Catching Up with Traffic Lights for Data Delivery in Vehicular Ad Hoc Networks

Chao Song[†*], Jie Wu[*], Wei-Shih Yang[‡], and Ming Liu[†]
[†]School of Computer Science & Engineering, University of Electronic Science and Technology of China
[*]Department of Computer and Information Sciences, Temple University
[‡]Department of Mathematics, Temple University
Email: {chaosong, csmliu}@uestc.edu.cn, {jiewu, yang}@temple.edu

ABSTRACT

The data delivery in vehicular ad hoc networks (VANETs) is based on the wireless communication among vehicles (V2V) and infrastructures (V2I). This delivery obviously 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 vehicle itself, but also by some external means, such as the signal operations of 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. However, the red light can also increase the opportunities of vehicles moving behind to catch up with the waited vehicles in forwarding messages. In this paper, we investigate the influence of the traffic lights on data delivery in VANETs, and we estimate the expected data delivery delay along a path with multiple traffic lights. Our intensive simulations verify the proposed model, and evaluate the influence of the traffic lights on data delivery.

Categories and Subject Descriptors

C.2.1 [**Computer Systems Organization**]: Computer-Communication Networks—*Network Architecture and Design*

General Terms

Design, Performance

Keywords

data delivery, mobile sensors, traffic light, traffic hole, VANET

1. INTRODUCTION

With the increasing demands of various applications on vehicles, both academic researchers and automotive industries pay a lot of attention to vehicular ad hoc networks (VANETs), which is a special type of mobile sensor networks [13]. For example, the vehicle-mounted sensors send harvesting data to a remote sink via VANETs. In VANETs, timely and lossless multi-hop data delivery among vehicles is essential. Routing protocols in VANETs can be classified into two categories [19], which are connection-based and movement-assisted routing protocols. The traditional connection-based routing protocols [10], which should establish a stable end-to-end path to transmit packets, is often infeasible due to low traffic density and the high mobility of vehicle nodes [18, 20]. By considering the delay-tolerant network (DTN) [2] for intermittent connectivity in VANETs, many researchers have proposed that routing protocols adopt the mechanism of carry-and-forward, which increases the data delivery delay for higher data delivery ratio. Specifically, a mobile node can carry the received packet on the move until it meets a node with a higher likelihood of transmitting the packet to the destination. 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 (e.g. data delivery delay). The directional propagation in VANETs can be divided into two categories [6]: (1) *reverse propagation* if the data are headed in a direction opposite to the direction of motion of vehicle, e.g. the sensed information of traffic jam or accident in front need to be propagated to the vehicle moving towards to it; (2) *forward propagation* if data are headed along the direction of motion of the vehicle, e.g. an ambulance wants to propagate a warning message to the vehicles in front for avoiding. Both of the two propagations are based on the mobility of vehicles.

However, the mobility of vehicles is not only affected by the vehicle itself, but also by some external means, such as the signal operations of traffic lights. Therefore, the traffic lights can affect the data delivery in VANETs. For example, while a vehicle carries a message to move along a path, it may stop at a red light, which increases the carrying delay with the waiting time. We call such a situation a *traffic hole* [14]. It has been observed that traffic holes can frequently happen during rush hours. On the other hand, the vehicles stopped by the red light could wait for the vehicles moving behind, which could increase the opportunities for vehicles moving behind to catch up in data forwarding. Specifically, while the stopped vehicles are still connecting with the vehicles on other roads, they can help to forward the messages across the intersection from the vehicles catching up to the next road, which can improve the forwarding opportunities at the intersection. In contrast, a green light can reduce the probability of catching up. For example, while two vehicles move on a path with the same speed, if

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Table 1: Notations

Notation	Description
I_i	The i^{th} intersection
r_{ij}	The road between I_i and I_j
τ_c	Cycle time of a traffic light
$\tau_r(\tau_g)$	Duration of a red (green) light
v	The moving speed of vehicles
L_{ij}	Length of the road r_{ij}
R	Wireless communication range
t_{hop}	Average wireless transmission delay per hop
Q	Queue length at the traffic light
t_c	Time for queue to clear
$P_i(k)$	Probability of k vehicles in the queue at I_i
T_{ij}	Travel time of the vehicle on r_{ij}
C_{ij}	Data delivery delay by catching up on r_{ij}
W_i	Waiting time of the data packet at signalized I_i
D_{ij}	Data delivery delay on r_{ij}

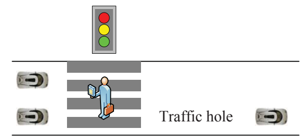
the traffic lights along the path are all green, the spacing between the two vehicles will not change. However, if the second vehicle keeps moving by the green light at the upstream intersection, and the first vehicle stops by the red light at the downstream intersection, then the second vehicle may catch up with the first one.

In this paper, we investigate the event of catching up with the waiting queue at the downstream intersection, for improving the performance of data delivery along a path with traffic lights. If there are no vehicles waiting at the traffic light, the data packet is carried by the vehicle to move, and the data delivery delay on the road is equal to the travel time of the vehicle. If there exists a waiting queue at the traffic light, the data packet can be immediately forwarded downstream when the carrying vehicle moves into the communication range of the queue. Thus, with the help of catching up, the data delivery delay on this road is reduced. We model the expected data delivery delay with a stochastic model for a given road or path. Our intensive simulations verify the proposed model, and evaluate the influence of the traffic lights on data delivery.

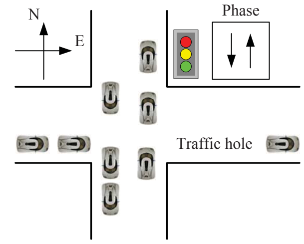
The remainder of this paper is organized as follows. In Section II, we review the most related work in VANETs. We present the assumption and introduce the traffic hole problem in Section III. We analyze the data delivery by catching up with the waiting queue at the downstream intersection in Section IV. We evaluate the efficacy of the analysis model and the data delivery with traffic lights in Section V. The last section concludes the paper with future work.

2. RELATED WORK

There are a lot of vehicular applications based on the communication among vehicles. Ahn *et al.* [1] present the Road Information Sharing Architecture (RISA), a distributed approach to road condition detection and dissemination for vehicular networks. SignalGuru [5] relies solely on a collection of mobile phones to detect and predict the traffic signal schedule. For such an infrastructure-less approach, multiple phones in the vicinity use opportunistic ad-hoc communications to collaboratively learn the timing patterns of traffic signals, and to predict their schedules.



(a) Pedestrian crossing



(b) Four-way intersection

Figure 1: The traffic hole problem

Wisitpongphan *et al.* [18] 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, which can only tolerate a network disconnection time of up to 2-3 seconds. In addition, some time-critical applications may not be able to function properly in a disconnected VANET, as the end-to-end delay could be on the order of several minutes. Zhao and Cao [20] make use of the predicable vehicle mobility, which is limited by the road traffic pattern and road layout. Based on the existing road traffic pattern, a vehicle can find the next road to forward the packet, as to reduce the delay. The estimation of packet forwarding delay through each road is based on some statistical data, such as the average vehicle density. Jeong *et al.* in [4] propose a trajectory-based data forwarding (TBD) scheme by utilizing vehicles' trajectory. They introduce an analytical link delay model for data delivery along a road, and an expected delivery delay computation based on individual vehicle trajectory.

In traffic engineering, many studies [9] pay attention to the traffic lights, which play an important role in the distribution of traffic flows. In [8], authors develop a system called POVA for traffic light sensing in large-scale urban areas, which employs pervasive probe vehicles that just report realtime states of position, and speed from time to time.

3. TRAFFIC HOLE PROBLEM

In this section, we give the assumptions, and then we will describe the traffic hole problem. Notations used in this paper are listed in Table 1.

3.1 Assumption

The well-known car-following model [12] 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. Vehicles communicate with each other through short-range wireless channels. Let R denote the communication range of each vehicle node.

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 red and green. The durations of a cycle, red light and green light, are denoted by τ_c, τ_r and τ_g,

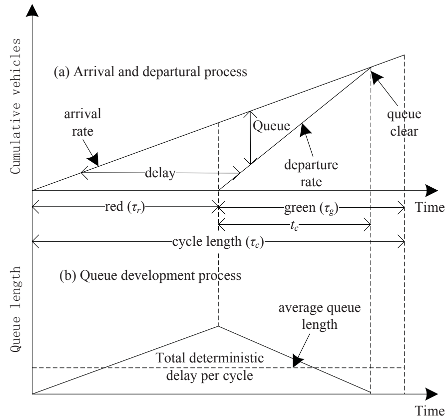


Figure 2: Relationship between arrivals, departures, queue length, and queuing delay

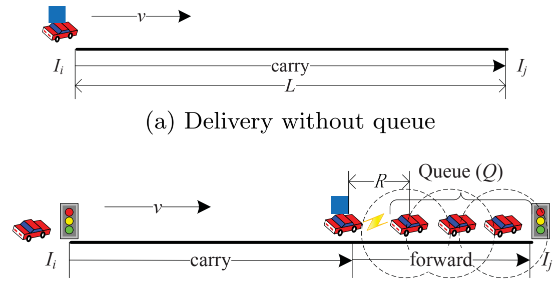
respectively. We assume that all the traffic lights are all asynchronous.

Some studies [7] have investigated the real-time queue length estimation. We assume that vehicles are equipped with pre-loaded digital maps, which provide street-level map and traffic statistics, such as traffic density and vehicle speed on roads at different times of the day, and the probability distribution of queue length at each traffic lights. We assume that the distribution of the queue length at each intersection are independent due to the asynchronous traffic lights. Let $P_i(k)$ denote the probability of k vehicles in the waiting queue at I_i.

3.2 Traffic Hole Problem

Traffic flow can be divided into two primary types [17]. The first type is called uninterrupted flow, and is regulated by the interactions among vehicles and interactions between vehicles and the roadway, such as the vehicles traveling on an interstate highway. The second type of traffic flow is called interrupted flow, which is regulated by an external means, such as a traffic light or pedestrian signal.

Based on the phenomenon of the interrupted flow, we can find the main contributing factors for the traffic hole problem. By the traffic lights, the traffic flow should be stopped for traffic signals and stop signs. In the scenario of pedestrian crossings (see in Figure 1(a)), to provide enough time for the pedestrians to cross the street, the traffic control system will block the vehicle traffic for a while. The duration for the pedestrian crossings is related to the width of the road and the requirements for the pedestrians. For a signalized four-way intersection (see in Figure 1(b)), we denote the movement as a specific direction and type of traffic flow, and the phase is a set of movements that concurrently have the right of way, as introduced in [3]. Some specific phases of the traffic light can block the vehicles to move into the road. In Figure 1(b), the traffic light under the current phase allocates the south-north traffic flow to through the intersection, and blocks the traffic moving into the eastern road. Thus, a gap appears at the entrance of the eastern road. If the length of this gap is larger than the communication range of vehicles (R), it can block the wireless communication among the vehicles. We term this gap as a traffic hole, whose length is larger than the communication range of the vehicles.



(a) Delivery without queue

(b) Delivery with queue

Figure 3: Data delivery along a road segment

4. CATCH UP

In this section, we illustrate the waiting queue at the signalized intersection with an example of D/D/1 queueing model, and then we investigate the data delivery with the help of the queue at the signalized intersection.

4.1 Waiting queue

At an intersection where the traffic light can stop the vehicles, queueing will inherently occur. Let $Q(t)$ denote the number of queued vehicles at time t. It is assumed that the cycle time τ_c is fixed, and for each approach, is split in a red phase ($0 < t \leq \tau_r$) and a green phase ($\tau_r < t \leq \tau_c$). If the number of queued vehicles at the start of the red phase is represented by $Q(0)$, the queue during the red phase is given by [21]:

$$Q(t) = Q(0) + A(t),$$

where $A(t)$ represents the cumulative arrivals of vehicles.

In order to illustrate the waiting queue at the signalized intersection, we take an example of $D/D/1$ queueing model [16], which assumes that arrivals and departures are deterministic. Using this form of queueing with an arrival rate λ, certain useful values regarding the consequences of queues can be computed, as shown in Figure 2.

During the red light (τ_r), the arrival vehicles with the rate λ wait at the traffic light, and the queue length increases. Let Q_{max} denote the queue length when the light turns green. Thus, the maximum number of vehicles in a queue can be found as: $Q_{max} = Q(0) + \lambda \cdot \tau_r$. After the time when the light turns green, the vehicles in the queue start to move onto the road with the departure rate s. Let ρ denote the arrival rate divided by departure rate, i.e. $\rho = \lambda/s$. Thus, the clearance time of the waiting queue can be calculated as: $t_c = \rho\tau_r/(1-\rho)$. While the time to queue clearance t_c is equal to, or larger than, the green time (i.e. $t_c \geq \tau_g$), the input of the traffic flow at the intersection is termed as *saturated* or *over-saturated* flow. While the time to queue clearance at the intersection is less than the green time, (i.e. $t_c < \tau_g$), the input of the traffic flow at the intersection is termed as *under-saturated* flow.

4.2 Catch up

As shown in Figure 3(a), a vehicle carrying the message moves onto a road segment with no vehicles, or there are no vehicles in front in its communication range during its moving on the road segment r_{ij}. The message delivery delay along this road segment is equal to the travel time of the vehicle (denoted by T_{ij}), which is equal to the moving time

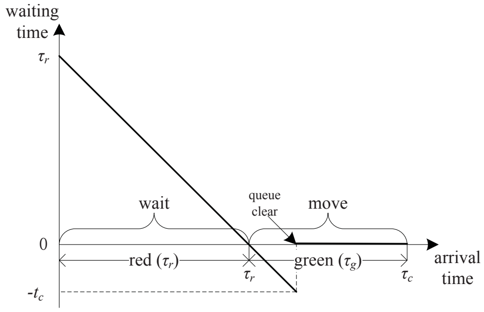


Figure 4: Waiting time of a data packet at a signalized intersection with different arrival time

along the road. Thus,

$$E[T_{ij}] = \frac{L_{ij}}{v} \tag{1}$$

When the downstream intersection has a traffic light, the vehicles moving on the road could be blocked at the signalized intersection, which cause queueing as shown in Figure 3(b). When the vehicle carrying the message moves into the communication rage of the vehicles in the waiting queue, the message can be immediately forwarded to the downstream intersection by wireless communication. Let Q denote the number of vehicles in the waiting queue, and the length of the queue (denoted by l_q) can be calculated as: $l_q = Q \cdot \Delta d$, where Δd denotes the average spacing of each vehicle in the queue. Thus, the message delivery delay along this road segment includes two parts: (1) carrying delay (denoted by d_c): the message is carried by the vehicle on the road until catching up with the waiting queue at the downstream signalized intersection with the speed of the vehicle; (2) forwarding delay (denoted by d_f): when the vehicle catches up to the queue, the message can be immediately forwarded to the downstream intersection by the vehicles in the queue with the speed of wireless communication. Let $C_{ij}(Q)$ denote the data delivery delay by catching up with the waiting queue involving Q vehicles on r_{ij}, which can be calculated as:

$$\begin{aligned} C_{ij}(Q) &= d_c + d_f \\ &= \frac{L_{ij} - R - l_q}{v} + \lceil \frac{R + l_q}{R} \rceil \cdot t_{hop} \end{aligned} \tag{2}$$

where t_{hop} denotes the average transmission delay per hop.

Compared with the delivery without queue, the saving data delivery delay with the help of waiting queue at traffic light is equal to: $\frac{R+l_q}{v} - \lceil \frac{R+l_q}{R} \rceil \cdot t_{hop}$. Based on the probability distribution of queue length at the traffic light $P_i(k)$, the expected delay along this road can be calculated as follows:

$$E[D_{ij}] = P_i(0) \cdot E[T_{ij}] + \sum_{k=1}^{\infty} P_i(k) \cdot C_{ij}(k) + E[W_i] \tag{3}$$

Here, $E[W_i]$ denotes the expected waiting time of a data packet at the upstream intersection I_i, by considering the beginning of effective green time as the initial point. As shown in Figure 4, if a data packet arrives at the traffic light at the beginning of the effective green time, its waiting time is equal to zero. Before the initial point, the packet should be carried by the vehicles waiting at the red light until the light turns green, because of the traffic hole problem. After the initial point, the data packet can be immediately forwarded onto the road during the clearance of the waiting queue. After the clearance of the waiting queue, the data packet is carried by the moving vehicle during the green time, so the waiting time is also zero. Thus, the expected waiting time at the upstream intersection can be calculated as follows:

$$E[W_i] = \frac{\tau_r^2 - [max\{\overline{t}_c, \tau_g\}]^2}{2\tau_c} \tag{4}$$

where $\overline{t}_c$ denotes the average time for queue to clear.

Given a routing path from the vehicle's current position to a target point in front, we suppose that the queue length distributions are independent of each other under the asynchronous traffic lights. As shown in Figure 5, the expected data delivery delay along a path with several road segments can be calculated as follows:

$$E[D_{path}] = \sum_{r_{ij} \in path} E[D_{ij}] \tag{5}$$

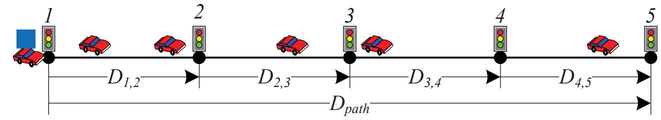


Figure 5: The expected data delivery of a path

Table 2: Default values of parameters

Parameter	Default value
Average arrival rate (veh/s)	0.1, 0.2
Average departure rate (veh/s)	0.3
Length of each road segment (m)	500
Cycle time of traffic light light (sec)	80
Duration of green light (sec)	40
Duration of red light (sec)	40
Communication range (m)	200
Average speed of vehicles (m/s)	9

5. PERFORMANCE EVALUATION

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

5.1 Simulation Setup

During the simulation time, vehicles arrive at the upstream intersection with the average rate of 0.1 or 0.2 veh/s. The length of each road segments divided by the traffic lights is 500m. The cycle time of the traffic lights is 80 seconds, and the default duration of both red light and green light is 40 seconds. The average speed with which vehicles move on the path is 9 m/s, and its communication range is 200m. The default values of parameters are listed in Table 2.

We evaluate the data delivery from the upstream intersection to the downstream intersection, with the metric of *data delivery delay*, which is the duration from the time when the upstream traffic light turns green to the time when a vehicle carrying the data packet arrives at the downstream intersection. We use the combination of SUMO [15] and NS-2 [11], for the simulations SUMO (Simulation of Urban

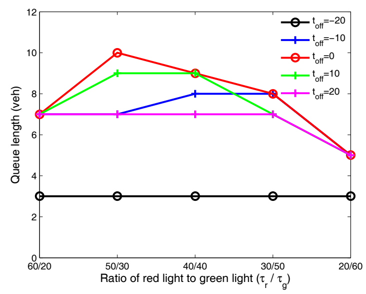


Figure 6: Queue length on a road

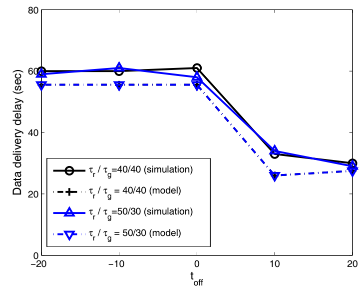


Figure 7: Data delivery delay on a road

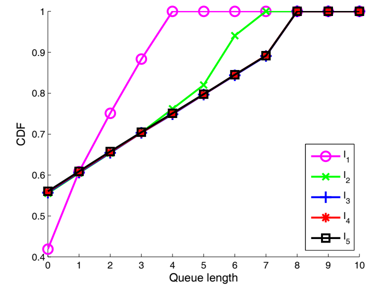


Figure 8: Distribution of queue length (equal cycles)

Mobility) is an open-source traffic simulator to model realistic vehicle behavior. NS-2 is an open-source discrete event network simulator that supports both wired and wireless networks, including most MANET routing protocols and an implementation of the IEEE 802.11 MAC layer.

5.2 Simulation results

With the fixed cycle time, we examine the queue length at the downstream intersection, under different ratios of traffic light (τ_r/τ_g) and the fixed offset t_{off} between the upstream and the downstream traffic lights. The simulation result by SUMO is shown in Figure 6. The average arrival rate of the vehicles is 0.2 veh/s. When the offset is equal to -20 seconds, the queue length is the shortest, which is about 3. The travel time of each vehicle on a road segment is about 55 seconds, and the cycle time of the traffic lights is 80 seconds. Thus, when the first vehicle from the upstream intersection arrives at the downstream intersection, it should wait about 5 seconds. Due to the short waiting time, the queue length is short. Because the upstream intersection is over-saturated, the number of vehicles departing from the upstream intersection is equal to $\tau_g \cdot s$, which is also the upper bound of the queue length at the downstream intersection. Therefore, when the offset is 0 seconds, and the ratio is 60/20 or 50/30, the queue length at the downstream reaches the upper bound. Increasing the red time τ_r can increase the waiting time at the downstream intersection, and also reduce the green time τ_g, which shortens the upper bound of the queue length. Thus, we notice that the queue length is not monotonically increasing while the red time increases. The results imply that the waiting queue length is affected by many factors, such as the cycle time, ratio and offset of the traffic lights at the upstream and downstream intersections, road length, and vehicular speed.

We evaluate the data delivery delay on the road segment, under different ratios of traffic light (τ_r/τ_g) and the offset between the upstream and the downstream traffic lights. The results are obtained by the simulation and the proposed analysis model, which are shown in Figure 7. We notice that the results obtained by the analysis model are approximated to the results obtained by the simulation. When the offset t_{off} is -20, -10, or 0 seconds, the vehicles departing from the upstream intersection cannot catch up to the vehicles waiting at the downstream intersection. Thus, the data delivery delay is equal to the travel time on the road. When the offset t_{off} is 10 or 20 seconds, the vehicles departing from the upstream intersection can catch up to the vehicles waiting at the downstream intersection, which has an average of 47% delivery delay reduction over those not catching up. The results imply that the event of catching up can obviously reduce the data delivery on a road, and the offset of the adjacent traffic lights can affect the data delivery on the road segment between them.

We exam the data delivery along a path with multiple traffic lights. During the simulation time (20,000 seconds), there are 2,000 vehicles moving on the path from one end to another. The path is divided into 5 road segments by the intersections, and each intersection has a traffic light for controlling the traffic flow. The data packets are generated at the exit of the first road segment, and the generating rate is 1 packet/second. We first evaluate the scenario that all the traffic light, have the same cycle time and ratio (40 seconds red time and 40 seconds green time). Figure 8 shows the cumulative distribution of waiting queue length at each traffic light (I_1, I_2, I_3, I_4 and I_5). We notice that the queue length at the first traffic light is less than five, but it has a lower likelihood of having zero queue length than do other traffic lights. The distributions of I_3, I_4, and I_5 are almost the same. For example, probabilities of queue length less than 5 at the three intersections are 0.7967, 0.7968, and 0.7975, respectively. Figure 9 shows the comparison of the data delivery along the path under different communication ranges of the vehicles, obtained by the simulation and the proposed analysis model. We notice that while the communication range is increasing, the data delivery delay is decreasing. The data delivery delay obtained by our proposed analysis model approximates to the simulation results.

We evaluate the scenario that all the traffic light have a different cycle time and ratio, and the τ_r/τ_g at the traffic lights are 40/40, 39/39, 38/38, 37/37, 36/36 and 35/35. Figure 10 shows the cumulative distribution of waiting queue length at each traffic light. We notice that the queue length at the first traffic light is less than five, but it has a lower likelihood of having zero queue length than other traffic lights. The distributions of I_2, I_3, I_4, and I_5 are almost the same. Figure 11 shows the comparison of the data delivery along the path under different communication ranges of the vehicles, obtained by the simulation and the proposed analysis model. We notice that while the communication range is increasing, the data delivery delay is decreasing. The data delivery under unequal cycle is lower than that under equal cycle. The data delivery delay obtained by our proposed analysis model approximates to the simulation results.

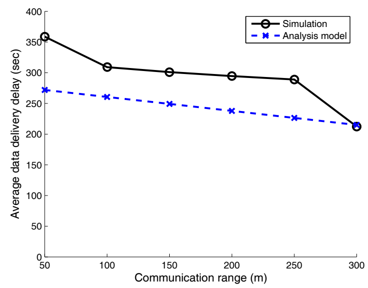


Figure 9: Impact of communication range (equal cycles)

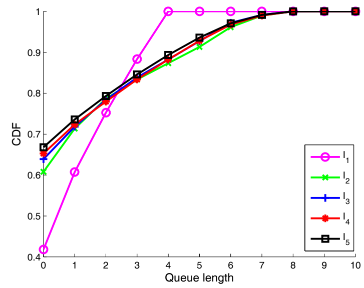


Figure 10: Distribution of queue length (unequal cycles)

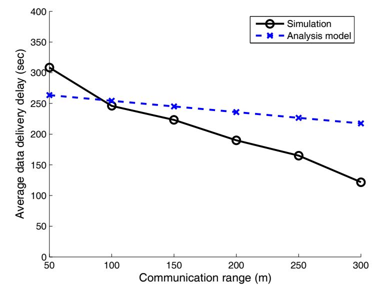


Figure 11: Impact of communication range (unequal cycles)

6. CONCLUSIONS

Traffic light affects the mobility of vehicles moving on the road, so it also affects the data delivery among vehicles in VANETs. The traffic light can stop the vehicles to increasing its travel time, and can also help the vehicles moving behind to catch up with the waiting vehicles for increase the forwarding opportunities. In this paper, we investigate the influence of traffic lights on data delivery in VANETs. We propose the utilization of the event of catching up to the waiting queue at the downstream intersection, as to reduce the delay. We model the expected data delivery delay with a stochastic model for a given road or path. Our intensive simulations verify the proposed model, and evaluate the influence of the traffic lights on data delivery. In our future work, we plan to evaluate the data delivery under a two-dimensions topology (e.g. grid).

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