On the Intermittence of Routing Paths in Vehicle-Formed Mobile Ad Hoc Networks on Highways

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Abstract—An information network built on top of vehicles using IVC (Inter-Vehicle Communications) can be viewed as a type of mobile ad hoc networks (MANET). Due to the high mobility of vehicles, the topology of an IVC network can change rapidly and thus an established routing path can easily break. One reason for path breakage is that a vehicle moves out of the wireless transmission range of its previous or next vehicle on the path causing a wireless hop of the path to break. On highways, however, due to lane-changing and car-following among vehicles, such a broken hop may later become reconnected and cause the path to become reconnected as well.

In this paper we use several vehicle mobility traces generated by a microscopic traffic simulator to answer the following question — How possible a broken path may later become reconnected if the routing protocol is willing to give it some time to recover before switching to another path. Our finding shows that the path-reconnection possibility is very tiny and it is not worth waiting for such an event to occur.

I. INTRODUCTION

In recent years, Intelligent Transportation Systems (ITS) is becoming popular and an important research topic. ITS aims to providing drivers with safer, more efficient, and more comfortable trips. For example, ITS wants to provide drivers with timely traffic congestion and road condition information so that drivers can avoid congested or dangerous areas. In addition, ITS wants to provide drivers with networking services so that they can exchange information, send/receive emails, browse web pages from the Internet, etc. To achieve these goals, timely and efficiently distributing and acquiring useful information among vehicles is necessary.

In the ITS research community, inter-vehicle communications (IVC) has attracted the interests of many automobile manufactures and researchers. In such a scheme, no infrastructure is required for communications between vehicles, and each vehicle is equipped with a wireless radio by which it can send and receive its own messages, and forward messages for other vehicles. The vehicles on the roads dynamically form an ad hoc network at any time. Information is distributed, acquired, or exchanged on top of this network. Such an information network can be viewed as a type of MANET. In the following of this paper, for brevity, we will simply call such a vehicle-formed MANET an IVC network.

Although many studies about MANET have been performed in the past, their results may not be applicable to an IVC network. In such a network, vehicles can move at a high speed such as 120 Km/hr. In past studies, however, mobile nodes are generally assumed to move at a much lower speed. In addition, vehicles generally move on paved roads with acceleration/deceleration, lane-changing, and car-following behaviors. However, mobile nodes in past studies are generally assumed to move freely in a random-waypoints fashion, which has recently been found to lead to unreliable results [1]. Due to these differences, the results obtained from past studies about MANET require re-inspection for their suitability for IVC networks.

In ITS, timely and efficient information distribution, acquisition, and exchange among vehicles is important. However, due to several reasons, it is not easy to achieve these goals. First, an IVC network can easily get partitioned. This situation can easily happen when traffic density is low (e.g., at midnight), when the wireless transmission range is small, when few vehicles are equipped with wireless radios, etc. Second, on an IVC network the data forwarding path (i.e., unicast routing path) between any pair of vehicles can easily break. This situation can easily happen when the source and destination vehicles are moving in opposite directions. It can also easily happen when these two vehicles are moving in the same direction but at different desired speeds. This is because in this situation lane-changing is very likely to occur.

Because network topology changes can happen so frequently on an IVC network, an established unicast routing path on such a network is not expected to last for a long period of time. As such, a routing protocol designed for IVC networks should be able to quickly detect that a path has become broken and find a new path to replace it. Otherwise, a lot of packets will still be sent over a non-existing path and get lost.

For each detected path breakage, a routing protocol normally will trigger its pair repair protocol to repair it. This, however, will incur much control packet bandwidth overhead.
and leave little bandwidth for useful application data on IVC networks. Nowadays most routing protocols proposed for MANETs such as AODV [2] and DSR [3] have their own path repair protocol. Generally, these protocols can be classified into one of two repair strategies. They are the local and global repair strategy, respectively. Using the local repair strategy, a protocol tries to set up a new path from the breaking point to the destination vehicle and reuse the path from the source vehicle to the breaking point. Using the global repair strategy, a protocol instead tries to set up a new path from the source vehicle to the destination vehicle. Some routing protocols use a hybrid approach in which the local repair strategy is used first, and if it fails, the global repair strategy is used next. Although these strategies are different, they are all costly because they all need to flood a lot of control packets over the network to search a new path.

In addition, constantly changing the path used between two vehicles will also harm the performances of the transport protocol and applications greatly. If a new path is used to replace an old path, several in-flight packets may get out-of-order due to traveling on different paths (i.e., the new path and the old one). Nowadays, TCP is the transport protocol that is used by most applications. For TCP, because each lost packet or several out-of-order packets will cause the TCP sender’s transmission rate to be reduced by a half (sometimes even causes the TCP sender to timeout for at least one second), constantly changing the path between two vehicles will harm the performance of TCP and its applications greatly.

Wisely triggering the path repair protocol therefore is important. By this, we mean that the path repair protocol should be triggered only when the path is really broken and there is little hope that the broken hop can become reconnected soon. On the other hand, if the broken hop can become reconnected soon (say, in 2 or 3 seconds) and applications can tolerate this delay, the routing protocol should avoid using its path repair protocol. This will not only reduce control packet bandwidth overhead, but also reduce the harm made to TCP and application performance.

On a highway IVC network, due to lane-changing and car-following behavior, a vehicle may constantly decelerate and accelerate. When the desired speed of a vehicle exceeds the speed of its lead vehicle on the same lane, it may decide to change its lane to the next lane to pass the lead vehicle. However, to avoid collision with vehicles moving on the next lane, it generally will decelerate a bit waiting for a safe opportunity to come. For safety reasons, the vehicles moving on the next lane generally will also decelerate when they detect that a vehicle is moving into their lane. After the lane-changing process is completed, generally these involved vehicles will accelerate to reach their desired speeds. As can be envisioned, a vehicle may thus constantly decelerate and accelerate on a highway.

For the above reason, the distance between a vehicle and its lead (or following) vehicle on the same lane may constantly change. Sometimes it is lengthened while sometimes it is shortened. Since the quality (power) of received wireless signal mainly depends on the distance, the wireless hop between a vehicle and its lead vehicle may be intermittent. That is, in most periods of time the wireless hop is working while in some periods of time it is not working. Since a path on an IVC network is composed of several wireless hops, we may expect that a path on an IVC network is also intermittent.

Understanding whether a path on a highway IVC network generally is intermittent or not is important. If generally a path is intermittent, the path breakage time is small (e.g., 2, 3, or 4 seconds), and the application can tolerate this delay (say, the ftp file transfer application), the routing protocol should not trigger its path repair protocol too aggressively. This will save a lot of control packet bandwidth overhead and reduce the harm made to TCP and application performance. On the other hand, if generally a path is not intermittent, (that is, when a path breaks, it breaks forever), then the routing protocol may trigger its path repair protocol aggressively to avoid losing a lot of packets sent over a non-existing path.

The contribution of this paper is a study on whether or not generally a path is intermittent on a highway IVC network. This study is based on more realistic vehicle mobility traces generated by a microscopic traffic simulator and has not been studied in the past.

The rest of this paper is organized as follows. Section II surveys related work. Section III describes the simulation environment and settings. Section IV explains the performance metrics used in this study. In section V, we present the simulation results. In section VI, we present a deeper analysis. In section VII, we discuss how our study would proceed in the future. Finally, we conclude the paper in Section VIII.

II. RELATED WORK

In the literature, several papers have discussed and studied the applications of MANET to IVC networks. In [4], the authors presented the framework and components of their “Fleetnet” project, which aims to efficiently exchanging information among vehicles. In [5], the authors proposed a GPS-based message broadcasting method for inter-vehicle communication. In [6], the authors proposed a GPS-based unicast routing scheme for cars using a scalable location service. In [7], the authors showed that messages can be delivered more successfully, provided that messages can be stored temporarily at moving vehicles while waiting for opportunities to be forwarded further. In [8], [9], the authors studied how effective a vehicle accident notification message can be distributed to vehicles inside a relevant zone. In [10], the authors focused on how to establish a direct transmission link between two neighboring vehicles.

This paper differs from these papers in two ways. First, it uses more realistic vehicle mobility traces generated by a microscopic traffic simulator to study IVC-related problems. In contrast, these papers do not use reasonable vehicle mobility traces to study these problems. Second, this paper studies the intermittence of routing paths on highway IVC networks. This topic has not been addressed in the past.
In [11], we studied the effectiveness of distributing information on an IVC network. The approach taken by that paper is similar to that used in this paper. However, the topic addressed by that paper is different from that of this paper.

III. SIMULATION SETTINGS

A. Traffic Simulator

The microscopic traffic simulator that we used to generate mobility traces of vehicles is VISSIM 3.60 [12], which is a commercial software developed by PTV Planung Transport Verkehr AG company, located in Germany. VISSIM uses the psycho-physical driver behavior models developed by Wiedemann [13], [14] to model vehicles moving on the highways. This includes acceleration/deceleration, car-following, lane-changing, and other driver behaviors. Stochastic distributions of speed and spacing thresholds can be set for individual driver behavior. According to the user manual, the models have been calibrated through multiple field measurements at the Technical University of Karlsruhe, Germany. In addition, field measurements are periodically performed to make sure that updates of model parameters reflect recent driver behavior and vehicle improvements.

B. Highways System

The topology of the highway used in this study is a rectangular closed system with 3 lanes in each direction. Its length and width are 8 Km and 5 Km, respectively. There are no entrances and exits on this highway system. Vehicles are injected into this system in both directions at the top-left corner. The injection rate is 1,000 vehicles per hour in each direction. After all vehicles have entered the system, they move freely in the highway system according to their respective desired speeds, vehicles characteristics, and driving behavior.

Since vehicles are assigned different desired speeds and different thresholds for changing lanes for achieving their desired speeds, a vehicle may thus (1) move at its desired speed when there is no slower vehicle ahead of it, (2) follow the lead vehicle patiently, which may happen when the lead vehicle is slower but the difference between the lead vehicle’s speed and its own desired speed is still tolerable, or (3) decide to change its lane to pass the lead vehicle if the speed difference is intolerable.

The vehicle mobility traces are taken after all vehicles have entered the highway system and have been moving for at least one hour. Many traces are taken and each one lasts for 300 seconds. In this paper, the reported performance results are derived from one of these traces. We have also processed other traces and found that their results are all consistent. Note that in this highway system, vehicles in different directions do not interact with each other. This is because in this topology a vehicle cannot leave the highway in one direction and then enter the highway in the opposite direction.

C. Vehicle Traffic

In this study, the total number of vehicles moving in the highway system is set to be 2,000 and a half of them are moving in each direction. The average distance between a vehicle and the vehicle immediately following it on the same lane can be calculated. It is $(26 \text{ Km/lane} \times 3 \text{ lanes/direction})/(1,000 \text{ vehicles/direction}) = 78$ meters.

The desired speeds chosen for these vehicles determine the absolute speeds of these vehicles and the relative speeds among them. The distribution of these desired speeds is $[20\%: 100 - 110 \text{ Km/hr}, 40\%: 90 - 100 \text{ Km/hr}, 20\%: 80 - 90 \text{ Km/hr}, 20\%: 70 - 80 \text{ Km/hr}]$, which means that 20% of the vehicles are moving at their desired speeds uniformly distributed between 100 Km/hr and 110 Km/hr, 40% of the vehicles are moving at their desired speeds between 90 Km/hr and 100 Km/hr, etc.

D. Wireless Radio

The transmission range of the wireless radios used in these vehicles is chosen to be 100 meters. It is a reasonable setting for the DSRC (Dedicated Short Range Communication) standards proposed for ITS applications.

Since this paper focuses only on the connectivity among vehicles rather than the achievable data transfer throughput among vehicles, this paper does not consider the bandwidth of wireless radios and the medium access control protocol used by them. Instead, we took a simplified approach to determine whether or not two vehicles can successfully exchange their messages. In our study, as long as two vehicles are within each other’s wireless transmission range, their message exchanges will succeed. Otherwise, their message exchanges will fail. This scheme is similar to that used in the ns-2 simulator [15], except that 250 meters is used as the transmission range of IEEE 802.11 wireless LAN in ns-2.

E. Maximum Path Breakage Time Allowed

This parameter MPBTA defines when the lifetime of a path without repairs ends. In this paper, the unit of path lifetime is set to be second. Suppose that a path without repairs breaks in T’th second. Then, in the (T+1)’th, (T+2)’th, ..., and (T+MPBTA-1)’th seconds, we test whether this path is still broken. If in any of these seconds (say T+2) the broken path becomes connected, the current path breakage testing is aborted. A new path breakage testing will be initiated when the path becomes broken again in the future (e.g., in (T+4)’th second). In this case, we say that the lifetime of this path is extended by using this OMC (One-More-Chance) mechanism. However, if in all of these seconds the broken path remains broken, we consider that the lifetime of this path ends and it ends in T’th second.

The lifetime of a path with repairs is defined as follows. Suppose that the initial path of such a path is P0. When the lifetime of P0 ends as defined above (say in T’th second), we use the global path repair protocol to find a new path (say P1) to replace it starting from T’th second. This path-changing process is repeated until when the lifetime of the current path
ends but no other path can be found to replace it, which marks the end of the lifetime of such a path. Suppose that a path with repairs starts in N'th second and ends in M'th second, then the lifetime of such a path is defined to be (M - N).

Suppose that a path P with repairs is repaired as \( P_0, P_1, P_2, ..., P_n \) different paths throughout the period of its lifetime. It is clear that the lifetime of P is the sum of the lifetime of these repaired paths. Actually, the lifetime of these repaired paths \( P_0, P_1, P_2, ..., P_n \) can be considered as the path repair time intervals of the path P. For this reason, in this paper we say the lifetime of a path P unless specified otherwise, we means the lifetime of P with repairs.

It is clear that the MPBTA parameter may affect the lifetime of a path (either without repairs or with repairs). A larger value of MPBTA gives a path more chances to extend its lifetime and thus may increase the lifetime of the path. Although choosing a larger value for this parameter may decrease the times the path repair protocol needs to be triggered and thus the control packet bandwidth overhead, it may affect applications and thus must be tolerated by them. In this paper, we choose three different values to test. They are 1, 2, and 3 seconds, respectively. We want to see whether different values of MPBTA would affect the lifetime of paths on a highway IVC network.

IV. STUDIED PERFORMANCE METRICS

The studied performance metrics are described in this section. For each metric, we analyze and show its performances in six different cases, which are the combination of the studied path population and the value of MPBTA.

We classify all paths in the highway system into two path populations and report their performances separately. We decide not to report the performances of the aggregation of these two populations because we found that some of their performances differ significantly and it is better not to mix them.

The first population consists of all of the paths whose source and destination vehicles are moving in the same direction in the highway system. The second population, on the other hand, consists of all of the paths whose source and destination vehicles are moving in the opposite directions in the highway system. It is clear that the aggregation of these two populations represents all of the paths in the highway system.

The tested values of MPBTA are 1, 2, and 3 seconds, respectively. Since each of these values is applied to each of the two path populations, we have six different cases in total. In the rest of the paper, they are named SameDirMaxBreakageTime1sec, DiffDirMaxBreakageTime1sec, SameDirMaxBreakageTime2sec, DiffDirMaxBreakageTime2sec, SameDirMaxBreakageTime3sec, DiffDirMaxBreakageTime3sec, respectively.

A. Lifetime Number Distribution

The first performance metric is the number distribution of the lifetime of all paths with repairs in a particular case. Starting from the first second of a trace, for every pair of vehicles, we check whether a path with repairs can start in each second. We say that a path with repairs between two vehicles starts in N'th second if there exists a path between them in N'th second. Once such a path is found (we choose the shortest path), in each subsequent second we then check whether its lifetime would end in this second using the procedure described in Section III-E. After the starting time and ending time of a path with repairs are found, its lifetime is determined and accounted.

Note that, according to the above definition, all paths that can be started in any second during the trace are accounted and processed separately. Also, although in this way each found path has a lifetime of at least 1 second, its exact lifetime actually may be less than 1 second.

The lifetime number distribution is useful. First, it can show how easily or difficulty a path can be found (set up) in a case. For example, in a 300-second trace, if more paths can be found in a case than in another case, then it means that it is easier to find (set up) a path in the former case.

Secondly, it can tell us whether different values of MPBTA would affect the lifetime of paths with repairs on an IVC network. If different values of MPBTA can make differences, these differences will be shown in the lifetime number distribution. For example, suppose that using a larger value of MPBTA can really increase the lifetime of paths with repairs, then we should see that the shape of the lifetime number distribution changes and is shifted to the right.

Thirdly, it can be translated into the lifetime percentage distribution by dividing each number by the total number. With the percentage distribution, we will have a sense of how long generally an established path can last with repairs on an IVC network. Clearly, we prefer to see long lifetime rather than short lifetime for these paths. Otherwise, many useful unicast-based applications such as email, ftp, http, and telnet are unlikely to be useful on an IVC network.

B. Path Repair Time Interval v.s. Lifetime

The second one is the relationship between the expected average path repair time interval of paths with repairs and their lifetime. The path repair time intervals of a path with repairs have been defined in Section III-E. Suppose that they are \( I_1, I_2, I_3, ..., I_N \), respectively (in seconds). Then the average path repair time interval of this path during its lifetime is defined to be \( (I_1 + I_2 + ... + I_N)/N \).

After the average path repair time intervals of all paths are calculated, for each specific lifetime, we then calculate the expected value of the average path repair time intervals of all paths whose lifetime is the same as that specified. This performance metric shows how frequently a routing protocol needs to use its path repair protocol to extend a path's lifetime. Clearly, we prefer to see a long time interval; otherwise, constantly triggering the path repair protocol will incur much control packet bandwidth overhead. This relationship can also let us know whether using a larger value of MPBTA can increase the lifetime of paths without repairs (i.e., the path repair time interval).
V. Simulation Results

1) Lifetime Number Distribution: Figure 1 shows the number distribution of the lifetime of paths with repairs found in the six different cases. The Y axis shows the number of those paths whose lifetime is exactly a specific value in the 300-second trace. The X axis shows the range between 1 and 50 seconds rather than the whole range between 1 and 300 seconds. This is because for these cases, over 93% of all paths with repairs in the trace have a lifetime less than 50 seconds. As such, we focus only on this range to see the details.

Surprisingly, the path number distributions of these six different cases are almost identical. This result gives us two insights. First, using different values of MPBTA makes tiny difference in changing the lifetime of a path on an IVC network. Second, when a vehicle wants to set up a path to another vehicle, it need not care about whether that vehicle is moving in the same direction with itself or not. This is because the distributions of the three SameDir cases are identical to their corresponding DiffDir cases.

2) Expected Average Path Repair Time Interval and Lifetime Relationship: Figure 2 shows the relationship between the expected average path repair time interval of paths with repairs (in seconds) and their corresponding lifetime. First, again we see that using a larger value of MPBTA makes tiny difference in changing the lifetime of a path without repairs. Second, from the absolute performance numbers of these curves, we see that the expected average path repair time interval on an IVC network on highways is very small and is only between 1 and 1.2 seconds. This is a bad news as the path repair protocol will need to be triggered very frequently and thus cause much control packet bandwidth overhead. Third, we see that the expected average path repair time intervals of the three SameDir cases are a little bit shorter than those of their corresponding DiffDir cases. This is interesting as in Figure 1 we see that when paths can be repaired, their expected lifetime are almost the same in the SameDir and DiffDir path populations. However, here we see that if paths cannot be repaired, their lifetimes are a little bit different in these two different path populations.

VI. A Deeper Analysis

Figure 1 and Figure 2 have shown us that using a larger value of MPBTA makes tiny difference in changing the lifetime of a path either with or without repairs. Here we use another approach to confirm the result.

First, for every path without repairs in the trace, we calculate how many times the OMC mechanism can be applied to it to extend its lifetime. These numbers are processed to make a fraction distribution about them, which is shown in Figure 3. Note that the total number of paths without repairs under this test is about $2 \times 10^9$ for these four different cases.

From the figure, we see that despite whether we use 2 or 3 seconds for MPBTA, the fraction of paths to which no OMC can be applied is as high as 0.999, the fractions for OMC=1 and OMC=2 are all very tiny, and it is almost impossible for a path to benefit from using OMC more than two times to extend its lifetime.

Second, for every path without repairs in the trace, we calculate how many extra seconds its lifetime can be extended by using the OMC mechanism. These numbers are processed to make a fraction distribution about them, which is shown in Figure 4. Again, the total number of paths without repairs under this test is about $2 \times 10^9$ for these four different cases.

From the figure, we see that despite whether we use 2 or 3 seconds for MPBTA, the fraction for 0 second extra lifetime extended is as high as 0.999 and the fractions for 1, 2, 3, .. seconds extra lifetime extended are all very tiny.

In summary, the above two figures confirm that using a larger value of MPBTA is not an effective way to extend the lifetime of a path.

VII. Future Work

In the future, we plan to use the NCTUs 1.0 network simulator [16] to study how real-world protocols would perform on IVC networks. The NCTUs 1.0 can take VISSIM’s
vehicle mobility trace output as its input and uses real-world TCP/IP protocol stack and applications to generate high-fidelity simulation results. This makes it a suitable tool for studying IVC-related problems.

VIII. CONCLUSIONS

In this paper, we study the intermittence of routing paths on a simulated highway IVC network. We analyzed how different values of the maximum allowable path breakage time parameter can affect the lifetime of paths, either with or without path repairs.

Our results show that, for a highway IVC network, using a larger maximum allowable path breakage time will not extend the lifetime of paths and thus reduce the frequency of triggering the path repair protocol. Instead, it will only delay the time to repair the broken path and thus harm the performance of applications. As such, when a path breaks on a highway IVC network, it is not worth for the routing protocol to wait for the broken path to become reconnected. Instead, the routing protocol should quickly trigger its path repair protocol to find a new path for the broken one.

ACKNOWLEDGMENTS

We would like to thank the anonymous reviewers for their valuable comments. This research was supported in part by MOE Program for promoting Academic Excellence of Universities under the grant number 91-E-FA06-4-4, the NSC under the grant number NSC 92-2213-E-009-063, and the Ministry of Transportation under the grant number MOTC-STAO-92-16.

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