2006 IEEE International Conference on
Systems, Man, and Cybernetics
October 8-11, 2006, Taipei, Taiwan

The Effects of Using Roadside Wireless Repeaters on Extending Path Lifetime in Vehicle-Formed Mobile Ad Hoc Networks on Highways

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Abstract— **Intelligent Transportation Systems (ITS) is an important research topic. One goal of ITS is to exchange information among vehicles in a timely and efficient manner. In the ITS research community, inter-vehicle communications (IVC) is considered a way that could achieve this goal without infrastructure support.**

An information network built on top of vehicles using IVC is a type of mobile ad hoc networks (MANET). In the past, many unicast routing protocols for MANET have been proposed. In these protocols, when a routing path breaks, they either locally or globally repair it. Because the topology of an IVC network changes very rapidly on the roads, an established routing path in such a network breaks very frequently. This phenomenon hurts the performance of applications running on an IVC network. In this paper, we investigate the effect of using roadside wireless repeaters on extending routing path lifetime in IVC networks on highways.

I. INTRODUCTION

Intelligent Transportation Systems (ITS) is an important research topic. ITS aims to provide drivers with safer, more efficient, and more comfortable trips. For example, ITS aims to provide drivers with timely traffic congestion and road condition information so that drivers can avoid congested or dangerous areas. In addition, ITS aims 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 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 sends, receives, and forwards messages for other vehicles. The vehicles on the roads dynamically form a mobile ad hoc network (MANET) at any time. Information is distributed, acquired, and exchanged on top of this network. 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 done in the past, their results may not be applicable to an IVC network. In an IVC network, vehicles can move at a high speed such as 110 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 been found to lead to unreliable results [1]. Due to these differences, the results of past studies about MANET may not be applicable to 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 short, when few vehicles are equipped with wireless radios, etc. Second, a routing path established between a pair of vehicles in an IVC network can easily break. A path can break easily when its source and destination vehicles move in opposite directions. Even if the path's source and destination vehicles move in the same direction, it can still break easily due to constant lane-changing activities occurring on the roads.

Because network topology varies frequently in an IVC network, an established routing path between two vehicles needs to be repaired frequently to maintain the path's connectivity. A routing protocol designed for IVC networks therefore should have a good path-repair design. Such a design should quickly find a backup path and incur minimum control packet bandwidth overhead. Otherwise, applications running on an IVC network will perform badly and the goodput of an IVC network will be low.

Designing a good routing protocol may help to find a backup path more quickly. However, if physically there is no backup path between a pair of vehicles, even the best routing protocol cannot maintain the path connectivity between them. The lifetime of the path between a pair of vehicles is mainly determined by the network topology rather than by the used routing protocol.

To extend the lifetime of paths in an IVC network on highways, increasing the number of wireless links in the IVC network is effective. This is because when more wireless links between vehicles exist in an IVC network, it is easier to find a backup path between a pair of vehicles to extend their path lifetime. One way to increase the number of wireless links in an IVC network is to deploy wireless repeaters along the highway. The function of a wireless repeater is very simple. It functions like a layer-1 Ethernet hub. When it receives a wireless packet, it immediately rebroadcasts the packet. If two vehicles are outside the wireless transmission range of each other but are within the wireless transmission range of the wireless repeater, they can successfully exchange their packets via the wireless repeater.

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With wireless repeaters deployed along the highway, one can expect longer path lifetime on highways. However, the cost of deployment and maintenance of these repeaters is the main factor determining the economic feasibility of this solution. Deploying a huge number of repeaters can make the network fully connected on highways. However, the cost of such a solution may be too high to be acceptable. The cost of this solution needs to be justified based on the advantages brought by this solution. To reduce the cost, one possible way is to increase the distance between two neighboring repeaters along the highway, which reduces the required number of repeaters. However, as such a distance increases, the path lifetime improvement may decrease.

The contribution of this paper is an investigation of path-lifetime improvement when roadside wireless repeaters are deployed in an IVC network on highways. We varied the distance between two neighboring wireless repeaters to study its effects on path lifetime improvement. This investigation is based on more realistic vehicle mobility traces 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 and presents the results. Finally, we conclude the paper in Section V.

II. RELATED WORK

In the literature, several papers have discussed and studied the applications of MANET to IVC networks. Due to the paper length limit, we can only briefly describe them here.

In [2], the authors presented the framework and components of their "Fleetnet" project, which aims to efficiently exchange information among vehicles. In [3], the authors proposed a GPS-based message broadcasting method for inter-vehicle communication. In [4], the authors proposed a GPS-based unicast routing scheme for cars using a scalable location service.

In [5], 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 [6], [7], the authors studied how effectively a vehicle accident notification message can be distributed to vehicles inside a relevant zone. In [8], the authors focused on how to establish a direct transmission link between two neighboring vehicles. In [9] , the authors studied the lifetime of routes in ad hoc networks assuming that node mobility can be described by a simple mathematic model.

In [10], the authors proposed some changes to AODV routing protocol for IVC networks. In [11], the authors proposed a position-based routing protocol for IVC networks in city environments. In [12], the author studied the effectiveness of distributing information on an IVC network. In [13], the author studied the effects of wireless transmission range on path lifetime in an IVC network. Recently, the authors in [14] proposed a practical routing protocol for vehicles moving on the roads.

Most of these studies proposed new routing protocols for providing timely and efficient information distribution, acquisition, and exchange on IVC networks. In contrast, the focus of this paper is not to propose a new routing protocol for IVC networks. Instead, in this paper we discuss the effects of using roadside wireless repeaters on extending routing path lifetime in IVC networks on highways.

Recently, in [15], the authors studied the strategy used to deploy wireless access points for outdoor wireless local area networks. Although they also studied the effects of AP distance on the performance of an outdoor wireless local area network, there are some important differences between the two papers. First, the approach taken in their paper (analytical) is different from that taken in this paper (trace-based simulation). Second, the performance metrics studied in their paper (link utilization) are also different from those studied in this paper (path lifetime).

III. SIMULATION ENVIRONMENT AND SETTINGS

A. *Traffic Simulator*

The microscopic traffic simulator that we used to generate mobility traces of vehicles is VISSIM 3.60 [16], 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 [17], [18] 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. *Highway System*

The topology of the highway used in this study is depicted in Fig. 1. It is a rectangular closed system with 4 circular corners and has 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.

Although the chosen highway topology may not be very realistic compared with highways in the real world, we think that their difference is not important from the viewpoint of DSRC (Dedicated Short Range Communication) wireless transmission. It is true that a real-world highway may not look like a rectangle and instead may have several curves. However, for the safety of high-speed driving, the radii of these curves usually are very large (say, a few kilometers). This property makes these curves effectively equivalent to straight lines when the 100-meter DSRC wireless transmission range is used.

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

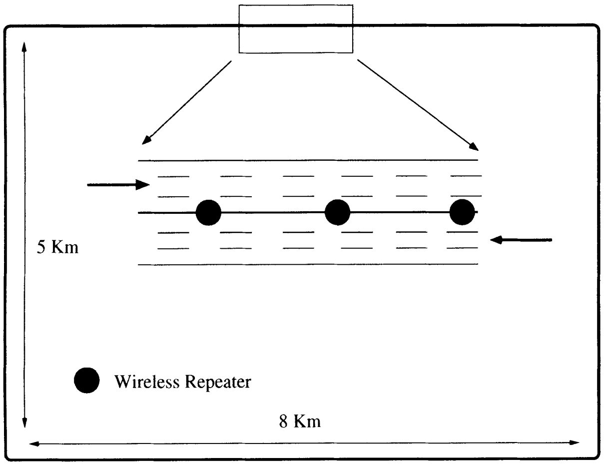

Fig. 1. The topology of the highway used in this study

to their respective desired speeds, vehicle 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 lanes 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. Ten traces are taken and each one lasts for 300 seconds. In this paper, the reported performance results are averaged results from these traces. We have also computed the standard deviation of a performance metric from these traces. These standard deviations usually are less than 5% of their corresponding averages. To make performance curves easy to read rather than being cluttered up with standard deviation points, in the presented performance plots, only average points are plotted and standard deviation points are omitted.

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 Km/lane * 3 lanes/direction)/(1,000 vehicles/direction) = 78 meters. This car-following distance is typical of a highway in which many vehicles use the highway but they move smoothly without congestion.

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 set to be [20%: 100 – 110 Km/hr, 40%: 90 – 100 Km/hr, 20%: 80 – 90 Km/hr, 20%: 70 – 80 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. We think that this distribution is typical of a highway in which various types of vehicles exist.

D. Wireless Radio

The transmission range of the wireless radios used in vehicles and wireless repeaters 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 them, 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 nodes (each one can be either a vehicle or a wireless repeater) can successfully exchange their messages. In our study, as long as two nodes 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 [21], except that 250 meters is used as the transmission range of IEEE 802.11 wireless LAN in ns-2.

E. Roadside Wireless Repeaters

Along the highway, wireless repeaters are deployed at the center of the six lanes (see Fig. 1). The distance between two neighboring wireless repeaters is set to a value larger than 100 meters so that there is no direct link between them. If the distance is set to a value smaller than or equal to 100 meters, the IVC network will become a fully-connected network. In such a case, there will always be a path between any pair of vehicles (This is because now these wireless repeaters form the backbone of the IVC network) and the lifetime of a path will last forever until the simulated period is finished. Because the above results are intuitive and uninteresting, we do not study the cases in which the distance between neighboring repeaters is less than 100 meters. Instead, we investigate only those cases in which the distance is greater than 100 meters.

F. Routing Protocol

Most existing routing protocols designed for MANET such as [19] and [20] implement their own path-repair designs. Generally, a path-repair design can be classified as either a local or a global repair design. In a local repair design, when a path breaks, the routing 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. In a global repair design, a routing protocol instead tries to setup a new path from the source vehicle to the destination vehicle.

When a path breaks, a local repair design can find another path to reconnect the source vehicle to the destination vehicle more quickly than a global repair design can do. This is because in a local repair design the breaking point need not send a path-broken error message to the source vehicle to initiate a global path search. Instead, it just needs to find a local path to connect the breaking point to the destination vehicle. One problem with this design is that such a local path may not exist however a new path from the source to the destination vehicles may indeed exist. As such, the lifetime of a path under a local design is theoretically shorter than that under a global repair design. For this reason, in this paper we assume that the routing protocol uses a global path repair design.

IV. PERFORMANCE METRICS AND RESULTS

The following metrics are chosen to observe the performance improvement when roadside wireless repeaters are used. For each metric, we analyze and show its performance under eight different wireless repeater distances. The eight distances are 110, 120, 150, 200, 300, 400, 500 meters, and ∞, respectively. In the last setting, no wireless repeaters are deployed on the highway.

A. Call Blocking Probability

The first metric is the call blocking probability during the period of a trace (which is 300 seconds in our study). In each second, each vehicle tries to build a unicast connection to every other vehicle. If there is a routing path from the source to the destination vehicles, the connection call will be successfully established. Otherwise, the connection call will be blocked. Ideally, if the IVC network is fully connected at all time, the maximum number of successful calls during the trace period is (300 seconds) * (2,000 vehicles * 1,999 other vehicles) / (2 symmetric factor) = 599,700,000 calls. If we define T as the total number of successful calls established during a trace, the call blocking probability can be calculated by $1 - (T/599700000)$.

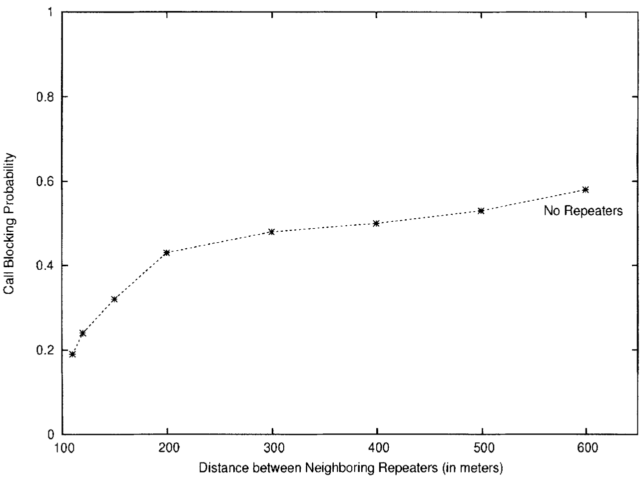

Fig. 2. The call blocking probability under different distances between neighboring repeaters

Fig. 2 shows the call blocking probability for the eight cases. Each point on the curve is the average call blocking probability calculated from the results of ten traffic traces. The point on the right represents the case with no repeaters. Comparing the cases with repeaters to this case, we see that deploying roadside wireless repeaters reduces call blocking probability as expected. On the other hand, one observes that when the repeater distance is only 110 meters, which is close to the wireless transmission range, the call blocking probability is still about 20%. Compared to the 0% call blocking probability when the repeater distance is less than 100 meters, this shows that setting the repeater distance to a value larger than the wireless transmission range may cause a non-negligible call blocking probability.

B. Path Lifetime

The second performance metric is the average lifetime of paths with different length in hop count. We define the lifetime of a repairable unicast path between two vehicles as the duration in which there exists one path between them. That is, during this period these two vehicles can find a path to exchange their messages, even though this path may need to be changed during this period. (For brevity, in the following of this paper we will simply use "unicast path" or "path" to represent "repairable unicast path.")

In our study, whenever there is a need to find a path between the source and the destination vehicles, we choose the shortest path between them. We set the unit of path lifetime to be one second. Starting from the first second of a traffic trace, for every pair of vehicles, we check whether a unicast path can start in each second. We say that a unicast path between two vehicles starts in N^{th} second if there exists a path between them in N^{th} second. Once a path is found (set up) between two vehicles, in each subsequent second we check whether it would break in this second. A unicast path is considered broken if any wireless link (i.e., hop) on its path no longer exists. If the path does not break in this second, we repeat this connectivity test in the next second.

Suppose that a path is found to be broken in M^{th} second. Because the global repair design is used, we try to find the shortest backup path between the source and destination vehicles. If no such backup path can be found, the lifetime of this repairable unicast path is now determined and it is $(M+1)-N$. On the other hand, if such a path can be found, the old path is replaced with this new path. After the new source-to-destination path is formed, its connectivity will be tested in each subsequent second as before.

We classify all paths into different hop-count classes by their initial path hop count. This means that no matter how many times a path's hop count changes during a traffic trace, only the initial hop count of a path is taken into account for our classification. In each traffic trace, in order to obtain the average path lifetime of a hop-count class, we average the lifetime of the paths belonging to that class.

Fig. 3 shows the relationship between average path lifetime and path length in hop count under different repeater distances. The results give us some insights. First, the

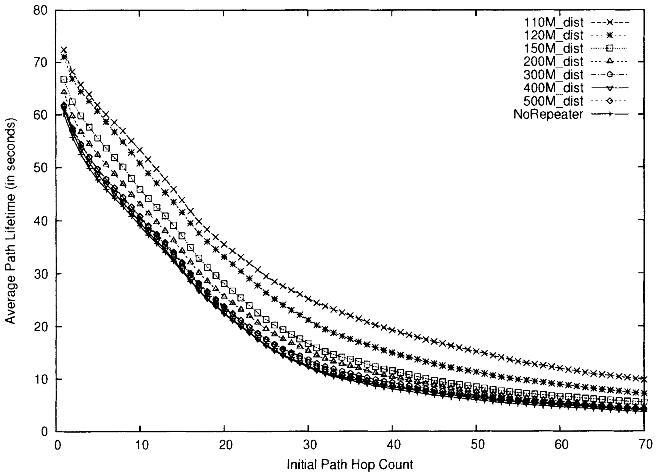

Fig. 3. The relationship between average path lifetime and their initial hop count under different repeater distance

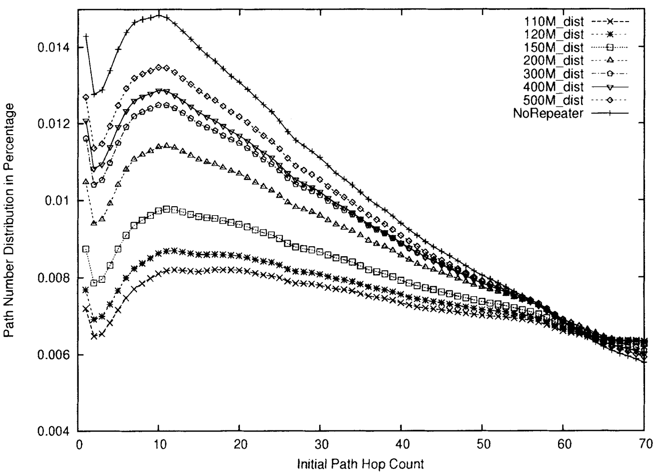

Fig. 4. The path number distribution in percentage under different repeater distances

deployed roadside wireless repeaters indeed extend path lifetime. Comparing the case of 110-meter repeater distance with the case using no repeaters, one sees that average path lifetime can be increased by 10 to 15 seconds when 110 meters is used as the repeater distance. From this figure, one also see that, the longer a path is, the shorter its lifetime is. For example, even in the 110-meter case, one sees that a path's lifetime is only about 20 seconds when its length is 40 hops. This is a bad news for applications which need to use long network connections to exchange data.

C. Path Number Distribution in Percentage

The third performance metric is the path number distribution in percentage for each case with different repeater distances. Like before, in each traffic trace, when a path is first established, it is classified into a hop-count class by its initial hop count, and the path counter of that class is increased by one. After a trace is processed, each hop-count class's path proportion is then calculated.

Fig. 4 shows the relationship between path number distribution in percentage and path length in hop count for the eight cases. The results show that when more roadside repeaters are deployed in the IVC network, the proportion of longer paths increases in the distribution curve. This phenomenon shows the effect of roadside repeaters on extending the path length. In addition, one sees that in each case the paths with initial length of about 10 hops constitute the most part of the distribution. This information can be provided to the routing protocol to best utilize the IVC network.

D. Path Repair Count

The fourth performance metric is the relationship between path repair count and initial path hop count under different repeater distances. Like before, in a traffic trace, when a path is first established, it is classified into a hop-count class by its initial hop count. Later on, when it is repaired due to a path break, its path repair count is increased by one. As such, we have the path repair count information of every path in the trace. To obtain the average path repair count of a hop-count class, we average the path repair counts of the paths belonging to that class.

This performance metric shows how frequently a routing protocol needs to use its path-repair design to extend a path's lifetime. Clearly, we prefer to see a small path repair count, otherwise, constantly triggering the path-repair design will incur much control packet bandwidth overhead and hurt the performance of applications.

Fig. 5 shows the relationship between average path repair count and path length in hop count under different repeater distances. From this figure one has the following findings. First, longer paths have smaller path repair counts. This is not because longer paths are more stable, but because they have shorter path lifetime. In other words, before the lifetime of a path ends, a longer path will experience fewer path repairs than a shorter path does. Second, one sees that, for each hop-count class, when the repeater distance becomes smaller in the IVC network, a path suffers from more path repairs. From Fig. 2, one sees that roadside repeaters help find paths between a pair of nodes. When the path is longer, the chance that there is at least one repeater that relays two vehicles and resides on the path becomes higher. However, because the location of the roadside repeater is fixed while the two vehicles move at high speeds, the two links between the repeater and each of the two vehicles will soon break. This explains why the path repair count increases when the repeater distance decreases. On the other hand, when the repeater distance is large, most found links are directly between two vehicles moving in the same direction. Such links can last longer before they break.

V. CONCLUSIONS

In this paper, we investigate the effects of using roadside wireless repeaters on extending routing path lifetime in IVC networks on highways. By using a microscopic traffic simulator, we generated several mobility traces of vehicles moving on the simulated highway. Based on these

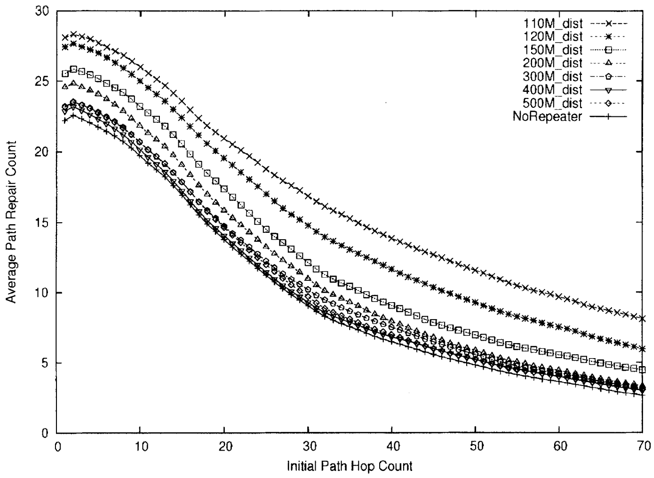

Fig. 5. The relationship between average number of path repairs and initial hop count under different repeater distances

traces and other settings, we analyze how different distances between neighboring repeaters would affect the call blocking probability, the path lifetime, the path number distribution, and the path repair count in the studied IVC network.

Our results show that, as conjectured, deploying roadside wireless repeaters can increase the path lifetime, and help find more paths in the IVC network. However, the average path repair count may increase. Our results show that using roadside wireless repeaters has its own advantages and disadvantages. These insights are useful for designing routing protocols and applications for IVC networks.

In the future, we plan to use the NCTUns 3.0 network simulator and emulator [22] to study how real-world protocols would perform on IVC networks with roadside wireless repeaters. NCTUns 3.0 can take VISSIM's vehicle mobility trace output as its input and uses real-world TCP/IP protocol stack and application to generate high-fidelity simulation results. These capabilities make it a suitable tool for studying IVC-related problems.

VI. ACKNOWLEDGMENTS

This research was supported in part by MOE Program for promoting Academic Excellence of Universities under the grant number 91-E-FA06-4-4.

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