Connectivity with Static Transmission Range in Vehicular Ad Hoc Networks

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Abstract

Connectivity in mobile wireless ad-hoc networks is maintained by setting the transmission range so that a node can establish a link to any other node in the network either directly or over multiple hops. Many analytical and experimental studies have focused on determining the minimum transmission range (MTR) that provides connectivity while minimizing transceiver power for various levels of node densities.

In this paper, we determine, using simulations, the MTR in vehicular ad hoc networks (VANET) of various road configurations. We show that in 1-lane, 2-lane, and 2-way roads, MTR values confirm the analytical relations developed in the literature for 1-dimensional networks until density increases beyond a critical vehicle density. Moreover, where traffic jams are forming at intersections, MTR values are not affected by the change in vehicle density. Therefore, a large static transmission range must be chosen in order to keep the network connected in all traffic scenarios.

Keywords— Connectivity, vehicular ad-hoc networks, VANET, minimum transmission range, mobility.

1. Introduction

Mobile ad hoc networks face the difficult challenge of maintaining connectivity so that a node may establish a communication link to any other node in the network. The connectivity of the network is affected by several factors including transmitter power, environmental conditions, obstacles, and mobility. For this reason, extensive research is dedicated to determine the optimal transmission range that guarantees the network's connectivity while saving power and maintaining high capacity through frequency reuse. This type of problem is known in the literature as the range assignment (RA) problem. The RA problem is quite challenging in ad hoc networks in particular because of the frequent topology changes.

In this paper we discuss the range assignment problem in vehicular ad hoc networks (VANET). This class of networks has been enjoying a growing interest recently due to their potential applications in intelligent transportation systems.

VANETs have a few mobility characteristics that distinguish them from other mobile ad hoc networks. For instance, vehicles' mobility is restricted to predetermined paths, which allow VANETs to be regarded as 1-dimensional networks. In addition, vehicle speed is greatly influenced by traffic density, which varies along the road due to the presence of constraints or some irregular driving behaviour. Although vehicles in VANETs are highly mobile, both velocity and flow of vehicles are dependent on vehicle density [1][2]. The increase in vehicle density causes traffic to shift from free-flow phase, where vehicles movement is unrestricted, to traffic jams caused by dense traffic.

The aim of this paper is to show that the characteristics of vehicle traffic make it difficult to maintain connectivity by assigning all vehicles a fixed transmission range. Such range must be very large to accommodate all traffic conditions. We use traffic simulations to determine the minimum transmission range (MTR) that guarantees the network's connectivity. A traffic simulator [3] is used generate vehicles movement in five road scenarios where traffic flow changes rapidly between free-flow and jammed phases as density changes. The results were compared to relevant theoretical analysis established in the literature.

The rest of this paper is organized as follows: Section 2 lists some related work in the literature. Section 3 describes the vehicle mobility model. Section 4 describes the simulation setup and summarizes the results. Section 5 provides discussion and conclusions.

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2. Related work

The range assignment problem can be expressed by the question: suppose nodes are placed in d-dimensional space of length *L* in each dimension; what is the minimum (critical) value of the transmission range r_c, such that the resultant graph *G*, among the nodes is connected? Researches find that the exact solution to the RA problem in one-dimensional networks is achievable, but only approximations are available in higher dimensions.

Wireless networks are often modeled by a graph $G(V,r_n)$ in which two nodes are connected if their Euclidean distance is no more than r_n. Most studies consider how the transmission range is related with the number of nodes *n*, dispersed according to uniform or Poisson distribution in a fixed area (or line).

Gupta and Kumar [4] study connectivity among nodes distributed uniformly in a unit disc. They determine that if $r_c = \sqrt{(\ln n + c(n))/\pi n}$, then the resulting network is asymptotically connected with probability of one iff $c(n) \to +\infty$. Philips, Panwar, and Tantwai [5] show that in order to cover a square area of *A* populated by repeaters of Poisson density λ, the MTR should grow as $r_{\text{cover}} = \sqrt{(1+\varepsilon)\ln A/\pi\lambda}$ as *A* grows, for any $\varepsilon>0$.

In the case of 1-dimensional models, Piret [6] finds that the lower bound of r_{cov} for nodes located according to Poisson distribution in a line of length *L* is $r_{\text{cover}} = \ln(L\lambda)/2\lambda$. The author shows that, if $r_c = k \cdot r_{\text{cover}}$, then connectivity among nodes approaches $\lim_{L\to\infty} q(r_c, L) = 1$ when $k>2$. Santi and Blough [7] provide tighter bounds on MTR. Their primary result shows that when nodes are distributed uniformly over a line of length *L*, the network is connected if $r_c \in \Theta(L \ln L)/n$, where $r_c>>1$. The lower bound is given as $r_c \in \Omega(L \ln L)/n$ when $1<<r_c<<L$. Desai and Manjunath [8] study connectivity in finite 1- and 2-dimensional networks and provide a probability for gap existence.

Dousse, Thiran and Hasler [9] approach the connectivity problem in both pure ad-hoc and hybrid networks. They conclude that connectivity is limited to short range communications in 1-dimensional and strip networks, because the network remains almost surely divided into an infinite number of bounded clusters.

Other approaches include the work of Bettstetter and Hartmann [10], which discusses connectivity in a shadow-fading environment where a link between two nodes may not exist even though they are located within the transmission range. Cheng and Robertazzi [11] use packet broadcast to derive a relationship between the expected number of broadcasts needed before a gap, the transmission range, and the node density. The authors assume nodes are distributed according to a Poisson distribution along a line. Another approach to solve the connectivity problem involves finding how many neighbours a node should be connected to in order that the overall network is connected. The work of Feng Xue and Kumar in [12] and the paper [5] are examples of such approach.

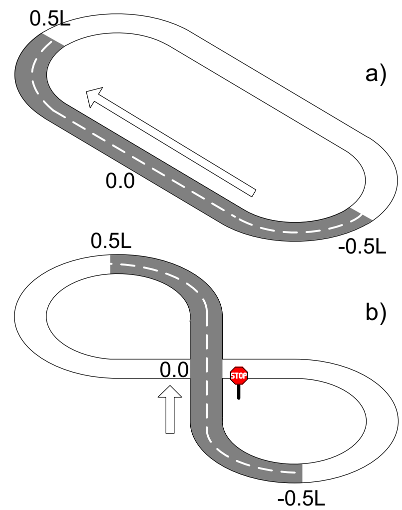

Fig. 1 Road configurations: a) racetrack, b) intersection.

In addition to analytical methods, simulation is used to find the MTR in stationary and mobile networks. Sánchez, Manzoni and Haas [13] present an algorithm to calculate the MTR required to achieve, (with some probability) full network connectivity. The main empirical results show that the MTR decreases as $\sqrt{\ln(n)/n}$ and, when considering mobility, the range has little dependence on the mobility model.

Most of the work presented above assumes that nodes are distributed according to uniform or Poisson distribution. Moreover, mobility is usually modeled in 2-dimensional space. The paper by Füßler et al. [14] focuses on vehicular networks. In the context of comparing various routing strategies, simulations are used to find the effect of the transmission range on the number of network partitions and provide an estimate of the transmission range that minimizes the partitions. It should be noted that the simulations in [14] are limited to free-flow traffic of low density. In [15], we study the effect vehicle density, distance, and speed on establishing connections between pairs of vehicles also under free-flow conditions.

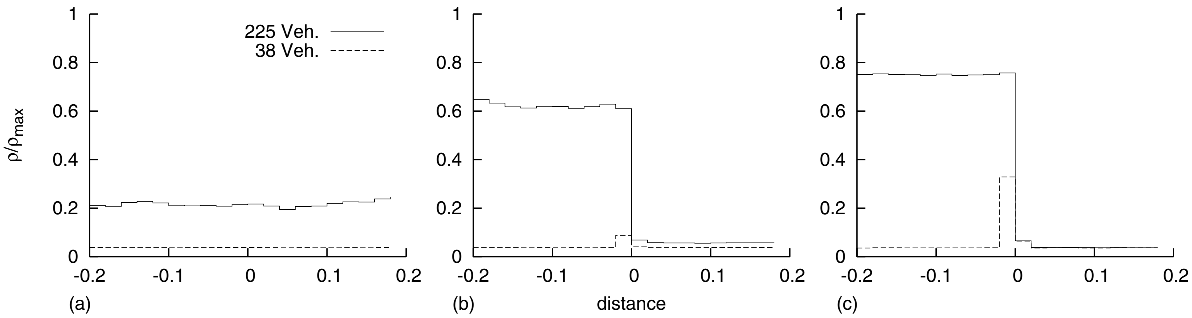

Fig. 2 Vehicle density in a) 1-lane road, b) near a yield sign, and c) near a stop sign.

3. Mobility model

Vehicles' movement traces are generated using a traffic microsimulator, *RoadSim* [3]. RoadSim is based on a cellular automata model that is capable of generating realistic vehicle traffic patterns. In order to observe the effect of various traffic conditions on the MTR, we create five road scenarios:

A, B) One- and two-lane roads. Vehicles in these scenarios travel in one direction. In one-lane road, passing is not allowed. When vehicle density ρ, is low, distance between vehicles is large enough to allow them to travel at free-flow speed. When vehicle density exceeds a critical density, ρ_c, traffic jams start to occur more often and the average speed of vehicles declines accordingly. Note that we denote vehicle density by ρ (veh/km/lane) to distinguish it from node density λ (node/km) that is used in Section 2. They are generally related by $\rho = \lambda / m$, where m is number of lanes.

C) Bi-directional road. In this scenario, vehicles travel in two lanes of opposite directions. All other parameters are similar to A).

D, E) Yield- and Stop-controlled intersections. In these scenarios two roads meet in an intersection controlled by a traffic sign. Vehicles on one road do not face any traffic sign, while vehicles on the other road encounter either a Yield or a Stop sign, which they must obey before crossing the intersection.

Fig.1 shows two road configurations that are used by all five scenarios. Scenarios (A)-(C) use road configuration of Fig.1a where vehicles travel in a closed loop that resembles a racetrack. Scenarios (D) and (E) are represented in Fig.1b, where vehicles cross an intersection in the middle of an 8-shaped road. Other simulation parameters are similar to those listed in [3][15].

The choice of the closed-loop road allows more control over the number of vehicles in the simulation. As a result, the global vehicle density can be made constant throughout the simulation. Local vehicle density, however, varies at different locations of the roads due to vehicle mobility. Therefore, to observe the effect of variable vehicle density, collection of simulation data is limited to the marked area of the road in Fig.1, which represents the total length of the test network, L=3.75km.

The simulation of closed-loop roads also has the disadvantage of creating some periodic traffic cycles. We eliminate the effect of these cycles by limiting the simulation time to the minimum time a vehicle needs to travel the entire road at free-flow speed.

Instead of specifying various vehicle speeds, all vehicles are assigned the same maximum speed. The mobility model varies vehicle's speed dynamically according to the distance between vehicles (i.e. density) regardless of their initial speed. The reason behind the choice of a single maximum speed is to prevent a situation where, in single-lane roads, fast vehicles are packed indefinitely behind vehicles of lower maximum speed; thus, creating unrealistic traffic jams.

It should be noted also that in vehicle traffic, mobility of vehicles (measured by average flow or velocity) is directly dependent on density. Therefore density plays a dual role in this work as the single factor affecting both mobility and connectivity of VANETs.

4. Simulations and results

We ran 40 simulations of each road scenario to generate vehicle movements for periods of 200s after discarding an initialization period. The number of vehicles in these simulations is chosen to create global densities in the range of 5-30 veh/km/lane. The plots of Fig.2 show the average vehicle density ρ, over time

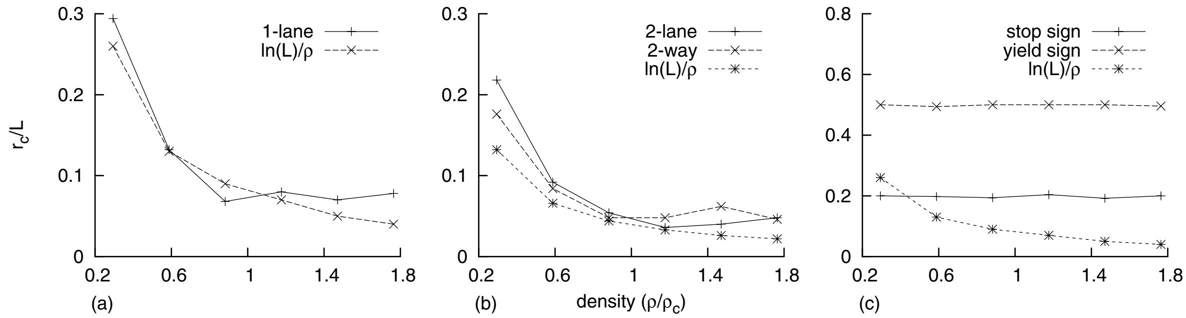

Fig. 3 MTR vs. normalized density in a) 1-lane road, b) 2- lane roads, and c) intersections.

as measured in sections of 75m long extended over 1.5km of the road. The horizontal axis is scaled to show the relative distance to the middle point of the marked road sections in Fig.1. While vehicle density remains equal, on average, in scenarios (a)-(c), Fig.2b,c indicates that intersections disrupt the regular flow of vehicles by creating traffic jams behind the Stop/Yield sign and cause a significant difference in traffic density at both sides of the intersection point. In case of higher densities, traffic jams propagate further upstream from the intersection and persist for longer period of time.

The computation of the MTR is performed as described in [13]. At every simulation time step, a graph, G, is constructed among vehicles within the marked section of the road. The Minimum Spanning Tree (MST) is determined using Prim's algorithm, and then the length of its maximum link is recorded as the value of r_c. Fig.3 shows a plot of MTR values as vehicle density changes in each scenario. Density values in the figure are normalized using the critical density ρ_c, beyond which traffic jams become more frequent and persist longer as density increases. In these simulations, this value is approximately 17veh/km [3].

The MTR values are compared to the relation, derived by Santi and Blough [7] under the assumption that the nodes in 1-D networks follow uniform distribution, which is a reasonable assumption in vehicular network of light density. Fig.3a,b show that $\ln(L)/\rho$ fits as a lower bound for r_c, in one- and two-lane roads. At some point around ρ_c, the value of r_c flattens or begins to increase slightly. Fig.3c shows that the value of r_c in the intersection scenario remains, contrary to intuition, flat for all densities. This phenomenon may be due to the observation that the gap between vehicles that just left the intersection and those that remain waiting for traffic to clear increases quickly as the leaving vehicles accelerate. As a result, a longer transmission range is needed to keep the network connected. This phenomenon persists regardless of vehicle density.

The effect of varying the transmission range, r, on connectivity is evaluated using two metrics: the number of partitions k, in the graph, and the connectivity function, ([13], equation 4), $q(G)=\sum_{i=1}^{k} n_i(n_i-1) \Big/ n_i(n_i-1)$,
where n_i is the number of nodes in partition. The remaining figures show results when the total number of vehicles in simulations is either (n=38), or (n=225), which create the conditions for free-flow (low-density) traffic, and high density traffic, respectively.

To see how a change in the transmission range affects the connectivity, the value of $r<r_c$ is set to 10-90% of the MTR value in each scenario and the average value of the connectivity function, $q(G)$ is calculated. The curves in Fig.4 show that, in 1- and 2-way roads, the connectivity increases almost linearly with the increase in transmission range regardless of the density. In intersection scenarios, there is a noticeable difference between curves representing low and high vehicle densities. Fig.4b shows that connectivity remains high even when the transmission range is reduced to r=0.3r_c.

Since the MTR value differs for each road configuration, the previous figure does not show how connectivity changes with respect to a common transmission range. Fig.5 provides this information, where the number of partitions in the network k, provides another measure of connectivity. A fully connected network has only one partition, k=1. As the transmission range decreases, the number of partitions increases and a node in any of these partitions become more isolated from the rest of the network. It can be noticed from comparing the two plots of Fig.5 that, in all but intersection scenarios, increasing traffic density results in a significant decrease in the transmission range required to create the same number of partitions.

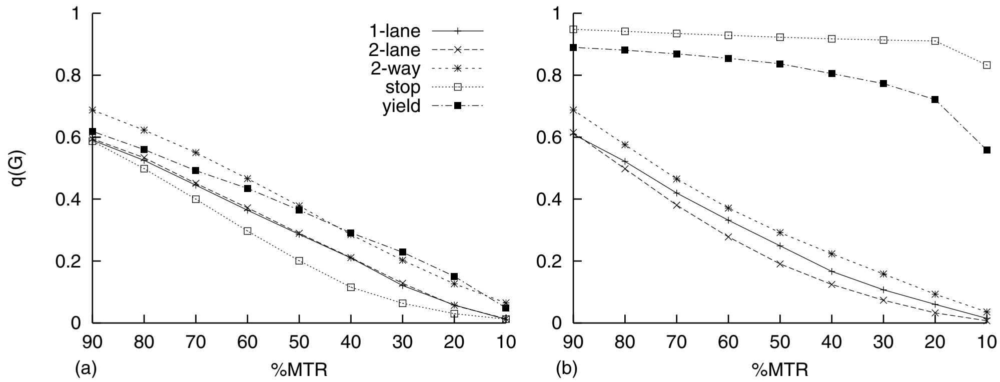

Fig. 4 Average connectivity vs. a fraction of MTR in a) low average density (5veh/km/lane), and b) high average density (30veh/km/lane)

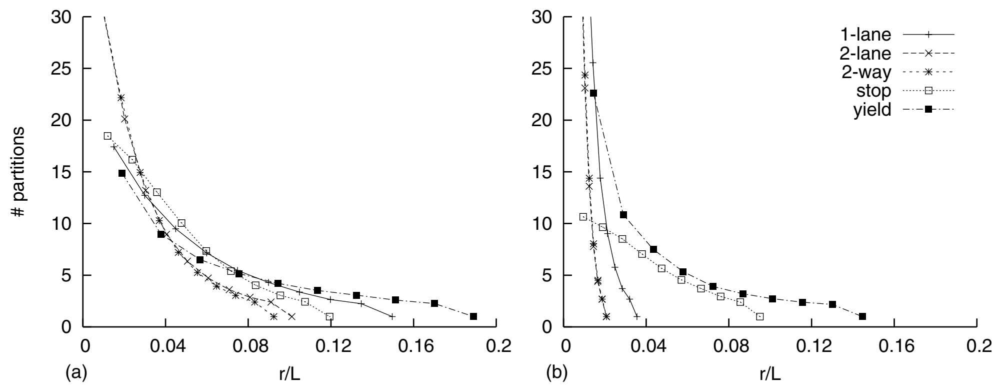

Fig. 5 Number of partitions vs. transmission range in a) low average density, and b) high average density

In intersection scenarios of high density, Fig.4 shows that the connectivity remains high even with a fraction of the original MTR is used. In contrast, Fig.5 shows that a high transmission range is still needed to keep the network connected. Although this may seem as a discrepancy, it can be explained as follows: The initial high value of MTR shown in Fig.3c is needed mainly to connect vehicles leaving the intersection. Decreasing the transmission range results in keeping only the vehicles behind the interaction connected in one big network partition that contains the majority of vehicles; therefore, the value of $q(G)$ does not decrease significantly until r is too small. The vehicles leaving the intersection remain scattered in many partitions when a short transmission range is used.

5. Discussion and conclusions

We have studied the effect of vehicle density on the value of the minimum transmission range (MTR) required to maintain connectivity in vehicular ad hoc network. Our simulations of five road scenarios show that road restrictions and vehicle density affect node distribution in vehicular networks; thus, they affect connectivity.

Road restrictions, such as intersections, create traffic jams that disrupt the homogenous distribution of vehicles on the road. Vehicle density has similar effect; increasing number of vehicles on the road does not simply increase the network's density. It also changes the traffic mobility and distribution. Low density creates free-flow traffic, a condition where traffic is homogenous and vehicles travel at their desired speed independent of other vehicles. Beyond a critical density, small driving fluctuations may cause traffic jams to occur and traffic become inhomogeneous. Vehicles mobility is also affected as drivers adjust their speeds to avoid collisions in dense traffic.

Traffic jam conditions are the main cause of the discrepancy between our simulation results and analytical relations reported in Section 2, which are based on the assumption of uniform or Poisson distribution of nodes and predict that MTR range should decrease as density increases.

Simulations show that in traffic flowing in one or two directions, the value of MTR decreases as vehicle density increases up to the critical density, then it remains flat or increases slightly. In intersection scenarios, where traffic jams occur before traffic signs, the value of MTR remains flat for all vehicle densities. Therefore, depending on road configuration, the rise in vehicle density may not always result in higher connectivity. This is a feature of VANETs that needs to be investigated further.

The above results also indicate that in order to maintain node connectivity in VANETs, a large static transmission range has to be chosen to accommodate bottleneck scenarios. This solution may not be acceptable because of its negative effect on the network's capacity where vehicle density is high. Therefore, unless the transmission range can dynamically adapt to the road configuration, there must be a trade-off between the transmission range and the desired level of connectivity.

We find that a transmission range of $r \geq 0.12L$ (=450m) is sufficient to reduce the number of network partitions to less than five in any scenario. Considering that this range is approximately twice that of a common standard such as IEEE802.11, we see the need for the ongoing effort to develop special standards for VANETs that adopt higher transmission range.

We expect that a transmission range that adapts dynamically to traffic density will provide better connectivity. A future work will focus on developing and evaluating an algorithm that sets the transmission range according to traffic flow characteristics.

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