# Chapter IX
# Integrating Traffic Flow Features to Characterize the Interference in Vehicular Ad Hoc Networks

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## ABSTRACT

*Vehicular Ad Hoc Networks (VANETs) are composed of vehicles equipped with advanced wireless communication devices. As a paradigm of decentralized advanced traveler information systems (ATIS), VANETs have obtained interests of researchers in both communication and transportation fields. The research in this chapter investigates several fundamental issues, such as the connectivity, the reachability, the interference, and the capacity, with respect to information propagation in VANETs. The authors' work is distinguished with previous efforts, since they incorporate the characteristics of traffic into these issues in the communication layer of VANETs; this mainly address the issue of the interference. Previous efforts to solve this problem only consider static network topologies. However, high node mobility and dynamic traffic features make the interference problem in VANETs quite different. To investigate this problem, this chapter first demonstrates the interference features in VANETs incorporating realistic traffic flow features based on a validated simulation model. Then, analytical expressions are developed to evaluate the interference under different traffic flow conditions. These analytical expressions are validated within the simulation framework. The results show that their analytical ~~characterization~~ performs very well to capture the interference in VANETs. The results from this work can facilitate the development of better algorithms for maximizing throughput in the VANETs.*

## INTRODUCTION

With increased urbanization, there are increasing concerns about congestion and severity of surface transportation incidents. It is no longer possible to address the issue of congestion management by adding new transportation infrastructure due to the significant costs involved and the impacts on land use. Transportation agencies in the United States and in other parts of the world are exploring innovative technology oriented methodologies which can alleviate congestion and safety problems. Recent years, Intelligent Transportation Systems (ITS) incorporated advanced information technologies have been claimed to perform efficiently. Among such systems, ATIS is considered to be a promising technology for improving traffic conditions by helping travelers use existing transportation facilities efficiently, and interpret the real-time traffic information correctly (Dia & Purchase, 1999; Jin & Recker, 2006; Lo & Szeto, 2004; Mouskos et al., 1996; Srinivasan & Mahmassani, 2003; Wang, 2007).

Some systems are already in place, such as Copilot in the U.S. and TomTom in Europe. All of these systems rely on a centralized system, such as the Traffic Management Center (TMC) to gather traffic information from probe vehicles or roadside sensors, generate route choice messages and disseminate route suggestions to drivers. However, the structure and mechanisms of these existing centralized approaches suffer from significant disadvantages, such as heavy infrastructure requirements, large computational needs, and high initial investment cost and so on. Hence, the current centralized ATIS is not fully satisfactory.

At the same time, the rapid advances in wireless communication technology make the tasks of collecting, interpreting, and disseminating information among vehicles feasible. ATIS based on the inter-vehicular communication is referred as to decentralized ATIS. Compared with the current centralized ATIS, it has several advantages: (i) they are infrastructure-light in that they do not rely on roadside sensors and traffic management centers. Instead, they exchange and collect traffic information by inter-vehicular communication; (ii) the decentralized system is robust in emergency and disaster related situations because it is self-organized and independent of fixed-infrastructures. (iii) Information exchange in the decentralized system can be used for other applications and file sharing such as 511.

Our study investigates vehicular ad hoc networks, in which vehicles serve as data collectors and anonymously transmit traffic and road condition information from every major road within the transportation network. Such information will provide transportation agencies with the information needed to implement active strategies to relieve traffic congestion and improve safety. Several fundamental problems such as the connectivity, the reachability, the capacity, and the interference in VANETs are explored in the related study before. These issues demonstrate the information propagation in VANETs from different views. Connectivity and reachability address the information propagation opportunities between any node pairs in VANETs at any time snapshot and in a short time interval respectively. The capacity defined in this study demonstrates the information dissemination capability in VANETs, which is limited by the interference between concurrent transmissions. Here, we briefly introduce the first three topics and then emphasize on the interference in VANETs, which is the main contribution of the proposed work in this chapter.

The rest of this chapter is organized as follows: section 2 introduces VANETs. Section 3 presents our research scope. Section 4 reviews the previous work about the interference in wireless network. Section 5 provides the background and assumptions for the study of the interference here. Section 6 describes our methodology and main results. Section 7 summarizes the results of this study.

## VEHICULAR AD HOC NETWORKS

Vehicular Ad Hoc Networks (VANETs), which are composed of vehicles equipped with advanced wireless communication instruments, such as Global Position Systems (GPS) receivers and Personal Digital Assistant (PDA) based cell phones, is a promising paradigm of the decentralized ATIS. This infrastructure-light and decentralized system is expected to provide tremendous benefits for alleviating traffic congestion, improving traffic safety, and further enhancing many other aspects of our life.

Nowadays, worldwide academia, industry, and governments are investing significant amounts of time and resources on studying, deploying, and testing the performance of VANETs. Several academic activities for VANETs were initiated such as ACM International Workshop on Vehicular Ad Hoc Networks with MOBICOM and Vehicle-to-Vehicle Communications Workshop (V2VCOM) with MobiQuitous. Many on-going national/international projects included consortia such as the Vehicle Safety Consortium (US), Car-2-Car Communication Consortium (Europe) and Advanced Safety Vehicle Program (Japan); standardization efforts like the Dedicated Short Range Communications (DSRC) and IEEE 802.11p (WAVE), and field trials like the large-scale Vehicle Infrastructure Integration Program (VII) in the US.

These initial works found that VANETs possess unique characteristics as compared to general mobile ad hoc networks (MANETs). For instance, high vehicular speed and unexpected driver acceleration or deceleration makes the topology of VANETs change much faster. The number of vehicles in VANETs cannot be scheduled or controlled in real-time because drivers will enter or exit at any time. These features further bring forth challenges in VANETs as below:

1. The high vehicular mobility makes VANETs subject to frequent fragmentation. Consequently, information dissemination becomes even difficult in VANETs as many information routing paths become disconnected before they are utilized. Therefore, building a stable connected VANET is a difficult but critical task.
2. The varying traffic flow characteristics in the transportation network could possibly lead each vehicle to experiencing different VANETs in a single trip. Hence, an adaptive and distributed topology control strategy should be developed for individual vehicles so that the inter-vehicle communications of VANETs perform well.
3. The poor quality of data associated with link/edge latencies and possibility of variation between the data obtained from different vehicles make developing a traffic routing algorithm even harder. This online traffic routing algorithm is necessary to build an advanced framework for the decentralized ATIS (Gao & Chabini, 2006; Jaillet & Wagner, 2006; Shavitt & Sha, 2005; Waller & Ziliaskopoulos, 2002).
4. The possibility of malicious messages and the accessibility of any traveler's origin destination information can pose a serious security and privacy problem. New approaches for communication security have to be designed to guarantee the reliable and secure services in VANETs.
5. All nodes sharing the same medium access channel leads to congestion in very dense networks. Moreover, unstable link connections only provide limited bandwidth. Both of these unfavorable conditions in VANETs result in low information transmission efficiency. Consequently, advanced medium access protocols are needed to improve the level of information transmission efficiency in VANETs.
6. Neither the simulation tools in transportation, such as PARAMICS, CORSIM and VISSIM, nor the simulation platforms in

communication networking such as ns2, OPNET and Qualnet can test and evaluate network protocols in VANETs. A new simulation platform, which integrates communication techniques and realistic transportation simulation, is desirable.

These application potential and research challenges aroused many interests of scholars in both the transportation area and the wireless communication area. Previous simulation works (Artimy et al., 2005a, 2004, 2005b, 2006) present the following points: VANETs are usually modeled as one-dimensional networks; a dynamic transmission range is expected to provide better connectivity; the connectivity of a VANET on the road with one lane is more sensitive to vehicle velocity than a VANET on the multi-lane roadway and so on. Note that the interaction between vehicular mobility and information propagation is usually studied by simulation methods, but analytical work is less present (Jin & Recker, 2006; Wang, 2007); most of the models for VANETs are built on stable traffic flow, but the unstable feature of traffic flow is not considered. Encouraged by the above points, we conduct analytical study on the information propagation in VANETs incorporating the traffic flow features, which will be discussed next.

## OUR STUDY SCOPE

In an effort to address some of the limitations of the previous work, this research investigates several properties of VANETs in consideration of the traffic flow characteristics. In particular, we address the geometric connectivity, reachability, capacity, and interference respectively.

The first topic regards the analytical expressions to characterize the connectivity of VANETs on freeway segments, which represents the probability that any two vehicles are connected at a given time instant (Ni & Chandler, 1994). Specifically, we considered a VANET as a nominal system with uncertain disturbance. The nominal system was represented by a free traffic flow, in which space headway was assumed to obey an exponential distribution. The unexpected driver behavior such as acceleration, deceleration, and lane changing were modeled as uncertain disturbance, which was further characterized by a robustness factor in our analytical model. Our regression results showed that the robustness factor is a function of the traffic flow parameters including average traffic speed, average space headway and its variance. The simulation validation demonstrated that our analytical expression can evaluate the geometric connectivity of VANETs more accurately than previous efforts in literature. The readers are referred to the complete analytical characterization of connectivity which is discussed in (Ukkusuri & Du, 2008).

Due to the observation that the relative movement between individual vehicles can create opportunistic connections between vehicles during a short time interval, connectivity, which demonstrates the opportunities that the information can go through the whole network at a given time instant, is sometimes not sufficient to fully understand the information propagation performance. We dealt with this problem in the second part of our research. We first defined an "information flow network" and then introduced "reachability" to characterize information propagation performance in a short time period. An information flow network is a time expanded graph composed of asynchronous communication links (based on geometric distance) and nodes (vehicles). The reachability is the probability that every two vehicles in the information flow network are connected in a given time interval. To capture various driver behaviors, we separated the drivers into three clusters which were aggressive, defensive, and slow drivers respectively. Correspondingly, we approximated the relative movement between individual vehicles by the relative movement between different driver clusters. Based on this approximation, we developed analytical formula to evaluate the reachability during a short time period. Our results showed that the relative movement between vehicles enables individual vehicles to communicate with more neighbors and therefore improves the opportunity that the traffic information is transmitted forward. Simulations were setup to validate our assumptions and analytical results. The reader is suggested to reach our completed work by Du and Ukkusuri (2008b).

While the first two topics focused on information propagation opportunities, the third topic considered the information dissemination among vehicles. Specifically, we studied the maximum concurrent transmissions in VANETs, which is referred to as the capacity of VANETs in this study. We first explored the capacity of VANETs using an integer programming (IP) formulation. Since the IP model is computationally hard to solve, we further developed a statistical model to characterize the capacity of VANETs in terms of some significant parameters in the traffic flow networks as well as the communication networks. To improve the prediction accuracy of the statistical model, the central composite experiment design method was applied. The interested reader can also reach the completed work by Du and Ukkusuri (2008a).

The next problem that we are interested in is the interference in VANETs considering the relative movement between individual vehicles. This problem will be discussed deeply in the following paragraphs in this chapter.

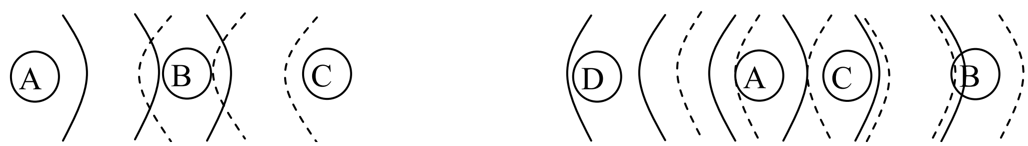
## INTERFERENCE IN VANETS

~~In the previous paragraph, we present a big picture of our research work. From now on, we focus on the main topics we will address: interference.~~ Informally speaking, interference can be modeled to a limited extent under the following assumption: a transmission from node u to node v is successful only if there is no other node w which has a connection to node v and transmitting to node v simultaneously (Burkhart et al., 2004; Rajaraman, 2002). Along the line of the above model, this study defines the interference as the number of reachable vehicles around each individual vehicle (two vehicles are in the transmission range to each other).

To understand interference clearly, we need to introduce two terms, hidden and exposed nodes, which are shown in Figure 1. Hidden nodes are two nodes that share the set of nodes within the transmission ranges of both, but they are not in the transmission range of one another. For example, in Figure 1 left, node A and node C are not in the transmission range of each other, but node B is in the intersection of node A transmission and node C transmission. Therefore, node A and node C cannot transmit information to node B at the same time, otherwise collisions will happen on B. Exposed nodes are two nodes which are within the transmission range of one another, thus, they cannot transmit information at the same time, and otherwise information collisions happen to both of them. As the example shown in Figure 1 right, if node A and node C transmit information to node B and node D respectively at the same time, then the collisions will not happen on B and D, but node A and node C are within the transmission range of each other, they will interfere with each other. Hence, only one of node A and node C can be active at a given time (Blum et al., 2004). Based on the description above, it is clear that interference is closely related to the node distribution and the transmission range.

Two direct reasons encourage us to investigate the interference of VANETs. First, interference is closely related to the trade-off between throughput1[1] and connectivity. (They together influence the performance of VANETs significantly). On the one hand, in order to reduce the interference (i.e. increase throughput), the small transmission range is preferred. On the other hand, there is surely a limit of decreasing the transmission range, while

*Figure 1. Hidden nodes and exposed nodes*




maintaining network connectivity. This trade-off makes the interference very important to the topology controlling in VANETs.

Second, vehicular mobility, unexpected driver behavior, and variable traffic flow condition make the interference that individual vehicle experiences in VANETs quite different with nodes in static networks. Specifically, the topology of VANETs changes quite rapidly from time to time, hence the number of neighbors which interferes the transmission of one vehicle is not constant. Moreover, the topology change depends on the macroscopic traffic condition, such as congestion level, as well as the microscopic traffic behavior, such as driver's acceleration, deceleration and lane changing behavior. Hence, measuring the dynamic interference of VANETs in view of vehicular mobility as well as traffic flow features is a challenging and important work. To the best of our knowledge, very little work has been done on this topic.

In view of above points, the following study is dedicated to addressing the interference of VANETs on a freeway segment from the transportation point of views. Our main contributions are in two folds: 1) based on simulation data, we explore the interference that individual vehicles experience under different traffic flow conditions; 2) incorporating both microscopic and macroscopic traffic features, we develop closed form stochastic expressions to characterize the interference in VANETs.

## RELATED WORK

Extensive work has been done for the interference in static wireless network. Most of the previous work addressed the interference issues implicitly by constructing topologies satisfying the features of sparseness or low node degree, such as (Hou & Li, 2006; Li et al., 2003; Ramanathan & Rosales-Hain, 2000). However, recent work revealed that the previous implicit notion of interference is not sufficient to reduce the actual interference (Burkhart et al., 2004). The following review the efforts on the explicit interference reduction in wireless network.

Heide et al. (2002) introduced an explicit definition of interference based on the current network traffic. The weakness of this definition is the requirement of a priori network traffic information, which is usually not available. With the assumption that each node can adapt their transmission power, they explore the trade-off between the congestion, power consumption, and dilation in a wireless network.

Burkhart et al. (2004) proposed another explicit definition: the interference of a link *(u, v)* is the number of nodes covered by two disks centered at node *u* and node *v* with transmission range *r*. Formally, the definition is shown below:

$$con(uv) = \{w \mid w \text{ is covered by } D(u \mid uv) \text{ or } D(v \mid uv)\} \quad (1)$$

where, *cov(uv)* denotes the set of nodes that can be affected by node *u* and node *v* when they communicate to each other with exactly the minimum power needed to reach one another. |uv| is the distance between node u and node *v*. D(u; r) denotes the disk centered at node *u* with transmission range *r*. This interference definition is also called interference based on the coverage model. Using this definition, the authors disprove the widely advocated assumption that sparse topologies imply low interference. Furthermore, they propose a centralized algorithm to compute an interference-minimal connectivity preserving topology. Nejad and Li (2005) adopt this definition and further develop another algorithm to construct the network topology so that the maximum interference is minimized.

Inspired by Fussen et al. (2004), Rickenbach et al. (2005) questioned the definition in (Burkhart et al., 2004) from two aspects: (i) It is sender-centric, i.e., the interference is considered to be an issue at senders instead of at receivers. Hence, this definition hardly reflects the real-world interference. (ii) It is of more technical nature and not robust enough to withstand the addition or removal of an individual node in the network. In contrast to this sender-centric interference definition, the authors present a receiver-centric interference model: the interference of a node *u* demonstrates the number of nodes covering node *u* with their disks induced by their transmission range reachable to node *u*. Furthermore, an algorithm with approximation ratio $\sqrt[4]{\Delta}$($\Delta$ is the maximum node degree) to find the optimal connectivity-preserving topology is proposed.

Since the coverage area of omni-directional antenna does not have a clear-cut boundary, Moscibroda and Wattenhofer (2005) studies the average interference problem, where the nodes are grouped into active nodes (A) and passive nodes (P). The interference of a node $p \in P$ is the number of nodes $a \in A$ whose transmission ranges cover *p*. Correspondingly, the average interference of a topology is the sum over all interference divided by the number of passive nodes. A greedy algorithm is proposed to compute an O(logn) approximation to the connectivity-preserving interference problem, where *n* is the number of nodes in the network.

So far, the studies for the interference reduction in wireless networks are based on the static network topology. Due to the high vehicular mobility, the topology of VANETs changes frequently. This leads to the results and algorithms of previous works possibly not applicable any more, but there are few efforts on investigating the dynamic interference in VANETs. Therefore, exploring new interference models for VANETs is necessary.

## SYSTEM MODEL

We begin our study with some assumptions. We consider VANETs with n vehicles equipped with wireless communication instruments moving on a freeway segment. Vehicles are homogenously distributed with traffic density λ. The communication radio is with the directional antenna, and referring the traffic density, its transmission range r can be adjusted adaptively so that certain number neighbors can be covered (Blough et al., 2006; Xue & Kumar, 2004). Let $n_i$ denote the vehicles *i*, then the distance between vehicles $n_i$ and $n_j$ is denoted by $x_{ij}$. When $x_{ij} < r$, we call node *j* is the neighbor of node *i*, vice versa. For the consecutive vehicles, $x_{ij}$ is also referred to as space headway.

*Medium access control.* Due to the time varying network topology and the lack of centralized control in VANETs, we assume medium access control applies the spirit of a random access scheme. Once the distance between two vehicles is less than their transmission range, the communication between them is triggered, but only successes if there is no interference. Additionally, we suppose a node may not send and receive messages at the same time but can transmit to more than one other node at the same time. Specifically, a transmission is successful if both of the following conditions are satisfied: (1) $x_{ij} \le r_i$, (2) any other node $n_k$, such that $x_{ik} \le r_k$ or $x_{jk} \le r_k$ is not transmitting (Jain et al., 2003).

*Preliminary interference calculation*. We assume that each vehicle has the same numbers of reachable-neighbors[2] (Blough et al., 2006; Xue & Kumar, 2004), and $K_c = \lambda r$. With these assumptions, we immediately find that under the static situation, the expected interference is equal to $3K_c$. From Figure 2, we observe that there are $K_c$-neighbors in the forward and backward direction which will interfere the transmission of vehicle *A*. Additionally, vehicle *A* itself will averagely cover $K_c$, therefore, there is one more $K_c$-neighbors will interfere the transmission of vehicle *A*. However, due to the high mobility of vehicles in VANETs, the network topology will change very quickly. Consequently, there is a high probability that other vehicles will move in or out the transmission range of the vehicles. This results in more than $K_c$ neighbors to interfere the transmission of an individual vehicle in a short time interval. This critical characteristic of the interference in VANETs has not been considered in the past efforts. The goal of this study is to further explore the interference of one successful transmission in a short time period, T, incorporating traffic flow conditions and relative movements between vehicles.

## EXPECTED INTERFERENCE UNDER DYNAMIC TRAFFIC CONDITIONS

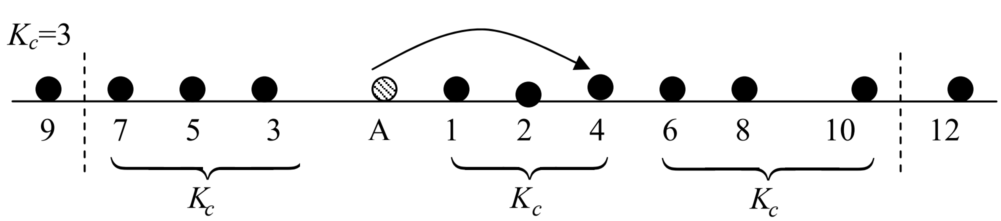
We now present our framework for modeling the interference in VANETs. We first do a simulation-based study, and then we present our method to measure the interference incorporating traffic flow characteristics. Both the macroscopic vehicle distribution and the microscopic relative movement between vehicles are considered in developing the models. Finally, we validate our stochastic models of interference in VANETs using a well calibrated simulation model.

### A Simulation-Based Study

To investigate how the influence of relative movement and the traffic flow congestion level impact the interference of VANETs, we first perform a simulation-based study based on an open source dynamic traffic simulation framework-MITSIMLab (Ben-Akiva et al., 2002), which is developed by MIT Intelligent Transportation System Program. We setup a one-way freeway segment, which is about 10000 ft long and has three lanes. Vehicles have different speed at each time instant but their speed limit is 65mph. Each simulation is conducted from 8:00am to 8:25am under constant traffic demand. The first 15 minutes is redeemed as warm-up time and data is collected from 8:15am to 8:25am. In order to obtain traffic flow under different congestion level, simulations with demand rates changing from 50vph (vehicle per hour) (very light traffic condition) to 8000vph (heavy congestion traffic condition) are conducted. Simulation outputs provide us individual vehicle position, speed and traffic density, λ per second.

In order to demonstrate the effect of relative vehicular movement on the interference of VANETs, we study the interference of individual vehicles in a short time interval, say 30s. In addition, our preliminary interference analysis shows that the number of reachable neighbors for individual vehicles is the key influencing variable to measure the interference (equal to $3K_c$). Therefore, the fol-

*Figure 2. The example of $K_c$ = 3*



lowing work focuses on exploring the reachable neighbors of individual vehicles.

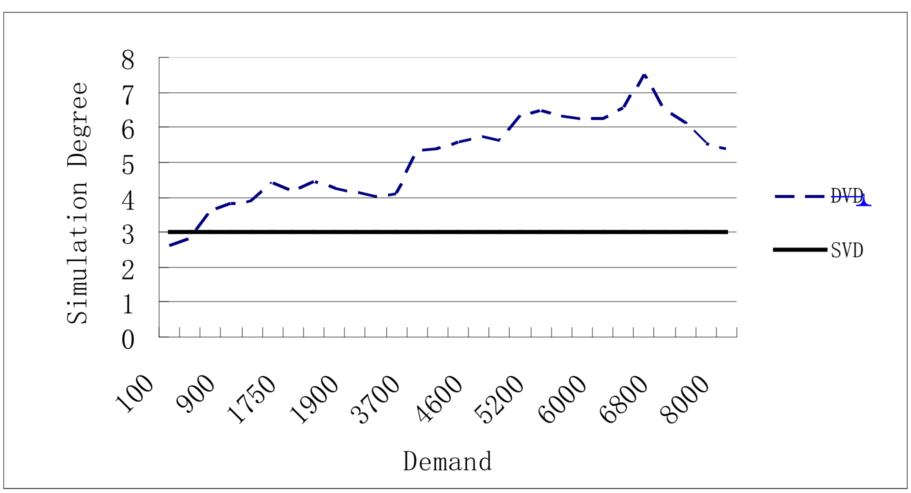
We name the average number of reachable neighbors for an individual vehicle under a static VANET topology as Static Vehicular Degree (SVD), but the average number of reachable neighbors for an individual vehicle in a time interval is referred to as Time-period Vehicular Degree (SVD). Without loss of generality, assuming SVD=*3*, and vehicular transmission range, $r = SVD/\lambda$ at each time interval, we check SVD during the interval T (=30s)[3].

The results reported in Figure 3 show that when we increase the traffic demand step by step, vehicles become more and more crowded. Consequently, the reachable neighbors of individual vehicles in 30s increase. This means that the probability of the interference will impact the transmission of individual vehicles. Moreover, carefully studying the curves in Figure 3, we obtain more insights:

1. Traffic Demand <500vph: Figure 4 shows traffic is sparse; Figure 3 shows SVD is smaller than SVD. This is reasonable since there are not enough neighbors around individual vehicles in a short time interval
2. 500vph < Traffic Demand < 3700vph: Figure 4 shows traffic is still in the free flow regime; Figure 3 shows SVD is close to 4, which is slightly higher than SVD. This phenomenon shows the relative movement between vehicles increases the opportunity that vehicles are in the transmission range of each other. Since the traffic is still light, SVD is only a little higher than the SVD.
3. 4000vph < Traffic Demand < 6200vph: Figure 4 shows traffic is light congested; Figure 3 shows SVD reaches to the highest value. This results from higher traffic density and relative vehicular movement together.
4. Traffic Demand > 6600vph: Figure 4 shows traffic becomes very congested; Figure 3 shows that SVD degrades. The reason is that when the traffic becomes heavy congestion, the relative movement between vehicles is limited. Consequently, fewer vehicles will show up around an individual vehicle close enough to interfere its transmission.

The above observations clearly demonstrate the interaction between the interference of VANETs and the features of traffic flow, such as the microscopic vehicular relative movement and the

*Figure 3. The number of reachable neighbors of individual vehicles in a time interval T = 30s under different traffic flow*



macroscopic traffic flow state. In the next section, we further explore the relationship between the interference of VANETs and traffic flow features by analytical methods.

## Investigating Time-Period Vehicular Degree analytically

Our analytical work first investigates the ~~SVD~~ of VANETs incorporating the microscopic traffic flow features, such as the relative movement between vehicles. The VANETs of interests are further modeled by the method used in (Du & Ukkusuri, 2008b). For completeness, we briefly introduce the main idea by the following points:

1. The VANETs are composed of the vehicles running on the road during the time interval, T. Vehicular velocity is assumed to be constant during the short time interval.
2. Based on the velocity of vehicles, we group the drivers into three categories: aggressive drivers (A), defensive drivers (D), and slow drivers (S). $\alpha, \beta, and\, \gamma$ are used to denote their proportions on the road, $\alpha + \beta + \gamma = 1$.
3. Define $p^{-}_{ij}$ as the probability that vehicle $i$ and $j$, $j > i$ are approaching to each other, and $p(\delta^{-}_{ij}) \geq p^{-}_{ij}$, then, we find there are three possible cases for node $i$ and $j$, ($j > i$) approaching each other. The corresponding probabilities are described below:
    - Vehicle $i$ is an aggressive driver and vehicle $j$ is a defensive driver, $p^{-}_{ij} = \alpha\beta$;
    - Vehicle $i$ is a defensive driver and vehicle $j$ is a slow driver, $p^{-}_{ij} = \beta\gamma$;
    - Vehicle $i$ is a ~~slow~~ driver and vehicle $j$ is a slow driver, $p^{-}_{ij} = \alpha\gamma$.
4. The relative velocity of any node $i$ and $j$ approaching each other, $\delta^{-}_{ij}$ is assumed to be represented by the relative speed between adjacent lanes with a white noise:

$$\delta^{-}_{ij} = \overline{\delta_L} + \varepsilon_{ij},\ \varepsilon_{ij} \sim N(0,\sigma^2), \qquad (2)$$

where, $\sigma^2$ is equal to the variance of the relative speed between any two vehicles which are ~~getting closer to each other~~. Note that $\varepsilon_{ij}$ may not be a normal distribution. The accurate distribution of $\varepsilon_{ij}$ can be obtained from microscopic traffic data in a transportation system. This work is beyond the scope of this study.

5. We numbered the vehicles from entry to exit at time zero, and then drew all communication link happened in the time interval on the topology of VANETs at time zero. This time expanded graph is referred to as Information Flow Networks (IFN). Based on the IFN, we develop the analytical expressions to measure the reachable neighbors for individual vehicles in a given time interval.

To facilitate the further discussion ~~for the further discussion~~, we need the following notations:

- $x^t_{ij}$: The distance between vehicle $i$ and vehicle $j$ at time $t$.
- $p^t_{ij}$: The probability of the event that $x^t_{ij} < r$, $0 < t \leq T$.
- $s_{ij}$: A random variable which denotes the event that $x_{ij} \leq r$ at time zero.

$$s_{ij} = \begin{cases} 1, & x^0_{ij} \leq r | i < j; \\ 0, & \text{o.w.} \end{cases}$$

- $w_{ij}$: A random variable which denotes the event that $x_{ij} \leq r$ after a time period $t$, if $x_{ij} > r$ at time zero. when

$$w_{ij} = \begin{cases} 1, & x^t_{ij} \leq r, \text{and}\ x^0_{ij} \geq r | i < j, 0 < t \leq T; \\ 0, & \text{o.w.} \end{cases}$$

- $z_{ij}$: A random variable which denotes the event that a node has chance to exchange

*Box 1.*

$$z_{ij} = \begin{cases} 1, & \text{node i exchanges messages with node j in the time interval } [0,T], \ i < j; \\ 0, & o.w. \end{cases}$$

message with its forward nodes during the whole time interval.

*(see Box 1)*

Here, the SVD of individual vehicles represents the average number of vehicles in the transmission rang of an individual vehicle during the time period. Therefore, it is composed of two components. The first one is the neighbors which exist at time zero and the other part is the neighbors which occur in (0, T]. Correspondingly, the following equations hold:

$$z_{ij} = s_{ij} + w_{ij}$$

$$\sum_{j=i+1}^{n} z_{ij} = \sum_{j=i+1}^{n} s_{ij} + \sum_{j=i+1}^{n} w_{ij}$$

$$E\left[\sum_{j=i+1}^{n} z_{ij}\right] = E\left[\sum_{j=i+1}^{n} s_{ij}\right] + E\left[\sum_{j=i+1}^{n} w_{ij}\right] \qquad (3)$$

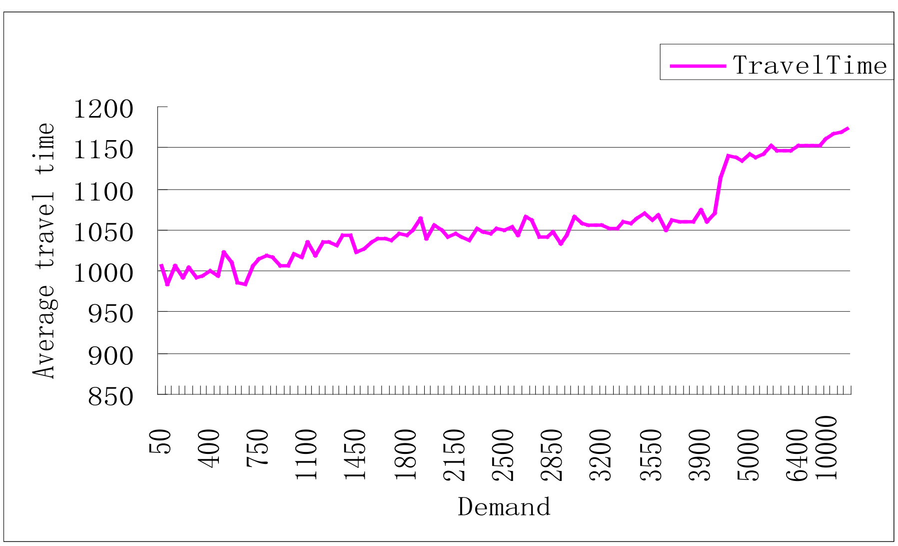
Since vehicle *i* can be aggressive (A), defensive (D), or slow driver(S), we can express the expected number of neighbors of an individual vehicle as below:

$$\begin{aligned} E\left[\sum_{j=i+1}^{n} z_{ij}\right] = p(i \in A)\left(E\left[\sum_{j=i+1}^{n} s_{ij}\right] + E\left[\sum_{j=i+1}^{n} w_{ij}\right]\right) \\ +p(i \in D)\left(E\left[\sum_{j=i+1}^{n} s_{ij}\right] + E\left[\sum_{j=i+1}^{n} w_{ij}\right]\right) \\ +p(i \in S)\left(E\left[\sum_{j=i+1}^{n} s_{ij}\right] + E\left[\sum_{j=i+1}^{n} w_{ij}\right]\right) \end{aligned} \qquad (4)$$

Note that $s_{ij}$ is only related to the traffic density and the vehicle's transmission range, and the mobility of vehicle has no effect on it. Thus, we have

$$E\left[\sum_{j=i+1}^{n} s_{ij}\right] = \lambda r \qquad (5)$$

*Figure 4. Traffic state*



However, the value of $w_{ij}$ is closely related to the relative movement between vehicles, so the value of $E(w_{ij})$can be derived as below:

$$E\left[\sum_{j=i+1}^{n} w_{ij}\right] = \sum_{j=i+1}^{n} E(w_{ij}) = \sum_{j=i+1}^{n} \left(p_{ij}^{T} \cdot 1 + (1 - p_{ij}^{T}) \cdot 0\right) = \sum_{j=i+1}^{n} p(r < x_{ij}^{0} < T\delta_{ij}^{-}) \quad (6)$$

When vehicle $i$ is driven by an aggressive, defensive or slow driver in time interval $T$, the probability that it is approaching the forward vehicles is different. Only considering the relative movement between different driver groups and referring to result of $\delta_{ij}^{-}$ and $p_{ij}$ at the beginning of this section, $E(w_{ij})$ is calculated below:

- Node $i$ is an aggressive driver.

$$E(w_{ij}) = \beta p\left(r < x_{ij}^{0} < r + T(\overline{\delta_L} + \varepsilon_{ij})\right) + \gamma p\left(r < x_{ij}^{0} < r + 2T(\overline{\delta_L} + \varepsilon_{ij})\right); \quad (7)$$

- Node $i$ is a defensive driver.

$$E(w_{ij}) = \gamma p(r < x_{ij}^{0} < r + 2T(\overline{\delta_L} + \varepsilon_{ij})) \quad (8)$$

- Node $i$ is a slow driver.

$$E(w_{ij}) = 0. \quad (9)$$

Inserting Equation (5), (7), (8), and (9) to Equation (4), the expected neighbors of node $i$ is equal to:

*(see Box 2.)*

Therefore, during a short time period, the interference of a successful transmission (EI (T)) is

$$E\left[\sum_{j=i+1}^{n} z_{ij}\right] = 3\lambda r + 3\left\{\alpha\lambda \sum_{j=i+1}^{n} p(r < x_{ij}^{0} < r + 2T(\overline{\delta_L} + \varepsilon_{ij})) + \beta(\alpha + \gamma) \sum_{j=i+1}^{n} p(r < x_{ij}^{0} < r + T(\overline{\delta_L} + \varepsilon_{ij}))\right\} \quad (11)$$

Equation (11) measures the interference of VANETs with a view to the relative movement between vehicles. Additionally, it shows that no matter under which kinds of traffic flow conditions, the relative movement between adjacent lanes will increase the interference of VANETs. In the next step, we calculate the distribution of vehicles on the road under different traffic flow conditions. This will allow us to obtain better insights into the expected interference in view of macroscopic traffic flow states.

## Expected Interference Under Different Traffic Conditions

Our analytical expression in (11) has shown that the interference of VANETs depends on space headway distributions under different traffic congestion levels. We therefore specify the macroscopic traffic feature (space headway distribution) and integrate it into the study of the VANET interference.

The immediate difficulty is that even though traffic time headway has been well studied under different traffic congestion levels, there are no well-developed stochastic models for space

*Box 2.*

$$E\left[\sum_{j=i+1}^{n} z_{ij}\right] = \alpha\gamma \sum_{j=i+1}^{n} p(r < x_{ij}^{0} < r + 2T(\overline{\delta_L} + \varepsilon_{ij})) + \beta(\alpha + \gamma) \sum_{j=i+1}^{n} p(r < x_{ij}^{0} < r + T(\overline{\delta_L} + \varepsilon_{ij})) + \lambda r. \quad (10)$$

headway distribution. Usually, corresponding to free flow, light congestion and heavy congestion traffic condition, time headway is classified into three states: random headway state, intermediate headway state, and constant headway state. Exponential distribution, Erlang distribution, and Normal distribution have been proved to be reasonable stochastic models for the three headway states (May, 1990). To apply these well-built time headway models to space headway, we make more assumptions: (i) the space head- ways between consecutive vehicles are independent and identically distributed; (ii) the vehicular speed is supposed to be uniform (Tsugawa & Kato, 2003) with mean. Thus, the relationship between space headway ($H_s$) and time headway ($H_t$) is

$$H_s = H_t, \tag{12}$$

where $\bar{\delta}$, is the average speed of vehicles. If $\bar{\delta}$ is a constant, the space headway will have the same distribution with the time headway. With above assumptions we explore the interference of one successful transmission under different space headway states.

Under random headway state (free flow condition), vehicles can be thought of as traveling independently. Except for the minimum headway specification, the time headway is considered as random headway. The random time headway is usually described by exponential distribution in analytical models (May, 1990; Saito, 2006; SchÄonhof et al., 2006). Similarly, we use exponential distribution to present the distribution of the space headway under free flow. The corresponding interference in a short time period can be written as shown in Box 3.

Under the intermediate headway state, the distribution of the time headway is approximated by Erlang distribution (May, 1990). Consequently, the space headway distribution can be modeled as Erlang:

$$f(x) = \frac{1}{\theta\Gamma(b)}\left[\frac{x}{\theta}\right]^{b-1} e^{-\frac{x}{\theta}} \tag{14}$$

where,

- x is the space headway.
- b is the shape parameter. $b = \frac{H_s^2}{\sigma_s^2}$
- $\frac{1}{\theta}$ is the scale parameter.

The mean of the space headway is $b\theta = H_s$, so the estimated scale parameter $\theta = \frac{\overline{H_s}}{b} = \frac{\sigma_s^2}{H_s}$ and traffic density $\lambda = \frac{1}{b\theta}$, Furthermore, $x_{ij}$, $j = i + 1, \ldots, n$ obeys Erlang distribution, so let $p(x_{ij} \le r) = Er(r,|j = i|b,)$ The interference can be written as shown in Box 4.

Under the constant headway state, the distribution of the time headway is described by normal distribution (May, 1990). We additionally use normal distribution to describe the space headway with mean $H_s$ and variance $\sigma_s^2$. Moreover, for $x_{ij}$,

*Box 3.*

$$E\left[\sum_{j=i+1}^{n} z_{ij}\right] = 3K_c$$
$$+3\left\{\alpha\gamma\sum\nolimits_{j=i+1}^{n}\left(E\left(\left(r + 2T(\overline{\delta_L} + \varepsilon_{ij})\right),|j-i|,\frac{1}{\lambda}\right) - E\left(r,|j-i|,\frac{1}{\lambda}\right)\right)\right.$$
$$\left.+\beta\left(\alpha+\gamma\right)\sum\nolimits_{j=i+1}^{n}\left(E\left(\left(r + T(\overline{\delta_L} + \varepsilon_{ij})\right),|j-i|,\frac{1}{\lambda}\right) - E\left(r,|j-i|,\frac{1}{\lambda}\right)\right)\right\}. \tag{13}$$

*Box 4.*

$$
\begin{aligned}
&E\left(\sum_{j=i+1}^{n} z_{ij}\right) = 3K_c \\
&+\left\{\alpha\gamma\sum\nolimits_{j=i+1}^{n}\left(Er\left(\left(r+2T\left(\overline{\delta_L}+\varepsilon_{ij}\right)\right),|\,j-i\,|\,b,\theta\right)-Er\left(r,|\,j-i\,|\,b,\theta\right)\right)\right. \\
&\left.+\beta(\alpha+\gamma)\sum\nolimits_{j=i+1}^{n}\left(Er\left(\left(r+T\left(\overline{\delta_L}+\varepsilon_{ij}\right)\right),|\,j-i\,|\,b,\theta\right)-Er\left(r,|\,j-i\,|\,b,\theta\right)\right)\right\}
\end{aligned} \tag{15}
$$

*Box 5.*

$$
\begin{aligned}
&E\left[\sum_{j=i+1}^{n} z_{ij}\right] = 3K_c \\
&+3\left\{\alpha\gamma\sum\nolimits_{j=i+1}^{n}\left(N\left(\left(r+2T\left(\overline{\delta_L}+\varepsilon_{ij}\right)\right),|\,j-i\,|\,H_s,|\,j-i\,|\,\sigma_s^2\right)-N(r,|\,j-i\,|\,H_s,|\,j-i\,|\,\sigma_s^2)\right)\right. \\
&\left.+\beta(\alpha+\gamma)\sum\nolimits_{j=i+1}^{n}\left(N\left(\left(r+T\left(\overline{\delta_L}+\varepsilon_{ij}\right)\right),|\,j-i\,|\,H_s,|\,j-i\,|\,\sigma_s^2\right)-N\left(r,|\,j-i\,|\,H_s,|\,j-i\,|\,\sigma_s^2\right)\right)\right\}
\end{aligned} \tag{16}
$$

$j > i + 1$, the distance between nonadjacent vehicles also obeys normal distribution with mean $|j-i|\overline{H}_s$ and variance $|j-i|^2\sigma^2_s$. Let $p(X_{ij} < r) = N(r, |j-i|\overline{H}_s, |j-i|^2\sigma^2_s)$, then the interference of a successful transmission can be measured by the equation shown in Box 5.

In Equations (13), (16), and (15), the composition of drivers and relative movement between adjacent lanes roughly present the relative movement between vehicles. Different space headway distribution characterizes the dynamic traffic flow state. Hence, we conclude Equations (13), (16), and (15) together analytically measure the interference of VANETs on account of both macroscopic and microscopic traffic flow features. To validate our analytical results, we perform the following experiments based on simulation.

## Validating the Expected Degree Under Different Traffic Flow Conditions

We have examined the expected vehicular degree under different traffic flow states by simulations, where $K_c = 3$, T = 30s, and demand changes from 50vph to 8000vph. Based on our VANET models and well-build time headway distribution models, we further developed the stochastic models to approximate the interference under different traffic headway states. Now, based on the simulation models we validate our stochastic models in Equation (13), Equation (15), and Equation (16). We consider the drivers as aggressive drivers, if their velocity is fifteen percent higher than the average velocity of all vehicles. Correspondingly, a driver is a slow driver if his/her velocity is 15% lower than the average speed. All other drivers are treated as defensive drivers. The relative movement between individual vehicles is substituted by the average relative speed between driver groups. The validation results are reported in Figure 5, Figure 6, and Figure 7 respectively. When time headway is under random state (free flow), the difference between simulation counts and analytical calculation on SVD is around 15%. While time headway under intermediate state (light congestion), or constant state (heavy congestion), the difference is about 10%. Clearly, our stochastic models perform reasonably good to evaluate the SVD in the time intervals.

*Figure 5. The relative difference between adegree and sdegree under free flow (abs(.): absolute value. adegree: the expected vehicular degree calculated by our analytical expression; sdgree: the expected vehicular degree measured by simulation)*

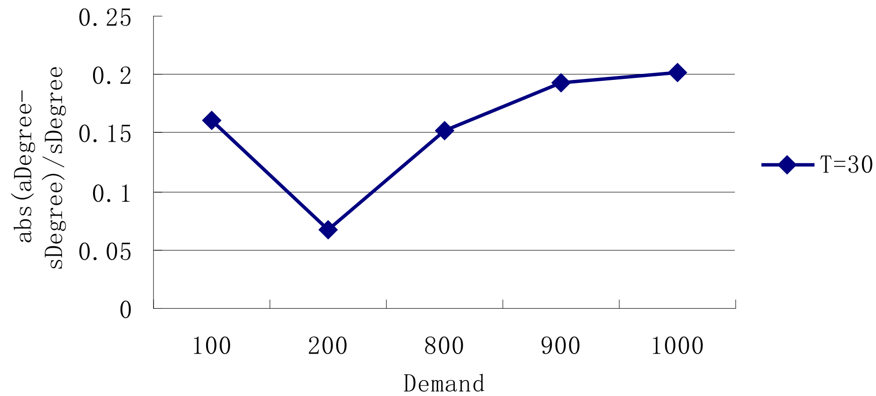



*Figure 6. The relative difference between adegree and sdegree under light congestion flow*

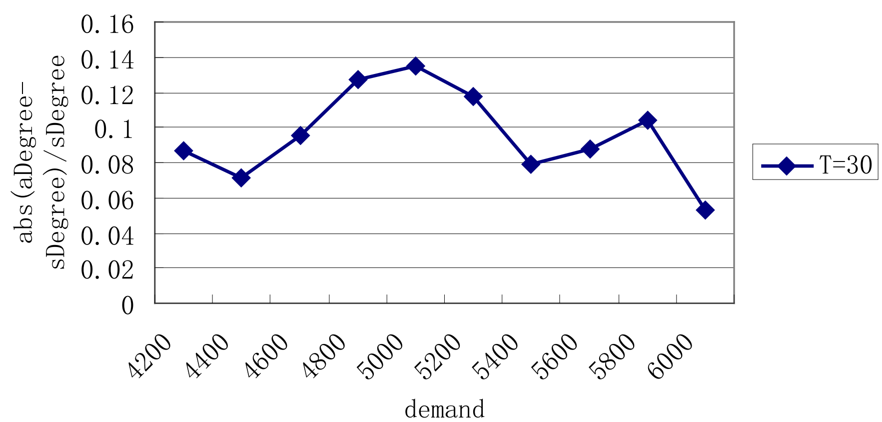
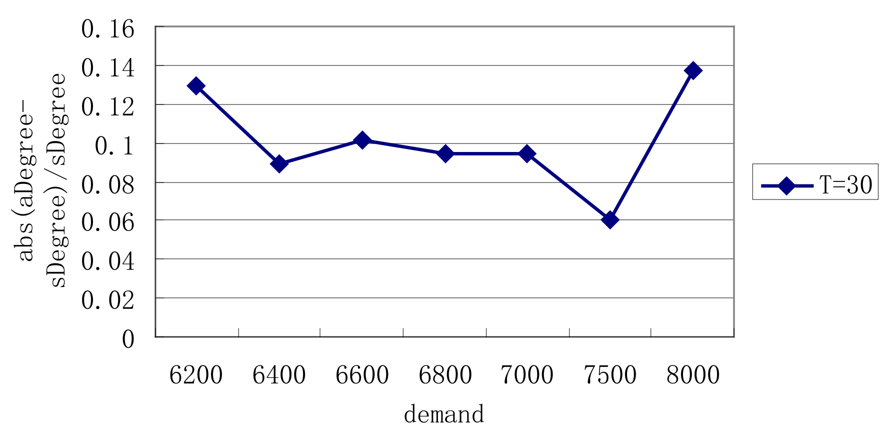



*Figure 7. The relative difference between adegree and sdegree under heavy congestion flow*



Our simulation experiments also demonstrate that the accuracy of our models can be improved with cost of adding more numerical computations to cluster drivers more accurately. For example, in our simulations, if we consider drivers as aggressive drivers by its velocity 13% higher than the average value, the performance of the analytical interference evaluation might become better.

## CONCLUSION

There are two interweaved layers within VANETs, namely, the communication layer and the transportation application layer. Most of the previous research about the communication layer treated VANETs as a special class of Mobile Ad Hoc Networks (MANETs) and ignored the traffic flow features. To overcome this deficiency, our research incorporated both macroscopic and microscopic traffic flow characteristics into the study of several fundamental issues in the communication layer of VANETs such as the connectivity, the reachability, and the capacity of VANETs.

Along the line of our completed work, the study presented here investigates another fundamental issue in VANETs: interference. Due to the high vehicular mobility and the dynamic traffic flow features, the interference in VANETs presents distinguishing features. To characterize the interference in VANETs, we first set up the simulation models to explore the interference under different traffic flow conditions. The results demonstrate: When each vehicle adjusts its transmission range to reach the same number of neighbors according to the traffic density, the interference of individual transmission in a short time interval, such as T = 30s, is much higher than the corresponding interference under static vehicle distribution; Relative movement between vehicles and traffic congestion level impact the interference of VANETs significantly; Under free and light congestion traffic condition, the interference increases with demand. However, under heavy congestion, the interference will decrease as demand increases.

Furthermore, under our assumptions, we develop the stochastic models to estimate the expected interference of VANETs. Our closed form expressions approximate the interference in VANETs taking accounting of both the macroscopic and the microscopic traffic flow characteristics. The validation results based on the simulation data demonstrate that our analytical expressions perform well under various traffic conditions. In summary, our research efforts try to investigate the information propagation in VANETs bridging the features in both the communication layer and the transportation layer and therefore help to build more efficient systems.

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## ENDNOTES

1 Throughput of an ad hoc network is usually defined as the maximum bits per second that is achievable by all source-destination pairs of nodes.

2 The vehicles which are in the transmission range of an individual vehicle.

3 To check TVD by simulation, the reader is referred to the algorithm described in Du et al. (2008b).