{i} equals to v_1 or v_2 which is the speed of queue who is going firstly.

C. INTERSECTION DATA DELIVERY USING LEFT-TURN LANE

We give the results of two-dimension topology which adds the left-turn lanes in the bidirectional roadways to decrease the delay. As shown in Fig. 6, when the S2N line waits in the intersection because of the red traffic light, the E2S line and W2N keep going because of the green light.

Theorem 3: When the straight lane is smaller than the length of left turn on the straight road ($v_2 t_{\mathrm{r}} - B < l_{\mathrm{q}}$), the data delivery delay is

$$D_{\mathrm{ij}}^{\mathrm{l1}} = \frac{L_{\mathrm{ij}} - R - l_{\mathrm{q}}}{v_2} + (\lceil \frac{l_{\mathrm{q}} + W}{R} \rceil + 1) t_{\mathrm{hop}}. \quad (9)$$

The E2S moving line's average speed is v_2. The value of $v_2 t_{\mathrm{r}} - B$ is the length that left turn enters the north road when

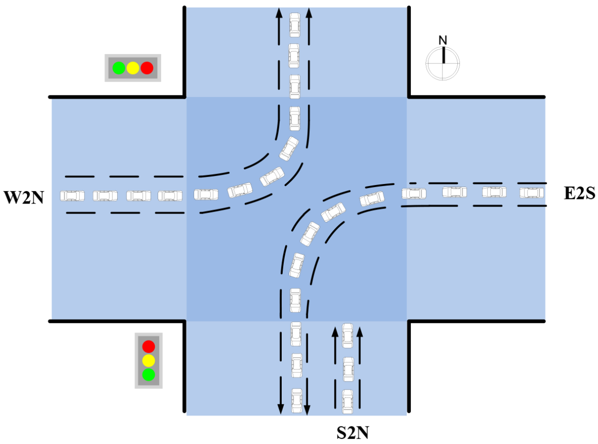

FIGURE 6. **Illustration of left-turn lane at the intersection.**

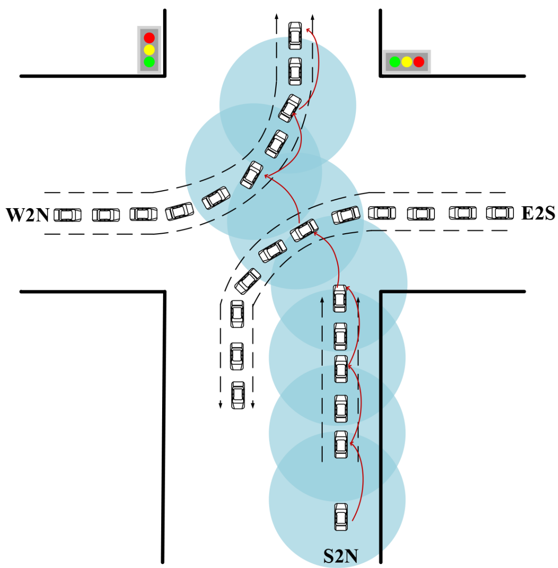

FIGURE 7. **Illustration of packet delivery when $v_2 t_r - B < l_q$.**

the straight lane waits for the red light. As shown in Fig. 7, the data packet floats from the S2N lane to the E2S lane and to the W2N at last. By using the left-turn lanes as relaying nodes, the data packet can pass the center of the intersection even though the traffic light is red so that this method can decrease the data delivery delay.

Proof: The length of carrying data packet is $L_{ij} - R - l_q$, and the average speed of S2N is v_2. Therefore the carry delay is $\frac{L_{ij}-R-l_q}{v_2}$. The length of multi-hop is $l_q + W$. Considering the communication range (R), the values of the multi-hop is $\lceil \frac{l_q+W}{R} \rceil + 1$. Therefore, the data delivery delay by adding the left-turn lane is

$$D_{ij}^{l1} = d_c + d_f = \frac{L_{ij} - R - l_q}{v_2} + \lceil \frac{l_q + W}{R} \rceil t_{hop} + t_{hop}.$$

□

Theorem 4: When the straight lane is longer than the length of left turn on the straight road ($v_2 t_r - B > l_q$), the data delivery delay is

$$D_{ij}^{l2} = \frac{L_{ij} - R + B - 2l_q - v_2 t_r}{v_2} + (\lceil \frac{v_2 t_r - B + W}{R} \rceil + 1) t_{hop} \tag{10}$$

On the case of $v_2 t_r - B > l_q$, the bidirectional roadway will further decrease the carry delay. As shown in Fig. 8, the head vehicular node in left-turn lane becomes the relay node on the straight road to decrease the carry delay. The data packet forwards in left-turn lanes (E2S and W2N) by reverse propagation.

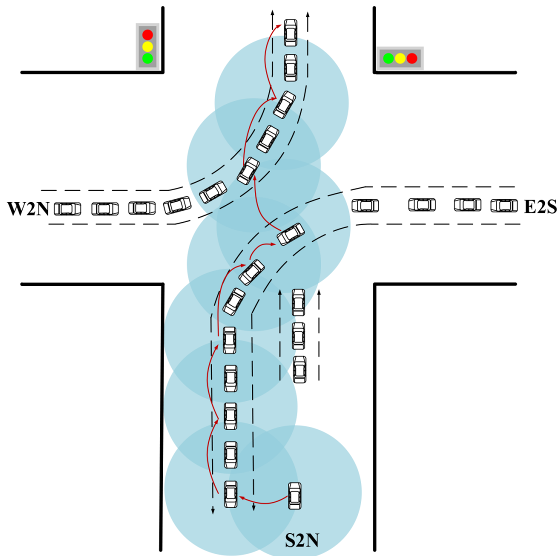

FIGURE 8. **Illustration of packet delivery when $v_2 t_r - B > l_q$.**

Proof: The carry delay in using the S2N as the relay node is $d_1 = \frac{v_2 t_r - B - l_q}{v_2}$. The time of using the E2S as the transmitting nodes by multi-hop is $\lceil \frac{v_2 t_r - B - l_q}{R} \rceil t_{hop}$. Therefore, the reduction of the total delay is

$$\Delta D_{ij} = d_1 - d_2 = \frac{v_2 t_r - B - l_q}{v_2} - \lceil \frac{v_2 t_r - B - l_q}{R} \rceil t_{hop}.$$

Therefore, the date delivery delay when $v_2 t_r - B > l_q$ is

$$D_{ij}^{l2} = D_{ij}^{l1} - \Delta D_{ij}.$$

Simplify the equation and the result is

$$D_{ij}^{l2} = \frac{L_{ij} - R + B - 2l_q - v_2 t_r}{v_2} + (\lceil \frac{v_2 t_r - B + W}{R} \rceil + 1) t_{hop}.$$

□

The process of data delivery is shown in Algorithm 1.

D. DATA DELIVERY DELAY FOR MULTIPLE INTERSECTIONS

The data delivery routing for gird topology can be designed based on delivery method at the road intersections. According to the different methods of data delivery at the road intersection, traveling in the straight road and passing the center of the intersection by opposite lane and left-turn lane produce delays. T_I is the average delay of passing the road intersection

Algorithm 1 Data Delivery Delay on Bi-Directional Roadways

s-source node, d-destination node,r-relay node
S_L-traffic light status, $\{I\}$-road intersection set
W-intersection length, R-transmission range
$\vec{d}$ -node's moving direction
Start data delivery:
Input: Position(s, d); Direction($\vec{d_r}$, $\vec{d_s}$)
if $\overline{sd} \bigcap \{I\} = \emptyset$ **then**
  carry-and-forward /*straight road only*/
else
  /*straight road and intersection*/
  if s in the straight road **then**
    carry-and-forward /*Theorem 4*/
  else
    if $W < R$ **then**
      relay packet by one hop /*Theorem 1*/
    else
      acquire the traffic light status S_L, $S_L \in \{G, R\}$
      if $S_L = G$ /*green light*/ **then**
        FindNode($< \vec{d_s}, \vec{d_r} >= \pi$) /*opposite lane*/
        AddNode(opposite lanes) as relay nodes
        relay packets /*Theorem 2*/
      else
        FindNode($< \vec{d_s}, \vec{d_r} >\in [\frac{\pi}{2}, \pi]$) /*left-turn lane*/
        AddNode(left-turn lanes) as relay nodes
        relay packets /*Theorem 3 & 4*/
      end if
    end if
  end if
end if
Return Nodes
End data delivery

and T_S is the average delay of moving on a straight road. The right-turn lane does not pass the center of the intersection, and the delay of right-turn lane will be ignored. When the packet arrives at the road where destination node sets, there is a average delay of queuing towards the destination as T_Q. The value of T_Q is not the constant because of the different routing and positions of destinations.

Theorem 5: The total data delivery delay from the source node to the destination node for grid topology is

$$D = N_I \cdot T_I + N_S \cdot T_S + T_Q. \tag{11}$$

Here, N_I is the number of passing the center of the intersection of a whole routing from source to destination. N_S is the number of straight road segments where data packets carry and forward.

Proof: The estimation of the total delay from the source to the destination in the grid topology is $D = \sum_{i=1}^{n} N_i D_i$. There are three kinds of delay in the grid topology, including the delay of passing the center of the intersection, the delay of travelling along the straight roads, and the delay of dealing with the data packet. So, $i = 3$. Therefore,

$$D = \sum_{i=1}^{n} N_i D_i = N_I \cdot T_I + N_S \cdot T_S + T_Q.$$

□

The routings from the source to the destination are different based on road segments in the grid topology. Find the route that can arrive at destination and calculate the total data delivery delay according to equation (11). Choose the routing which has the least total data delivery delay to transmit the packet from source to destination.

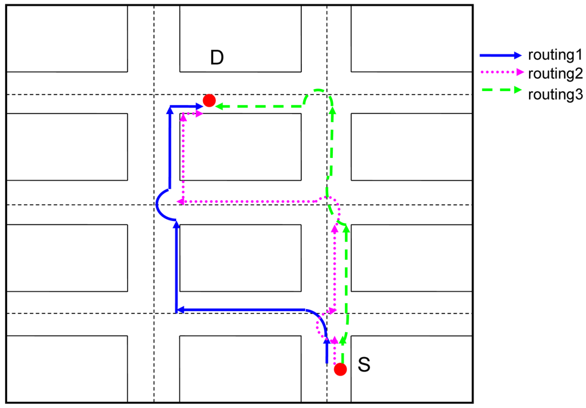

FIGURE 9. Illustration of an example of routing choice process.

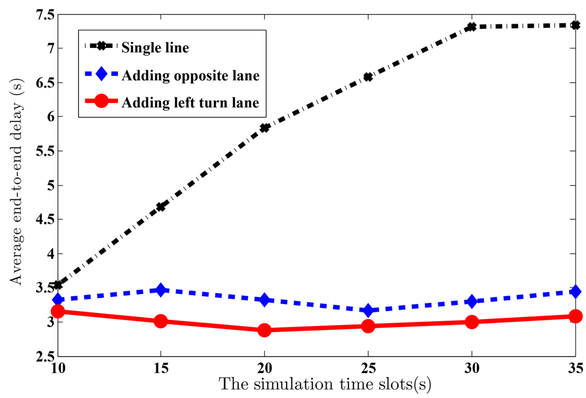

FIGURE 10. The average end-to-end delay improvement.

The example is shown in the Fig. 9. The three routings shown in Fig. 10 can delivery the packet from source to destination. According to the equation (11), the total delay of routing 1 is $2T_I + 3T_S + T_{Q1}$. The detail of routing 2 is different from routing1, however the total delay of them are the same. The total delay of routing 3 is $3T_I + 2T_S + T_{Q2}$. The value of T_{Q1} and T_{Q2} are different because of the destination's position in the grid road.

The process to calculate the total delivery delay and the method of optimizing the choice of routing is shown in the Algorithm 2.

Algorithm 2 Routing Choice Algorithm in Grid Topology

```
Input N_I = {a_1, a_2 ... a_n}
Input N_S = {b_1, b_2 ... b_n}
Input T_Q = {T_Q1, T_Q2 ... T_Qn}
for i=1 do
    D_i = a_i T_I + b_i T_S + T_QI
    i=i+1
    D = {D_1, D_2 ... D_N}
end for
routing j = min{D_1, D_2 ... D_N}
Output routing j, D_j
```

E. DISCUSSION

According to the analysis of the different cases about the road intersection, we know that the bidirectional roadway can decrease the data delivery delay by using the opposite lane and left-turn lane vehicles as relay nodes. This method by changing directional propagation can be used in the practical traffic scenario to relay the data packet in some emergencies. The decrement of delay at road intersections can influence the routing's performance in grid topology.

Theorem 1 and Theorem 2 propose the data delivery delay on the case of using opposite lane in bidirectional roadway of two-dimension square. Adding the opposite lane as the transmitting nodes can decrease the delay of passing the center of the road intersection. The parameter which influences the results of Theorem 1 and Theorem 2 is the relationship between the length of intersection and the range of wireless communication. We can make the balance between the range of wireless communication and the length of the road intersection in practical VANET's application in order to decrease the delay at the intersections.

The Theorem 3 and Theorem 4 focus on the traffic lights' influence on delivery delay and aim to decrease the data delivery delay by adding the left-turn lane when the traffic lights are red. According to the different length of left turn and the waiting queue, the optimal transmit routing is different. Theorem 5 extends the scenario from a single road intersection to the grid road topology, which can be used in the future improvement of routing protocols and optimization of traffic predictions.

V. SIMULATION

In this section, we simulate the data delivery mechanism and routing choice in grid road topology according to Algorithm 1 and Algorithm 2. Comparing with the delay and the packet delivery fraction, the simulation results demonstrate that the bi-directional roadway topology can improve the performance of data delivery at road intersections and verify the theoretical results.

A. PARAMETERS

VantMobiSim and NS-2 are used as the simulators in our numerical evaluation. The traffic pattern can be set up in software named VanetMobiSim. The traffic scenario parameters includes vehicular mobility distribution, road segments' length, intersections' position, intersection's size, traffic lights' periods and the signal operation regulations. VanetMobiSim outputs a xml file, which records the vehicular mobile trace, including the vehicular nodes' positions and speed. Based on the xml file of VanetMobiSim, NS-2 can simulate the performance of data delivery according to proposed communication topology. It records the status and process of data delivery from the source to destination. The end-to-end delay is the main performance parameter of data delivery. The factors, such as the source node's position, the destination's position and the moving direction, may influence the average end-to-end delay. In our simulations, source node and destination have the same moving direction, but they are in different road segments. The data packets should pass one road intersection. The end-to-end delay is the duration that a data packet delivery from the source node to the destination node. The source node sends packets at a rate of 0.1.

The standard of the traffic scenario is 2000×2000 square meters. The traffic lights in the grid road topology are synchronized. The default ratio of green light and red light is 1:1, which means that the green light and red light are both 60 seconds. The number of vehicular nodes varies from 100 to 500 and the velocity of free traffic flow on road segment is 20 m/s. The mobility model of vehicles in VanetMobiSim is polito.uomm.IDM_IM. A road intersection, which varies from 50 meters to 250 meters, exists between source node and destination node. The mobile nodes that deployed OBUs use the IEEE802.11 wireless communication protocol and the transmission range is 250 meters. The detail values of simulation parameters are shown in the TABLE 2.

TABLE 2. Simulation parameters.

simulation parameters	values
scenario length (m)	2000
scenario width (m)	2000
traffic lights' period (s)	120
red light time (s)	60
green light time (s)	60
average speed of mobile nodes (m/s)	20
default number of mobile nodes	100
range of mobile nodes	100∼500
range of $\frac{R}{W}$	0.2∼ 1
default number of $\frac{R}{W}$	0.2
communication range (m)	250
CBR send rate	0.1
total simulation time (s)	300

B. SIMULATION RESULTS

The paper [14] focuses on the data delivery delay in single line and one direction. We simulate the data delivery mechanism and routing choice in grid road topology according to Algorithm 1 and Algorithm 2.

1) THE EVALUATION OF DIFFERENT SIMULATION TIME SLOTS

We suppose the length of road intersection is smaller than the length of transmission range. We simulate the data delivery delay at a single road intersection. The packet sending rate is 0.1, therefore we set 5 seconds as a simulation time slot to analyse the average delay from source node to destination node. The average end-to-end delay of different simulation time slots is shown in Fig.10. We analyse six time slots. Comparing with the average end-to-end delay varying from 3.5 seconds to 7.5 seconds in the scenario of single lane, the average end-to-end delay at road intersection by using bidirectional roadways is reduced to 3 seconds. The two methods deliver the data packets in the signal operations at the road intersection. Therefore, the trends of adding opposite lane and adding left-turn lanes are similar. The end-to-end delay of the bidirectional roadway by using left-turn lane outperforms the bidirectional roadway by using opposite lane, because the left-turn lane can relay the packets at red light, which the opposite lane should waiting at the road intersection. The simulation result shows that bidirectional roadway topology can reduce the intersection's data delivery delay of different simulation time slot.

The detail results of performance parameters is shown in the TABLE 3. From the table, we can know that, because of adding bidirectional roadway lanes as helper nodes, the average end-to-end delay is reduced by nearly 46.7%. The first packet received time and the average end-to-end delay of bidirectional roadway is less than the single line topology's. The opposite lane and left-turn lane as relay nodes to decrease the carry delay at the road intersection. The simulation results show that the bidirectional roadway in two-dimension square can improve and optimize the performance of intersection's data delivery, which verify our formulation's correctness.

TABLE 3. The end-to-end delay and first packet receive time.

	end-to-end delay	first packet receive time
single line	6.058s	7.717951s
opposite lane	3.259s	2.572944s
left-turn lane	3.241s	2.533252s

2) THE EVALUATION OF DIFFERENT NUMBER OF MOBILE NODES

We suppose the length of road intersection is smaller than the length of transmission range. In the same simulation time, the value of vehicular nodes varied from 100 to 500. The simulation result shows the average end-to-end delay at the road intersection is influenced by the number of mobile nodes. Fig.11 shows that the average end-to-end delay varies from 1.4 seconds to 1.6 seconds on the traffic scenario of single lane in one-dimension. The average end-to-end delay of bidirectional roadway topology is around 0.2 seconds, which is decreased more than 1 seconds. According to the theorem 3 and theorem 4, the delay delivery delay decreases when the length of waiting queue increases. The lines of adding opposite lane and adding left-turn lane in the Fig. 11 show the some trend, which is in accordance with our theoretical analysis.

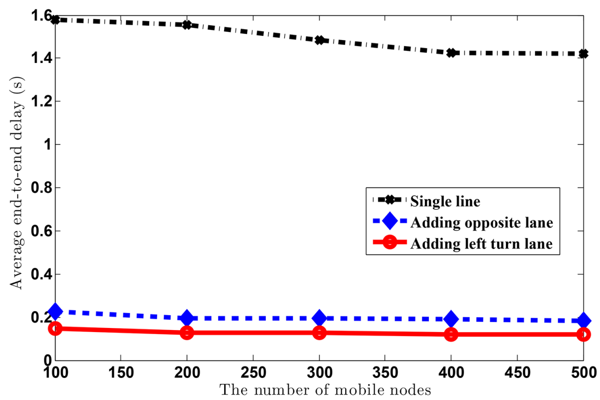

FIGURE 11. The average end-to-end delay improvement.

Moreover, because the bidirectional roadway by using left-turn lane can transmit the data packet when the traffic light is red, the scenario by adding left-turn lane has the better performance on decreasing delay than the scenario by adding the opposite lane. Comparing with the average end-to-end delay of single lane in one-dimension, the delay of using bidirectional roadway is less and more stable of different number of mobile nodes. The simulation results show that bidirectional roadway on two-dimension can improve and optimize the performance of intersection's data delivery, which verify our formulation's correctness.

3) THE EVALUATION OF DIFFERENT VALUES OF R/W

The simulation reflects the relation's influence on data delivery delay between transmission range and length of intersection. We set the parameter of R/W to reflect the relation of transmission range and the size of intersection. For instance, the value of R/W equals 0.5, the length of road intersection is 500 meters according to the description in TABLE 2. The result of average end-to-end delay by using a single lane, adding opposite lane and adding left-turn lane is shown in the Fig.12. The simulation result shows that the end-to-end delay is reduced on bidirectional roadways in the same value of R/W. When the size of road intersection is smaller than the wireless communication range (e.g. R/W varies from 0.2 to 0.9.) The data delivery delay on the scenario of single line varies from 4.3 seconds to 2 seconds. The performances of bidirectional roadways by adding opposite lane and left-turn lane are around 1.7 seconds. The trends of adding opposite lane and adding left-turn lanes are similar, but the performance of adding left-turn lane outperforms that of adding opposite lane, which can relay the data packets when the traffic light is red. When the size of intersection equals the length of road intersection ($R/W = 1$), the data packet can

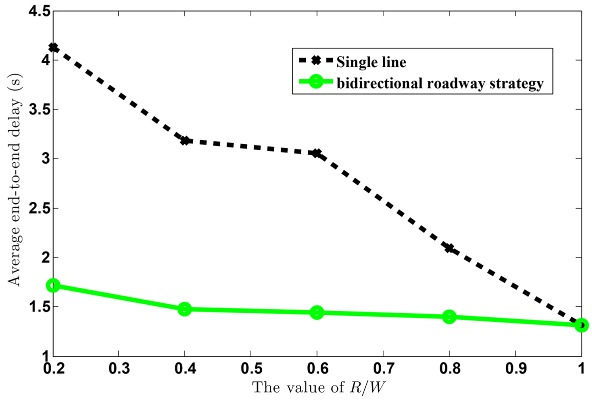

FIGURE 12. The average delay between the single line and bi-directional roadway of different values of R/W.

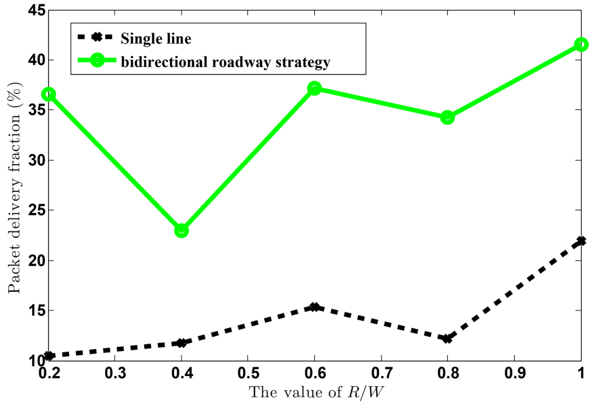

FIGURE 13. The packet delivery fraction between the single line and bi-directional roadway of different values of R/W.

be delivered by one hop (Equation (6)), which verities our theoretical results.

Fig. 13 shows the performances of packet delivery fraction of different values of R/W. We simulate the R/W from 0.2 to 1.0 to proof bi-directional roadway's advantage. The simulation results show that the average packet delivery fraction on the traffic scenario of single line in one-dimension is from 10 percent to 20 percent. The average end-to-end delay on the traffic scenario of using bidirectional roadway is from 25 percent to 40 percent. The packet delivery fraction is improved because bi-directional roadway can decrease the data packet's waiting time when the traffic light is red, which may cause the data packet's loss. The trend of packet delivery fraction is uncertain because there are other factors to influence the results, including the vehicular mobile topology and interference between the mobile nodes. Comparing with the packet delivery fraction of single line in one-dimension, the delivery fraction of using bi-directional roadway is higher in different value of R/W. The simulation results show that the scenario of bidirectional roadway in two-dimension square can improve and optimize the performance of intersection's data delivery, which verify our formulation's correctness.

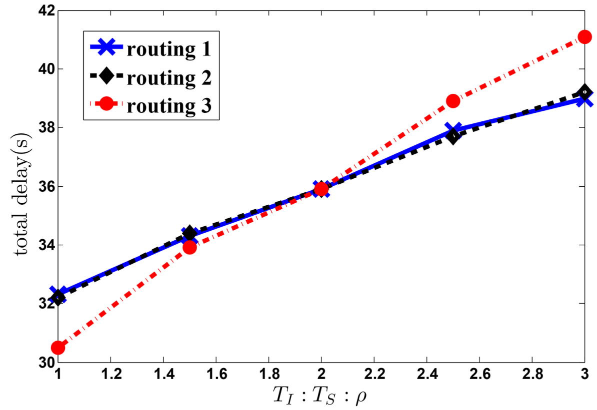

FIGURE 14. Delay of different routings in grid-road.

4) THE SIMULATION FOR GRID TOPOLOGY

We simulate the example illustrated in Fig. 9. The total delay of routing 1, routing 2, routing 3 are $2T_I + 3T_S + T_{Q1}$, $2T_I + 3T_S + T_{Q1}$ and $3T_I + 2T_S + T_{Q1}$. Because the routing 1 and routing 2 have the same total delivery delay, we compare the total delay from source to destination of routing 1 and routing 3 in the different value of $T_I/T_S/\rho$. ρ is related to the destination's position on the road. The value of the ρ is T_Q/T_S. Fig. 14 shows the total delay of routing 1, routing 2 and routing 3. From the simulation result, when the T_I/T_S is under 2ρ, the routing 3 has the fewer delay, when the T_I/T_S is more than 2ρ, the routing 1 can delivery the packet earlier.

VI. CONCLUSION

In this paper, we analyse the bidirectional roadway to reduce the data delivery delay at road intersections. The bi-directional roadway use the opposite lane and left-turn lane to relay packets in order to pass the center of the road intersections. Further, we extend the scenario from a single road intersection to a grid-road. We give the formulae of computing the delay of passing the center of the intersections and the total delay from source to destination in grid road topology. According to the simulation results, we find that the opposite lane and left-turn lane can decrease the data delivery delay compared with one-dimension lane. We present a routing scheme from source to destination based on the total delay. At last, we find the simulation performances are coincided with our theoretical results. In the future work, we plan to consider the improvement of bidirectional roadway topology by adding RSUs.

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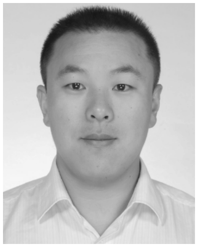

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