



# Analysis of the information storage capability of VANET for highway and city traffic

Bojin Liu <sup>a,\*</sup>, Behrooz Khorashadi <sup>a</sup>, Dipak Ghosal <sup>a</sup>, Chen-Nee Chuah <sup>b</sup>, H. Michael Zhang <sup>c</sup>

<sup>a</sup> Department of Computer Science, University of California, Davis, United States

<sup>b</sup> Department of Electrical and Computer Engineering, University of California, Davis, United States

<sup>c</sup> Department of Civil and Environmental Engineering, University of California, Davis, United States

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## ABSTRACT

Vehicles in VANET can form wireless ad hoc mesh networks (VMeshes) that are mobile, constantly changing both in size and the geographic area they cover. We focus on how the VMeshes can be used to capture and retain certain transient information on the road within a given region of interest for a certain period of time, without any infrastructure support. In this paper, we study this “storage capability” of VANET for highway and city traffic. Particularly, we studied different properties (average life time and deletion time) of the VANET storage for both 1-D highway traffic and 2-D city wide traffic. Through theoretical analysis and detailed simulation validated by the realistic mobility trace observed in San Francisco Yellow Cabs, we found that the same system parameters (e.g., transmission range and the size of the region of interest) can have different impact on VANET storage properties under different mobility patterns. Particularly, the size of the region of interest where the information needs to be stored has a large impact on the lifetime of the storage for the 2-D city-wide traffic, while the transmission range of wireless communication has large impact on the lifetime of the storage for 1-D highway traffic, and also on the success rate of deleting the information and the mean time to delete the information. Furthermore, the simulation analysis using SF Cab trace shows that even with low density of cabs, the average life time of VANET storage can be in order of minutes, demonstrating that it is possible to build realistic applications using VANET storage.

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## 1. Introduction

Vehicular Ad-hoc Networks (VANETs) are mobile wireless networks formed by vehicles with Dedicated Short Range Communication (DSRC)/Wireless Access in Vehicular Environment (WAVE) (Uzcategui and Acosta-Marum, 2009) and positioning capabilities. VANET has been envisioned to have many potential applications in areas such as road condition monitoring, vehicular traffic control, and location-based commercial applications. Many of these applications require a location based information to be passed to nearby vehicles within a given region and for a specific period of time. With the help of vehicular communications, vehicles can achieve the task of “storing” this transient location-based information within a certain region by holding and cooperatively passing it among themselves. We call this the “storage” capability of VANET (Liu et al., 2010). While it is possible to implement similar functionalities provided by a “VANET storage” using current infrastructure based networks and systems (traditional Intelligent Transportation System (ITS), road side WiFi (Ott and Kutscher, 2004), and

\* Corresponding author. Address: Department of Computer Science, University of California, Davis One Shields Avenue, Davis, CA 95616, United States. Tel.: +1 858 651 4024.

E-mail address: [frdliu@ucdavis.edu](mailto:frdliu@ucdavis.edu) (B. Liu).

centralized cellular based data networks (Eriksson et al., 2008), etc.), the distributed, infrastructure-less nature of the VANET storage could provide more agile solutions and can result in lower cost and shorter feedback control loop.

This paper is a major extension of Liu et al. (2010), in which the concept of “VANET storage” was first introduced and basic properties of the VANET storage such as average life time for some traffic scenarios were studied. In this paper, we provide complete analytical models for 1-D highway traffic and conduct detailed simulation analysis for both 1-D highway traffic and 2-D city wide traffic. In addition to the primitive results of storage life time shown in Liu et al. (2010), we further present the impacts of different system parameters on the life time of the VANET storage for all traffic scenarios. Particularly, in evaluating the 2D city wide traffic, we employ a more realistic mobility model (Choffnes and Bustamante, 2005), instead of the random way point model used in Liu et al. (2010). Also, evaluation using SF Cab trace (Cabspotting, 2006) are performed on both highway traffic and city traffic. In addition to the lifetime of VANET storage, we also analyze how we could invalidate/delete a VANET storage’s content, which was not discussed in Liu et al. (2010). Different properties of the VANET storage invalidation process are studied, including invalidation success rate and average invalidation time.

The remainder of the paper is organized as follows. Section 2 gives some motivating examples of the VANET storage problem and definitions of terms. Section 3 presents analytical models for 1-D highway traffic. Section 4 presents the simulation setup and the sections of the SF Cab trace, which was used to evaluate the “storage” scheme proposed in this paper. Section 5 discusses the results for the 1-D highway traffic. Section 6 discusses the results for 2-D city-wide traffic. Section 7 presents the analysis of invalidation process of the VANET storage. Section 8 presents related work. Finally, Section 9 concludes the paper.

## 2. Motivating examples and definitions

The VANET storage capability can serve as the basis for various applications such as zero-infrastructure traffic warning system, ad hoc road condition monitoring, casual car-pooling, location-based commercial advertisements, among others. We consider the following motivating example. Suppose a hazardous road condition appears on the highway, such as a heavy item (e.g., ladder, furniture) that has dropped off of a vehicle, or a dangerous unnoticeable pothole created by heavy rain. Currently, traffic control and monitoring system relies on drivers and relatively in-frequent physical monitoring to detect the incident. Then the appropriate authorities responsible for the repair/removal operations set up warning zones. However, this entire process could take as long as over 10 min (PB2, 1999), during which time, drivers in the affected region remain vulnerable. However, with the help of local communications among vehicles, and locationing capability provided by GPS, a warning message about the hazardous condition could be passed to vehicles entering the road system within a certain region around the scene. This message could be generated by the first unlucky vehicle that discovers the hazardous condition. It is desirable that even when the first vehicle travels out of the warning region, the message still remains within that region, until the problem is solved. In this case, the ad hoc communication solution is complementary to the infrastructure based solutions.

Another application that can benefit from local communication among vehicles is casual car-pooling (Casual Car-Pooling, 2008) in which drivers and passengers meet, without specific prior arrangement, to share rides to save gasoline and toll fees and minimize emissions. Right now, casual car-poolers have to meet at specific locations for pickup. With the help of short-range communications, it would be more convenient if a car-pooler’s inquiry can be passed among vehicles in a certain region around the car-pooler. In this example, when a car-pooler’s inquiry is fulfilled, other vehicles should also be notified. Note that in both the above applications, the information (hazardous condition and car-pooling request) has both a spatial (geographic) and temporal relevance. In our proposed system, the task of “storing” the information within the region of interest (region of geographic relevance) is achieved through local communication and cooperation among vehicles. In addition, the task of “removing” the information in a timely manner (temporal relevance) can also be achieved through communication among vehicles and/or explicit time out mechanism. The specific method will be determined by the application.

Some of the applications that can benefit from the proposed “storage” scheme can also be implemented as web-based mobile applications such as Inrix (Inrix, 2004), depending on Wireless Wide Area Network (WWAN) technologies such as WiMax and 3G/4G cellular networks for information dissemination. However, WWAN based services alone have a few limitations. First, the cellular network capacity is limited in densely populated areas. Especially due to the increasing demand of cellular data services, the contention on both the uplink and downlink of the cellular networks has been increasing drastically (<http://www.nytimes.com/2009/09/03/technology/companies/03att.html>). Given the long Round Trip Time (RTT) seen in current cellular data networks, which is in the range of hundreds of milliseconds, this contention will further increase the delay of information dissemination, which might be an issue for time sensitive applications such as traffic alert systems. Therefore, applications solely based on cellular data networks will not be as response as DSRC based ad hoc solutions. Second, cellular network’s coverage is sparse in some places especially in mountain area. Vehicles travelling in those area will not have reliable cellular network service. Third, due to the centralized structure, in case of natural disasters, cellular networks might fail, while vehicular ad hoc mesh networks can still function. Last but not the least, even with a functioning cellular data network, it is still beneficial to introduce redundancy to improve the resilience of the system. The focus of this work is to investigate the performance of such local storage system based on local short-range communications. We believe the proposed scheme could not only work on its own, but also be able to serve as a complementary solution to other centralized, WWAN based schemes.

Note that we use traffic alert and casual car-pooling only as motivating examples. The VANET storage capability has many other potential applications as well, where a local information is needed to be retained in a specific region for a certain period of time. These applications include infotainment applications, commercial applications, publish/subscribe systems, just to name a few. This paper does not discuss design issues about any specific applications, which tend to have different metrics of interest of their own. The focus of this paper is on analyzing the properties of the underlying VANET storage capability, namely, the life time and invalidation time of the storage, which depend on the vehicular mobility and wireless transmission range. All of the VANET storage properties studied in this paper are agnostic to any specific applications.

We define the following terms:

- **VMesh**: A contiguous sequence of vehicles which form a wireless mesh. A message could be transmitted to all the vehicles in the same VMesh through broadcast or multi-hop relay.
- **Event of Interest (EOI)**: This represents the information that is of interest to vehicles within a certain region. An EOI could be “picked up” by a VMesh if the EOI’s location is within the coverage of that VMesh. Also, an EOI might be transient in nature, i.e., if the EOI is not picked up when it appears, it may disappear, and be considered lost. In real applications, not all EOIs are transient. However, we want to conduct a baseline study of the VMesh storage capability based on this assumption, which places a stricter requirement for the lifetime of the VMesh storage. We also assume that each participating vehicles is equipped with positioning device such as GPS, so that the vehicles are location aware. We also assume the size of the EOI message to be very small so that it can be transmitted very fast. In addition, we only focus on the scenarios where the EOI is stationary.
- **Region of Interest (ROI)**: ROI defines a physical region within which we want the information pertaining to the EOI to be stored.

Based on the above examples and definitions, we define the problem as follows. An EOI occurs on the road. With a certain probability, this EOI is picked up by a VMesh. Then, this EOI information can remain in the ROI for a certain period of time, with the help of VMeshes cooperatively holding and passing it among themselves. We define the following two metrics to characterize the transient information storage capability of VANET: (1) Mean Time to Information Loss (MTTIL) is defined as the time from when the EOI is captured by a VMesh until the moment when there is no vehicle in the ROI that holds the EOI and (2) Mean Time to Information Deletion (MTTID) is defined as the time from the generation of the first invalidation message (which are broadcasted periodically) until all copies of EOIs within the ROI are invalidated. We will examine these VANET storage properties for one-dimensional (1-D) highway traffic and two-dimensional (2-D) city-wide traffic.

### 3. Analytical models for 1-D highway traffic

For the 1-D highway traffic scenario we consider two cases. First, we consider one way highway traffic and derive the MTTIL. Next, we consider the two way highway traffic and derive an approximate analysis of the MTTIL.

#### 3.1. Assumptions for analytical models for 1-D highway traffic

For the purpose of modelling the VANET storage problem for the 1-D highway traffic, we make some assumptions on the 1-D traffic. We will validate the impacts of these assumptions in Section 4 with simulation of realistic 1-D vehicular mobility.

1. **Poisson Arrivals**: We assume the vehicle arrival times follow a Poisson process. This is a common assumption that is made for free flow traffic in transportation research (Breiman, 1963).
2. **Free Flow Traffic**: We assume that all vehicles are moving at the same free flow speed, i.e., we do not consider congestion or random slow downs. This assumption is not realistic for all highway traffic conditions. However, as later results show, it is a reasonably good approximation of free flow traffic, as validated by realistic mobility trace.
3. **Directed Lines as Highways and Points as Cars**: We model a one-way highway a directed line, and each vehicle is modeled as a point, occupying no space, and moving along the line. This assumption will also be examined in Section 4.

#### 3.2. One-way highway traffic

In this scenario, each vehicle has an effective transmission range of  $T_x$ . We consider two vehicles to be connected if the physical gap (spatial headway) between them is no bigger than  $T_x$ . Fig. 1 shows a scenario of the one-way traffic. The ROI is the region of length  $D$  centered around the EOI. The grey boxes represent the VMeshes formed by cars (notice that single car can also form a mesh by itself).

##### 3.2.1. Headway, size and length of the VMesh

We assume that traffic arrives into a section of the highway following a temporal Poisson process with rate  $\lambda$  vehicles per second. Let  $T_i$  be the random variable that denotes the inter-arrival time between vehicle  $i$  and  $i + 1$  (temporal headway). All the vehicles travel at a free flow speed of  $v$  meters per second. Then  $T_i$  has the density function  $f_{T_i}(t) = \lambda e^{-\lambda t}$ , ( $t \geq 0$ ). Let  $D_i$  be



### 3.2.3. Probability of capture ( $P_c$ )

It is also interesting to study the probability that the EOI will be captured, if we assume the location of the EOI is uniformly distributed along the road. The cars on the street form a spatial poisson process, with spatial density  $\lambda_s$ . Then we have that for any point on road, the probability that within range  $S$ , there are  $k$  cars is given by

$$P\{X(S) = k\} = \frac{[\lambda_s A(S)]^k e^{-\lambda_s A(S)}}{k!}, \quad (6)$$

where  $A(S)$  represents the length/area/volum of range  $S$ . In our case,  $S = T_x$  and  $A(S) = A(T_x) = 2T_x$ . Thus the probability that there are  $k$  cars within  $2T_x$  is given by

$$P\{X(T_x) = k\} = \frac{[2\lambda_s T_x]^k e^{-2\lambda_s T_x}}{k!}. \quad (7)$$

As EOI occurs randomly along the stretch of road at position  $x$ , probability of capture  $P_c$  is equal to the probability that within  $2T_x$  of  $x$ , there is at least one car. Therefore, probability of capture  $P_c$  is equal to probability that within  $2T_x$  there is at least one car which is  $1 - P\{X(T_x) = 0\} = 1 - e^{-2\lambda_s T_x}$ . Thus,

$$P_c = 1 - e^{-2\lambda_s T_x}. \quad (8)$$

### 3.3. Two-way highway traffic

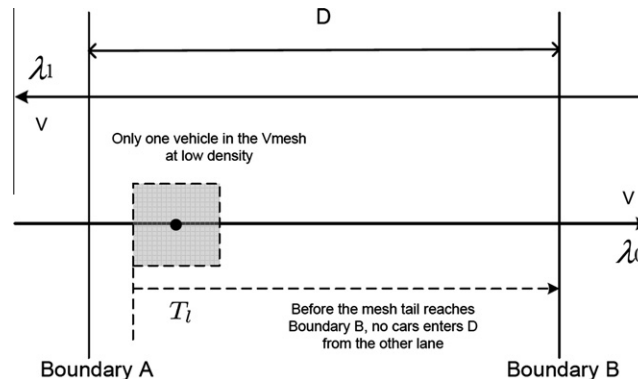
In this scenario, the traffic flow in the opposite directions on two lanes. We assume that when VMeshes from different lanes are partially overlapped, they are connected and messages can be passed from one VMesh to another. Therefore, in this two-way case, the EOI information can be passed back and forth between different VMeshes travelling in opposite directions. Essentially, the EOI message is ping-ponged between two lanes. The MTTIL for the two-way case is more complicated than that of the one-way case. Here we present an approximate analysis for two different traffic conditions.

#### 3.3.1. Approximation for low density traffic

At low traffic density, it is highly likely that the headways between vehicles are larger than the vehicle's transmission range. Therefore, for the low traffic density scenario, we can assume that each VMesh only contains one vehicle. Fig. 2 shows the moment when the vehicle in East Bound (EB) lane enters into the ROI and picks up the EOI. Since we are assuming each VMesh only contains one vehicle, in order for the EOI to remain within the ROI, this vehicle needs to pass the EOI to another vehicle from West Bound (WB) lane before it travels out of the ROI. After the WB vehicle picks up the EOI, it may continue to pass to another EB vehicle before it travels out of the ROI. This process of EOI being ping-ponged between vehicles from different lanes continues until the vehicle in either lane cannot pass EOI to a vehicle from the other direction anymore, before it travels out of the ROI.

We define  $T_l$  to be the time from the moment a vehicle picks up the EOI until it travels out of the ROI. At the moment of picking up the EOI, if this vehicle can pass the EOI to the other lane, there has to be another vehicle coming into the ROI before  $T_l$ . This implies that the headway of the vehicle from the other lane should be smaller than  $T_l$ . Therefore we have the probability that, at the moment of picking up the EOI, the vehicle can pass the EOI to another vehicle from the other direction be:  $P_p = P_T[t < T_l] = F_T(T_l)$ . Suppose vehicles from both lanes can successfully pass the EOI to the other lane for  $K - 1$  times, and at the  $K$ th time, the vehicle cannot pass the EOI to the other lane anymore. The random variable  $K$  thus has a geometric distribution:

$$p_K(k) = P_p^{(k-1)}(1 - P_p), \quad (9)$$



**Fig. 2.** At low density, the moment when a vehicle picks up the EOI. The EOI will be lost if no vehicle picks the EOI up from the other lane, before it exits the ROI.

Therefore,  $E[K] = \frac{1}{1-F_T(T_l)}$ . Since it is difficult to obtain the distribution of  $T_l$ , we use the time needed to travel the entire ROI to approximate  $T_l$ , i.e.,  $T_l \approx \frac{D}{v}$ . Since the EOI will be passed  $K - 1$  times before the last vehicle travels out of ROI, the MTIL thus is the sum of the  $K$  steps of passing. Since each step of passing takes  $T_{lk}$ , ( $k = 1, 2, \dots, K$ ), and each  $T_l$  is smaller than the time to travel the entire ROI ( $T_{roi} = \frac{D}{v}$ ), thus the MTIL for two-way highway at low traffic density denoted by  $MTIL_{tw,ld}$  can be approximated as:

$$MTIL_{tw,ld} = E[K] \times \frac{D}{v}. \quad (10)$$

### 3.3.2. Approximation for high density traffic

The approximation of Eq. (10) depends on the assumption that at low density there is only one vehicle in the VMesh. At higher density, more vehicles will be in a VMesh, and it will take longer time for a VMesh to travel out of the ROI than in the low density case. Therefore it is more reasonable to use MTIL for one-way traffic to approximate  $T_l$  than using  $\frac{D}{v}$ . Therefore, the MTIL for the two-way case at higher density denoted by  $MTIL_{tw,hd}$  can be approximated as:

$$MTIL_{tw,hd} = E[K] \times MTIL, \quad (11)$$

where MTIL is given by Eq. (5). In summary, our approximation is divided into two phases: at lower density, Eq. (10) is used and at higher density Eq. (11) is used:

$$MTIL_{tw} = \begin{cases} MTIL_{tw,ld} & \text{if } \lambda < d, \\ MTIL_{tw,hd} & \text{otherwise,} \end{cases} \quad (12)$$

where  $d$  represents the threshold of arrival rate above which Eq. (11) is used. This threshold could be decided empirically when Eq. (10) starts to underestimate the MTIL.

### 3.3.3. Probability of capture ( $P_c$ )

For two-way highway traffic, the probability of capture  $P_c$  is the probability that an EOI is captured by at least one mesh in one lane. This is the complement of the case that no mesh in neither lane captures the EOI. Since we already have  $P_c$  for single lane case from (8) and the two lanes are independent, the probability of capture for the two-way case  $P_{c2}$  is given by

$$P_{c2} = 1 - (1 - P_{c'}) (1 - P_{c''}) = 1 - e^{-(2\lambda_{s1}T_x + 2\lambda_{s2}T_x)}, \quad (13)$$

where  $\lambda_{s1}$  and  $\lambda_{s2}$  are spatial traffic density of each lane and  $P_{c'}$  and  $P_{c''}$  are probability of capture for each lane.

## 4. Simulation setup and mobility trace

Some assumptions were made in modelling the 1-D highway traffic in order to make the model tractable. Particularly, the assumption that all vehicles are travelling at the same constant speed, and that vehicles do not occupy space are not realistic in real vehicular environment and needed to be evaluated. We use simulation with realistic vehicular mobility model to study the impact of these assumptions. Also we examine how different system parameter (e.g., vehicle average arrival rates, transmission range, and size of ROI) affect the MTIL for 1-D highway traffic. As the movements of highway traffic are restricted to a “line”, it is comparatively easy to derive analytical results. For 2-D city wide traffic, we examine the VANET's storage for city-wide traffic scenarios through a detailed simulation study. We examine the impacts of  $D$  and  $T_x$  on the MTIL using the STRAW mobility model with San Francisco city map.

For both 1-D highway traffic, and 2-D city traffic, it is also desirable to examine how the “storage” scheme works under real traffic mobility. Therefore, for each traffic type, we also examined the MTIL using real vehicle traffic traces generated by San Francisco Yellow Cabs (SF Cab) (Cabspotting, 2006). This section describes details of the simulation framework of both 1-D highway and 2-D city traffic, and the mobility trace of SF Cab.

### 4.1. Simulation setup for 1-D highway traffic

For 1-D highway traffic, we used VGSim (Liu et al., 2009) to simulate the VANET storage for both one-way and two-way cases. VGSim is an integrated VANET simulation platform with realistic microscopic vehicular traffic mobility model and full stack network protocol simulation support. Details of VGSim and its validation with empirical data are documented in Liu et al. (2009). The following are the key simulation parameters: vehicle arrival rate ( $\lambda$ ) for each lane, vehicle speed ( $v$ ) for each lane, vehicle transmission range ( $T_x$ ), size of the ROI ( $D$ ) that covers the EOI, and simulation duration. The size of the EOI message is around 13 bytes, including information such as timestamp, location of the EOI, location of forwarding vehicle, size of the ROI, etc. We simulate a stretch of the highway that is ten times the length of the ROI. The simulation duration is set to 108,000 s (3 h). Each vehicle is simulated to have one radio antenna that enables wireless communication among the vehicles.

At the start of the simulation, each lane generates vehicles according to the specified arrival rates, and the vehicles move along the road as simulation time progresses. After the entire lane is populated by vehicles, an EOI is generated uniformly



along the stretch of the road. If the EOI is captured by a VMesh, that VMesh will be marked as carrying the information, and it broadcasts the EOI message to all vehicles within its transmission range. Each recipient of the EOI will rebroadcast it to all its neighbors after a small retransmission time (0.1 s). For each vehicle with the EOI information, this broadcast process continues until the vehicle travels out of the ROI. All message transfers are based on UDP and follow the IEEE 802.11b MAC layer protocol with two-ray path loss model underneath.

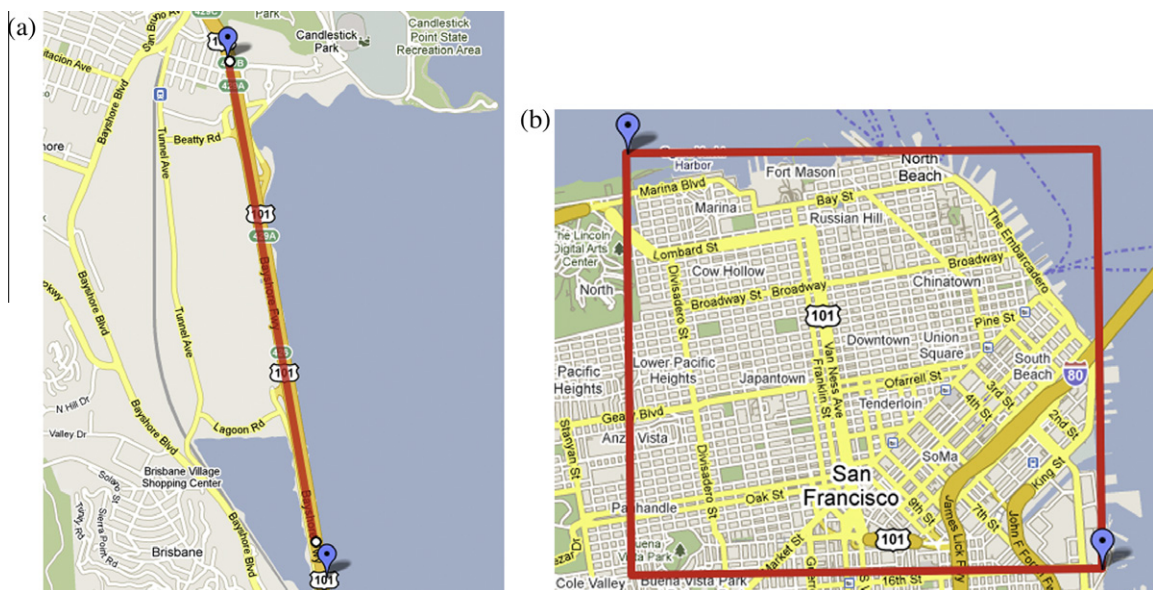
#### 4.2. Simulation setup for 2-D city traffic

We simulated a 2-D city wide traffic scenario using Jist/SWANS (Jist/SWANS, 2004). We adopted the STRAW mobility model (Choffnes and Bustamante, 2005). In STRAW the node movement is constrained to streets defined by map data for real US cities and their mobility is also limited by vehicular congestion and simplified traffic control mechanisms (Choffnes and Bustamante, 2005). In order to compare the results between STRAW and SF Yellow Cab's trace, we built the road networks for the same marked region in Fig. 3b from US Census Bureau's TIGER data files (Miller, 2000). After the simulation starts, vehicles are populated randomly in the region, and move according to the STRAW model. After a warmup period of 60 s, an EOI is randomly generated in the region, the rebroadcast process of vehicles that contains the EOI is similar to 1-D highway traffic described in the above section. MTTIL is measured when the EOI information is lost. We measure MTTIL under different arrival rates, sizes of the ROI and transmission ranges. Similarly all message transfers are based on UDP over IEEE 802.11b with two-ray path loss model underneath.

#### 4.3. Real highway and city-wide traffic in San Francisco Yellow Cab mobility trace

We also use the mobility trace of San Francisco Yellow Cab provided by Cabspotting (2006) to evaluate the performance of the vehicular “storage” under different traffic patterns. Cabspotting traces San Francisco's taxi cabs as they travel throughout the Bay Area. Once every minute or so, each cab reports its GPS location to the central dispatch (Cabspotting, 2006). The particular dataset that we used in our simulation is obtained from CRAWDAD data repository (CRAWDAD, 2009). It contains GPS coordinates of approximately 500 cabs during the period May 17 June 10, 2008. While cabs in this trace travel around the Bay Area, we only considered two regions: (1) for 1-D highway traffic, a straight portion of highway CA101 in south San Francisco and (2) for 2-D city-wide traffic, a rectangular region around San Francisco downtown area.

The marked section in Fig. 3a shows the CA101 section. This portion of CA101 is nearly straight, has two way traffic and no cross traffic, which makes it a perfect section representing 1-D highway traffic. We performed simulation using the CA101 section of the trace to generate vehicular traffic, and measured the MTTIL for different sizes of the ROI and transmission ranges. The CA101 trace shows different arrival rates at different hours of the day. We chose the time period from 12:00 pm to 17:00 pm everyday to generate the EOIs, during this time period the arrival process was very close to a Poisson process, and the variant arrival rates had small variance (between 0.03 and 0.05 vehicles per second).



**Fig. 3.** Regions in the SF Cab trace that have been used in this study. (a) The section of highway CA101 for 1-D two-way high way traffic. (b) The region for 2-D city-wide traffic.

The marked square in Fig. 3b shows the downtown San Francisco region, which showcases a typical 2-D city-wide road network. We performed simulation using this section of the mobility trace to simulate the 2-D city-wide traffic. One property of the 2-D city-wide traffic trace of San Francisco downtown area is that the vehicles (cabs) are unevenly distributed within the area. While the global density is very low (between 3 and 11 vehicle/km<sup>2</sup>), there are many high density (over 90 vehicle/km<sup>2</sup>) local clusters within the region. This property is very important as vehicular density has a large impact on the lifetime of VANET storage. As a result, we repeatedly generate the EOI through out a day, at fixed location near high density clusters. The transmission range ( $T_x$ ) of each vehicle is set to 300 m and the radius of ROI ( $D$ ) is 200 m.

Notice that in all the above simulations, transmission range were set to more than 100 m. Although typical transmission range for 802.11b is within 100 m, the DSRC/WAVE standard specifies transmission range up to 1 km for vehicular communication (Jones, 2005). Therefore, transmission range over 100 m in vehicular environment is reasonable.

## 5. 1-D highway traffic simulation results and discussion

### 5.1. One-way highway traffic

Figs. 4 and 5 present the analytical and simulation results of MTIL for the one-way case for different system parameters. The bars around each data point of VGSim's data represent the 95% confidence interval of the simulation results. In general, in all cases, as the arrival rate ( $\lambda$ ) increases, the MTIL also increases. As expected, Fig. 4 show that for the same arrival rate  $\lambda$ , as  $D$  increases, so does the MTIL. Eq. (5) shows the relationship between  $D$  and MTIL. For  $T_x$ , Fig. 5 shows that MTIL increases exponentially with  $T_x$ . This also confirms Eq. (5).

As discussed in Section 4, the assumptions of our analytical model needs to be validated against realistic vehicular mobility. With VGSim's ability to reproduce realistic vehicular traffic and conduct detailed wireless communication simulation, we

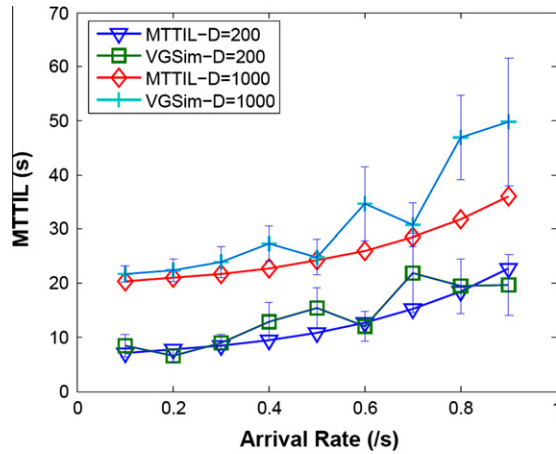


Fig. 4. One-way highway traffic MTIL as a function of arrival rate for different ROI ( $D$ ), ( $T_x = 100$  m).

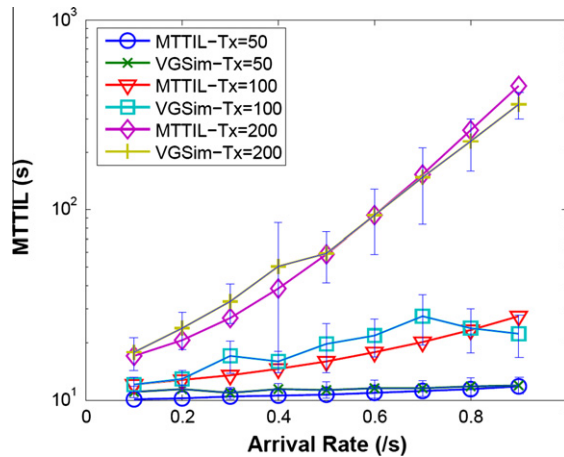


Fig. 5. One-way highway traffic MTIL as a function of the arrival rate for different transmission range  $T_x$ , ( $D = 500$ ).



can evaluate the impacts of our assumptions on MTIL. From Figs. 4 and 5 we can see that, generally the model and the VGSim results are close to each other. Most of the analytical results fall within the 95% confidence interval of the VGSim simulation results. However, the model tends to underestimate the MTIL, especially at higher traffic densities. This is because the headway between vehicles in a realistic traffic is not fixed. One assumption of our model is that the headways between vehicles remain the same due to constant speeds of vehicles. Another assumption is that EOI message propagation is instantaneous within a VMesh. However, in real traffic, vehicles can accelerate and decelerate, so the headway between vehicles may change. Therefore, it is possible that, at the time an intermediate node re-broadcast the message, previously disconnected vehicles can come within the transmission range of each other. As a result, more vehicles can receive the EOI information, leading to longer MTIL.

Finally, Fig. 6 shows the analytical and simulation results of  $P_c$  for different values of transmission range. In these simulations, size of the ROI ( $D$ ) is set to 500 m. For all different transmission ranges, the simulation and analytical results match very closely.

In general, the assumptions that we made for our analysis for the one-way case do have impact on the MTIL. Our model tends to underestimate the MTIL in some cases. Also, it is validated by both the analytical model and VGSim simulation that increasing the transmission range has a much higher impact on increasing the MTIL than ROI.

## 5.2. Two-way highway traffic

In the following discussion, unless specifically stated, the arrival rate for both lanes are set to the same value in the simulation.

Fig. 7 shows the analytical and simulation results of MTIL for two-way highway traffic for different sizes of the ROI and transmission ranges. The bar around each simulation data represents the 95% confidence interval. For the sake of clarity, only Fig. 7a includes the analysis results, the accuracy of which is discussed later. Fig. 7a and b shows that  $D$  has a much larger impact on MTIL for two-way traffic than  $T_x$ . In addition, two-way traffic results in significantly longer MTIL than one-way traffic even with smaller  $D$  and  $T_x$ . This is because for two-way traffic, the key factor in determining the MTIL is the number of times the captured EOI is passed between VMeshes moving in opposite directions. This number is primarily determined by  $D$  than  $T_x$ , as indicated by Eq. (10). Intuitively, this means that the larger the size of the ROI, the higher the chance that a vehicle can pass the EOI to a vehicle from the other direction, before it travels out of the ROI.

Fig. 7a compares the analytical and simulation results. In the figure, the dash lines near each of the simulation results represent MTIL obtained using the approximate analysis, calculated with the corresponding parameters. In general, the approximation yields results that follow the trend of MTIL of two-way traffic obtained using realistic traffic. It provides a generally accurate approximation at lower density, and it tends to overestimate MTIL at higher density.

The reason for the difference between the analytical and simulation results can be explained through Eq. (12). Our approximation includes two phases: a lower density phase (corresponding to densities in the range 0.1–0.3), and a higher density phase (corresponding to densities greater than 0.3). In the lower density phase, Eq. (12) generally makes a good approximation, except in the case when  $D$  is large ( $D > 150$  m). The overestimation at lower arrival rate is because we are using  $\frac{D}{v}$  (the time to travel the entire  $D$ ) to estimate  $T_i$  (time spend in each step of transition). This is an over estimation, which is magnified at larger  $D$ .

In the higher density phase, our approximation tends to overestimates the MTIL when  $D$  is small ( $D = 150$  m and  $D = 200$  m). This overestimation is mainly from the overestimation of the number of steps of passing the EOI from one lane

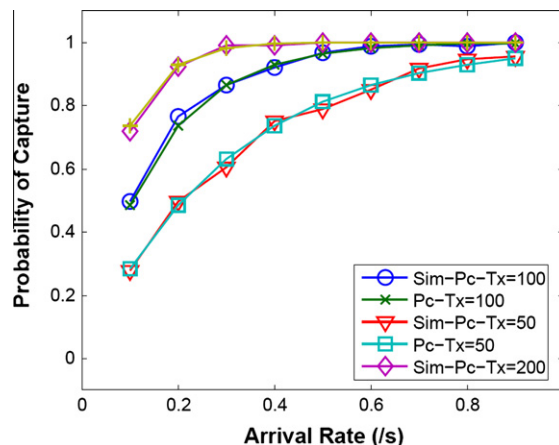
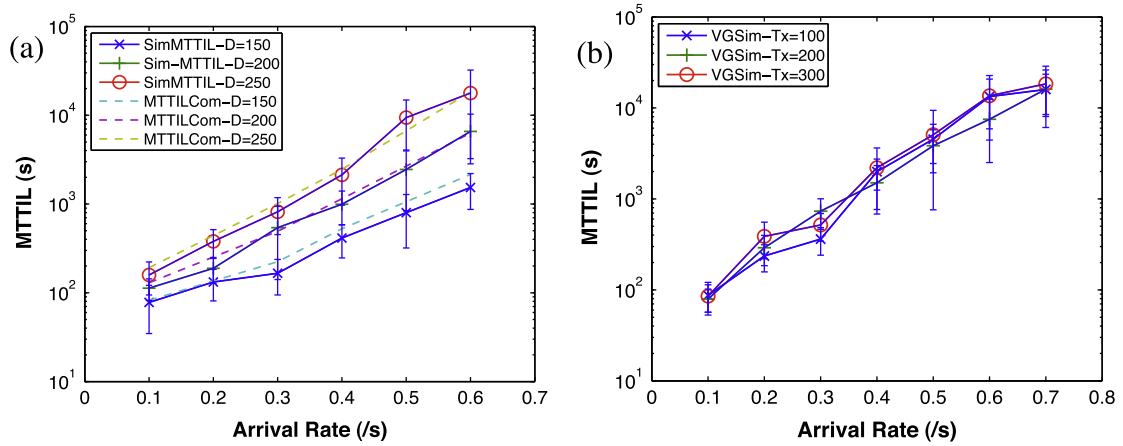


Fig. 6.  $P_c$  as a function of arrival rate with different  $T_x$  for unidirectional case ( $D = 500$  m).



**Fig. 7.** MTTIL for 1-D two-way highway traffic. (a) Analytical and VGSim results for MTTIL with different arrival rate and the size of ROI  $D$  ( $T_x = 200$  m). (b) VGSim results for MTTIL with different arrival rate and transmission range  $T_x$ . ( $D = 200$  m).

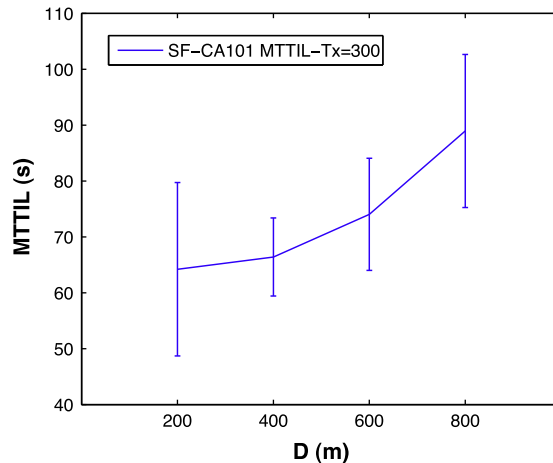
to the other. This is due to the fact that since the average size of the VMesh is larger at higher density,  $P_p$  in Eq. (9) is much larger. This eventually results in overestimation of the number of times the EOI is passed between lanes. Even though our model is only an approximation, it does provide a close prediction and capture the trend of the MTTIL values.

Fig. 8 shows the impact of the size of the ROI ( $D$ ) on MTTIL for simulation using SF Cab trace. Similar to the results for 1-D two-way highway traffic, as  $D$  increases, so does the MTTIL. Although it is difficult to do a head-to-head comparison between our analytical model and the CA101 traffic due to varying and different arrival rates in each direction, our analytical and simulation results still present the same trend as observed in real traffic. Finally, Fig. 9 shows the analytical and simulation results for  $P_c$  with  $D = 500$  m and  $T_x = 100$ . Similarly, the simulation and analytical results are very similar to each other.

## 6. 2-D city-wide traffic simulation results and discussion

### 6.1. MTTIL with STRAW mobility model

Fig. 10a and b shows the impacts of  $D$  and  $T_x$  on MTTIL. The x-axis represents different traffic densities in terms of the number of vehicles per square kilometers.  $D$  represents the radius of the ROI in meters. Similar to the results of two-way highway traffic, the MTTIL increases with the increase in density. Furthermore,  $D$  has much larger impact on MTTIL than  $T_x$ . This is because of a similar reason as in the two-way highway traffic case. In particular, larger  $D$  results in higher chance that a vehicle can pass the EOI to another vehicle in the ROI, before it travels out of the ROI.



**Fig. 8.** SF Cab CA101 traffic MTTIL for different ROI  $D$  ( $T_x = 300$  m).

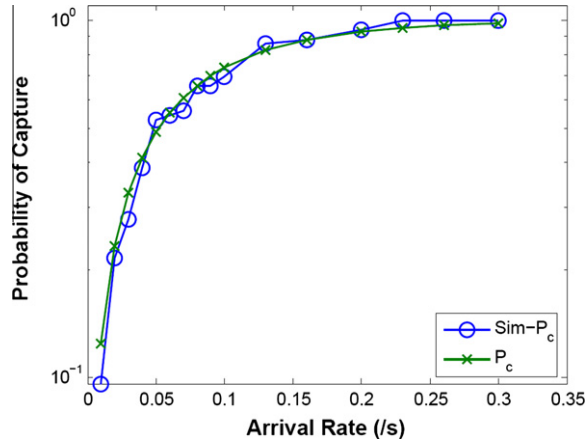


Fig. 9.  $P_c$  for the bidirectional flow ( $D = 500$  m,  $T_x = 100$  m).

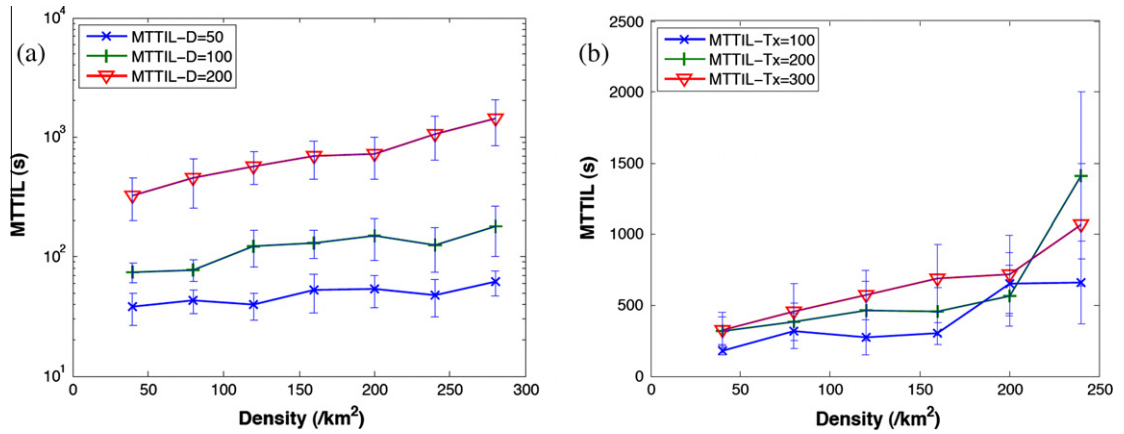


Fig. 10. MTTIL for 2-D city-wide traffic. (a) MTTIL with STRAW mobility model with different vehicle density and the size of ROI  $D$  ( $T_x = 300$  m). (b) MTTIL with STRAW mobility model with different vehicle density and transmission range  $T_x$  ( $D = 200$  m).

## 6.2. MTTIL using San Francisco Yellow Cab mobility trace

The MTTIL for both SF Cab trace and STRAW model is shown in Fig. 11. The  $x$ -axis is the local density, which is calculated as the time-averaged number of vehicles within the ROI over the area of the ROI. In general, Fig. 11 shows that as the local density increases, so does the MTTIL for both the SF Cab trace and the STRAW model. Furthermore, it shows that STRAW model produces longer MTTIL than the SF Cab trace. From the visual inspection of the simulation, this is because in the STRAW model, nodes are more evenly distributed than in the SF Cab trace. This results in higher MTTIL for the STRAW model, since a more even node/vehicle distribution increases the chance that a vehicle might meet another vehicle and pass the EOI before it travels out of the ROI. Notice that the SF Cab trace only contains mobility of cabs, which contributes to only a small percentage of the total traffic on the road. As Fig. 11 shows, even with participation of only cabs, the MTTIL can be in order of minutes at medium and high densities. With more participation of other types of vehicles such as buses and regular passenger cars, the density could be much higher than in SF Cab, and thus result in even longer MTTIL. With MTTIL in orders of minutes or more, it is realistic to build applications such as the road condition warning systems or casual car-pooling based on the VANET storage.

## 7. Invalidation/deletion of VANET storage content

In the above sections, we studied the lifetime of VANET storage. In some cases, the EOI might need to invalidate itself within the ROI. Although the EOI can “expire” on its own when the last vehicle travels out of the ROI, there might be cases that the EOI needed to be invalidated within the ROI before that. In the casual car-pooling example, suppose a car picks up the car-pooler after it receives the car-pooler’s request. At this moment, there might still be copies of the car-pooling request passing among cars within the ROI. It would be desirable if these car-pooling requests could be invalidated, so that no other

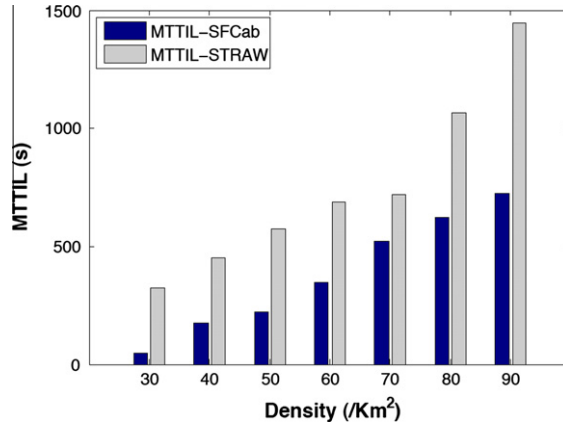


Fig. 11. MTTIL for SF Cab trace compared with STRAW model with different local vehicle density ( $D = 200$  m,  $T_x = 300$  m).

cars need to consider picking up the car-pooler again. Similar scenarios can also happen in the hazardous road condition warning system.

There could be different ways to invalidate/delete the VANET storage information. The solution we examine requires the vehicles passing the invalidation message among themselves within the ROI. Specifically, the EOI, after it has been “fulfilled” by some VMesh, starts sending the invalidation/deletion request. Upon receiving an invalidation request, a VMesh deletes its old EOI, if there is any, and rebroadcast the invalidation requests to others. The EOI keeps on sending the invalidation requests at its original location until all copies of the old EOI have been invalidated/deleted. This process is considered unsuccessful if the EOI expires on its own. We would like to examine two aspects of this invalidation process: (1) invalidation success rate, (2) Mean Time To Deletion (MTTD) which is the average time from the beginning of the invalidation process until it ends. Please notice that MTTD is only meaningful and measurable when the deletion process does not fail, in which case all the EOI information within the ROI are explicitly deleted by the invalidation process.

We performed simulation study using the 2-D city-wide traffic trace of SF Cab. In each simulation, we first generate an EOI at the same location as chosen in Section 4.3. If it is successfully picked up by any VMesh, we wait for 10 s, and then repeatedly generated EOI invalidation messages every 10 s. Each vehicle that received this invalidation message rebroadcast this message until it travels out of the ROI. This process continues until all EOIs are invalidated or the storage expires on its own. We measure the success rate of VANET storage invalidation and corresponding MTTD. The initial wait time of 10 s is to make sure that the EOI has enough time to propagate through vehicles. On the one hand if this time is too short, the invalidation process becomes trivial since there are not too many vehicles to invalidate. On the other hand if this wait time is too long, the EOI may be loss on its own before the need of the invalidation.

Topologically, each VMesh is a connected component. Since communications between vehicles within one VMesh is much faster than inter-VMesh communication, in order to have shorter MTTD, the number of connected components within the ROI should be small. For a fixed ROI, the number of connected components is related to the distribution of nodes (vehicles) and the transmission range of each node/vehicle. Fig. 12 shows the number of connected component as vehicle’s transmission range is increased. Notice that, when transmission range is larger than 500 m, all vehicles within the ROI are connected

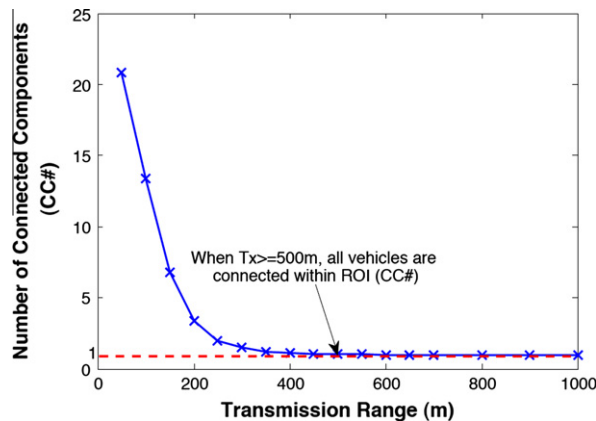


Fig. 12. Average number of connected components (VMeshes) for different transmission range ( $D = 1000$  m).

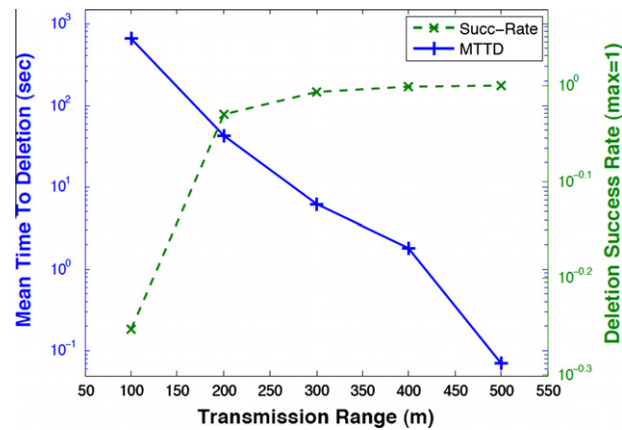


Fig. 13. Mean Time To Deletion (MTTD) and corresponding deletion success rate under different transmission range ( $D = 1000$  m).

within one single VMesh. In this case, the MTTD is only the time it takes to broadcast the invalidation message within the VMesh.

Fig. 13 shows the invalidation success rate and MTTD for different transmission range. As transmission range increases to 500 m, the success rate increases to 1, and the MTTD decreases to below 0.2 s. It is worth noticing that, at low transmission range, as there are more VMeshes/Connected Components in the ROI, the success rate could be very low and the MTTD could be very long. This is due to the fact that, at low transmission range, the VMeshes around the edge of the ROI may need to meet other VMeshes in around the center of the ROI to get the invalidation message, this may take a very long time as the VMeshes at the edge can keep on forwarding old EOI messages to new vehicles entering into the ROI. Also, it is worth noticing that, in the 2D city-wide traffic scenario, unlike for MTTIL, the transmission range has huge impact on the MTTD and invalidation success rate. In addition, please notice that  $D$  was set to 1000 m in these experiments as compared to a few hundred meters in previous experiments. This is intentional, since if  $D$  was set too small, there will be very few connected components within the ROI, and the invalidation process would become almost instantaneous and thus trivial.

## 8. Related work

Short range wireless communication among vehicles can enable many types of applications. Many of the proposed safety, non-safety, or data management applications can be related to the VMesh storage problem. In Mangharam et al. (2007), the authors proposed a scheme to support transmission of traffic alert messages with bounded latency. In Frey and Roman (2007) concepts similar to EOI and ROI were proposed for context-aware publish/subscribe system, but their focus was on the design of the publish/subscribe system interface. Similarly, in Leontiadis et al. (2009) and Leontiadis and Mascolo (2007), protocols were designed and evaluated for publish/subscribe systems that allow specific contents to be retained in certain regions for a certain period of time. Simulations based on real city maps were also performed to evaluate the proposed protocols, but the focus of these two works was on protocol design and evaluation. The concept of time stable stored geocasting discussed in Maihöfer et al. (2003) and Maihöfer et al. (2005), are also similar to VMesh storage. However, their work focus more on system design and performance evaluation around delivery ratio and network load. In Lindemann and Waldhorst (2006), a scheme for disseminating temporal information in highly partitioned mobile ad hoc network was proposed. While these works proposed some concepts or applications similar to what the VMesh storage can offer, our work on VMesh storage focus more on analyzing the general framework of how to retain temporal and spatial relevant information through communication among distributed vehicles.

In addition, certain aspects of VMesh storage is similar to the ideas behind Delay Tolerant Networks (DTN) (Fall, 2003; Burleigh et al., 2003), and real life testbeds of DTNs such as the DOME and DiselNet projects (DOME, 2009; DiselNet, 2009) can be employed to examine the performance of VMesh storage in real environment. While bearing similarities, the VMesh storage mechanism and DTN have fundamentally different focus. While the VMesh storage focuses on the life time of the temporal storage under different traffic mobility models, research works in DTN focus more on the performance of message delivery among mobile nodes. For example, the data custody transfer mechanism (Cerf, 2001; Seligman, 2006) in DTN requires mobile nodes holding packets locally before transferring the delivery responsibility to other nodes, which is similar to the VMesh storage's "store and forward" transmission scheme for nodes within ROI. However, the purpose of custody transfer is to enhance the message deliver reliability, while the VMesh storage focuses on storing the local transient information within the ROI as long as possible. In addition, the impact of node mobility on DTN and the VMesh storage is different. For DTN, node mobility normally results in intermittently connected links, which may require passive (Fall, 2003; Jain et al., 2004) or proactive mechanisms (Zhao et al., 2005) to address the end-to-end deliver reliability issue. In



VMesh storage, MTTIL can benefit from diverse node mobility as evidenced by longer MTTILs for two-way and city-wide traffic compared to one way traffic.

Another focus of this work is to provide analytical models for the VMesh storage under one-way and two-way highway traffic models. There have also been various analytical works on different aspect of VANET under highway traffic models. Specifically, in [Resta et al. \(2007\)](#) the authors provided detailed analysis on emergency message propagation in VANET. Under both single and multi-hop message dissemination schemes, the authors studied the tradeoffs between message reliability and delay, both of which are important metrics for emergency applications in VANET. Another analytical study that is closely related to our work was presented in [Wu et al. \(2009\)](#), in which analytical models were developed to study the impact of vehicular traffic characteristics on information propagation for one way and two way traffic. The notion of VANET partitions and their evolution overtime is similar to the freeway traffic scenario for VANET storage. However, in [Wu et al. \(2009\)](#), the authors focused on how information propagate through traffic, while the focus of our paper is on how long we could retain the information within a local region. In our study, we also considered 2D city traffic, while only 1D traffic was considered in [Resta et al. \(2007\)](#) and [Wu et al. \(2009\)](#). In [Jin et al. \(106\)](#), an analytical model for multi-hop inter-vehicle communication under highway traffic was proposed. In [Yuen et al. \(2003\)](#) highway node mobility's impact on mobile information network was also examined.

## 9. Conclusion

With the help of inter-vehicle communication capability, vehicles on the road can form wireless ad hoc mesh networks. In this paper, we evaluate how these vehicular meshes can help to retain certain transient information in a specific region for a period of time, by cooperatively passing the information among themselves. We term this the VANET “storage” problem. We first examine different properties observed in San Francisco Yellow Cab mobility trace. Then we analyze different properties of the VANET storage for both 1-D highway traffic and 2-D city-wide traffic. For 1-D highway traffic, we provided analytical models for estimating MTTIL. We validated our model assumptions through simulation using VGSim and the SF Cab mobility trace. For the 2-D city-wide traffic, we first conduct simulation analysis using STRAW model. Then we compare the results of STRAW model with simulation using San Francisco Yellow Cab's mobility trace. The results show that for 2-D city-wide traffic, the size of the ROI has higher impact on MTTIL than the transmission range. Also it shows even with cabs' low traffic density, the MTTIL can be in order of minutes, which makes it possible to build realistic applications using the VANET storage capability. We also examine the invalidation process of VANET storage. Our results show that, for 2-D city-wide traffic, transmission range has large impact on the success rate and MTTD of the invalidation process.

## Acknowledgement

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## Appendix A. Derivation of mean time to information loss

This section describes the details of how to derive MTTIL for one-way highway scenario. Each vehicle has an effective transmission range of  $T_x$ . We consider two cars to be connected if the physical gap (spatial headway) between them is no bigger than  $T_x$ . A mesh is a sequence of connected cars with a head and a tail. Since there is only one lane, and all vehicles are travelling at the same free flow speed, each mesh is defined by the number of cars that comprises the mesh; a VMesh refers to a mesh that consists of  $K$  cars. Each VMesh covers a contiguous stretch of road, and each car can only be in one

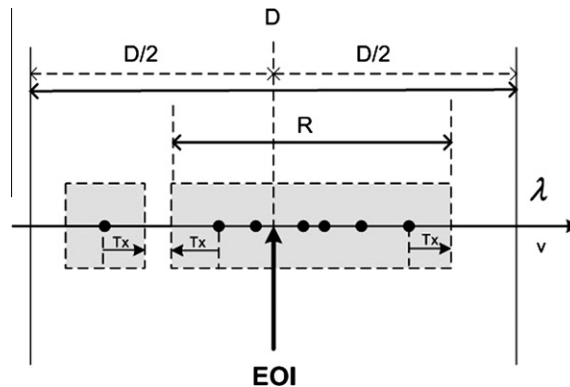


Fig. A.14. A scenario depicting the case for single lane unidirectional traffic flow. The shaded areas are the VMeshes.

VMesh. Note that in the one-way highway case, MTTIL means the time from the EOI is captured until the tail of the VMesh travels out of the ROI of size  $D$ .

Fig. A.14 shows a scenario for single lane unidirectional case. As mentioned before, the ROI is a region of length  $D$  centered around the location where the EOI occurs. The grey boxes represent the VMeshes formed by cars (notice that single car can also form a mesh by itself). In order to obtain  $P_c$  and MTTIL, we need to analyze some properties of the VMeshes for the unidirectional flow case.

### A.1. Temporal and spatial headways

We assume that traffic arrives into a section of the freeway following a temporal Poisson process with rate  $\lambda$  vehicles per second. Let  $T_i$  be the random variable that denotes the inter-arrival time between vehicle  $i$  and  $i + 1$  (temporal headway). Since there is no congestion the vehicles travel at a freeflow speed of  $v$  miles per second. Then  $t_i$  has the following density function:

$$f_{T_i}(t) = \lambda e^{-\lambda t}. \quad (\text{A.1})$$

Let  $D_i$  be the random variable that denotes inter-vehicle distance between vehicle  $i$  and  $i + 1$  (spatial headway). Based on our assumptions  $D_i = v \times T_i$ . Consequently, the density function of  $D_i$  is given by:

$$f_D(d) = \frac{\lambda}{v} e^{-\frac{\lambda}{v}d}. \quad (\text{A.2})$$

We assume that  $D_i$  and  $T_i$  are independent and identically distributed for all  $i$  and thus the cumulative distribution of  $T$  and  $D$  are given by

$$P(D \leq d) = F_D(d) = \int f_D(d) dd = 1 - e^{-\frac{\lambda}{v}d}, \quad (\text{A.3})$$

$$P(T \leq t) = F_T(t) = \int f_T(t) dt = 1 - e^{-\lambda t}. \quad (\text{A.4})$$

We define  $\lambda_s = \frac{\lambda}{v}$  as the spatial process density. Then the expectation and variance of  $T$  and  $D$  are  $E[T] = \frac{1}{\lambda}$ ,  $\text{Var}[T] = \frac{1}{\lambda^2}$ , and  $E[D] = \frac{1}{\lambda_s}$ ,  $\text{Var}[D] = \frac{1}{\lambda_s^2}$ , respectively.

### A.2. Distribution of the size of VMesh

Let  $K$  be the random variable that denotes the size of the mesh. The probability that  $K$  vehicles can form a VMesh is the probability that for first  $K$  vehicles that arrives at the road, all the spatial headways are smaller than  $T_x$  and the  $K + 1$ th and  $K$ th vehicle has spatial headway larger than  $T_x$ . Since there are  $K - 1$  headways between  $K$  vehicles. We have,

$$P(K = k) = P(d \leq T_x)^{k-1} (1 - P(d \leq T_x)). \quad (\text{A.5})$$

This implies that the random variable  $K$  has a geometric distribution given by

$$p_K(k) = F_D(T_x)^{k-1} (1 - F_D(T_x)) = e^{-\lambda_s T_x} (1 - e^{-\lambda_s T_x})^{k-1}. \quad (\text{A.6})$$

As a result the mean and variance of  $K$  are given by

$$E(K) = e^{\lambda_s T_x}, \quad (\text{A.7})$$

and

$$\text{Var}(K) = \frac{p}{(1-p)^2}, \text{ where } p = 1 - e^{-\lambda_s T_x}, \quad (\text{A.8})$$

### A.3. Length of a VMesh

Each VMesh covers a contiguous region, and in the single lane unidirectional case, only the length of the VMesh is of interest, and is required for determining MTTIL. We denote  $R$  as the length of the coverage by VMesh. We define the distance between the first and last vehicle in a VMesh to be  $R'$ . As we can see in Fig. A.15,  $R' = R - 2T_x$ , and  $R' = \sum_{i=1}^{k-1} d'_i$ . Therefore,

$$R = \sum_{i=1}^{k-1} d'_i + 2T_x. \quad (\text{A.9})$$

We let  $D'$  be the random variable that denotes the headway between any two vehicles within the mesh.  $D'$  is the spatial headway of vehicles given the condition that it is smaller than  $T_x$  as the vehicles are in the mesh. Therefore, from Eqs. (6) and (A.3), the density function of  $D'$  is given by

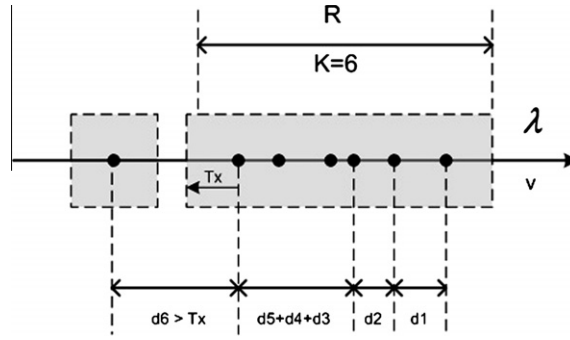


Fig. A.15. Relationship between  $R$  and  $R'$ .

$$f_{D'}(x) = \begin{cases} \frac{1}{p_{in}} f_D(x) & 0 < x \leq T_x \\ 0 & x > T_x. \end{cases} \quad (\text{A.10})$$

where  $p_{in} = P[D \leq T_x] = F_D(T_x)$ . Using Eqs. (A.10) and (A.2), the mean of  $D'$  is given by

$$\begin{aligned} E[D'] &= \int_0^{T_x} x f_{D'}(x) dx \\ &= \frac{1 - e^{-\lambda_s T_x} (\lambda_s T_x + 1)}{\lambda_s (1 - e^{-\lambda_s T_x})}. \end{aligned} \quad (\text{A.11})$$

Furthermore, the variance can be derived from

$$E[D'^2] = \frac{2 - e^{-\lambda_s^2 T_x^2} (\lambda_s^2 T_x^2 + 2\lambda_s T_x + 2)}{\lambda_s^2 (1 - e^{-\lambda_s T_x})}, \quad (\text{A.12})$$

so that

$$\text{Var}[D'] = E[D'^2] - E^2[D']. \quad (\text{A.13})$$

Recall that  $R'$  is the sum of  $K - 1$  number of headway  $D'$ . In order to find the expectation of this random sum, we can calculate the conditional expectation of  $R'$ , and apply the theorem of total expectation to obtain

$$\begin{aligned} E[R'] &= \sum_{k=1}^{K-1} (k-1) E[D'] p_K(k-1) \\ &= E[D'] (E[K] - 1). \end{aligned}$$

Similarly, through the Laplace Transform of  $D'$  and applying the theorem of total Laplace–Stieltjes Transform, we can get the probability density function of  $R'$ :

$$f_{R'}(r) = (\alpha - 1) \lambda_s e^{(\alpha-1)\lambda_s r} + (1 - 1/\alpha) \delta(r), \quad (\text{A.14})$$

where  $\alpha = 1/F_D(T_x)$ , and  $\delta(r)$  is the Dirac Delta function of  $r$ . Therefore, the expected length of the VMesh is:

$$E[R] = E[R'] + 2T_x, \quad (\text{A.15})$$

with the variance of the size of VMesh given by

$$\begin{aligned} \text{Var}[R] &= \text{Var}[R'] \\ &= \text{Var}[D'] (E[K] - 1) + E^2[D'] \text{Var}[K], \end{aligned} \quad (\text{A.16})$$

Finally, from Eq. (A.14), we get the pdf for  $R$  which is given by

$$f_R(r) = (\alpha - 1) \lambda_s e^{(\alpha-1)\lambda_s (r-2T_x)} + (1 - 1/\alpha) \delta(r - 2T_x). \quad (\text{A.17})$$

#### A.4. MTIL

Given  $E[R]$  as above, the MTIL could be derived as specified in Section 3.2.2.

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