CONNECTIVITY IN INTER-VEHICLE AD HOC NETWORKS

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Abstract

A two-stage simulation model is developed to investigate the effects of free-flow traffic on connectivity in inter-vehicle ad hoc networks. A traffic microsimulator generates vehicles movement in a multi-lane, unidirectional highway, and a simple network model maintains connectivity graphs between the moving vehicles. The free-flow conditions allow vehicles to travel at their maximum velocities, virtually unobstructed by other vehicles because of low vehicle density.

We examine some factors that determine the network's ability to maintain an active communication session between a pair of vehicles. Vehicle density, relative velocity, and number of lanes are found to have a key influence on connectivity. The effect of distance, however, depends on the communication range. We also find that the probability distribution of connection lifetime resembles a power law function.

Keywords: Inter-vehicle communication; ad hoc networks; connectivity; traffic microsimulator; mobility.

1. INTRODUCTION

Among the challenges of Mobile Ad hoc Networks (MANET) is the frequent change of their topologies caused by the mobility of the participating nodes. For this reason, evaluation studies of MANETs often involve a discussion of node mobility. Many mobility models found in the literature describe people motion in different environments, indicating the interest in applying MANETs in inter-personal communications [1].

Recently there has been growing interest in using MANETs for inter-vehicle communication because of their promising applications [2]. Consequently, applying a suitable vehicle traffic model is an essential step in evaluating inter-vehicle ad hoc networks (IVAN). Despite their common use, mobility models used in [1] are not suitable for vehicle movement patterns. Neither are the models used in the studies of cellular systems, which focus on aggregate statistics, such as road capacity and cell residence time [3]. Evaluation of inter-vehicle ad hoc networks requires mobility models that provide a detailed description of individual vehicle movement. A class of vehicle traffic models known as microscopic models can provide this movement.

The main objective of this paper is to use a vehicle traffic model to investigate the effect of various road dynamics on connectivity of IVANs in highway environments. We define connectivity as the condition when a valid communication route between two vehicles exists in order to exchange data packets. Several factors may contribute to the possibility of finding a valid route between any two communicating vehicles. Among the considered factors are density, velocity, and distance between vehicles in free-flow conditions. These conditions represent a highway environment where vehicles are distributed sparsely and travel, unobstructed, at velocity close to the maximum allowed speed. Moreover, we also examine the probability distribution function of connection lifetimes.

The simulation environment used here is composed of two components; a traffic microsimulator that generates vehicle mobility traces, and a simple network simulator that maintains a connectivity graph between moving vehicles. The choice of simple network model is necessary as a preliminary step in investigating the main factors affecting connectivity before employing more detailed, and power demanding, network simulators.

The paper is organized as follows. The next section describes the simulation environment followed by the experimental setup in Section 3. The results and their analysis are described in Section 4. Related work is listed in Section 5. Section 6 concludes the paper.

2. SIMULATION ENVIRONMENT

This section introduces the simulation environment used to evaluate connectivity in inter-vehicle ad hoc networks. Subsections 2.1 and 2.2 describe the traffic model and the traffic characteristics, respectively. Subsection 2.3 describes the network model.

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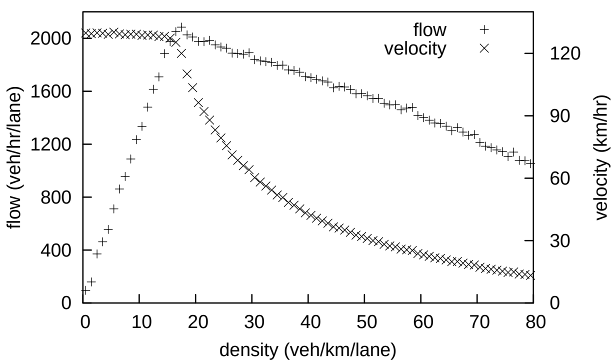


Fig. 1 Flow-density and velocity-density curves

2.1 Vehicle Mobility Model

We developed a traffic microsimulator based on the Nagel/Schreckenberg cellular automata model [4], [5]. The model segments a road with periodic boundary conditions (ring) into L sites of length l_c=7.5m, where l_c is chosen to represent the average length a vehicle occupies in a jam. Sites can be either empty, or occupied by exactly one car traveling at integer velocity values, $u=0..u_{max}$, Each time step of 1s, vehicles move u number of sites, provided that no obstacles are encountered. Taking l_c and the time step into account, one finds that selecting a maximum speed of $u_{\max}$=5 sites/s corresponds to a realistic highway speed of 135 km/h. The maximum density approaches ρ_{max}=1/7.5m≈133 veh/km/lane.

The configuration of the road is updated at the beginning of each time step according to a set of rules that is applied to all vehicles simultaneously. The rules use the distance to neighboring vehicles and their velocities to calculate the new velocity and position of each vehicle [6]. As a result, all vehicles appear to be of the same type (say, passenger cars) and follow the same driving rules such as acceleration/deceleration, and lane change. The rules do not favor one lane over the others; therefore, vehicles remain equally distributed among all lanes.

The model takes road length, L (sites), number of lanes, K, and number of vehicles, N, as input parameters. Since N remains constant, due to the closed boundary conditions, the system density $\rho_{sys}=N/L$ is also constant. The output produced each time step comes in the form of an array of vehicles whose i^{th} item is a tuple, (v_i, x_i, y_i, u_i), that contains a vehicle ID, cell, lane, and speed, respectively.

2.2 Traffic Flow Characteristics

The characteristics of the traffic module are illustrated in Fig. 1. The figure combines the output of multiple simulation runs, with different values of ρ_{sys}. Although ρ_{sys} is constant throughout the simulation, local vehicle density ρ varies in different sections of the road at different times. Therefore, each data point in the plot represents an average of measurements of density, flow, and velocity taken in a fixed highway section of $(5\times l_c)$ length over 3-minute period [6].

We rely on the traditional traffic flow theory [7] to interpret Fig. 1. The theory defines a relationship among three main quantities, vehicle density, flow, and velocity. The density of vehicles ρ, is obtained by counting the number of vehicles between two positions on the highway at fixed times. If the vehicle length is ignored, the density is defined as $\rho=1/d$, where d is the average distance between the vehicles.

It can be shown that, at any point along the road, the velocity of a vehicle depends only on the density of vehicles in that location,

$$u = u(\rho)\,. \qquad (1)$$

The flow q is defined as the number of vehicles that pass an observer within a certain time period. The flow is related to the other quantities by $q=\rho\cdot u$. Since the velocity is also a function of density,

$$q = \rho \cdot u(\rho)\,. \qquad (2)$$

The relationships (1) and (2) are depicted in the velocity-density and flow-density curves of Fig. 1. The flow-density curve shows that flow increases linearly as density increases, until it reaches its peak at a critical density, ρ_c. Below this density, the velocity-density curve indicates that a car could travel near its maximum speed without interference from other vehicles. As density increases, traffic jams become more common and velocity is decreased gradually until vehicles come to complete stop in jams, i.e. $u(\rho_{max})=0$.

The flow in the region below ρ_c is known as free-flow traffic and vehicle velocity in this region is defined as the free flow speed, u_f,

$$u_f = u(\rho) \quad 0 < \rho \le \rho_c\,.$$

It appears from the figure that the critical density ρ_c≈17 veh/km/lane traffic. The flow reaches its peak at $q(\rho_c)$≈2100 veh/hr/lane. The free flow velocity approaches u_f≈129 km/hr.

2.3 Network Evaluation Model

The network model omits issues such as contention, delay, and transmission errors in order to focus on connectivity. The model assumes that all N vehicles in the road are equipped with wireless transceivers and are cooperative (i.e. willing to forward packets for other vehicles). Since the vehicles are the transceiver nodes that form the ad hoc network, both terms are used interchangeably throughout the paper. Some vehicles

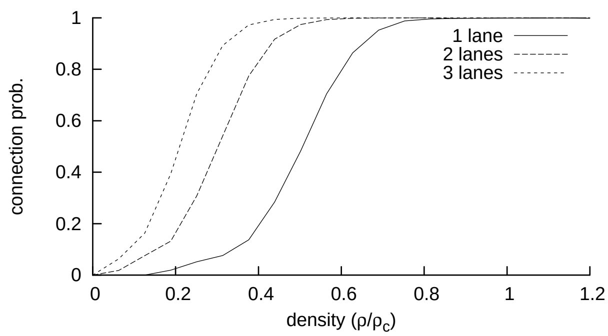


Fig. 2 Vehicle density vs. connectivity

participate in a communication session, a connection, with another vehicle as the sending, *s*, or the receiving, *r*, node.

A connectivity graph is maintained between all nodes on the road. The connectivity graph is the graph $G = (V, E)$, such that:

$$V = \{v_1, v_2, \cdots v_N\}$$

A communication link is established between nodes v_i and v_j if both nodes are within the transmission range R of each other. The links represent the edges in G.

$$e_{i,j} = [v_i, v_j]$$

$$E = \{e_{i,j} \mid i \neq j, dist(v_i, v_j) \leq R\}$$

Due to the circular shape of the road, the distance between any two nodes is defined as the minimum of the distances measured in the clockwise and counterclockwise directions:

$$dist(v_i, v_j) = \min(|x_i - x_j|, L - |x_i - x_j|) \tag{3}$$

At each simulated time step, the output of the traffic simulation model is used to construct the graph G. The network model searches for a path, $P_{s,r}$, that connects each communicating pair (s, r).

$$P_{s,r} = (v_1, v_2 \cdots v_m) \quad v_1 = s, \quad v_m = r$$

The existence of such a path indicates the possibility of routing data packets along the path. The network model assumes that the time required updating a connectivity graph and searching of all paths is negligible. Therefore, delay is not considered.

3. EXPERIMENTAL SETUP

The traffic simulation is set for a one-way highway section of 7.5km length (L=1000). Different simulation runs are carried out using system densities, ρ_{sys}, of 1 to 20 veh/km/lane as input parameters. The number of lanes, K, also varies from one to three lanes.

Each simulation generates 17.5 hours of vehicle movement. The first 7.5 hours are discarded to remove the transition period. The trace of vehicles position and velocity of the remaining 10 hours is supplied to the subsequent network simulation. The simulator generates a total of 12,000 hours of vehicle movements.

The network simulation starts by randomly creating N/2 connections. Each time step, the simulator updates the connectivity graph based on the new vehicle positions, and searches for valid paths between the communicating pairs. In all scenarios, the transmission range is fixed at R=250m which is roughly the radio range of IEEE802.11.

The network simulation generates a database that includes more than 1.7×10^8 records. Each record includes data related to a single connection and accompanying road conditions. This data is used in the following section to demonstrate the effect of vehicle traffic characteristics on connectivity.

4. RESULTS AND ANALYSIS

We begin the analysis by introducing some definitions. Let $M_{s,r}$ be a set that includes all vehicles located in the shortest distance between the communicating pair (s, r), $M_{s,r} = \{s, r, v_i \mid dist(s, v_i) + dist(v_i, r) = dist(s, r)\}$.

Given the dynamic nature of traffic, the local values of some quantities such as velocity and density are measured using the vehicles in the set $M_{s,r}$. For instance, the local density of the vehicles between the pair (s, r) is given by:

$$\rho_{s,r} = \frac{n-1}{K \cdot dist(s,r)}, \tag{4}$$

where $n=|M_{s,r}|$ is the number of vehicles in the set.

Furthermore, let $X(s, r)$ be a random variable that takes the values 1 or 0, reflecting the status of the path $P_{s,r}$.

$$X(s,r) = \begin{cases} 1 & iff\ P_{s,r}\ exists, \\ 0 & otherwise. \end{cases} \tag{5}$$

Therefore, the probability of obtaining an active connection (valid route) between vehicle pair (s, r) is $p[X(s, r)=1]$.

In the analysis of the simulation data, we use conditional probability as a metric to measure connectivity while a specific road factor exists. To explain by example, the conditional probability of finding an active route given there is a specific vehicle density, is given by:

$$p[X(s,r)=1 \mid Z = \rho_{s,r}] = \frac{p[X(s,r)=1 \cap Z = \rho_{s,r}]}{p[Z = \rho_{s,r}]} \tag{6}$$

where Z is a random variable that takes the value of a local vehicle density $\rho_{s,r}$, and $p[Z=\rho_{s,r}]$ is the probability of occurrence of this density.

The value of (6) is obtained from the simulation output database using [8]:

$$p[X(s,r)=1 \mid Z = \rho_{s,r}] \approx \frac{c(active, \rho_{s,r})}{c(\rho_{s,r})}. \tag{7}$$

The quantity $c(\rho_{s,r})$ denotes the count of all database records that include a vehicle density of value $\rho_{s,r}$. The quantity $c(active, \rho_{s,r})$ denotes the count of all records in

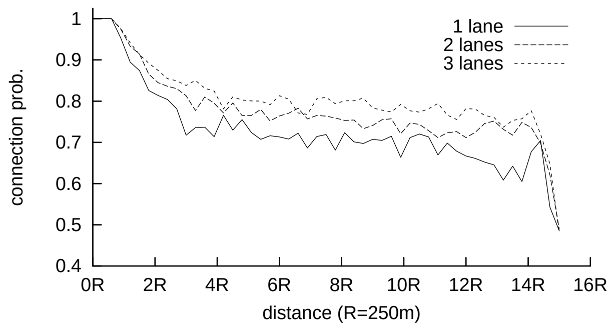


Fig. 3 Distance vs. connectivity

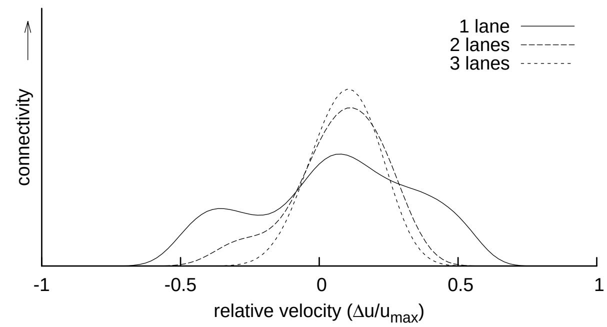


Fig. 4 Relative velocity vs. connectivity

which the route is active while the local density exists. Database records that include higher vehicle densities ($\rho_{s,r} > \rho_c$) are removed to ensure that all factors are considered under free-flow conditions only (i.e., $\rho_{s,r} \leq \rho_c$).

In the following sections, equations similar to (6) and (7) are used also to measure the influence of distance and relative velocity on connectivity. Discrete values of these quantities are obtained using histograms to break up data into disjoint ranges and count the number of records in each interval.

4.1. Density Effect

Fig. 2 shows the probability of having an active connection between two vehicles as a function of vehicle density as defined in (7). The horizontal axis represents the density ratio, (ρ/ρ_c). The different curves correspond to different number of lanes.

The plot confirms the intuition that increasing vehicle density improves connectivity. For 1-lane road, the conditional probability increases to its maximum near ρ_c as the density increases. In multi-lane road, the probability of having an active link is higher relative to 1-lane road due to the increased number of vehicles and increased mobility.

Although we only study free flow traffic in this paper, we also notice the effect of congestion on connectivity (not shown in the figure). The data suggests that once density exceeds the critical density $\rho>\rho_c$, the conditional probability declines again in a single-lane road. This behavior can be attributed to the uneven distribution of vehicles caused by traffic jams in high densities. If one vehicle is trapped in a jam while the other is escaping it, the distance between them increases beyond the network's ability to maintain an active link. This phenomenon is less noticeable in a multi-lane road because of the vehicles ability to change lanes to avoid being held by slower vehicles.

4.2. Distance Effect

Fig. 3 shows the connectivity relation to the distance between the communicating vehicles. The horizontal axis is given relative to the transmission range, R. The distance between any communicating pair of vehicles is determined using (3). Due to the ring shape of the road, the maximum distance between any two vehicles in the ring is $dist_{max}(r, s)=L/2=3.75\text{km}=15R$.

The plot confirms that finding a valid connection is guaranteed when the distance between the communicating pair does not exceed R. Connectivity drops rapidly beyond that point because of relying on intermediate nodes, which may not always be available. Connectivity loses its sensitivity to distance and declines at a slower rate as the distance increases. The curves show also that increasing the number of lanes improves the connectivity.

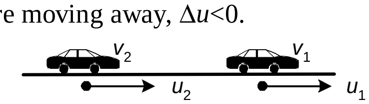
The drop in connectivity towards the maximum distance is a result of the network model. In routes that span distances near the maximum, any slight change in the distance between the communicating pair around the $L/2$ point changes the direction of the route search towards the shortest arc in the ring. This causes a frequent change of routes and a drop in connectivity.

4.3. Velocity Effect

Relative velocity, Δu, between any two vehicles traveling in the same direction is given by,

$$\Delta u = u_2 - u_1$$

Since the result can be negative, the sign is interpreted as: 1) vehicles are closing on each other, $\Delta u>0$, or 2) vehicles are moving away, $\Delta u<0$.



The average relative velocity, $V_{s,r}$, among all vehicles traveling between the communicating pair (s,r) is calculated using,

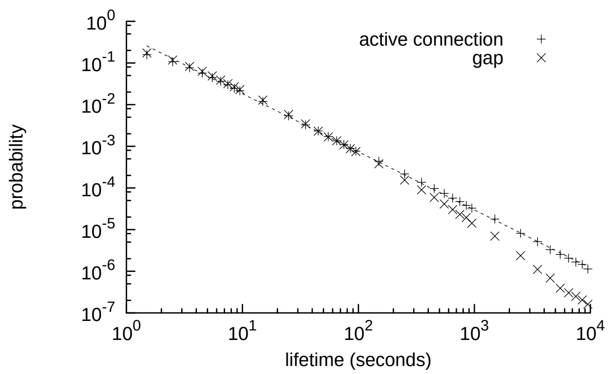


Fig. 5 Probability distribution of connection and gap lifetime

$$V_{s,r} = \frac{2}{n(n-1)} \sum_{i=1}^{n} \sum_{j=i+1}^{n} u_i - u_j \ ,$$

where $n=|M_{s,r}|$.

The horizontal axis in Fig. 4 represents the relative velocity, $V_{s,r}$. The curves are smoothed to emphasize general trends rather than precise probabilities. The figure shows that vehicles in multi-lane roads are more likely to maintain an active connection while they are closing on each other at similar speeds, i.e. u_2 slightly higher that u_1. Such a situation is possible because vehicles are able to maintain consistent speed by changing lanes. As Δu increases, vehicles move apart and the connection breaks. In 1-lane roads a vehicle's movement is more restricted and its velocity has to adapt to the vehicle ahead. This causes connectivity to be lower relative to multi-lane roads. Yet, it occurs at a wider range of relative velocities.

4.4. Connection Lifetime

This section discusses the effect of vehicle mobility on connection lifetime. The connection lifetime $\tau_{i,j}$ is defined as the longest time interval [t_1, t_2] during which the connection is active given that there is no connection at time t_1-ε and time t_2+ε. To define connection lifetime formally, a time notation is added to the definition in (5), in order that $X(s, r, t)$ represents the status of a connection at time step, t. Therefore,

$$\tau_{s,r} = \begin{cases} t_2 - t_1 & \text{iff } \forall t \ \ t_1 \le t \le t_2, \varepsilon > 0 : X(s,r,t) = 1, \\ & X(s,r,t_1-\varepsilon) = X(s,r,t_2+\varepsilon) = 0, \\ 0 & \text{otherwise.} \end{cases}$$

A histogram of active connection time periods is plotted using data taken from all simulation scenarios. In order to get enough data for smooth averages, a numerical cutoff limit is imposed on connection lifetime by removing any connection period of 10^4 seconds or longer from consideration. The resultant plot represents averaged data from about 5×10^6 events.

The double log plot shown in Fig. 5 indicates that, for $\tau > {\sim}7$, the active connection lifetime follows a power law probability distribution function (pdf),

$$p_T(\tau) \approx \lambda \tau^{-(\alpha+1)} \ , \qquad (8)$$

where α and λ are constants. The dotted line in Fig. 5 represents the function $0.45\tau^{-1.3942}$. The power law distribution shows that communication sessions break frequently at high rate due to vehicle movement. In fact, the pdf in (8) does not have a finite mean.

This proximity to the power law is observed over four orders of magnitude because of the imposed limit. The behavior persists for a larger cutoff limit. However, to get enough data for accurate measurements, more simulation runs are needed.

If we let $\lambda=\alpha\beta\alpha$, the probability of connection survival for a certain time is related to (8) by

$$\Pr_{surv}(T > \tau) = \int_{\tau}^{\infty} p_T(t) \cdot dt \approx \left(\frac{\tau}{\beta}\right)^{-\alpha} \quad \tau \ge \beta \ , \qquad (9)$$

which is a Pareto distribution with α and β as the shape and scale factors, respectively.

Fig. 5 shows also the pdf of gap duration, the time when a connection is inactive because no valid route is found. Unlike connection time, the probability distribution of gap duration deviates from a straight line as time increases.

5. RELATED WORK

Few studies focused on vehicles as the primary type of mobile nodes in MANETs; even fewer used special mobility models for vehicle movements or traffic simulators. We introduce here three papers that used traffic microsimulators to study some aspects of inter-vehicle networks under free-flow conditions.

In [9], a traffic microsimulator is used to create a two-way highway stretch, and a network simulator is used to send data packets from one vehicle to another that is 10km away. The paper reports that vehicle mobility contributes to successful message delivery. Factors such as increased vehicle density, bi-directional traffic, and multiple lanes, lower the end-to-end transmission delay.

Another traffic microsimulator is used in [10] to create a bi-directional, 2-lane highway with an average vehicle density of 6 veh/km/lane and velocity of 130 km/hr. It is observed that network partitions (due to gaps) are frequent even when vehicle density is high. Increasing the transmission range or relaying packets over the incoming vehicles can reduce these partitions. A similar behavior is observed in our simulations when vehicle density surpasses the critical density in 1-lane road.

Traffic simulators and analytical methods are used in [11] to find the probability distribution function of the communication duration between vehicles in different highway scenarios. The reported results show discrepancies with our simulation results. The main reason is the initial assumptions made in [11] regarding the velocity distribution function, which is used also as an input parameter to the simulation. Vehicles in our network model have a virtually constant velocity under free-flow conditions.

6. CONCLUSIONS AND FUTURE DIRECTIONS

This paper discusses connectivity for inter-vehicle networks in highway environment. A vehicle traffic microsimulator is used to generate free flow vehicle movement where vehicle travel at velocities near their maximum without being restricted by other vehicles. The probability of maintaining an active connection is used as a metric to measure connectivity.

The paper shows that, under free flow conditions, connectivity increases as either the density or the number of lanes increases. The distance between the communicating vehicles has a major impact on connectivity within 3-4 times the communication range. Beyond this distance, the connectivity declines slowly. The results regarding the effect of velocity show that connectivity is likely to occur when the two communicating vehicles travel at the same speed in multi-lane roads. Furthermore, the results demonstrate that the probability distribution of active connection lifetime can be approximated by a power law function.

This paper is a part of our ongoing efforts in the area of inter-vehicle ad hoc networks. One future objective is to expand the work presented here by investigating the effect of bi-directional traffic and traffic jams on maintaining connectivity. Traffic jams are common at busy intersections or when accidents occur. Some of the preliminary trials indicate that jams may have an adverse effect on connectivity.

In various MANET studies, mobility is measured using a metric based on one or a number of factors such as nodes pause time, velocity, or neighbor change rate. Understating the various factors that affect connectivity will lead to the development of a suitable mobility metric that takes into account all factors that contribute to the dynamic nature of MANETs. The developed metric will be useful in measuring the performance of MANET protocols under various traffic scenarios.

The distribution of connection lifetime raises an important question about the ability of current ad hoc routing protocols to react properly to the frequent breaks in connection. Future work will evaluate some common ad hoc routing protocols under the same conditions presented here using more detailed network simulators.

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