Red or Green: Analyzing the Data Delivery with Traffic Lights in Vehicular Ad Hoc Networks

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***Abstract*—The data delivery in Vehicular Ad Hoc Networks (VANETs) depends on the mobility of the vehicles (e.g. with carry-and-forward). However, the mobility of the vehicles is not only affected by the nodes themselves, but also by some external means such as the traffic lights. The red light stops the vehicles at the intersection, which will increase the delivery delay of the messages carried by the vehicle with waiting time. On the contrary, this may also increase the opportunities of vehicles moving behind to catch up in forwarding messages. In this paper, we investigate the negative and positive influences of the traffic lights on data delivery in VANETs. We develop an analysis model for evaluating the data delivery among the vehicles that move along a path with multiple traffic lights. Based on the model, vehicles can estimate the reachability of destinations and the data delivery delay. Thus, we propose a transmission control scheme by the given deadline of reachable destinations, in order to improve the data delivery. Our intensive simulations verify the proposed model, and evaluate the influence of the traffic lights on data delivery.**

Keywords*—*traffic hole, traffic light, VANET

I. Introduction

With the increasing demands of various applications on vehicles, such as road condition sensing, traffic management, location-based services, and so on [1], [2], both academic researchers and automotive industries pay a lot of attention to Vehicular Ad-hoc Networks (VANETs). As presented in [3], although the aforementioned services can be supported by a wireless infrastructure (e.g., 3G), the cost of doing this is high, and may not be possible when such an infrastructure does not exist or is damaged. Timely and lossless multi-hop data delivery among vehicles is essential for VANETs. The traditional connection-based routing protocols [4], which should establish stable end-to-end paths to transmit packets, are often infeasible due to low traffic density and the high mobility of vehicle nodes [3], [5]. By considering the delay-tolerance network (DTN) [6] for intermittent connectivity in VANETs, many have proposed that routing protocols adopt the mechanism of carry-and-forward, which increases the data delivery delay for a higher data delivery ratio. Therefore, the mobility of vehicles not only affects the connections or the forwarding opportunities among vehicles, but also affects the performance of data delivery with carrying.

However, the mobility of vehicles is not only affected by itself, but also by some external means, such as the traffic lights. While a vehicle carries a message to move along a path, it may stop at a red light, increasing the carrying delay with the waiting time. From a macroscopic view, a traffic flow could be interrupted by the signal operations of the traffic lights or pedestrian crossings, resulting in network partitioning. We call such a situation a *traffic hole* [7]. It has been observed that traffic holes can happen even during rush hours. The traffic hole could stop the data delivery along a particular traffic flow, which could prevent the data from reaching.

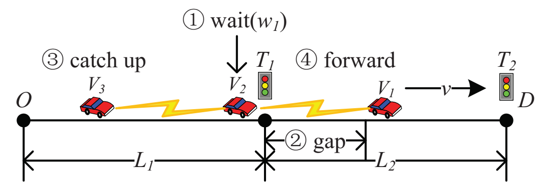


Fig. 1. The impact of a traffic light on vehicle-to-vehicle communications

On the other hand, the vehicles stopped by the red light could wait for the vehicles moving behind, which can increase the opportunities for vehicles moving behind to catch up in data forwarding. In particular, while the stopped vehicles are still connecting with the vehicles on other roads, they can help to forward the messages across the intersection. We term this as *catch up* [8], which can improve the forwarding opportunities at the intersection. On the contrary, a green light could reduce the probability of catching up. For example, two vehicles move on a path under all green lights with the same speed, so the spacing between them will not change. However, if the first vehicle stops at the red light at an intersection, then the second vehicle could catch up the first one. Therefore, the traffic lights could help in forwarding the data packets.

In this paper, we conduct a comprehensive investigation of the influence of traffic lights on the data delivery in VANETs. Compared with our previous work [7], [8], we investigate the traffic hole problem and the approach of catching up with traffic lights, from a microscopic view. Our technical contributions are multi-fold, including:

- We develop an analytical model to evaluate the data delivery among the vehicles along a path with multiple traffic lights, given the initial headway time among the vehicles, and schedules of the traffic lights.
- Based on this model, we propose a transmission control scheme to decide which data packets can be delivered, by giving the deadline of reachable destinations, in order to reduce the resource consumption.
- Our intensive simulations verify the model, and evaluate the influence of the traffic lights on data delivery.

The remainder of this paper is organized as follows: we present the assumption and discuss the influence of traffic lights on the data delivery in Section II. We present our analysis model and propose the transmission control scheme in Section III. We evaluate the efficacy of the analysis model and the data delivery with traffic lights in Section IV. In Section V, we review the related work in vehicular ad hoc networks. The last section concludes the paper with future work.

II. Influence of Traffic Light

A. Assumption

Vehicles communicate with each other through short-range wireless channels. Let R denote the communication range of each vehicle. Let t_{hop} denote the average wireless transmission delay per hop. The well-known car-following model [9] states that a vehicle moves at, or near the same speed as, the vehicle in front of it, while there is a vehicle within a sufficient range of the current vehicle. Thus, with the speed limit, we assume that the velocities of the vehicles on a road are all the same. The velocity is denoted by v. Similar to many studies in VANETs [3], [10], we assume that the vehicular distribution is sparse (or the traffic density is low), and there is no jam at each intersection. Under the low arrival rate of vehicles in sparse vehicular networks, the length of the waiting queue at each intersection could be very short, and we assume that the length of each vehicle can be ignored, compared to their communication ranges and the length of the road.

A path is divided by multiple traffic lights into several road segments. Let V_i denote that the i^{th} vehicle moves onto the path. We denote the k^{th} traffic light from the entrance of the path (initial point) as T_k, and the length of the k^{th} road segment from T_{k-1} to T_k is denoted by L_k. In general, the signal operations of the traffic lights are periodic, and a cycle in the signal operation is defined as a complete sequence of intervals or phases. Under a simple traffic control system, the traffic flow has two states in a cycle, which are the red and green states. The durations of a cycle, red light and green light, are denoted by d_c, d_r and d_g, respectively.

B. Influence of Traffic Lights on Data Delivery

Figure 1 shows the data delivery from an initial point O to the destination D by the way of carry-and-forward among the three vehicles. There is a traffic light in the middle of the path, and the distance from O to D is $L_1 + L_2$. The headway is a measurement of the distance or the time between vehicles in a transit system. Compared to the path without traffic light, the path with traffic light may increase the travel time of vehicles, and it can also change the headway among the vehicles. Thus, the influence of the traffic light on the data delivery among the three vehicles includes:

1) Increasing delay by stopping vehicles: If there is no traffic light in the path, the delivery delay of a message carried by a vehicle from O to D is equal to $\frac{L_1+L_2}{v}$. While the vehicle moves on the path with traffic lights, the carrying delay should include the waiting time at the traffic light T_1 (denoted by w_1). Thus, T_1 increases the carrying delay of the messages, which can be calculated as: $\frac{L_1+L_2}{v} + w_1$.

2) Traffic hole problem: When a vehicle stops at the intersection due to the red light, the vehicle ahead goes away, and a gap appears between them. The length of the gap is increasing during the red time (d_r). When the length of the gap is larger than the communication range of vehicles (R), no messages can be delivered between them. We term this gap as a *traffic hole* [7], which partitions the traffic flow and breaks the connections among the vehicles in the traffic flow.

3) Catch up: As shown in Figure 1, when the vehicle V_2 arrives at the traffic light T_1, the light turns red and stops it. During its waiting time, V_3 moves into its communication range. We term this event as *catch up* (denoted by C) [8]. Thus, V_3 can transmit the message to V_2. Meanwhile, V_1 is still in the communication range of V_2, so V_2 could immediately transmit the message to V_1. We term this event as *immediate transmission* (denoted by I). Thus, the red light can help to deliver the message across the intersections in two steps: (1) the third vehicle V_3 catches up to the second vehicle V_2 and forwards the message to it before the traffic light ($V_3 \overset{C}{\to} V_2$), (2) the second vehicle V_2 immediately transmits the message to the first vehicle V_1 across the intersection ($V_2 \overset{I}{\to} V_1$).

III. Analysis Model

In this section, we investigate the vehicles moving over a path with m traffic lights, which is a linear topology. Our goal is to evaluate the impacts of traffic lights on the data delivery performance among the vehicles, in terms of the data delivery delay and reachable destination. Our analysis is proceeded in two steps, which are mobility prediction and estimation of data delivery. Based on this model, we propose a transmission control scheme to decide which packets could be delivered for reducing the resource consumption.

A. Mobility Prediction

We suppose that q vehicles sequentially move onto a path with m traffic lights, which partition the path into m road segments. All the traffic lights have the same signal operations (i.e. the same d_c, d_g and d_r), and all traffic lights start at the red light. For evaluating the mobility of vehicles along the path with traffic lights, we define four sets of time as follows:

- *Initial time* ($\mathcal{U}$): let u_i in $\mathcal{U}$ denote the departure time of V_i at the initial point O. While the q vehicles sequentially move onto this path, $0 \leq u_1 \leq u_2 \leq \cdots \leq u_q$.
- *Departure time* ($\mathcal{T}$): let $t_k(u_i)$ in $\mathcal{T}$ denote the function for calculating the departure time of V_i at the k^{th} traffic light T_k. $t_0(u_i)$ denotes the time when V_i departs from the initial point O.
- *Arrival time* ($\mathcal{S}$): we define $s_k(u_i)$ in $\mathcal{S}$ as the function for calculating the arrival time of the vehicle V_i at the traffic light T_k. Obviously, $s_k(u_i)$ is equal to the departure time from the previous traffic light ($t_{k-1}(u_i)$) plus the travel time of the vehicle on the road segment ($\frac{L_k}{v}$).
- *Waiting time* ($\mathcal{W}$): let w_k in $\mathcal{W}$ denote the function for calculating the waiting time of V_i at the traffic light T_k. When the light is green, the vehicle will go through the traffic light, and the waiting time is zero. When the light is red, the vehicle will wait at the light until it turns green.

Therefore, we can recursively calculate the three sets ($\mathcal{T}$, $\mathcal{S}$ and $\mathcal{W}$) of the vehicle V_i based on its initial time (u_i) at the traffic light T_k ($k \geq 1$) as follows :

$$\begin{cases} t_0(u_i) = u_i \\ s_k(u_i) = t_{k-1}(u_i) + \frac{L_k}{v} \\ w_k(u_i) = [d_r - \beta(s_k(u_i))]^+ \\ t_k(u_i) = s_k(u_i) + w_k(u_i) \end{cases} \quad (1)$$

where $\beta(x)$ is the modulo operation as: $\beta(x) = x \bmod d_c$.

By considering the interval time of starting up for each vehicle at the intersection, we can update the departure time of each vehicle based on Equation 1, as follows:

$$t_k(u_{i+1}) \Leftarrow t_k(u_{i+1}) \vee (t_k(u_i) + \frac{1}{s}), \quad (2)$$

where s denotes the the saturation flow rate departure from the traffic lights, and $\vee$ denotes the maximum.

Based on the temporal description of the vehicular mobility along the path with traffic lights, we can obtain the spatial description. We define $K_i(t) = k$ if, at time t, the vehicle V_i is in the k^{th} road segment, i.e.

$$K_i(t) = k, \text{if } t_{k-1}(u_i) < t \leq t_k(u_i). \quad (3)$$

$x_i(t)$ is defined as the function for calculating the distance of the vehicle V_i from the initial point O at time t. When the time is before its initial time u_i, we define the distance as zero. After moving onto the path, we calculate the road segment that the vehicle moves on by comparing it with the departure time of each traffic light. If the vehicle is on the k^{th} road segment at time t, the time should be satisfied by $t_{k-1}(u_i) < t \leq t_k(u_i)$. Thus, $x_i(t)$ should be equal to the distance from the initial point O to the traffic light T_{k-1} plus the travel distance on the k^{th} road segment. We define $\alpha_k(u_i, t)$ as the duration while the vehicle V_i has moved on the k^{th} road segment with the speed v at time t. If the vehicle is moving at time t, the duration $\alpha_k(u_i, t)$ is equal to $(t - t_{k-1}(u_i))$. If the vehicle is waiting at the traffic light at time t, the duration $\alpha_k(u_i, t)$ is equal to $(s_k(u_i) - t_{k-1}(u_i))$. $\alpha_k(u_i, t)$ can be calculated as: $t \wedge s_k(u_i) - t_{k-1}(u_i)$, where $\wedge$ denotes the minimum. Therefore, $x_i(t)$ can be calculated as follows:

$$x_i(t) = \begin{cases} 0, & \text{if } 0 \leq t \leq u_i \\ \sum_{r=1}^{K_i(t)-1} L_r + v\alpha_{K_i(t)}(u_i, t), & \text{if } t > u_i \end{cases} \quad (4)$$

B. Data Delivery with Traffic Lights

Based on the mobility model, in this subsection we discuss the problem of data delivery along a path with m lights by q vehicles. The vehicle V_q is defined as the first car that receives a message at the initial point O, and σ_q denotes the time when it receives the message.

For the data delivery by the q vehicles that move on the path, we define σ_i ($1 \leq i \leq q$) as the time when the vehicle V_i receives the message. Obviously, σ_i depends on the events of how V_i receives the message from V_{i+1}, as follows:

- Immediate transmission: When V_{i+1} receives the message at time σ_{i+1}, V_i is in the communication range of V_{i+1}, where it can immediately receive the message. We denote this event by $V_{i+1} \xrightarrow{I} V_i$. Thus, the receiving time of V_i is equal to the receiving time of V_{i+1} plus the wireless transmission delay per hop (t_{hop}).
- Catch up and transmit: When the vehicle V_{i+1} receives the message at the k^{th} road segment, and the vehicle V_i is out of the communication range of V_{i+1}. V_i may become caught up and transmitted with V_{i+1} on the j^{th} road segment where $k \leq j \leq m$. We denote the combinational events by: $V_{i+1} \underset{j}{\xrightarrow{T}} V_i, (K_i(\sigma_{i+1}) \leq j \leq m)$. Thus, the receiving time of V_i is equal to the time when V_{i+1} moves in the communication range of V_i plus the wireless transmission delay per hop.
- Otherwise, the vehicle V_i cannot receive the message before the traffic light T_m, so σ_i is denoted by ∞.

Based on the receiving time σ_{i+1} and the aforementioned events, σ_i can be recursively calculated as follows:

$$\sigma_i(\sigma_q) = \begin{cases} \sigma_{i+1} + t_{hop}, & \text{if } V_{i+1} \xrightarrow{I} V_i \\ s_j(u_{i+1}) - \frac{R}{v} + t_{hop}, & \text{if } V_{i+1} \underset{j}{\xrightarrow{T}} V_i \\ \infty, & \text{Otherwise} \end{cases} \quad (5)$$

The condition that the vehicle V_{i+1} can immediately transmit the message to the vehicle V_i means: when the vehicle V_{i+1} receives the message at time σ_{i+1}, V_i is in its communication range. Thus, the condition can be calculated with the indicator function, as follows:

$$\mathbb{1}_{V_{i+1} \xrightarrow{I} V_i} = \mathbb{1}_{x_i(\sigma_{i+1}) - x_{i+1}(\sigma_{i+1}) \leq R}. \quad (6)$$

The condition that the vehicle V_{i+1} does not catch up V_i at the j^{th} traffic light means: before V_i leaves the j^{th} traffic light, V_{i+1} cannot arrive in its communication range. Thus, the condition can be calculated as follows:

$$\mathbb{1}_{V_{i+1} \underset{j}{\overset{C}{\nrightarrow}} V_i} = \mathbb{1}_{x_i(t_j(u_i)) - x_{i+1}(t_j(u_i)) > R}. \quad (7)$$

On the contrary, the condition that the vehicle V_{i+1} can catch up to V_i at the j^{th} traffic light means: before V_i leaves the j^{th} traffic light, V_{i+1} can arrive in its communication range. Thus, the condition can be calculated as follows:

$$\mathbb{1}_{V_{i+1} \underset{j}{\xrightarrow{C}} V_i} = \mathbb{1}_{x_i(t_j(u_i)) - x_{i+1}(t_j(u_i)) \leq R}. \quad (8)$$

The condition that the vehicle V_{i+1} catches up with V_i and transmits the message at the j^{th} traffic light means that it cannot catch up before the j^{th} traffic light, after it receives the message, and it catches up with V_i at the j^{th} traffic light. The road segment where V_{i+1} catches up with V_i should be between the road where V_i is when V_{i+1} receives the message, and the m^{th} road segment, i.e. $K_i(\sigma_{i+1}) \leq j \leq m$.

$$\mathbb{1}_{V_{i+1} \underset{j}{\xrightarrow{T}} V_i} = \begin{cases} 0, & \text{if } j < K_i(\sigma_{i+1}) \\ \prod_{K_i(\sigma_{i+1}) \leq r < j} [\mathbb{1}_{V_{i+1} \underset{r}{\overset{C}{\nrightarrow}} V_i}] \mathbb{1}_{V_{i+1} \underset{j}{\xrightarrow{C}} V_i}, & \text{if } K_i(\sigma_{i+1}) \leq j \leq m \end{cases} \quad (9)$$

As in our aforementioned discussion, the mobility prediction calculates the three time sets ($\mathcal{T}$, $\mathcal{S}$, and $\mathcal{W}$) for q vehicles, based on their initial times ($\mathcal{U}$) at the initial point O, and each time set has m elements for each vehicle at the m traffic lights. For obtaining the time of q vehicles at m traffic lights, the computational complexity of each time set is $O(q \cdot m)$. Based on the three time sets ($\mathcal{T}$, $\mathcal{S}$, and $\mathcal{W}$) for the q vehicles at m traffic lights, it can calculate the distance of the vehicle V_i from O at time t ($x_i(t)$). The estimation of data delivery is based on the calculation of the data receiving time of each vehicle (σ_i). Under the condition of $V_{i+1} \overset{I}{\rightarrow} V_i$, the computational complexity is $O(q)$. Under the condition of $V_{i+1} \underset{j}{\overset{T}{\rightarrow}} V_i$, the calculation should involve all possible road segments, so the maximal computational complexity is $O(q \cdot m)$.

C. Reachable Destinations

Nodes in VANETs could be either vehicles or roadside units (RSUs). We define *reachability* of the destination as whether the data packets could be successfully delivered from the source to it. Thus, we will discuss the data delivery for the two types of nodes as the destination.

1) RSU as Destination: We consider that the destination is a RSU at T_k, which is a static node placed on the roadside.

Because the data packets are delivered by way of carry-and-forward along the path, the destination which is an RSU can receive it from vehicle nodes. Thus, the RSU destination is reachable for the data delivery.

Let $\mathcal{M}$ denote the set of vehicles which have received the message. Thus, we define $min(\mathcal{M})$ as the index of the vehicle, which delivers the message to the destination. The delivery delay of this message from the source V_q to the destination at T_k can be calculated as follows:

$$d_{V_q \rightarrow T_k} = \sigma_{min(\mathcal{M})} \vee s_k(u_{min(\mathcal{M})}) - \sigma_q. \tag{10}$$

2) Vehicle as Destination: We consider that the destination is a vehicle V_p, which is moving ahead of the source V_q.

If the message is reachable from V_q to the vehicle V_p ($p < q$), then the receiving time of the vehicles between V_q and V_p should be less than the departure time of V_q at the m^{th} traffic light (i.e. $t_m(u_q)$). Thus, the reachability of the message from V_q to V_p (denoted by $r_{q\rightarrow p}$) can be calculated as follows:

$$r_{q\rightarrow p}(u_q) = \prod_{i=p}^{q} \mathbb{1}_{\sigma_i < t_m(u_q)}. \tag{11}$$

If the message is reachable to V_p, $r_{q\rightarrow p}$ is equal to 1, and the arrival time at V_p is equal to σ_p. Thus, the delivery delay from V_q to V_p can be calculated as: $d_{V_q \rightarrow V_p} = \sigma_p - \sigma_q$. The distance from the place where the packet is received or generated by V_q to the place where it is received by the destination can be calculated as: $x_i(\sigma_i) - x_i(\sigma_q)$. If the message is unreachable to V_p, $r_{q\rightarrow p}$ is equal to 0.

Theorem 1 (Temporally Reachable): On a finite path with m traffic lights, if the data packet carried by V_i, whose destination is V_j, is unreachable at time t_0, and thus is in the future time $t_0 + \Delta t$ ($\Delta t > 0$), it is also unreachable.

Proof: We assume in the future time $t_0 + \Delta t$ ($\Delta t > 0$) that the data packet carried by V_i is reachable to V_j. That means the data packet can be carried by V_i from time t_0 to time $t_0 + \Delta t$, and then V_i could deliver the packet to V_j, which is reachable. Thus, by the way of carry-and-forward, the data packet carried by V_i is reachable to V_j. However, it is against our assumption that the data packet carried by V_i, whose destination is V_j, is unreachable at time t_0. Therefore, the theorem is proven. ■

Algorithm 1 Transmission control scheme

Input: F/G, the sets of the received/generated packets
Output: S, the set of the packets which need to be sent
1: Select Reachable packets in F and G to S;
2: Clear the sets of F and G;
3: Sort the packets in S by their deadlines in ascending order;

Definition 1 (Deadline of Being Reachable): the last time that a data packet is able to reach V_p from V_q(denoted by $DR_{q\rightarrow p}$). The data packets sent by V_p before this deadline can be received by V_p. Thus, it can be described as follows:

$$\exists DR_{q\rightarrow p} : r_{q\rightarrow p}(u_q(t)) = \begin{cases} 1, \text{if } \sigma_q \leq t \leq DR_{q\rightarrow p} \\ 0, \text{if } t > DR_{q\rightarrow p} \end{cases} \tag{12}$$

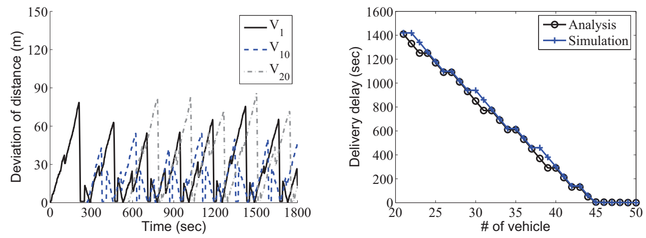
For example, the vehicle V_q receives the message at time σ_q. The furthest vehicle (V_1) has the earliest deadline of being reachable, and the nearest vehicle (V_{q-1}) has the latest deadline of being reachable. A *reachable destination* V_p for V_q at time t should be that the time t is earlier than the its deadline of being reachable, i.e. $t \leq DR_{q\rightarrow p}$. For V_q, an *unreachable destination* V_p at time t should be that the time t is later than its deadline of being reachable, i.e. $t > DR_{q\rightarrow p}$.

Theorem 2 (Spatially Reachable): At the time t_0, if the vehicle V_l is the reachable destination for the data packets carried by V_i, it is also the reachable destination for the data packets carried by V_j ($j < i$), which moves in front of V_i along the path.

Proof: We assume that V_l is the unreachable destination for the data packets carried by V_j at the time t_0. That means that no data packet can be delivered from V_j to V_l after the time t_0. Because V_i is behind V_j along the path, the data packet delivered from V_i to V_l should be past V_j. Likely, no data packet can be delivered from V_i to V_l after the time t_0. This is against our assumption that V_l is the reachable destination for the data packets carried by V_i at the time t_0. Therefore, the theorem is proven. ■

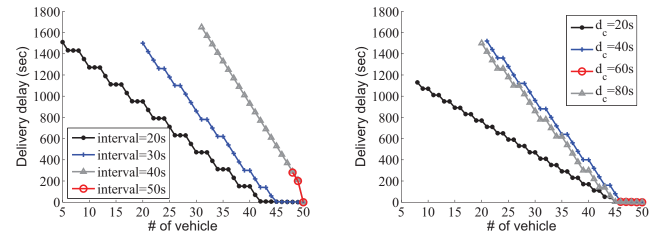
D. Transmission Control Scheme

While several vehicles move on the path with multiple traffic lights, each vehicle has some data packets headed to different destinations, including the vehicles and RSUs ahead. Due to the limited resources in VANETs (such as bandwidth and buffer of the vehicle), each vehicle should only transmit the packets which are reachable. We assume that there are some inductive-loop traffic detectors at the entrance of the path, which can detect vehicles passing or arriving at a certain point. While a vehicle arrives at the initial point and communicates with the RSU, it will receive the initial times ($\mathcal{U}$) of the vehicles moving ahead from the inductive-loop traffic detectors, and also the schedules of traffic lights along the path. Thus, the vehicle can evaluate the reachability of the generated or received data packet. Then, the vehicle evaluates the deadline of being reachable for each data packet, and sorts them by their deadline of being reachable in ascending order (Algorithm 1). By applying the scheme of earliest deadline first (EDF), the



(a) Mobility of vehicles (b) Data delivery delay

Fig. 2. Analytical model compared with simulations



(a) Interval of arrival time (b) Cycle time of traffic light

Fig. 3. Impact on data delivery delay

vehicle adds the reachable packets to the sending buffer, and the packet with the earliest deadline of being reachable is on the top in the buffer, which will be sent first.

IV. Performance Evaluation

In this section, we present the simulation setup, and then verify our proposed analysis model with simulations to ensure the correctness. We will give more results for investigating the influence of traffic lights on the data delivery in VANETs.

A. Simulation Setup

In our simulations, 50 vehicles move on a path, where the length of each road segment divided by the 20 traffic lights is 1,000m. The default cycle time of the traffic lights is 80 seconds, and the default duration of both red and green lights is 40 seconds. The average speed with which vehicles move on the path is 9 m/s, and its communication range is 300m. The headway time of vehicles at the initial point of the path is 30 seconds. We let the last car receive the message when it moves at the initial point. We evaluate two metrics as follows: (1) *delivery delay*: the duration of the message delivered from the source to the destination. (2) *number of reachable destinations*: the number of reachable destinations, which are the vehicles moving ahead of the source.

B. Verification

We use the combination of SUMO [11] and NS-2 [12] for the simulations, and compare them with our proposed analytical model. We evaluate the metric of $deviation\ of\ distance$, which is the absolute value of deviation of the moving distance from the initial point obtained by our proposed analysis model and SUMO-based simulation, i.e. $|calculated\ x_i(t) - simulated\ x_i(t)|$. 20 vehicles sequentially move onto the path with 20 traffic lights, and the length of each road segment between two lights on this path is equal to 1,000m. The signal operations of the lights are all the same, which include 40 seconds of red light and 40 seconds of green light. We compare the moving distance of three selected vehicles (V_1, V_{10} and V_{20}) from the initial point, obtained by the two approaches during the simulation time of 1,800 seconds, and the deviation of distances are shown in Figure 2(a). We notice that, although there is an accumulation error while the vehicle moves on the road segments, the deviation is smaller than 100m, which is much smaller than the length of each road segment (1,000m). When the vehicles are stopped by the red light at an intersection, the deviation could be reduced to an approximation of zero, due to the same schedules of the traffic lights being adopted by the two approaches.

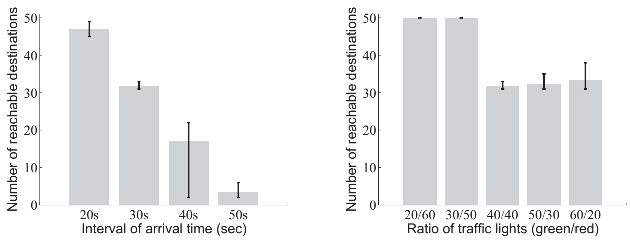
We evaluate the proposed data delivery model, compared with the simulation in terms of data delivery delay. In this comparison, 50 vehicles sequentially move onto the path with 20 traffic lights. When the vehicle V_{50} enters the path, it generates a message for delivering to the vehicles ahead. We compare the delivery delay to the vehicles by the two approaches as shown in Figure 2(b). We notice that the vehicle ahead, with a smaller index, has a longer delivery delay. The vehicles whose indexes are larger than 20 could receive the message before the traffic light T_{20}, i.e. only 30 vehicles are reachable. Based on the performance of our mobility model, the delivery delay obtained by the proposed data delivery model is also approximated to the simulation results.

C. Data Delivery Delay

In this subsection, we investigate the impact of vehicular distribution and signal operations on the data delivery among vehicles by our analysis model. 50 vehicles sequentially move onto the path with 20 traffic lights, and the length of each road segment between two lights is also 1,000m. The signal operations of the lights are all the same, including the start time, the cycle time, and the duration of green light and red light. When the vehicle V_{50} enters the path at the initial point, it generates a message for delivering to the vehicles ahead.

We evaluate the message delivery delay to the vehicles with four initial headway times of the vehicles (20, 30, 40, and 50 seconds) at the initial point, as shown in Figure 3(a). We notice that the vehicles with shorter interval times have a shorter message delivery delay to the same vehicle as the destination. For example, the message delivery delay to the vehicle V_{31} with the four headway times (20, 30, 40, and 50 seconds) are 471 seconds, 781 seconds, 1,650 seconds, and unreachable, respectively. We notice that the vehicles with shorter headway times have more reachable destinations. As shown in Figure 3(a), the number of the reachable destinations with the four intervals are 48, 31, 20 and 5, respectively. For the two vehicles V_i and V_{i+1}, their arrival time and departure time at the k^{th} traffic light are relative to their initial time (u_i and u_{i+1}) according to Equation 1. Thus, shorter initial headway times between two vehicles could have shorter intervals of departure time at each traffic light. Based on Equation 9, shorter interval times could mean a higher probability of catching up.

We evaluate the message delivery delay to the vehicles with different cycle times of traffic lights (20, 40, 60 and



(a) Interval of arrival time (b) Ratio of traffic lights (green/red)

Fig. 4. Reachable destinations

80 seconds), as shown in Figure 3(b), and where the ratio of the signal operation (d_r/d_g) is 1. We notice that the delivery with a cycle time of 60 seconds is the worst, and has 5 reachable destinations. The message delivery with the cycle time of 20 seconds is the best, and has the minimal delay and the maximal number of reachable destinations. Longer green time (60 seconds) may mean a higher probability of the vehicles ahead running away, and shorter green time (20 seconds) may also mean a higher probability of stopping by red light, which causes the traffic hole problem. The results imply that the red light may not only cause the traffic hole problem to block message delivery, but also helps the vehicle carrying the message to catch up with the vehicles ahead.

D. Reachable Destinations

We evaluate the number of reachable vehicles with four initial headway times of vehicles (20, 30, 40 and 50 seconds). The initial time of the first vehicle changes from 0 to 80 seconds, which is the cycle time of the traffic lights, and we obtain the average, maximal, and minimal delivery delays, as shown in Figure 4(a). We notice that the vehicles with the shortest initial headway time (20 seconds) have the maximal reachable destinations. As in the aforementioned discussion, shorter initial headway times could mean a higher probability of catching up, according to Equations 1 and 9. Even under the same initial headway time, the numbers of reachable destinations with different initial arrival times are different. This is because of the opportunities with the traffic lights.

We examine the number of reachable vehicles with different ratios of traffic lights (d_g/d_r: 20/60, 30/50, 40/40, 50/30 and 60/20). The initial time of the first vehicle changes from 0 to 80 seconds, which is the cycle time of the traffic lights, and we obtain the average, maximal, and minimal delivery delays, as shown in Figure 4(b). The initial headway time of vehicles at the initial point is 40 seconds. We notice that the traffic lights with the ratio of 40/40 have the minimal reachable destinations. When the signal operation of the traffic light is 20/60 or 30/50, all the vehicles are reachable. This implies that a shorter duration of green light and a longer duration of red light may equate to more reachable destinations.

V. Related Work

Many protocols in VANETs assume that the intermediate nodes can be found to set up an end-to-end connection; otherwise, the packet will be dropped. Wisitpongphan *et al.* [5] indicate that, although the average re-healing time for an I-80 type of freeway is, on average, less than 30 seconds, such a long network disconnection time could be a major problem for conventional ad hoc routing protocols, such as AODV [4], which can only tolerate a network disconnection time of up to 2-3 seconds. Zhao and Cao [3] make use of the predicable vehicle mobility, which is limited by the road traffic pattern and road layout, to reduce the data delivery delay. Many studies also pay attention to the traffic light sensing [13], which play an important role in the distribution of traffic flows.

VI. Conclusions

Traffic light affects the mobility of vehicles moving on the road, so it also affects the data delivery among vehicles in VANETs. In this paper, we investigate the influence of traffic lights on data delivery in VANETs. We propose an analysis model to evaluate the influence by given initial headway times of vehicles, and the schedules of traffic lights. Based on the analysis model, we propose a transmission control scheme at the transmitters; this scheme filters suspicious transmission requests, which are unlikely to be accomplished. The proposed analytical model is under a linear topology. In our future work, we plan to evaluate the data delivery under a two-dimensional topology, such as a ladder or a grid.

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