Performance Analysis of Inter-vehicle Communications in Multilane Traffic Streams

Xiaoyan Sun, Yuanlu Bao, Jun Dai, Wei Lu, Renhua Gao

Abstract— **Inter-vehicle communications (IVC) based on mobile ad hoc networks have attracted increasing attention of researchers recently. In this paper, we study the communication performance of IVC networks in multilane dynamic traffic streams. We are concerned with the influence of several traffic factors on multilane communications, such as vehicles' high mobility, traffic directions or relative speed, and traffic density. So several simulations were conducted in network simulator 2 with Monte Carlo method for a penetration rate of 10%. The simulation results show that vehicles' high mobility does not greatly affect the communication of vehicles on different lanes; traffic streams running to opposite directions will distinctly affect each other's communication performance, but the unidirectional traffic streams with a relative speed of 30km/h has no obvious impact; under the bidirectional condition, the increasing of traffic density on one lane cannot markedly improve the communication performance of the IVC networks. These results help to better understand the communication of multilane traffic streams under high mobility scenarios.**

I. INTRODUCTION

Mobile ad hoc networks (MANET) have received much attention in recent years. Vehicles' high mobility makes it difficult to maintain the topology of IVC networks. Especially when there are few vehicles equipped with communication units, it is fairly hard to establish communication paths between source nodes and destination nodes. In addition, it is common to have multi-lane roadways in real life: vehicles move separately in different lanes in the same direction or opposite directions. We are concerned with the communication performance of IVC networks under these conditions. For instance, the mutual influence between traffic streams on different lanes, the affect of travel directions and vehicle speeds on communication performance measures, etc.

There have been many projects concerning IVC systems, for example, PATH, CarTALK2000 [1], and FleetNet [2], etc. Some studies focus on the protocols' improvement on different layers of networks. Some other studies, for example, [4], [5], propose the influence of penetration rate on communication performance. [5] also adopts the Monte Carlo method to carry out simulations. [3] and [6] discuss the IVC performance of traffic streams moving towards opposite directions. Due to the randomness of establishing communication links, [7] studies on the probability of successfully establishing a routing path along bidirectional traffic streams.

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[8], [9] propose a model to analyze the relationship between the connectivity of IVC networks and some parameters, such as the transmission range of the wireless units and the penetration rate of equipped vehicles. Although [10] studies the throughput of an IVC network along a unidirectional four-lane traffic stream, the assumption is that four lanes can be viewed as one single lane which has a four times density. [11] investigates the performance of IEEE 802.11 protocol in networks with high mobility like vehicular networks.

Due to the expensive cost of testbed experiments, we adopt simulation method to analyze the communication performance of IVC networks in multilane traffic streams. In this paper, we simulate four different scenarios: on-lane unidirectional, four-lane unidirectional, two-lane unidirectional and two-lane bidirectional. From these scenarios, we analyze the average throughput, end to end delay and number of hops under different traffic densities and transmission ranges of the wireless units. Therefore, we could obtain some useful results concerning communications between different lanes. Not all the vehicles are equipped with communication units and the probability of equipped vehicles is defined as penetration rate. Whether a vehicle is equipped or not follows a Bernoulli distribution. Therefore, whether a routing path can be set up between communication nodes is uncertain when the penetration rate is low. So we adopt Monte Carlo method to repeat a large number of random trials to get the average performance measures. Detailed introduction about Monte Carlo method can be found in [10]. The simulation tool is network simulator 2 (ns-2) [12].

The paper is organized as follows. Section 2 introduces the basic traffic flow theories and the definition of some performance measures used in this paper. In section 3, we describe the mobility model of vehicles and present several simulation scenarios in ns-2. In section 4, the simulation results are discussed. Finally in section 5 we conclude our work.

II. MODEL BACKGROUND

A. Traffic Flow Theories

The traffic flow theories can be classified into two categories: macroscopic and microscopic models. In macroscopic traffic flow theories, traffic is described in terms of fluid behavior, so the traffic stream is treated as one dimensional compressible fluid [13]. This leads to two basic assumptions: (I) traffic flow is conserved, which leads to the conservation or continuity equation, and (II) there is a one-to-one relationship between speed and density or between flow and density. Therefore, the conservation equation of Lighthill Whitham

Richards (LWR) model can be used to calculate the vehicles trajectories:

$$\frac{\partial \rho(x,t)}{\partial t} + \frac{\partial q(x,t)}{\partial x} = 0 \qquad (1)$$

where $q(x,t) = v(x,t)\rho(x,t)$, $q(x,t)$ is the flow rate of a traffic flow, $v(x,t)$ is the speed of a traffic flow and $\rho(x,t)$ is the density of a traffic flow.

B. Definition of Performance Measures

- Throughput can be calculated by (2) as follows:

$$T = \frac{\sum_i p_i}{t_i - t_0}, \qquad i = 1, 2, 3 \ldots \qquad (2)$$

Where i is the sequence number of packets, t_i is the time when packet i is received by the destination node, t_0 is the time when packet 0 is received by the destination node, p_i is the packet size of packet i.

- Average end to end delay represents the average transmission delay between the emission of a packet by a source node till its reception by a destination node:

$$D = \frac{\sum_i (t_r(i) - t_s(i))}{n}, \qquad i = 0, 1, 2 \ldots \qquad (3)$$

Where i is the sequence number of packets, $t_r(i)$ is the time when packet i is received by the destination node, $t_s(i)$ is the time when packet i is sent by the source node, n is the total number of packets received by the destination node.

- Average number of hops needed when a packet is delivered from the source node to the destination node can be computed by:

$$H = \frac{\sum_i h_i}{n}, \qquad i = 0, 1, 2 \ldots \qquad (4)$$

Where i is the sequence number of packets, h_i is the number of hops when packet i is delivered from the source node to the destination node, n is the total number of packets received by the destination node.

With the Monte Carlo method, an equipped vehicle's average throughput, end to end delay and number of hops at position x after M times' experiments can be calculated by (5) (6) and (7):

$$T_M = \frac{\sum_j T_j}{M}, \qquad j = 1, 2, \ldots M \qquad (5)$$

$$D_M = \frac{\sum_j D_j}{M}, \qquad j = 1, 2, \ldots M \qquad (6)$$

$$H_M = \frac{\sum_j H_j}{M}, \qquad j = 1, 2, \ldots M \qquad (7)$$

Here T_j, D_j and H_j are respectively the average throughput, end to end delay and number of hops of each time's experiment.

III. SIMULATION IMPLEMENTATION

A. Mobility Model

The initial coordinates of mobile nodes at time $t = 0$ and the coordinates of vehicle k at time $t = \tau$ can be computed by (8) and (9):

$$x_k(0) = x_0(0) + k\Delta x \qquad (8)$$

$$x_k(\tau) = x_k(0) + v\tau \qquad (9)$$

Where $x_k(0)$ is the position of vehicle k at time $t = 0$, $x_0(0)$ is the position of vehicle 0 at time $t = 0$, Δx is the spacing between two consecutive vehicles which can be calculated by $\Delta x = \frac{1}{\rho}$, ρ is the density of the traffic stream, v is the vehicles' speed.

B. Simulation Scenarios

This study simulates four different scenarios to analyze the performance measures of the IVC networks, some parameters could be determined according to [10] and [11].

- the penetration rate of equipped vehicles μ: 10%;
- the transmission range of wireless communication units: 500m or 200m;
- the number of vehicles on the disturbing lane: 5, 20 or 50.

1) Scenario 1-unidirectional, uniform traffic stream on one lane: In this simulation, we consider one lane of 50km. The length of the traffic stream is 10km, and the traffic density ρ_1 is 56 veh/km/lane, vehicles' travel speed $v1$ is 125km/h. The penetration rate is 10%. The transmission range is 500 m or 200 m (Fig. 1).
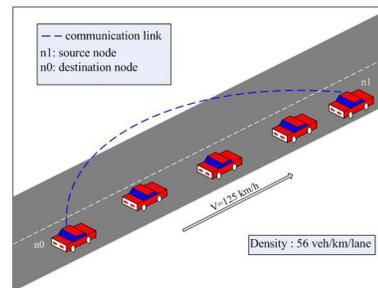

Fig. 1. Unidirectional, uniform traffic stream on one lane with density of 56veh/km/lane

2) Scenario 2-unidirectional, uniform traffic streams on four lanes with the same speed: In order to study the communication performance of a multilane roadway, we here simulate a four-lane roadway. The width of each lane is 3.5 meters. All the parameters are the same with scenario 1 except the density of traffic stream. We distribute the vehicles in scenario 1 equably to 4 lanes, which means the density is 14 veh/km/lane. All the vehicles move towards the same direction. In order to better study the influence of high mobility on communication between lanes, here we do not consider the relative speed of vehicles on different lanes. That is, all the vehicles move with a speed of 125km/h. The traffic stream on each lane starts to move at a random time, thus the distance between vehicles on different lanes will be random in each simulation. By doing this we can avoid the influence of having same inter-vehicle distance in all simulations. The penetration rates on the four lanes are all 10%. From the simulation results of this scenario, we can make clear whether the high mobility of vehicles will make information propagate along a single lane or interact with other lanes (Fig. 2).
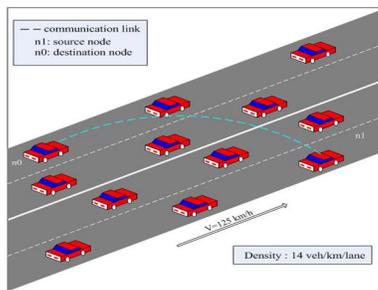

Fig. 2. Unidirectional, uniform traffic stream on 4 lanes with a density of 14veh/km/lane and a null relative speed

3) Scenario 3-unidirectional, uniform traffic streams on two lanes with a relative speed of 30km/h: There are two lanes in this part: a main lane and a disturbing lane. The width of each lane is 3.5 meters. The parameters on the main lane are the same with scenario 1. The disturbing lane is of the same length with the main lane but the traffic density ρ_2 is 2 veh/km/lane. The traffic streams on the two lanes are moving in the same direction, but vehicles on the disturbing lane move with a speed of 95 km/h. All the vehicles on the disturbing lane are equipped with communication units to get rid of the influence of penetration rate and make it easier for results analysis. From this scenario we can know the influence of relative speed on communication performance when the traffic streams on different lanes run towards the same direction (Fig. 3).
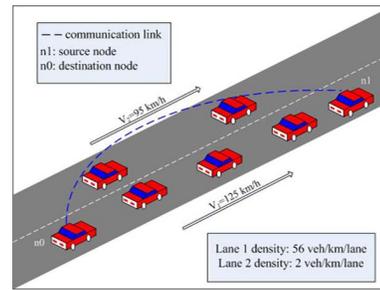

Fig. 3. Unidirectional, uniform traffic stream on 2 lanes with a relative speed of 30km/h

4) Scenario 4-bidirectional, uniform traffic streams on two lanes with a relative speed of 250km/h: The concept of this scenario is almost the same with the previous one except the vehicles on the two lanes are running across each other with a speed of 125 km/h. The number of vehicles on the disturbing lane could be 5, 20 or 50 in a distance of 10km. We can compare the result of this scenario with scenario 3 and have a better understanding about the impact of vehicles' running directions on communication performance. We can also know whether different traffic densities on the disturbing lane would affect the performance measures of the IVC network on the main lane (Fig. 4).
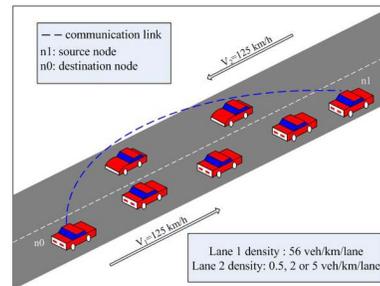

Fig. 4. Bidirectional, uniform traffic stream on 2 lanes with a relative speed of 250 km/h

IV. SIMULATION RESULT AND DISCUSSION

We configure parameters in ns-2 according to [10] in order to make some comparisons with his work. At the application layer, we use constant bit rate (CBR) generator with packet size 230 bytes and inter-packet delay 0.02s. UDP protocol is used at the transportation layer because the result of TCP connections is more complex to analyze and it wastes network resources for acknowledgement messages. AODV is the protocol at network layer for shorter time to establish routing paths than DSR. IEEE 802.11 DCF is the

default setting for ns-2.33 at the MAC layer. The two-ray ground model is chosen for long distance communication in this study because it considers the paths of reflections from ground. For each Bernoulli trial, the ns-2 simulation time is 120s. Here the simulation times M is 500. It has been proved to generate relatively stable results by our former tests.
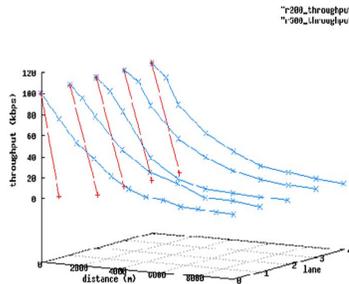

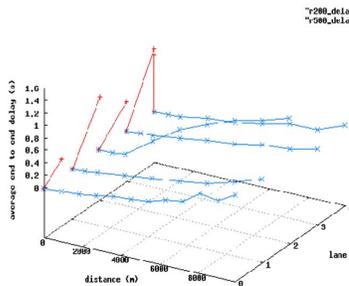Fig. 5.   Average throughput of a receiver for different lanes in multilane condition

Fig. 6.   Average end to end delay of a receiver for different lanes in multilane condition
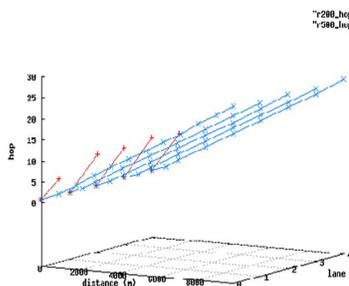

Fig. 7.   Average number of hops of a receiver for different lanes in multilane condition

In this section, we present and analyze the simulation results of different scenarios. From scenario 1 and 2 we can get Fig. 5 to Fig. 7. What should be pointed out is that in Fig. 5 to Fig. 7, lane 1 to lane 4 represents the 4 lanes in scenario 2, but lane 0 represents the single lane in scenario 1. Here we show them in the same figures in order to make comparisons between scenario 1 and scenario 4. From these figures we can see that, no matter the transmission range is 500 m or 200 m, the communication performance measures of traffic streams on different lanes are almost the same. In Fig. 5, traffic streams on lane 1 to lane 4 have similar average throughput and all decrease with distance increasing. When the transmission range changes from 500 m to 200 m, the average throughputs on different lanes all decrease because it is more difficult to successfully establish a communication path between the source nodes and destination nodes. In Fig. 7, the increasing in distance and transmission range can increase the average number of hops on all lanes. When the transmission range decreases, the packets have to be delivered to the destination nodes with more hops. Therefore, the increasing in distance and decreasing in transmission range can also increase the average end to end delay (Fig. 6). It shares the same altering trend with number of hops. More importantly, the communication performance measures on a single lane with a density of 56 vehicles/km/lane and those on four lanes with densities of 14 vehicles/km/lane are almost the same. That is, no matter a vehicle is in a one-lane roadway or in a multilane roadway, the communication performance measures are almost equal as long as the density of the road way is the same and vehicles move towards the same direction with a certain speed. This result shows an important conclusion: information is propagated among several lanes rather than along one single lane. Actually, the lane width of 3.5m can almost be ignored compared to the communication units' transmission ranges of 500m or 200m if the traffic is static. Here from the simulation we can see, neither does the high mobility of vehicles change the characteristics of routing method.
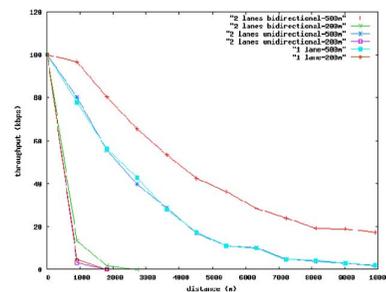

Fig. 8.   Average throughput of a receiver under different scenarios

From scenario 1, 3 and 4 we can get Fig. 8 to Fig. 10. These figures show that with the same transmission range, the communication performance measures of a unidirectional
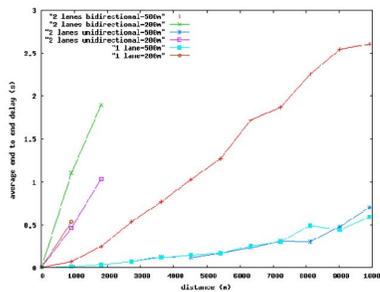
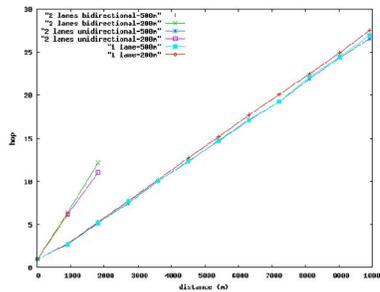Fig. 9.   Average end to end delay of a receiver under different scenarios

Fig. 10.   Average number of hops under different scenarios

relative positions change; vehicles on the two lanes can communicate with each other without great difficulty when they are in each other's transmission range. It should also be noticed that although the number of hops are the same (Fig. 10), the average end to end delay is longer in bidirectional traffic streams than in one-lane traffic or unidirectional traffic streams with a relative speed of 30km/h (Fig. 9). Since when the relative speed is high, longer time is needed to set up routing paths between nodes. We have specific experiment results to prove this conclusion but here we won't present for the limited length of the paper.
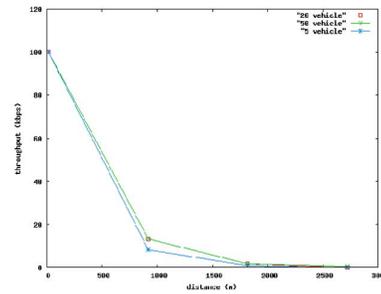

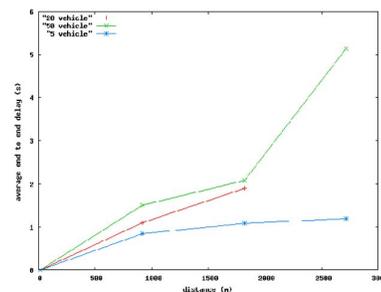Fig. 11.   Average throughput of a receiver with different traffic densities in disturbing lane(scenario 4)

Fig. 12.   Average end to end delay (scenario 4) with different traffic densities in disturbing lane(scenario 4)

two-lane traffic stream are almost identical to those of a single-lane traffic stream. The lines for these two conditions nearly overlap in the figures. This means that a relative speed of 30km/h for the two unidirectional traffic streams has no distinct effect on improving the communication performance of the main lane. As we pointed before, the increasing in distance and the decreasing in transmission range can decrease the average throughput (Fig. 8). Meanwhile, these changes can increase average end to end delay (Fig. 9) because more hops are needed to deliver packets from a source node to a destination node (Fig. 10). We also notice that the number of hops just depends on the transmission range and the distance between source nodes and destination nodes and it has no relationship with the running directions and speeds of vehicles.

Compared to unidirectional traffic streams, however, the bidirectional traffic streams can improve the average through-put of the main lane markedly(Fig. 8). This can be interpreted by the high relative speed of the two bidirectional traffic streams. The vehicles on the two lanes change their relative positions quickly and the inter-vehicle distances decrease compared to one-lane traffic. We can also easily elicit that the decreasing of inter-vehicle distance on the two lanes facilitates the communication paths' establishment: more vehicles are available to transmit information when the

We are also concerned that whether the traffic densities on the disturbing lane will influence the communication performance of the main lane under the bidirectional scenario (scenario 4). We change the number of vehicles to 5, 20 or 50 but the traffic lengths or spans are all 10km. The transmission range here is 200 m. Fig. 11 to Fig. 13 present results under these conditions. We notice that the average throughputs are almost equal when there are 20 or 50 vehicles on the disturbing lane and slightly smaller when 5 vehicles (Fig. 11). Although average number of hops with same distance are almost identical (Fig. 13), the average end to end delay is a little longer when there are more vehicles (Fig. 12).
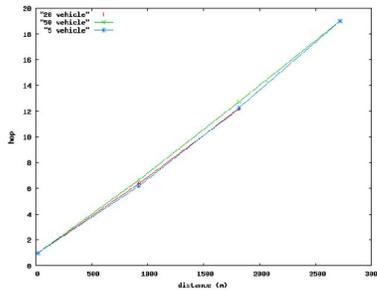
Fig. 13. Average number of hops with different traffic densities in disturbing lane(scenario 4)

This can be explained that longer time is needed to deal with collisions in the MAC layer since several transmissions interfere with each other when there are more vehicles. In actual fact, the performance measures are not affected by the number of vehicles greatly due to the same traffic spans or lengths. [11] has shown that the traffic spans of the disturbing lane impact communication performance distinctly. Here we will not describe them in detail.

V. CONCLUSION

In this paper, we conducted several simulations in ns-2 to study the communication performance of IVC networks in multilane traffic streams. Problems we want to make clear are the impact of high mobility of vehicles, traffic directions, relative speeds and numbers of vehicles or traffic densities on the communication performance measures. The vehicles' trajectories are obtained from traffic flow theories, such as LWR model and Car-following model. Considering now the development of IVC networks is still at an early stage, we simulate all the scenarios with Monte Carlo method for a penetration rate of 10%. First we investigated when the relative speeds between lanes are null, whether the high mobility of vehicles will affect the communication between different lanes and make information propagates along a single lane. The answer is negative. When all the vehicles move with the same speed, the high mobility of vehicles has no distinct influence on the communication between lanes. Vehicles on different lanes can interact with each other without great difficulty. Second, we studied the relationship between communication performance and traffic directions or relative speed. From the simulation results we could see, the disturbing lane with a relative speed of 30km/h in the unidirectional traffic streams can hardly improve the communication performance of the main lane. The traffic of an opposite direction, however, can markedly increase average throughput of the main lane and end to end delay as well. Third, we changed the traffic density on the disturbing

lane and found that it has a slight influence on average throughput when the vehicle number is 5, but almost no influence when 20 or 50. But the increasing of vehicle numbers makes the average end to end delay longer. In addition, all the results share several same characteristics: the increasing of distance or transmission range increase end to end delay and decrease average throughput; average number of hops only depends on the transmission range and the distance between source nodes and destination nodes.

VI. ACKNOWLEDGEMENT

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