INTERNATIONAL JOURNAL OF INTELLIGENT CONTROL AND SYSTEMS
VOL. 10, NO. 1, MARCH 2005, 86-93

An Epidemic Routing Strategy For Vehicular Ad Hoc Wireless Networks In Intelligent Transportation Systems

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Abstract- **The inter-vehicle communication is a key technique of intelligent transport systems (ITS). Moving vehicles on highways can easily construct ad-hoc networks if they are equipped with WLAN-based communication equipments. However, since the traffic density is time varying, it is likely that such networks are disconnected. This paper proposes and tests the hypothesis that the motion of vehicles on a highway can contribute to successful message delivery provided that messages can be stored temporarily at moving nodes while waiting for opportunities to be forwarded further. Using vehicle movement traces from a traffic microsimulator, we measure average message delivery time and find that it is shorter than that when the messages are not relayed. We conclude that ad hoc relay wireless networks, based on wireless LAN technologies, have potential for many emerging intelligent transportation applications.**

***Index Terms*—Inter-vehicle, routing, and transportation**

1. INTRODUCTION

The increasing availability of wireless technologies presents a great chance for the automotive industry. Vehicles are no longer isolated systems since their communications with the outside world enable completely new types of applications. Major carmakers are rolling out infrastructure-based low bandwidth wireless services supporting for automotive applications. Such applications are a combination of telecommunication and computation, such as route planning using GPS signals or remote diagnostics using data from sensors built into vehicles.

In vehicle-to-vehicle communication, network topology may change randomly and rapidly at unpredictable times because vehicle positions constantly change. Therefore, centralized control by a base station is not feasible, and autonomous decentralized control is required. Ad hoc networks formed by rapidly deployable, short-range wireless devices, such as those based on IEEE 802.11 wireless LAN standard, are well suited for moving vehicles. Their deployment on individual vehicles doesn't require any infrastructure; also, ad hoc routing can easily adapt to node mobility.

Recently, ad-hoc networking in the vehicular environment was investigated [3][6][9][18]. The ad-hoc connection of vehicles within a limited area can make message dissemination more flexible because of its self-organizing property. Two passing cars can exchange data (single hop), or data can pass several other cars when they act as routers/relays (multihop). With this principle, highly efficient accident warning systems are possible; cars involved in an accident can send warning messages back over a pre-defined number of other vehicles, thus avoiding motorway pileups and enhancing the traffic safety.

With ad hoc networks deployed on moving vehicles, network partition due to the limited radio range becomes inevitable when the traffic density is low, e.g., at night, or when only a limited number of vehicles carry wireless devices [5][12]. However, it is still possible to deliver messages along vehicles moving on highways in spite of sparse density. By taking advantage of their nature of relative movement on highways, vehicles can create opportunities to relay messages in a store-and-forward fashion. This paper proposes and tests the hypothesis that the motion of vehicles on a highway can contribute to successful message delivery, provided that messages can be relayed—temporarily stored at moving nodes while waiting for opportunities to be sent further. This work intends to test this hypothesis by simulating the movement of vehicles on a highway via CORSIM [8], simulating an ad hoc network over the vehicles via NS2 [20], and measuring the performance of the network as traffic density decreases. To the authors' knowledge, no such research work has been reported in the literature.

In Section 2, the related work is reviewed. Section 3 introduces a new packet forwarding scheme for ad hoc wireless networks. Section 4 is the framework of simulation environment both for communication and transportation. Section 5 presents and discusses the experimental results. The paper ends with conclusions and future research directions in Section 6.

2. ROUTING CHALLENGES AND MOBILITY

Forwarding packets within a vehicular MANET is extremely difficult while their average velocity is much higher than that of low-mobility nodes in a regular MANET. The idea of using node mobility to improve network performance was extensively investigated. In general, these proposals mainly aim at optimizing routing protocols, network throughput, message delay, connectivity and energy conservation. A position-aware protocol is proposed for inter-vehicle communications in the highway environment, and multihop connectivity for high and low traffic density is investigated by using accurate vehicles' position information which is time-varying [14]. A multicast protocol is proposed for the

Manuscript received May 18, 2004; revised November 31, 2004. This work was supported in part by National Natural Science Foundation of China under Grant No. 60228004 and 60334020.

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highway environment [4]. The fraction of nodes to which aggressively forwarded messages are successfully delivered in a fixed amount of time is measured under such a multicast protocol.

Starting from a model with random node movements, the work [13] shows that the motion leads to constant throughput as the network size increases. A Space Division Multiple Access (SDMA) is proposed for robust ad hoc vehicle communication networks [1]. The idea is to divide the geographical space into many non-overlapped smaller places and to allocate each neighboring zone different bandwidth division of time slots or frequency division.

The work [11] proposes to use the concept of microcells that allow base stations located along highways to store and deliver packets to vehicles. The work [17] examines a scenario in which the mobile nodes are under their control, so that the trajectories can be modified to reduce delay. A geographical adaptive fidelity algorithm is introduced to reduce energy consumption in ad hoc networks [19]. By identifying nodes that are equivalent from a routing perspective and turning off unnecessary nodes, it can consume significantly less energy than conventional routing protocols do.

In the context of inter-vehicle communication, research always includes two aspects of the related issues: transportation and wireless networking. Therefore, accurate modeling traffic of highways is required. The studies in [14] and [4] use simple highway models thus their results cannot reflect real traffic environment. Additionally, power consumption is no longer a critical problem for a vehicle driving on highways because its battery is continuously being charged. Then, research should focus on basic communication performance. Due to the high mobility of highway traffic, any position-based routing protocols may have trouble in disseminating accurate geographic location information in a real time way. Hence, their conclusions are not always reasonable.

This work studies inter-vehicle communications on the basis of an authoritative transportation simulation tool, TSIS 5.0. Many traffic parameters, such as traffic density, highway lanes, and average vehicle travel time and mileage, can be easily set or acquired. The work, hence, reflects nearly real transportation environment. Moreover, the proposal does not require accurate geolocation information, which is required by some existing routing algorithms. In other words, the scheme will function properly with any routing protocols with or without geolocation requirements. Hence, the results of this paper render a valuable and significant guide for future research and design of ad hoc inter-vehicle communication.

3. EPIDEMIC BEST-EFFORT FORWARDING

3.1 Definition

In ad hoc vehicular wireless networks, each node serves as a router that can forward packets to its appropriate neighbors. In case of low density, the network could be partitioned due to disconnectivity. If a vehicle fails to relay packets to its next hop, packets arriving from other one-hop neighbors will be dropped at the node according to the previous proposals. Then this data transmission is failed and future retransmission will be necessary.

This work suggests that each packet is buffered at this node once it is stuck and waits for future opportunities to be forwarded. Messages without the next hops can remain on intermediate nodes for certain pre-determined time, depending on applications, hoping that the physical movement of network nodes eventually creates a forwarding opportunity. For example, in a geographic routing protocol such as those in [15][16] coupled with this kind of forwarding, messages is not dropped, but instead held and then forwarded greedily as soon as a new neighbor node closer to the destination is detected. One packet is dropped only in two cases. The buffer is full or the period of a packet staying within the buffer exceeds certain threshold. Figures 1 and 2 give two examples of this scheme. Figure 1 shows that a proceeding vehicle A cannot forward packets received from its following neighbors within one hop to its proceeding next hop neighbor because no vehicle ahead is within A's communication radius. In such situation, packets received at node A should be temporarily stored and then forwarded until A is close enough to a proceeding vehicle so that they are within its radio range. Let r denote the radio transmission range.

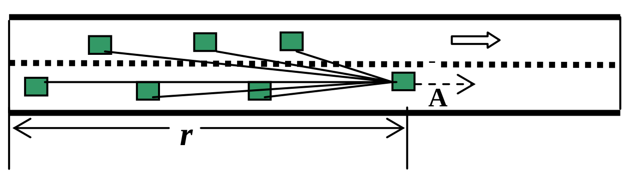

Fig. 1. Node A can forward packets from its following neighbors

A's next hop is not necessarily its proceeding neighbor. Its following neighbor could also be A's next hop if a connection is launched by A's proceeding neighbor and the destination is some hops away behind A. Figure 2 illustrates such scenario. Again, node A may succeed in delivering stored packets to its following neighbors by taking advantage of the nodes' relative speeds.

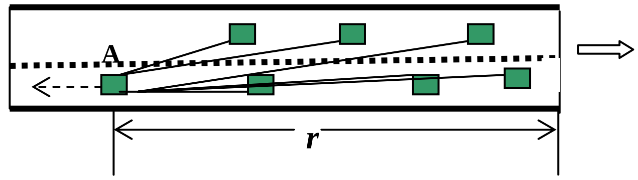

Fig. 2. Node A can forward packets from its proceeding neighbors.

This best-effort forwarding strategy is similar to the forwarding principle in wireline IP networks. The idea here is based on an assumption that there are relative speeds among moving vehicles. Hence, one vehicle may eventually reconnect to its proceeding/following node if they are getting closer, or its following/proceeding neighbors become its proceeding/following neighbors and then probably make the network connected again. Whatever situation it is, the possibility of successful transmission of messages is expected to be higher.

As stated above, vehicles could be distributed unevenly due to the existence of relative speeds even though the traffic density may be moderate. Then the whole network might possibly be partitioned into isolated small groups whose members have similar group mobility characteristics, such as average velocity, direction and common reference point, e.g., clusterhead in a cluster-based ad hoc network [2]. In Fig. 3, groups A and B have the same moving directions but different velocities. Successful message delivery between groups A and B requires that one of the edge nodes eventually get closer with its corresponding receiver. This probability for the successful message delivery is P_d, called service capture probability.

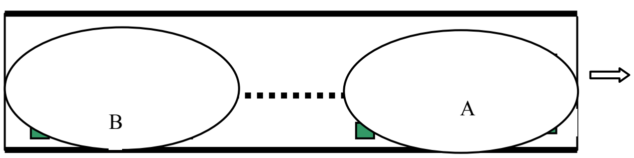

Fig. 3. Isolated groups along a highway.

Obviously, P_d is determined by many factors, such as traffic time, average speed, driver's behavior, even the type of cars. Eventually, it is up to the traffic density. For very high density, it is almost impossible for vehicles to keep their gaps beyond one direct communication radius. Therefore, P_d is always 1 and the idea then has no use. This paper only concerns about the low traffic density scenario, which makes our idea useful for relaying messages along a highway.

Apparently, both transportation and communication issues are involved if our proposal is used. To focus on the communication essence, the work uses a standard simulation tool to provide real transportation scenario and pay main attention on the related performance. The examples include proper buffer sizes under different network load, throughput improvement, relationships among throughput, and buffer length and average delay. In the next section, mathematical analysis is conducted to examine the basic requirement and performance of our scheme.

3.2 Analysis

We assume that the buffer size of each vehicle is K and the number of its neighbors is N which equals to $r \cdot l \cdot d$, where l is the number of lanes and d is the density of per lane (vehicles/km). Note that only radius is calculated here because another half of neighbors should be empty according to Figures 1 and 2.

It is reasonable to assume that packet arrival is a Poisson process and packet arrival rate from every vehicle is λ. The service time, however, is not deterministic because it is mainly determined by traffic density. For moderate density, the service capture probability is fixed and the service time is deterministic, so the best-effort scheme can be modeled as an M/D/1/k queuing system. For low density, a node cannot transmit packets from its buffer immediately if its next hop node is unavailable. In some moderate density cases, one node may not start immediate forwarding either. For instance, this happens when the traffic is not evenly distributed and there is a gap between node A and its next hop. If the gap is long enough (beyond one-hop radius), node A cannot relay packets even though the overall traffic density is high. The service rate depends on service capture probability, and thus is treated as a random variable. We call it modulated service rate.

Generally, the traffic on highways could be thought of as Poisson distribution [7][10]. To simplify the analysis, we assume that the service time is the product of P_d and μ which follows exponential distribution. Hence the average service rate at each node is μP_d.

Apparently, this model is a hybrid M/M/1/K finite waiting space queuing system. Therefore, we can calculate related parameters as following:

The average number of packets is

$$L_s = \frac{\rho}{1-\rho} - \frac{(K+2)\rho^{K+2}}{1-\rho^{K+2}}, \quad \rho = \frac{N\lambda}{\mu P_d}$$

The average number of packets in the buffer is

$$L_q = L_s + \frac{1-\rho}{1-\rho^{K+2}} - 1$$

The average waiting time of each packet

$$W_q = \frac{L_q}{N\lambda(1-\rho^{K+1} p_0)}$$

where

$$p_0 = \frac{1-\rho}{1-\rho^{K+2}}$$

For the case of high density and high packet generation rate, λ/μ is close to 1. Typical r is about 200m to 500m and traffic density is 160 cars/km. Then N falls into the range between 20l and 40l. So ρ>>1, usually, K>>1, then, it is easy to learn that $L_q \approx K$ and $W_q \approx L_q / N\lambda$. When ρ is close to 1, it can be proved that this conclusion still stands. Intuitively, when the network load is large enough then the buffer size would grow linearly.

Even though a buffer can create the chances of successful data delivery, we cannot expect that its size is unconstrained. Larger buffer size also results in longer delays. There is a trade-off between network throughput and packet delay. Our purpose is to find out the relationship between the network load, λ, the throughput and the buffer utilization under different circumstances (μ).

4. SIMULATION ENVIRONMENT

The simulation environment consists of two parts. The first part is a traffic microsimulator that produces accurate movement traces of vehicles traveling on a highway. The second is a network simulator that models the transport of messages among the vehicles. This work uses the following traffic scenario. A single packet is sent by each car entering the highway. The destination of a packet is chosen to be 10km away in the entering car's direction; however, if no such car happens to be within 10km away, then no packet is sent. The best-effort delay and conventional delays are obtained on the highway traces, for radio range r=250m. The time period for caching each packet is set to 10 seconds.

4.1 Traffic microsimulator

CORSIM (Corridor Simulator) used in this work is a microscopic traffic simulator developed by the Federal Highway Administration. CORSIM models the behavior of human drivers by approximating a set of common driver decisions [7], such as slowing down or changing the lane in the vicinity of slower vehicles ahead. These decisions cause the acceleration and orientation of vehicles to change, resulting in realistic movement patterns.

There are three inputs to the simulator: a highway geometry, a free-flow speed, and an input rate. The geometry in our simulation is basically the same as depicted in Figure 4. It is a straight highway segment with two directions, each composed of multiple lanes.

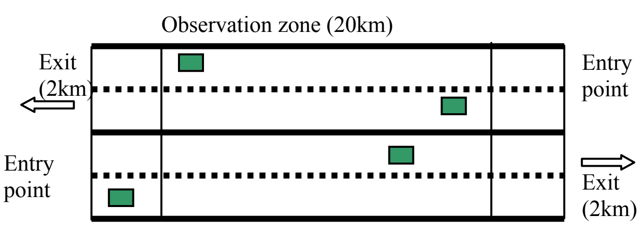

Fig. 4. An illustration of highway geometry used in the traffic simulator.

The free-flow speed parameter is the mean speed that travelers achieve when they move freely, i.e, as they are not constrained by other vehicles or obstacles. The actual free-flow speeds assigned to vehicles are distributed normally around that mean, with a default standard deviation of 12.8km/h. The free-flow speed parameter used in our simulation is 100km/h.

The input rate parameter controls the period at which the simulator generates new vehicles. At the end of each period, a new vehicle is placed at one of the entry points as indicated in Fig. 4, but only if enough room is available. In case of congestion, no new vehicles are generated.

Vehicles near the entries move into the observation zone normally or uniformly according to the process of vehicle generation. Only when they reach the sections under observation are their positions recorded. Once they leave these sections, vehicles are removed from the simulation.

The output of each simulation is a trace of vehicle positions taken at one-second intervals. Each of simulation lasts 30000 simulation seconds and about 20000 vehicles are used at each time. We ran a total of 150 simulations with different random seeds, for highways with one to five lanes on each side. Then totally around 3,000,000 vehicles are examined. The average vehicle densities observed in the 150 simulation runs are summarized in Table 1. For small numbers of lanes, maximum traffic densities are constrained by the capacity of the highway.

Table 1: Summary of the highway traces obtained from CORSIM and used to drive network simulations.

Numbers of Lanes	Lowest density (cars/km)	Highest density (cars/km)
1	3.1	79
2	3.1	172
3	3.2	273
4	3.2	336
5	3.5	325

4.2 Network Simulator

We simulate a wireless network over vehicles driven by the traces summarized in Table 1. Assume that the wireless devices installed on vehicles all have the same fixed radio range r. Our simulator uses the default routing protocol, i.e., Ad hoc On Demand Distance Vector (AODV) and default radio propagation model, i.e., omnidirectional antenna, 802.11 Media Access Control. It maintains a network connectivity graph, and positions and age of the messages in transit. Messages are propagated greedily each timestep, by hopping to the neighbor closest to the destination. This amount of information is sufficient for the purpose of finding the delay due to mobility status.

Under the conventional forwarding, we measure the average amount of time that a sender S waits before a direct routes to a destination D becomes available. We obtain this time directly from the movement traces as a half of the average duration of network partitions between S and D, and calculate it as the conventional delay. We note that such delay is a lower bound only observable in an ideal network with perfect routing information (either local or global) – in practice, route computation may be affected by additional factors, such as timing information of a particular routing protocol. For example, suppose that the network uses a geographic routing algorithm. Then, even though a destination D becomes reachable from source S due to the movement of some nodes, the messages from S will not reach D until the new topology information is learned using beaconing between neighbors.

With best-effort forwarding, messages are not dropped until the buffer is filled. Hence we measure the average time messages spent in the network. We call this value as the best-effort delay.

5. SIMULATION RESULTS

We begin by describing the experimental setup, and proceed with a set of measurements. Our work measures performance as average the delay required to traverse a certain fixed distance. The observation zone includes 2 lanes in one way and the number of a node's neighbors is 30, which reflects low or moderate density cases according to Table 1.

5.1 Comparing Best-effort and Conventional Delays

Figure 5 shows the behavior of measured best-effort and conventional delays as the density of vehicles on the highway increases. At the high densities, both delays are close to zero since the likelihood that a destination is unreachable is very low. However, conventional delay rises more sharply than best-effort delay as the density falls, indicating that mobility succeeds in helping the delivery of best-effort messages. The significance of this result lies in showing that a network taking advantage of node mobility can operate in lower densities while maintaining same average delay.

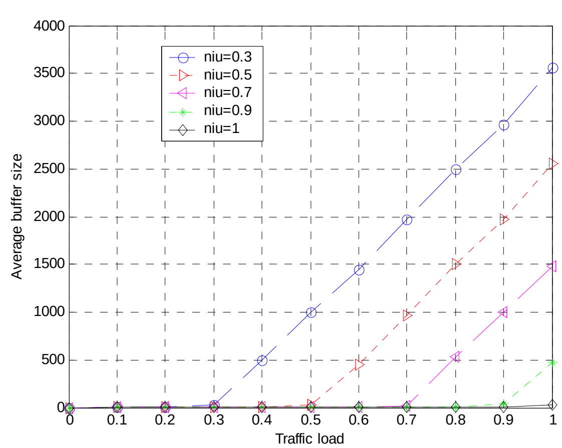

Fig. 5. The traffic load vs. the average per node buffer length.

5.2 Buffer utilization vs. traffic load

According to the discussion above, the buffer usage is determined by the packet arrival rate λ and the modulated service rate. We assume that a node can make full use of available bandwidth once it can send packets to its neighbors. So the modulated service rate is the product of service capture probability and the deterministic service rate. Based on different network load, we record the used buffer size of a node during each time slot. Then we repeat calculation along 10,000 time slots to get the average buffer usage of this node. The process is repeated for every node within the observation zone and finally the average buffer usage per node of this network versus the network load is obtained as plotted in Fig. 6. Theoretically, buffer size is unlimited and can be increased linearly along with the network load after certain points. However, the network load is limited at the same time [13]. Moreover, only finite buffer length is practical. Figure 5 shows that when the network load is greater than a certain value, the buffer size grows rapidly so that it is impossible to implement it.

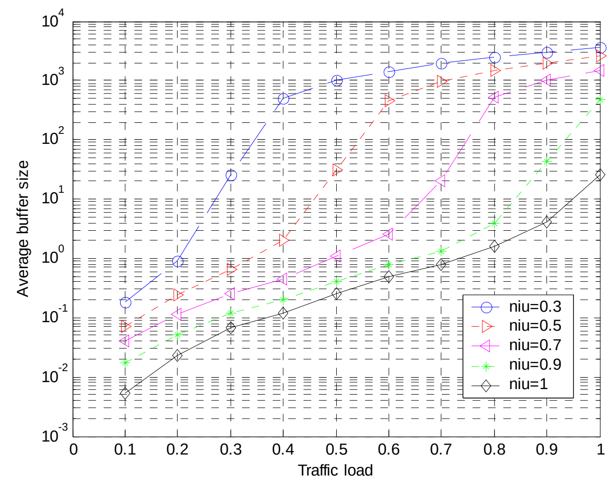

Fig. 6. The traffic load vs. the average per node buffer length with logarithm scale.

In Fig. 6, it can found that the higher service capture probability, the less buffer length needed. The reason is that once a vehicle node has more opportunities to contact others, less buffer space it needs to temporarily store packets.

5.3 Throughput vs. traffic load

The average throughput using the same process is examined. The throughput of one node forwarding packets is defined as: the total transmitted packets divided by the total packets it can send. Figures 7 and 8 give the simulation results with different buffer length. Again, high service capture probability has better throughput as expected.

5.4 Delay vs. traffic load

This work also investigates the average node forwarding delay by simulating the average delay value per node. The forwarding delay here is the time difference from the moment a packet arrives at the buffer and the moment it is served. Previously, it is simply proved that

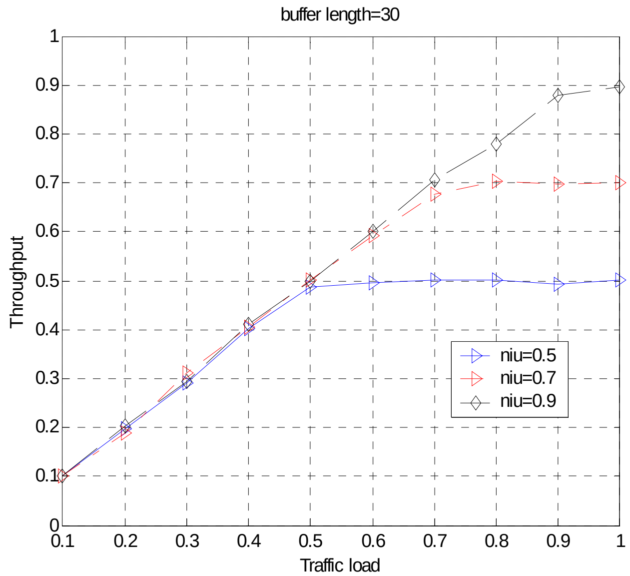

Fig. 7. The traffic load vs. the average per node throughput with buffer size 30.

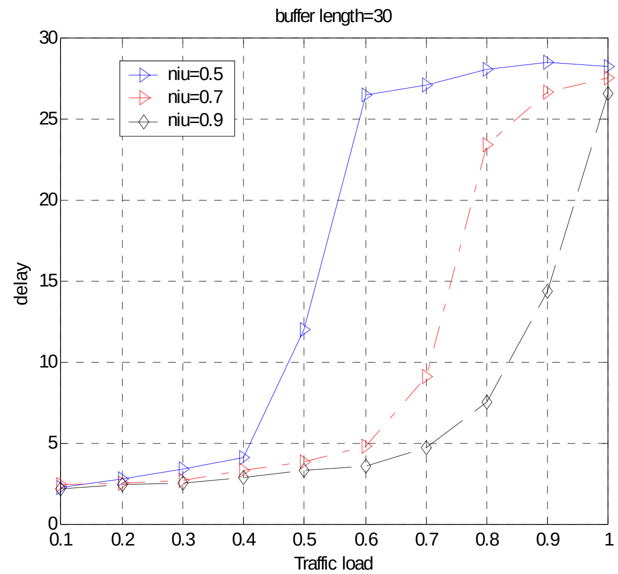

Fig. 9. The traffic load vs. the average delay per node with buffer size 30

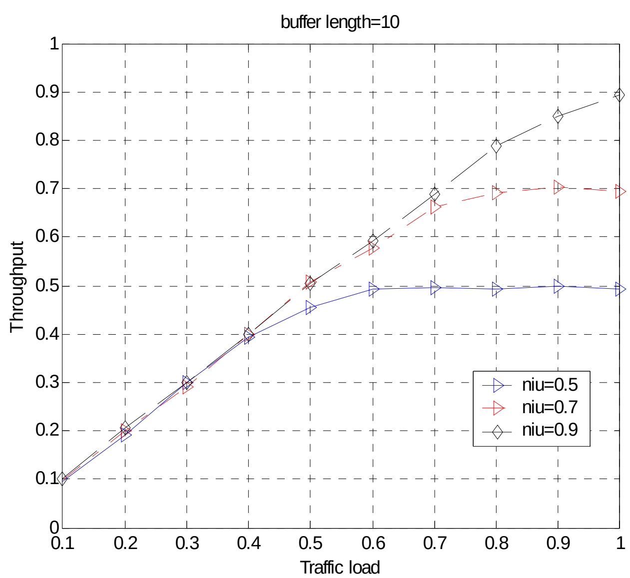

Fig. 8. The traffic load vs. the average per node throughput with buffer size 10.

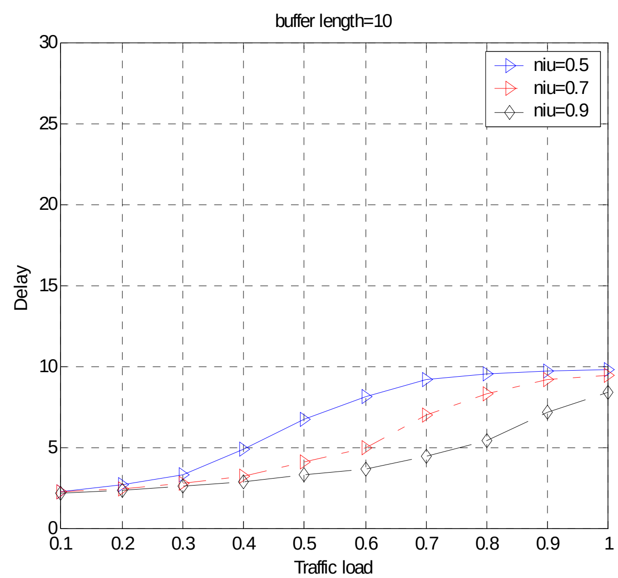

Fig. 10. The traffic load vs. the average delay per node with buffer size 10.

the delay (waiting time) is related to traffic load and the buffer size. Apparently, the length of the buffer makes contribution of the average delay. Larger buffer size causes more delay even though more messages can be stored in buffer.A buffer discards all the coming packets once it is full. Then the upper bound of the average delay can be found from Figs. 9 and 10.

5.5 Delay vs. throughput

The relationship between throughput and delay is also examined using simulations with different buffer length. It is observed that the delay is quite large when high throughput can be achieved. Besides that, it is obvious that higher service capture probability results in higher throughput at the same delay level. It makes sense as higher probability, higher traffic density meanwhile.

6. SUMMARY

This paper addresses how the mobility of vehicles can improve the performance of ad hoc wireless networks formed among vehicles on highways. In conclusion, epidemic routing improves message delivery by exploiting the vehicle's mobility. First, it is found that high mobility of nodes on the highway improved end-to-

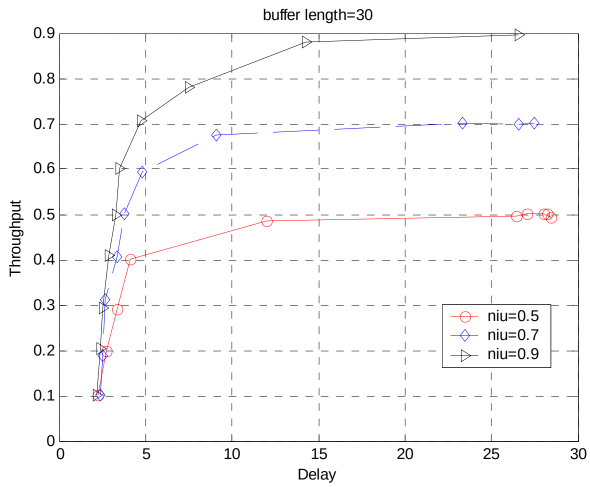

Fig. 11. The delay vs. throughput per node with buffer size 30.

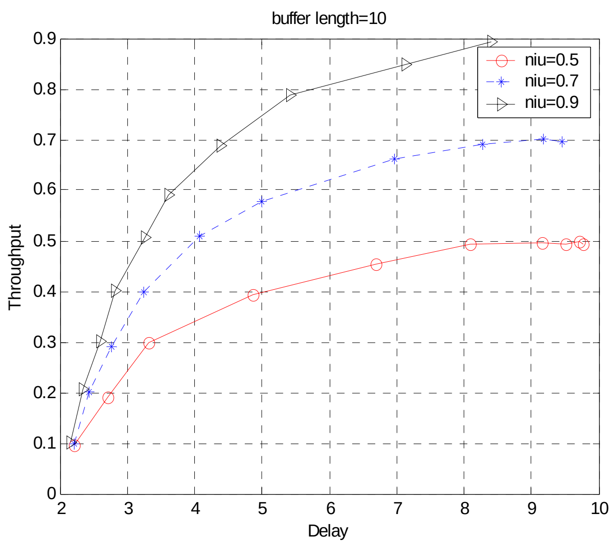

Fig. 12. delay vs. throughput per node with buffer size 10.

end transmission delay if messages were relayed—that is, if they were held at intermediate nodes until favorable forwarding paths appeared. The improvement leads to practical delay values at smaller traffic densities than that for conventionally forwarded messages with ideal routing information. Thus, the hypothesis is verified via simulation and well matches our expectation. Next, the improvement was higher for traffic scenarios with more relative movement. There were two sources of relative movement: traffic in opposing directions on bidirectional highways, and muti-lane traffic within the same direction.Finally, since the delays measured at low vehicle densities increase to the order of seconds, such conditions cannot support delay-sensitive applications, e.g., interactive multimedia. However, there are many non critical applications, such as some of the localized applications which are delay-tolerant and are therefore suitable for this environment.

This proposal does not achieve much improvement in terms of latency and throughput for high density cases since the chance of network partitioned is little. In future research, taking advantage of opposing direction traffic should be included so that it makes our proposal more practicable. Moreover, most ad hoc networks have hierarchical architectures. Then clustering technique should be combined with our proposal and the new topology model should be considered. At last, suitable buffer management schemes could be developed, for example, priority-based, hop count, etc.

ACKNOWLEDGEMENT

The authors would like to thank the comments provided by the anonymous reviewers and editor, which help the authors improve this paper significantly. We would also acknowledge the help on transportation simulation from Professor Stven Chien of New Jersey Institute of Technology.

REFERENCES

[1] Bana, S.V., and Varaiya, P., "Space Division Multiple Access (SDMA) for Robust ad hoc Vehicle Communication Networks", *IEEE Intelligent Transportation Systems Conference Proceedings 2001*, Oakland, CA, pp. 962~967, August 2001

[2] Bechler, M., Hof, H.J., Kraft, D., Pahlke,F. and Wolf, I., "A Cluster-Based Security Architecture for Ad Hoc Networks", *IEEE INFOCOM2004*, Vol. 4, pp. 2393-2403 Hong Kong, March 2004

[3] Blum, J., Eskandarian, A., and Hoffman, L., "Challenges of Intervehicle Ad Hoc Networks", *IEEE Transactions on Intelligent Transportation Systems*, Vol. 5, No. 4, Dec 2004

[4] Briesemeister, L. and Hommel, G., "Role-Based Multicast in Highly Mobile but Sparsely Connected Ad Hoc Networks", *Proceedings of the First Annual Workshop on Mobile Ad Hoc Networking & Computing (MobiHOC)*, pp45-50, Boston, MA, USA, August 2000

[5] Chen, Z. D., Kung, HT., Viah, D., "Ad Hoc Relay Wireless Networks over Moving Vehicles on Highways", *Proceedings of the 2001 ACM International Symposium on Mobile ad hoc networking & computing,* PP247-250, October 04-05, 2001, Long Beach, CA, USA

[6] Chiang ,T.C., "Applying Wireless Location Technologies To ITS", *Proceedings of the 2004 IEEE International Conference on Networking, Sensing & Control*, Taipei,Taiwan, March 21-23,2004

[7] Chien, S., K. Mouskos, and S. Chowdhury, "Generating Driver Population for the Microscopic Simulation Model (CORSIM)", *SIMULATION*, Vol. 76, No.1, pp40~45, January 2001

[8] CORSIM Manual, The Federal Highway Administration, US Department of Transportation

[9] Dillenburg, John F., Nelson, Peter C. and Wolfson, Ouri, "Applications of a Transportation Information Architecture", *Proceedings of the 2004 IEEE International Conference on Networking, Sensing & Control,* Taipei,Taiwan, March 21-23,2004

[10] Feller, W., *An Introduction to Probability Theory and Its Applications, Volume II*, John Wiley & Sons, Inc., New York, 1971

[11] Dolil, S.A., Wong, W.C., and Steele, R., "Teletraffic Performance of Highway Microcells with Overlay Macrocell", *IEEE JSAC*, Vol. 7, pp:71-78, Jan 1989

[12] Gavrilovich, C.D., "Broadband Communication on the Highways of Tomorrow", *IEEE Communications Magazine*, PP146-154, April 2001

[13] Grossglauser, M., and Tse, D., "Mobility Increases the Capacity of Ad Hoc wireless Networks", *Proceedings of Infocom 2001*, Vol. 3, PP1360-1369, Anchorage, AK, USA, April 2001

[14] Hartenstein, H., Bochow, B., and Ebner, A., "Position-Aware Ad Hoc Wireless Networks for Inter-Vehicle Communications: the Fleetnet Project", *ACM MobilHoc2001*, Long Beach, CA, pp259~262, 2001

[15] Karp, B. and Kung, H.T., "Greedy Perimeter Stateless Routing for Wireless Networks", in *Proceedings of the Sixth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 2000)*, PP243-254, Boston, MA, USA, August 2000

[16] Li, J., Jannotti, J., De Couto, D.S.J., Karger, D.R. and Morris, R., "A Scalable Location Service for Geographic Ad Hoc Routing", in *Proceedings of the Sixth Annual ACM/IEEE International conference on Mobile Computing and Networking (MobiCom 2000)*, PP120-130, Boston, MA, USA, August 2000

[17] Li, Q. and Rus, D., "Sending Messages to Mobile Users in Disconnected Ad hoc Wireless Networks", *In Proceedings of the Sixth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 2000),* PP44-45, Boston, MA,USA, August 2000

[18] Morris, R., Jannotti, J., Kaashoek, F., Li, J., and Decout, D., "CarNet: A Scalable Ad Hoc Wireless Network System", in the *Proceedings of the 9th ACM SIGOPS European Workshop*, PP61-65, September 2000

[19] Xu, Y., Heidemann, J., and Estrin, D., "Geography-informed Energy Conservation for Ad Hoc Routing", *Proceedings of the Seventh Annual ACM/IEEE International Conference on Mobile computing and Networking 2001*, PP70-84, July pp16-21, 2001, Rome, Italy.

[20] Network Simulator Manual, http://www.isi.edu/nsnam/ns/

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