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MANET ROUTING FOR VEHICULAR AD HOC NETWORK IN CITY ENVIRONMENT

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2006

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A thesis submitted to the Nanyang Technological University in
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ABSTRACT

Mobile Ad-hoc network (MANET) is an autonomous system that is made up of mobile nodes communicating through wireless links in an environment without the need for any static infrastructure. There is a growing deployment of this technology in the commercial world, especially in Inter-Vehicular Communication Systems (IVCS) over the recent years.

One of the most challenging problems in ad hoc networking is routing. Much work has been done in this area and many protocols have been proposed. Existing MANET routing protocols work well in scenarios where nodes are basically random and mobile. However, the same could not be applied to IVCS as vehicular travel is often restricted by roads and traffic patterns and transmission is more likely to be blocked by obstacles, like buildings.

A group project called BUSNet was initiated to study the performance of MANET routing algorithms for IVCS in a city environment, in which the public buses form the communication backbone. The focus of my research in this project is to develop MANET routing protocols for the BUSNet. My contribution to the project is the development of a novel local recovery mechanism and a position-based routing protocol, which caters to the characteristics of IVCS in a city environment.

A local repair mechanism, named Proximity Approach To Connection Healing Algorithm (PATCH), is proposed to improve the scalability of the topology-based on-demand routing protocol to improve its performance, thus making it suitable for small size IVCS environment. Simulation results show that DSR with PATCH reduces the

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control overhead by 30-50% as compared to normal DSR, or even AODV with local recovery. It also improves the delivery ratio and reduces the end-to-end delay.

For IVCS over a large metropolitan area, a new position-based routing scheme named Anchor-based Street and Traffic Aware Routing (A-STAR) is proposed. A-STAR is designed specifically for IVCS in a city environment to explore the spatial awareness, and traffic awareness of future smart vehicles. Unique to A-STAR is the usage of information on city bus routes to identify an anchor path with high connectivity for packet delivery. Together with a new recovery strategy for packets routed to a local maximum, A-STAR shows significant performance improvement over other position-based routing protocols. Equipped with a simple reactive location service (RLS), A-STAR also shows performance advantage over well-known reactive routing protocol – AODV.

Chapter 1

Introduction

1.1 Background and Motivation

Nowadays, portable devices like cell phones, notebooks and personal digital assistants (PDA) are gaining acceptance among users. Consumers are more and more interested in up-to-date information. “‘Information Anytime Anywhere’ is the new motto of this communication era. We are undoubtedly in a new era: the era of mobile communication” [10].

Providing motorists access to information is steadily gaining importance for the mobile workforce. Drivers and passengers may like to chat with other vehicle's passengers, access the internet and receive information about traffic jam and accident in the vicinity. Thus, more and more car manufacturers are including wireless devices and navigation facilities in vehicles. The use of the traditional cellular network system for car-to-car communication is not effective for the following reasons:

- The cost of building and maintaining the cellular infrastructure is very high.
- The end-to-end delay may become long as the communication need to go through base stations, and such delay may become unbearable in IVCS for some interactive application, e.g. gaming.

Thus, a better way for car-to-car communication is necessary if IVCS is to be prevalent. In recent years, Mobile Ad hoc NETworks (MANET) emerged as a competitive

technology for IVCS. It can also be used to compliment and increase the coverage of cellular network.

A mobile ad-hoc network is an autonomous system that is made up of mobile nodes communicating through wireless links in an environment without the need for any static infrastructure. Nodes in this network are self-organizing and rely on each other to relay messages between nodes. As the nodes are free to move around randomly, the network topology changes dynamically. Thus, the routing protocol must be adaptive and able to maintain routes in spite of the changing network connectivity. Because of its nature, infrastructureless, such network was initially explored for military use and other tactical applications such as emergency rescue or exploration missions. In recent years, there is growing research on the deployment of this technology in the commercial world, especially in IVCS. Examples of applications and implementation of MANET technology in IVCS have been shown in FleetNet [1], VICS [2], CarNet [3].

1.2 BUSNet - an approach to IVCS

1.2.1 Characteristics of IVCS

Routing is one of the most challenging problems in MANET. Much work has been done in this area and many protocols have been proposed. However, the use of MANET routing protocols in IVCS is certainly not optimal given the special characteristics of IVCS. Some of the characteristics of IVCS, which affect the performance of MANET protocols, are as follows:

- Vehicles are forced to move along the roads, thus with constrained mobility patterns.

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- There are many high buildings in city area that may effectively block the transmission signal of vehicles.
- Vehicle density is not evenly distributed: on certain roads, e.g. bus route, the vehicle traffic is much higher than the other parts.
- IVCS may need to cover large areas.
- Number of mobile nodes may be very high in total.

Several projects have been started to address the problem of applying MANET technology in IVCS, such as FleetNet [1], VICS [2], CarNet [3], etc.

1.2.2 Related work

1.2.2.1 FleetNet

To promote the development of IVCS, the project "FleetNet - Internet on the Road" was set up by a consortium of six companies and three universities [1][10]. FleetNet aims to develop and demonstrate a platform for inter-vehicle communication systems using wireless ad hoc network technology. Some of the key design requirements of FleetNet include the capability to distribute locally relevant data, and to satisfy the vehicle drivers' and passengers' needs for location-dependent information. Location awareness and position data play a crucial role not only for FleetNet applications but also for the communication protocols. While trying to apply MANET technology in IVCS, FleetNet chose the position-based routing protocol, GPSR, as its basic routing protocol.

1.2.2.2 CarNet

CarNet [3] is described as an application for a large ad hoc mobile network system that scales well without requiring a fixed network infrastructure to route messages. CarNet is targeted to support IP connectivity as well as applications such as highway congestion

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monitoring, fleet tracking and discovery of nearby points of interest. In CarNet, every car is a MANET node, which communicate using Grid [3], a position based scalable routing system. Grid uses geographic forwarding and a scalable distributed location service, GLS[11][12], to route packets from car to car without flooding the network.

1.2.3 BUSNet

The basic idea behind BUSNet [13] is that in a metropolitan area, there are usually a large number of regular moving vehicles, especially public buses. Buses always run along regular bus routes, at lower speeds compared to other private vehicles and bus routes runs along main traffic road, thus high vehicle density. For MANET, high regularity, low mobility and high density usually means high stability and reliability. Thus, in IVCS these characteristics of buses and bus routes make the buses and vehicles along the bus routes an ideal communication “backbone”, thus conceives the BUSNet project.

Figure 1 [13] shows an overview of the BUSNet architecture. BUSNet is basically a virtual mobile backbone infrastructure that is constructed using public buses and other vehicles along the bus routes. It is a virtual infrastructure, as it does not require the setup of any physical infrastructure. Thus, it can be deployed rapidly into any metropolitan environment that has a regular public bus service.

Figure 1: Overview of the BUSNet Architecture

For example, in Figure 1, while Car E and Car A may be geographically far apart, they are able to interact with one another through the BUSNet. As it is possible for the BUSNET backbone to be the bottleneck of the network due to congestion, it is not required that all inter-vehicular communications must traverse the backbone. Vehicles are given the ability to communicate without going through the backbone provided that there is a direct or shorter route between them. For example, communications between Car C and Car B can communicate directly with each other instead of going through the BUSNet backbone. Thus, the BUSNet backbone is used only when needed.

1.3 Objectives

The ultimate objective of BUSNet is to create, using the regular, deterministic and predictable nature of public bus services, a highly robust mobile backbone infrastructure

that would be as reliable as placing static transceivers at each bus stop along the bus routes.

The focus of this project in BUSNet is to design an ad hoc routing protocol, which is suitable for use in metropolitan area IVCS. To try to meet this goal two tasks are necessary.

The first task is to build a simulation model that can be used to simulate the MANET scenario in metropolitan environment. This model needs to consider the IVCS characteristics described in section 1.2.1. The second task is to design an ad hoc routing protocol using the regularity and predictability of bus movement. It is to be tested with the simulation model developed for the metropolitan area.

1.4 Outline

The rest of this report is organized as follows:

Chapter 2: A Review of Current MANET Routing Protocol – This chapter reviews the state-of-the-art MANET protocols categorized into 2 main categories: topology-based and position-based.

Chapter 3: PATCH - A Novel Local Recovery Mechanism for MANET – This chapter describes the idea of PATCH, a local recovery mechanism that helps improve the performance of on-demand routing protocol.

Chapter 4: Anchor-based Street Traffic Aware Routing Protocol – A-STAR – This chapter describes the proposed spatial and traffic aware, position-based forwarding routing protocol designed for BUSNet.

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Chapter 5: Conclusion and Future Work – This chapter concludes this report and highlight some of the outstanding challenges of BUSNet and inter-vehicular communication using MANET protocol.

Chapter 2

A Review of Current MANET Routing Protocol

Many routing protocols have been developed for MANET. These protocols can be divided into two major categories according to their routing strategy: (1) Topology-based routing protocol and (2) Position-based routing protocol. This chapter briefly discusses each of these categories, highlighting their strength and shortfalls.

2.1 Topology-based Routing Protocol

Based on the route discovery mechanism, the topology-based routing protocols can be further divided into 1) Proactive, 2) Reactive and 3) Hybrid.

2.1.1 Proactive Routing Protocol

Proactive protocols follow an approach similar to the wired routing protocols. By continuously evaluating the known and attempting to discover new routes, they try to maintain the most up-to-date map of the network. This allows them to immediately forward packets, as the route is known at the time when the packet arrives at the node. In order to maintain an accurate network graph in the constantly changing environment, nodes in the network would require continuous updates resulting in high network bandwidth overhead - clearly a disadvantage in the wireless world, where bandwidth is a sparse resource. Well known protocols of this type include Destination-Sequenced

Distance-Vector Routing (DSDV) [14], Fisheye State Routing (FSR) [16] and Optimized Link State Routing (OLSR) [65].

2.1.1.1 Destination-Sequenced Distance-Vector Routing (DSDV)

DSDV [14] uses a table-driven distance-vector algorithm based on the classical Bellman-Ford routing mechanism. The main enhancement made to the Bellman-Ford algorithm involves ensuring the absence of loops in routing tables. DSDV protocol requires each mobile station to advertise its own routing table to all of its current neighbors (for example, by broadcasting its table entries). The routing table at each node would contain a list of all available destinations and the number of hops to each other. Additionally, each entry in the table is tagged with a sequence number, which is embedded in the route update message. When a node receives a route update message with a newer sequence number from the destination, it updates its routing table. In a highly dynamic ad hoc network, the routing advertisement must be made every time the topology changes to ensure that each mobile node has the most current route information about all stations in the network. To alleviate the potentially large amount of network traffic overhead that routing update can generate, two types of notification packets are proposed. The first is known as a "full dump", which carries its entire routing information and naturally consumes more bandwidth. These packets are transmitted during periods of major route changes. The second type of update packet is known as "incremental update" packet, which is smaller and chosen when there are minor changes in the network.

DSDV has a major disadvantage when used in large ad-hoc network. This is due to the size of the routing table that grows linearly with the size of the network. Hence, in large dynamic ad hoc network, DSDV will suffer from serious bandwidth problem, because of the size and number of control data generated.

2.1.1.2 Fisheye State Routing (FSR)

Figure 2: Scope Division of Network (Fisheye)

FSR [16] is a type of classical link state routing. FSR is an implicit hierarchical routing protocol that subdivides the network into scopes of different coverage. The scopes are defined as the set of nodes that can be reached within a given number of hops as shown in Figure 2. The reduction of routing update overhead is achieved by using different exchange periods for different entries in the routing tables. To be more precise, entries corresponding to nodes within the smaller scope are propagated to the neighbors more frequently than entries corresponding to nodes far away from the center node. In FSR, update information exchange are done periodically. One advantage of FSR is the dynamic division of the network: each node builds its own view of the network.

2.1.1.3 Optimized Link State Routing (OLSR)

OLSR [65] uses an optimization of the link state algorithm tailored to the requirements of a mobile wireless network. The key concept used in the protocol is that of multipoint relays (MPRs) [66]. MPRs are selected nodes which will forward broadcast messages during the flooding process. This substantially reduces the control packet overheads. Further optimization is achieved by minimizing the "contents" of the control messages

flooded in the network: node declares only a small subset of links to its neighbor nodes, rather than all links to all neighbors. This information is then used by the OLSR protocol for route calculation. As a consequence hereof, routes in OLSR contain only the MPRs as intermediate nodes from a source to a destination.

2.1.2 Reactive Routing Protocols

Reactive routing is also known as on-demand routing. Reactive routing protocols do not maintain route to each destination in the network on a continual basis. Instead, routes are established on demand by the source, thus it reduces routing overhead caused by route exchange. When a route is needed, the source conducts a route discovery procedure. Firstly, the source node floods the network with a route request packet a request packet to discover a path to the destination. Upon receiving route requests, the destination picks the best route based on the route selection algorithm. Route reply packet is sent to the source via the newly chosen route. Here it is assumed that the communication link is symmetric. Numerous protocols of this type have been proposed. Dynamic Source Routing (DSR) [8] Temporary Ordered Routing Algorithm (TORA) [19][20], Ad-Hoc On Demand Distance Vector (AODV) [5] routing, Associativity-Based Routing (ABR) [56] and Signal Stability-Based Adaptive (SSA) [22] routing protocols are examples of on-demand routing protocols. The following sections describe some of the above-mentioned protocols.

2.1.2.1 Dynamic Source Routing (DSR)

DSR [8] is an on-demand routing protocol that is based on the concept of source routing. The packet contains the entire path from the source to destination, i.e., the path traversed by the packet is recorded in the packet and used by intermediate nodes for

making routing decision. Mobile nodes maintain a route cache of known source routes. DSR consists of two phases: route discovery and routes maintenance. In order to establish a route to the destination, the source first checks its route cache to see whether it already has the route to the destination; if not, it floods the network with a route request message with a unique request ID. When the route request message reaches the destination or a node that has a cached route to the destination, a route reply message is built and sent to the source. Route maintenance is accomplished through the use of route error messages and acknowledgments. Route error packets are generated and sent back to the source when a node along the route path cannot forward the packet to the target due to link failure. When a route error packet is received, the hop in error is deleted from the node's route.

2.1.2.2 Temporally Ordered Routing Algorithm (TORA)

TORA [19][20] is a highly adaptive, loop-free, distributed routing algorithm based on the concept of link reversal. It is source-initiated and provides multiple routes for each source-destination pair. The protocol is designed to minimize reaction to topological changes. A key concept in its design is that it decouples the generation of potentially far-reaching control message from the rate of topological changes. To that end, nodes need to maintain routing information about adjacent (one hop) nodes. TORA is an on-demand routing protocol that has three basic operations: route creation, route maintenance and route erasure. During the route creation and maintenance phases, nodes use a height metric that is a time-dependent array to establish a Directed Acyclic Graph (DAG) to the destination. Based on the relative height of the neighboring nodes, links are assigned to be either upstream or downstream. The key property of TORA is that all possible routes to the destination are stored during route creation. Upon failure of all routes to a

destination, the protocol generates an update packet to reconstruct the DAG rooted at the destination in finite time. Route erasing is performed by broadcasting a Route Clear packet through the network.

2.1.2.3 Ad Hoc On-Demand Distance Vector (AODV)

AODV [5] is a pure table-driven on-demand routing protocol built on the earlier described DSDV. Contrary to DSDV, where routes to all nodes in the network are maintained through periodic broadcast, AODV minimizes the numbers of required broadcasts by creating routes on an on-demand basis. A node requiring a route to some destination broadcasts a Route Request (RREQ) packet across the network. When either the destination or an intermediate node with a current route to the destination receives the RREQ, it responds by sending a Route Reply (RREP) to the source node. Once the source node receives the RREP, it can begin using the route for data packets transmission. For route maintenance, when a link breaks along an active route, the node upstream to the break sends a RERR message to any of its upstream neighbors, which were using that link to reach the destination. When a source node receives a RERR message, it re-initiates route discovery if it still requires the route.

2.1.2.4 Associativity-Based Routing (ABR)

ABR [56][57] differs from other on-demand routing protocols in its route selection. ABR defines a new routing metric for ad hoc network that is known as the degree of association stability. Each node periodically generates a beacon to indicate its presence. Upon receiving this beacon, the neighboring nodes update their associativity tables, by increasing their associativity metric accorded to the beaconing station. During the route discovery phases, a route is selected based on nodes having high associativity states that imply periods of stability. In this manner, the routes selected are likely to be long-lived

and hence less likely to have link breakage, resulting in lower control overhead and higher attainable throughput.

2.1.3 Hybrid Routing Protocols

This category of routing algorithms tries to combine the advantages of the previous two categories to produce a hybrid routing protocol. An example is Zone Routing Protocol (ZRP) [24] which combines proactive and reactive algorithms; another example is Terminode [25] which combines topology-based proactive and position-based forwarding and it will be discussed in section 2.2.2.3.

ZRP divides the network into many routing zones and specifies two totally detached protocols that operate inside and between the routing zones.

- The IntrAzone Routing Protocol (IARP) operates inside the routing zone and learns the minimum distance and route to all the nodes within the zone. The protocol is not defined and can include any number of proactive protocols, such as distance vector or link-state routing. A node can use different intrazone protocols as long as the protocols are restricted to those zones. A change in topology means that update information only propagates within the affected routing zones as opposed to affecting the entire network.
- The second protocol, the IntErzone Routing Protocol (IERP) is reactive and is used for finding routes between different routing zones. This is useful if the destination node does not lie within the routing zone. The protocol then broadcasts (i.e. bordercast) a Route Request (RREQ) to all border nodes within the routing zone. This procedure is repeated until the requested node is found and

a route reply is sent back to the source indicating the route. IERP uses a Bordercast Resolution Protocol (BRP) that is included in ZRP.

2.2 Position-Based Routing Protocol

With the latest advent of GPS, each node in the network can be equipped with low cost receiver to furnish each node with its geographical position. Many position-based routing protocols have been proposed. Today this category of protocol is gaining importance, due to its ability to perform packet routing based solely on the location of the destination and local information. Position-based protocols can be seen as an extension and enhancement of the existing topology-based routing approaches. Using position-based routing protocols, a node needs to learn the position of the destination and the position of one-hop neighbors before sending a packet. Position information of the one-hop neighbor is gained by periodic one-hop broadcasting from each node in the network.

Position-based routing generally consists of two phases: a location search phase where the node looks for the location of the destination using location service and a packet forwarding phase where the node routes the packet to its destination.

2.2.1 Location Services

The distribution of destination geographical location can be achieved by means of a location service. The simplest form of location service is where each node periodically broadcast its position information to the whole network, and each node maintains the position information to all the other nodes thus it is able to use whenever it is needed. However, this simple location service using periodic broadcast is bandwidth consuming and non-scalable. To improve the performance, more sophisticated algorithms are

needed. In [26], a survey on location services is provided. Here, brief descriptions of Grid Location Service [27] and Reactive Location Service [28] are presented.

2.2.1.1 Reactive Location Service (RLS)

Reactive Location Service (RLS) [28] is a simple reactive location service, inspired by DSR route discovery: whenever the position of a node is required, the node looking for position information broadcast a location request message containing the destination node ID. The request message also contains the ID and position of the source node. When a node receives a request message containing its ID, it replies to the source node. In order to reduce the range of the flooding of the broadcast request message, an expanding ring search can be performed: the flooding starts with a range of 2 hops and is repeated with exponentially increasing range when no response is received during a certain time.

2.2.1.2 Grid Location Service (GLS)

In GLS [27] the world is subdivided into squares, where an n -order square is one-fourth the area of an $n+1$ -order square. GLS is based on the idea that a node maintains its current location in a number of location servers distributed throughout the network. These location servers are not specially designated. Each node can act as a location server on behalf of some other nodes. GLS avoids technique such as leader or Cluster Head in order to balance the location server work load across all the nodes. GLS ensures that nodes are allocated unique random IDs by using a strong hash function to obtain an ID from a node unique name (for instance the IP address, the Internet host name or the MAC address of a node). In each square order a node will elect a location server, which is the node with the least ID greater than its own ID. An important assumption is that each node is able to scan an entire square to choose the appropriate node as its active server. In

order to distribute its location data to the appropriate server in an order-n square, the node of this order-n square may know about each other. To inform all nodes in the same square about its location and learn the location of others, HELLO messages are periodically interchanged between nodes of that zone. To perform a location query for a destination D, a source node S chooses a node from its own database and sends a query message. The node chosen should be the one with the least ID greater than or equal to D's ID. The same procedure is performed at every intermediate node and the location query message will reach the destination after a few rounds. Finally, D sends the up-to-date position back to S.

2.2.2 Forwarding Strategies

In position-based routing, the forwarding strategy is responsible for making the decision on how the packets are relayed. DREAM [33], GPSR [34] and GSR [36] are some examples of position-based forwarding strategies.

2.2.2.1 *Greedy Perimeter Stateless Routing Protocol (GPSR)*

In GPSR [34], packets are assumed to be marked by their originator with the destination location. GPSR consists of two packet forwarding methods: greedy forwarding, which is used wherever possible; perimeter forwarding, which is used in regions where greedy forwarding cannot be employed.

Figure 3: Greedy forwarding mechanism (GPSR)

Greedy forwarding is performed based solely on information about node's immediate neighbors in the network topology. A simple beaconing algorithm provides all nodes with their neighbors' positions. During forwarding, the intermediate nodes always make the greediest move: choose the node which is nearest to the destination from its one-hop neighbors. Thus, packet forwarding in this manner ensures the packet is closer to the destination at each successive hops.

When a packet reaches a region where greedy forwarding is not possible, also known as dead-end or local maximum, i.e. none of the neighbor nodes are nearer to the destination than the current node, the algorithm enters into the perimeter forwarding mode. The perimeter mode of GPSR consists of two elements: *i)* a distributed planarization algorithm and *ii)* an online routing algorithm for planar graphs which employs the well-known "right hand rule". The planarization algorithm transfers (locally) the network connectivity graph into a planar graph by eliminating "redundant" edges. A connectivity graph without "redundant" edges is shown in Figure 4. When the source s tries to send a packet to destination d following the greedy forwarding scheme, the packet will stop at node y as it can not find a nearer neighbor to d . The packet now enters the perimeter

mode at node y . By running the planarization algorithm, y gets the local view of the planar connectivity graph which is the part inside the circle centered at y as shown in Figure 4. The radius of the circle is the transmission range. It is known that the right-hand rule traverses an exterior of a closed polygonal region (a *face*) in counterclockwise edge order. Following the “right hand rule”, the next edge traversed from y is the one sequentially counterclockwise about y from link (y, d) , which is the edge (y, x) . Thus, the next hop is node x . By repetitively applying perimeter forwarding at each intermediate node, the packet traverses the exterior of the closed polygonal region of $y \rightarrow x \rightarrow z \rightarrow w \rightarrow d$. The packet will finally be able to reach the destination d , or reach a node which is nearer to d than y , at which it will switch back to the greedy forwarding mode and continue.

Figure 4: Perimeter forwarding of GPSR

2.2.2.2 Geographic Source Routing (GSR)

GPSR works best in a open space scenario with evenly distributed node density. However, this may not be true in a city scenario. In FleetNet [36], the deficiencies of the GPSR approach for the case of city scenarios are studied. A brief summary of these deficiencies are listed here:

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- **Network disconnection:** City scenarios – with area between streets covered with buildings – significantly limit the applicability of purely greedy position-based routing and of corresponding recovery strategies. Due to these obstacles, nodes that would otherwise have been reachable in a free space model are no longer reachable. Since the planarization methods of GPSR assume that the connectivity between nodes only depends on node distances, planarization of the neighborhood in the presence of obstacles can lead to network disconnection.
- **Too many hops:** A planarized connectivity graph for vehicles along a single street essentially leads to a graph where a vehicle no longer sends packets to the neighbor with the largest forwarding progress.
- **Routing Loops:** Mobility can induce routing-loops for packets being routed in perimeter mode.
- **Wrong Direction:** The perimeter mode following the ‘Right Hand Rule’ is biased towards a specific direction when selecting the next hop.

The FleetNet project proposes GSR to overcome the identified deficiencies. GSR benefits from the idea of both Spatial Aware Geographic Forwarding [37] and the Terminode Routing [25].

GSR is a position-based routing protocol supported by the city map. With the position information of destination, source and the digitized city map, the sending node can compute an “anchor path” to the destination by using the underlying map of the streets. In other words, the sender computes a sequence of junctions the packet has to traverse in order to reach the destination. The sequence of junctions can be put into the packet

header – as it would be done in Terminode – or it can be computed by each forwarding node. Forwarding a packet between two successive junctions is done on the basis of greedy forwarding since here no ‘obstacles’ should block the way. The path between source and destination is determined by a Dijkstra shortest path algorithm based on the street map. When the greedy forwarding fails at some node, GSR uses some simple recovery strategies (fall back on greedy mode) to by-pass this particular node.

2.2.2.3 Terminode Routing Protocol

Similar to ZRP, Terminode [25] routing protocol is a zone based and a hybrid of proactive and position-based routing protocol. It combines two protocols: Terminode Local Routing (TLR - to reach a close destination) and Terminode Remote Routing (TRR - to send data to distant destinations).

- TLR uses local routing tables that each node proactively maintains for its nearby nodes inside its local zone.
- TRR uses position-based forwarding for remote transmissions inter zones. It employs the technique of “anchor path”. An anchor path is a list of geographic points, used as loose source routing information. Anchors help to circumvent large holes in nodes distribution by directing packets around the problem region. TRR without anchors works well if, at any intermediate location, greedy forwarding brings the packet closer to destination. This may fail in irregular networks, in which case TRR uses anchors. Two methods for computing anchors are proposed: Friend Assisted Path Discovery (FAPD) and Geographic Map-based Path Discovery (GMPD).

2.3 MANET Routing Protocol for Vehicular Ad Hoc Network in City Environment

Currently there is some research work in the area of MANET routing protocol for vehicular ad hoc network in city environment. The CarNet [3] project is using a routing protocol similar to GPSR. The FleetNet project proposes GSR [36] to overcome the deficiencies of GPSR as covered in section 2.2.2.2. GSR benefits from the idea of anchor-based routing from Terminode Routing [25] and spatial aware routing from the Spatial Aware Geographic Forwarding [37].

Anchor-based routing is analogous to the source routing of DSR. In anchor-based routing, the source node includes in each packet a route vector composed of a list of anchors or fixed geographic points, through which packets must pass. Between anchors, greedy position-based routing is employed. Both Terminode Remote Routing (TRR) [25] and Geographic Source Routing (GSR) are examples of algorithms that employ anchor-based routing to forward packets to remote destinations.

In spatial aware routing, spatial information such as a street map of a city or a description on how several towns are connected by highways is utilized to assist in making routing decisions. The spatial information reflects the underlying node distribution and topology of the network. Spatial aware routing is usually used in conjunction with anchor-based routing, such as in TRR and GSR where anchor paths are computed using the spatial information.

2.4 Summary

In this chapter, a brief introduction on MANET routing protocols is given and the advantages and limitations of each category are discussed. In general, a proactive algorithm attempts to continuously evaluate the routes within the network. When a packet needs to be forwarded, the route is already known and can be immediately used. A reactive algorithm invokes a route discovery procedure on demand. Thus, when a route is needed, some sort of global search procedure is employed. A hybrid algorithm provides route discovery by using different routing strategies for local and remote routing.

The advantage of a proactive algorithm is the small initial route determination time. For reactive protocols, because route information may not be available at the time a datagram is to be transmitted, the delay in determining the route can be quite significant. Furthermore, the global search procedure of the reactive protocols requires significant control traffic overhead. Because of this long delay and excessive control traffic, pure reactive routing protocols may not be applicable to real-time communication. However, pure proactive schemes are likewise not appropriate for the mobile ad hoc networking environment, as they continuously use a large portion of the network capacity to keep the routing information current. Since nodes in an ad hoc network move quite fast, and as the changes may be more frequent than the route requests, most of the routing information are not used, thus, an excessive waste of the scarce wireless network capacity. A hybrid scheme thus tries to gain the advantage by initiating the route-determination procedure on-demand, but at limited search cost.

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Because of the possible low cost of GPS deployment, position-based routing protocols have attracted much research recently. Relying only on position information of destination and neighbor, position-based routing protocols are more scalable for routing through large area. Thus, it is suitable for metropolitan-scale IVCS. GSR uses such routing scheme in large size IVCS environment. We independently work out an approach similar to GSR, which will be covered in Chapter 4.

Chapter 3

PATCH: A Novel Local Recovery Mechanism for MANET

For a small town with size around 4~6km², the local IVCS system needs a routing protocol with simple design and it does not have high requirement on scalability. In such case, on-demand ad hoc routing protocol is a good choice because of its simple design and fast response to the high mobility of the IVCS system.

On-demand ad hoc routing protocols discover a route between communicating node pair only when required. However, due to the dynamic and mobile nature of the nodes in IVCS, intermediate nodes in the route may lose connection with each other during the communication process. When this occurs, an end-to-end route discovery is usually performed to re-establish the connection. Such route repair mechanism causes high control overhead and long packet delay. In this chapter, a novel local recovery mechanism, Proximity Approach To Connection Healing (PATCH), is proposed. It aims to reduce the control overhead and achieve fast recovery when route breakage occurs. Simulation results have shown that PATCH is simple, robust and effective. On-demand routing protocols incorporated with PATCH would be a good candidate to serve a small town IVCS environment.

Motivation of the local recovery is explained in section 3.1. Some related work is presented in section 3.2. Our proposed PATCH approach is described in section 3.3.

Simulation environment and parameters is presented in section 3.4. In section 3.5, simulation results are presented and analyzed to illustrate the performance benefits of using PATCH.

3.1 Motivation

On-demand routing protocol relies on global flooding of route request packet for route discovery. Once the source performs the route discovery successfully, data is sent via the discovered route. However, due to the dynamic and mobile nature of the nodes, intermediate nodes in the route tend to lose connection with each other during the communication process, that is, the route is likely to be broken. When this occurs, different protocols may take different actions to re-establish a route in order to maintain the communication link between the source and destination nodes.

Figure 5: A typical routing scenario in MANET

For example, with reference to Figure 5, a route is discovered and established between the source node S and the destination node D . Nodes A and B are intermediate nodes in the established route path. In the situation that the link between A and its next node B breaks, the route between S and D is broken. In the case of DSR, A sends back an ERROR message to the data source S after which S initiates another round of route discovery process in an attempt to find a new route to D . This mechanism, used by DSR,

is also known as end-to-end route recovery and is not scalable. This mechanism will cause long delay, high overhead and low delivery ratio when deployed on a large area.

The motivation behind the on-demand protocols is that the control overhead is typically less as only the actively used route is maintained. However, in a large and highly mobile network, frequent route breakage would occur resulting in more route recovery and higher control packet overhead. Thus, there is a need for effective route repair mechanisms that could provide fast recovery with minimal control packet overhead. Some well known local recovery mechanisms are local recovery mechanism of AODV, SLR (Source Routing with Local Recovery) [67], ABR (Associatively-Based Routing Protocol) [56] and RDMAR (Relative Distance Micro-discovery Ad-hoc Routing Protocol) [23].

Our proposal, Proximity Approach To Connection Healing (PATCH) mechanism attempts to overcome some of their shortfalls while keeping the complexity of the algorithm to the minimum. Complexity is an important attribute because nodes in MANET are generally small, portable devices with little processing power.

3.2 Related Work

AODV protocol has a local recovery mechanism. Its local recovery mechanism attempts to repair the broken route at the intermediate node instead of having the source node perform the entire route discovery process again. Figure 5 illustrates its local recovery mechanism.

If intermediate node A finds that the link to node B is broken, and if it finds that it is nearer to D than source S , it will start a local recovery process which is the same as the

normal route discovery by broadcasting route requests. The only difference is that A broadcasts the route requests within limited TTL which is the estimated distance to destination D . However, such local recovery still relies on flooding large area of the network, which consumes considerable amount of bandwidth.

SLR [67] is based on DSR. In SLR, a technique called by-pass recovery is used to reduce the frequency of route request floods triggered by broken routes. Specifically, when a broken link is detected, a node patches the affected route using neighborhood information and thereby by-passes the broken link. The neighborhood information may come from route cache and local route recovery.

ABR [56] selects the routes most likely to be long-lived. However, if link breakage occurs, the following actions are performed:

- If A is located along the first half of the route (i.e, it is nearer to the source than to the destination), a route error is reported to the source, and the source will initiate an end-to-end route discovery to recover the route.
- If A is located along the second half of the route. A will broadcast a route request with a hop limit equal to the remaining number of hops that it was supposed to travel before the route was broken. Only the destination is able to reply to the route request. If this succeeds, this route is remedied and no route error will be reported. Otherwise, a route error will be reported to the host preceding A , which will in turn repeat the above process. This is recursively repeated until either the broken route is remedied or one host at the first half of the original route is reached.

As can be seen, this approach may incur more bandwidth and longer delay if the above recursion keeps on failing.

3.3 Proximity Approach To Connection Healing algorithm (PATCH)

With reference to Figure 5, if the direct link ($A \rightarrow B$) breaks, there should exist in most cases some alternate route from A to the original next node B through some neighbor node C . In these situations, if a request packet is sent out to find the original next hop or other nodes which is along the original route at the further part of the original route with limited time-to-live (eg. 2 hops), the possibility of repairing the current route should be quite high and the overhead should be much lower than using end-to-end global recovery. With the above assumptions, a new algorithm for the proposed PATCH mechanism is described as follows:

When an intermediate node A discovers that the link to the next hop is broken, it would:

- a. Save the data packet into local repair data buffer, set a timeout timer with a timeout value T .
- b. Send out a n -hop wide local recovery request, containing a sequence of nodes including all the farther nodes on the original route from A till the destination node D . Any node, on receiving the local recovery request, will check whether it is on the node list, and if it is, would send back a local recovery reply.
- c. On receiving local recovery reply from an intermediate node, A salvages the data packet at the local repair buffer and transmits it using the repaired route. At the same time, it would send the repaired route and broken link information back

to the source S . The source would use the repaired route for future communication.

- d. If no reply is received after the local repair timer expires, the data packet is dropped, and an error message is send back to the source from A , the source may then initiate a new round of end-to-end route discovery

Local recovery timeout value T is set to an estimate of the round trip time for local recovery packet to traverse back: $T = n * 2 * NODE_TRAVERSAL_TIME$. In AODV [7], $NODE_TRAVERSAL_TIME$ is defined as “a conservative estimate of the average one hop traversal time for packets and should include queuing delays, interrupt processing times and transfer times” with a default value of 40 milliseconds. The timeout value for PATCH was set to the same value used by AODV, e.g. 0.16 second for 2 hops, 0.24 second for 3 hops and so on.

The setting of the propagation limit n of the local recovery request affects its success rate. The larger the propagation limit, the higher is the probability of successful local recovery. However, it is at the expense of higher control overhead. In section 3.5.1, a set of simulation results is presented to show the performance comparison when $n = 2, 3$ and 4.

3.4 Simulation Environment and Parameter

3.4.1 Simulation Environment

In this project, ns-2 [9] is chosen as the simulation tool for the ad hoc network. The original DSR in ns-2 is extended to include PATCH. Performance is compared among the

original DSR without local recovery (DSR-NOLR), DSR with the proposed local recovery mechanism (DSR-LR) and AODV with its local recovery mechanism enabled (AODV-LR).

The version used for this project is ns-2.1b8a. Some important configuration parameters for the simulation in this report are:

- Propagation model: TwoRayGround
- MAC: IEEE 802.11b with 2 Mbps throughput
- IFQ: PriQueue with size = 50
- Antenna: Omni directional
- The Sharedmedia interface is initialized to make it work like the 914 MHz Lucent WaveLAN DSSS radio.

3.4.2 Mobility Model

One important parameter of the MANET simulation is the mobility pattern. Mobility pattern, also known as mobility model, refers to the simulation model of the node movement in a specific environment. A survey of mobility model is given in [53]. The Random Waypoint Model [53] is used for the simulation in this section. In section 4.4.2, a new mobility model Metropolitan Grid (M-Grid) [62] is discussed.

Random waypoint is the most commonly used mobility pattern in MANET research. For this mobility pattern, the nodes are moving in a random manner. It depicts an open space environment. The parameters for a node's movement are as follows: average speed, pause time, and destination. Initially, all nodes are randomly distributed in an open area.

A node will then pick a random speed and destination, and move towards the destination at the selected speed. On reaching the destination, it pauses for a fixed time period, after which it picks a new destination and speed and starts moving to the new destination. Different mobility is simulated by changing the speed and pause time. In ns-2, a program is provided to help to generate the random waypoint node movement file, with parameters such as the number of nodes, average speed, pause time and map size. The node density can be changed by changing the node number and/or map size.

3.4.3 Simulation Parameters

The simulation parameters are presented in Table 1. High mobility scenarios are used so that route breakages can be observed. 20 pairs of Constant Bit Rate (CBR) transmissions at 4 packets/sec are used to simulate a moderate traffic load. To emphasize the effectiveness of the proposed mechanism, a long rectangular map of $4000 \times 300 \text{m}^2$ was used, such that the average route length is generally long. A large map of $2000 \times 1600 \text{m}^2$ was also simulated. Lastly, simulations were run across various node densities. With increasing node density, the average degree (number of neighboring nodes) of the node also increases, thus improving the probability of successful local recovery. All the results were averaged over 20 sets of simulation runs.

Table 1: Simulation parameters for DSR with PATCH

Mobility pattern	Random waypoint
Traffic	20 pairs of CBR transmission(4 packets/sec)
Mobility	Pause time 20 sec, speed 0-20 meter/sec
Map size	4000x300m ² , 2000x1600m ²
Node number	40, 60, 80, 100, 120, 140
Simulation time	200 sec
Transmission Range	250 meter

3.4.4 Performance Metrics

The following performance metrics are used for the performance comparison:

- **Data Delivery Percentage:** This represents the total number of packets delivered successfully to the destination over the total number of packets sent from the source.
- **Routing Protocol Control Overhead:** This represents the total number of control packets transmitted and forwarded over the total number of data packets successfully transmitted.
- **Average End-to-End Delay:** This represents the average delay incurred by the successfully delivered data packets.
- **Average Route Length:** This represents the average number of hops (route length) traversed by the successfully delivered data packets.
- **Average Successful Local Recovery Ratio:** This metric is defined by the number of successful local recovery divided by the number of local recovery triggered when using PATCH.

3.5 Simulation Result and Analysis

3.5.1 Analysis of Propagation Limits Setting on PATCH

The objective of PATCH is to repair the broken route locally with minimum control overhead. An important parameter that affects its performance is the propagation limit, i.e. the number of hops for the local flooding. Increasing the propagation limits would result in higher probability of successful local recovery at the cost of higher control overhead. In this section, the performance of PATCH with different propagation limits is studied. The performance of DSR-LR (DSR with PATCH) with PATCH propagation limits of 2 hops, 3 hops and 4 hops are compared. Node number of 60 and 120 are chosen, and map size of $4000 \times 300 \text{m}^2$ and $2000 \times 1600 \text{m}^2$ are used. The simulation results are shown in Figure 6 and Figure 7.

For map size of $4000 \times 300 \text{m}^2$ shown in Figure 6, with larger propagation limits of 3 and 4, DSR-LR shows higher delivery ratio with higher successful local recovery ratio, but the improvement is quite limited, less than 1% when compared with the performance of propagation limit of 2. The End-to-End delay for higher propagation limit also increases. This is because with larger propagation limit, there are more successful recoveries. Those new successful recoveries incur longer recovery delay. The local recovery with higher propagation limits also injects more control packets into the network. These control packets consume more bandwidth and also effectively results in longer End-to-End delay. At node number of 120, DSR-LR with propagation limit of 4 experiences 13% higher delay than the DSR-LR with propagation limit of 2. This delay is not surprising when there is 41% increase in control overhead. With propagation limit of 2 hop, PATCH can

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repair most of the broken routes that can be repaired and achieve high delivery ratio. With larger propagation limit, successful local recovery ratio and delivery ratio shows marginal improvement. The improvement is at the expense of large increase in control overhead and delay.

For map size of $2000 \times 1600 \text{m}^2$ shown in Figure 7, the delivery ratio improvement is only marginal. As the objective of PATCH is to provide a fast local recovery scheme with minimum control overhead, propagation limit of 2 is the best option. In the following sections the propagation limit is set to 2.

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Figure 6: DSR-LR performance with different PATCH propagation limits (map of 4000x300m²)

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Figure 7: DSR-LR performance with different PATCH propagation limits (map of 2000x1600m²)

3.5.2 Performance of PATCH in small map (map size of 4000x300m²)

Figure 8 shows the simulation results for the long rectangular map of 4000x300m². From Figure 8(e), it can be seen that the average successful local recovery ratio keeps increasing as the density increases. At low density, PATCH does not show much advantage, especially when node number is less than 40. This is because the connectivity of the whole network is low and there is frequent network partitioning. Most of the successful transmissions are between nodes that are in close proximity. Thus, the local recovery mechanism would not be of much impact in such condition. Simulated data delivery ratio shows little improvement at low density.

However, as the node density increases, the connectivity of the network becomes higher enabling longer end-to-end connection. In such a situation, the local recovery starts to show obvious advantage over end-to-end recover scheme, as the local recovery only floods the request in a small region while the end-to-end recovery floods the entire network. Successful local recovery ratio increases as the average degree of node increases. The overall control overhead saving becomes very obvious, and reaches as high as 50% at high density e.g. at node number of 140, compared with both DSR-NOLR and AODV-LR. Because of source routing, DSR-NOLR generally shows longer delay than AODV-LR. DSR-LR, benefited from both the reduction of the congestion level caused by control packet and the fast local recovery. The end-to-end delay decreases by as much as 50% compared to the delay of the DSR-NOLR, and comparable with AODV-LR. When link breakage occurs, PATCH helps to salvage the data packet locally using the repaired route, thus improving the data delivery ratio by as much as 10%. As seen

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from Figure 8(d), local recovery causes longer route length than normal DSR-NOLR, but still comparable with AODV-LR.

(a) Delivery Ratio

(b) End-To-End Delay

Figure 8: Simulation results of a 4000x300m²

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(c) Control Overhead

(d) Average Route Length

Figure 8: Simulation results of a 4000x300m² map (Continued)

(e) Average Successful Local Recovery Ratio

Figure 8: Simulation results of a 4000x300m² map (Continued)

3.5.3 Performance of PATCH in large map (map size of 2000x1600m²)

Figure 9 shows the simulation results for a large map of 2000x1600m². From Figure 9(e), it is shown that the successful local recovery ratio is always lower than the results for the same number of nodes in Figure 8(e). This is because the average node density of this scenario is much lower.

Obvious performance improvement can still be observed in such a map. DSR-LR still achieves the highest delivery ratio as seen from Figure 9(a), and has the least control overhead as seen in Figure 9(c). In Figure 9(d), its average route length is comparable to AODV-LR, but longer than DSR-NOLR. For the End-to-End delay shown in Figure 9(b),

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although DSR-LR shows improvement over DSR-NOLR, but still incurs longer delay than AODV-LR. This is because the source routing employed by DSR generally tags each packet resulting in bigger sized header and thus incurs longer transmission delay.

(a) Delivery Ratio

Figure 9: Simulation results on a 2000x1600m² map

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(b) End-To-End Delay

(c) Control Overhead

Figure 9: Simulation results on a 2000x1600m² map (Continued)

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(d) Average Route Length

(e) Successful Local Recovery Ratio

Figure 9: Simulation results on a 2000x1600m² map (Continued)

3.6 Summary

We have presented a new local recovery mechanism, called PATCH, for on- demand routing algorithms. In contrast to the end-to-end recovery mechanism, PATCH relies on broadcast of route request within vicinity of the link breakage to repair the broken route quickly, thus providing fast recovery. As PATCH only floods a small region, with the radius of 2 hops, it will outperform end-to-end recovery in scenarios with bigger map size and higher density. Hence, it provides scalable solution for the route re-discovery process.

On the whole, big improvements could be seen with the incorporation of the proposed local recovery scheme in DSR-LR. DSR with PATCH consistently achieves higher data delivery ratio, which can be as high as 10% improvement over DSR-NOLR. Control overheads are dramatically reduced by 30-50% compared to DSR-NOLR or AODV-LR. The saving in bandwidth is especially high in the scenario with high density. Furthermore, PATCH also reduces the end-to-end delay significantly, which can be as high as 50% compared to DSR-NOLR, and is comparable with AODV-LR. One shortfall of PATCH is that the results show a higher average route length than that of the DSR-NOLR but it's comparable to results from AODV-LR. This is because some packets that could not be delivered previously can now be delivered by PATCH but they have higher route length. Sending gratuitous reply in DSR-LR has eased this problem of increase route length. By incorporating further "route-shortening" algorithm such as the techniques proposed in [57] into the proposed mechanism, we will further ease the problem of long route length.

Chapter 4

Anchor-based Street and Traffic Aware Routing

A reactive routing protocol combined with PATCH from chapter 3 is a good candidate for IVCS in a small town area with the size around 4~6km². For a bigger area, traditional topology-based routing suffers from high control overhead. Thus, for a metropolitan-scale IVCS, larger than 6km², a more scalable routing approach is needed. Position-based routing is found to be a very promising routing strategy for large scale IVCS [1]. However, position-based routing for IVCS in a built-up city environment faces greater challenges because of potentially greater uneven distribution of vehicular nodes, constrained mobility, and difficult signal reception due to radio obstacles such as high-rise buildings. This chapter proposes a new position-based routing scheme called Anchor-based Street and Traffic Aware Routing (A-STAR), designed specifically for IVCS in a city environment. Unique to A-STAR is the usage of information on city bus routes to identify an anchor path with high connectivity for packet delivery. Along with a new recovery strategy for packets routed to a local maximum, the proposed protocol shows significant performance improvement over other similar routing approaches. Equipped with a simple reactive location service (RLS), A-STAR also shows performance advantage over topology-based reactive routing protocol AODV.

The remainder of the paper is organized as follows. With an example, section 4.1 discusses the challenges faced by position-based routing in IVCS. Section 4.2 presents

some related works in this area. Section 4.3 describes the proposed A-STAR protocol. The simulation environment and parameters are explained in section 4.4. Performance results and analysis are presented in section 4.5. Finally, a summary is given in section 4.6.

4.1 Challenges of Position-Based Routing in IVCS

The challenges of position-based routing in a city environment have been discussed in [36], and have been briefly discussed in section 2.2.2.2. An example is given here to illustrate the problems GPSR encounters when deployed directly to IVCS. Figure 10 shows a partial city environment, assuming that the transmission range is larger than the grid size.

Suppose node s wants to send a packet to node d . Greedy forwarding will fail in this case as there is no neighbor of s , which is nearer to d than s itself. This situation is commonly known as *local maximum* [34]. Following the strategy in GPSR, the protocol enters into perimeter-mode, using the right hand rule to send the packet through each node on the dotted route, including nodes a , b and c . At b , it is found that c is nearer to d than s , at which the protocol enters into perimeter-mode. Thus, the protocol switches back to greedy mode at b and packet reaches its destination d through c . It can be seen that this route is very long in terms of hop count. s should be able to reach a and a should be able to reach b , directly as their distance is less than the grid size. This shows that the perimeter-mode which the protocol employs to recover from local maximum is very inefficient and time-consuming.

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Another observation is that the packet can actually travel from s to d via a route that passes through e and f (shown as solid line), which is much shorter. However, this route is not exploited because the perimeter-mode of GPSR based on the right hand rule is biased to a specific direction when selecting the next hop.

It should be noted that in a city environment, the constrained mobility and frequently encountered obstacles can force GPSR to use perimeter-mode frequently. As a result, the performance of GPSR could deteriorate dramatically, and therefore may not be suitable for IVCS.

Figure 10: Challenges of Position-Based Routing in IVCS

4.2 Related Work

4.2.1 Location service

Position-based routing algorithms eliminate some of the limitations of topology based routing and scale well even if the network is highly dynamic. The main prerequisite for position-based routing is that a sender can obtain the current position of the destination. The sender uses location service to determine the position information of the destination and include it in the packet header. The routing decision at each node is then based on the destination's position contained in the packet and the position of the forwarding node's neighbors. In order to provide each node's position to other network nodes, a distributed location service has to be used. A survey of location service is provided in [26]. Grid Location Service (GLS) [27] is a very promising solution in which all nodes "proactively" update their location information. In [28], Reactive Location Service (RLS) is proposed, which is an on demand flooding based mechanism. It can be considered as an adaptation of DSR's route discovery mechanism to the location based domain. A comparison of RLS to an ideal omniscient location service (OLS) as well as to the complex GLS has been conducted in [28]. It is shown that the available bandwidth imposes a serious limitation on the scalability of GLS.

4.2.2 Position-Based Forwarding Strategy

With an appropriate location service, a sender can obtain the destination's location information. To send a packet, an appropriate forwarding strategy is needed. A survey of position-based forwarding strategy is available in [26]. Greedy packet forwarding is the most common forwarding strategy: when an intermediate node receives a packet, it

forwards the packet to a neighbor lying in the general direction of the destination. Generally, there are different strategies a node can use to decide the next forwarding node. One intuitive strategy is to forward the packet to the node that makes the most progress towards the destination. This is the strategy adopted in GPSR. Other strategies include Nearest with Forward Progress (NFP) [60], compass routing [61], etc. Other position-based forwarding concepts include anchor-based routing and spatial aware routing which are covered in section 2.3.

4.3 Anchor-based Street and Traffic Aware Routing (A-STAR)

Considering the challenges routing protocols face in a city environment, a new position-based routing scheme called A-STAR is proposed. Similar to GSR, A-STAR adopts the anchor-based routing approach with *street awareness*. The term “street awareness” is preferred over “spatial awareness” to describe more precisely the use of street map information in our routing scheme for anchor path computation. But unlike GSR, A-STAR computes the anchor paths using *traffic awareness*. “Traffic” herein refers to vehicular traffic, which are ad hoc nodes, e.g. cars, buses. There are two parts in A-STAR: the reactive location service and the A-STAR forwarding strategy.

4.3.1 Reactive Location Service (RLS)

A-STAR can be used with any type of location service. At the current implementation, RLS is used. [28] shows that RLS, with its on-demand characteristic, outperforms GLS in high node density/mobility environment. The basic RLS operates as follows: when a source wants to query the location information of a destination, it sends out a query message that floods the whole network. The destination node upon receiving the location

query message sends back a unicast reply to the source using the A-STAR routing strategy. The following optimizations are implemented to minimize the location discovery overhead in RLS.

Expanding ring search

The source starts the search for the location information of the destination from its neighborhood region and gradually increases the search area. This is achieved by initially setting the query packet Time To Live (TTL) value to a small $TTL = 2$. If a timeout occurs, the query packet TTL is increased linearly with increment of 2 hops each time and a new location discovery is initiated. If the destination is not found after the TTL has reached the maximum network diameter in number of hops, a long timeout value of 10 seconds is set to reschedule a new location discovery later.

Cache

Every node in the network is responsible for forwarding location query, location reply and data packets. By analyzing the location information carried in these packets and caching this information locally, a node can gather lots of information. When the need arises, a node can query the information locally instead of flooding the whole network. This could help reduce a lot of location discovery overhead and discovery delay. Proper time-out value should be used to avoid obsolete data polluting the cached information. In [28], cache time out value of 5 seconds is used. A time out value of 6 seconds is used because the average vehicle speed is around 8-10 meter/second, vehicle will move around 60 meters in 6 seconds and this is reasonably small compared with the transmission range of 350 meters. Thus, even after considering the obstacles in-between the roads, the probability that the data becomes obsolete in 6 seconds is reasonably low. However, the

use of cache will consume storage and cause overhead of data caching. Cache of 64 entries is used for this study. The cache entry replacement strategy is that the oldest entry is replaced by the latest entry when the cache is full. The optimal value of the timeout value and cache size remains for future research.

Destination Location Updates

After a source obtains the location of a destination, it starts to transmit its data packet belonging to this source-destination connection continuously using the location information until all packets are transmitted. If the destination moves too far from the original position, the subsequent data packets will not be able to reach the destination and thus dropped. In such situation, one solution is to ask the intermediate node to inform the source about the error and trigger a new round of location discovery. This solution is complex and bandwidth consuming.

Another solution is for the destination to send periodic location updates to the source. This is the solution adopted by A-STAR. Once a source sets up a data connection with a destination, the destination will periodically send location update packets back to the source until the data connection is terminated. The current simulation chooses the update period of 10 seconds. Within 10 seconds, the node moves by an average distance of 100 meters away from the previous update location. Moreover, the destination is configured to explicitly send back location updates to the source if it finds the location information in the data packet differs by more than 100 meters from the current location. This way, the error of the position information is always within 100 meters. As the packet rate for location update is only 0.1 packet/sec and there is no data payload (information embedded in the protocol header), the overhead is trivial compared with the normal CBR

data rate of 4 packet/sec. As position-based routing does not rely on accurate position information, the above mechanism provides sufficiently accurate location information and incurs low overhead traffic.

Passing-Packet Updates

When forwarding the data packet, the intermediate nodes check the destination location information carried in each data packet and updates the destination's location in the packet if it has fresher information. New anchor path is calculated if the destination's location has been updated. This way it ensures that the data packet is forwarded using the most accurate information when approaching the destination.

4.3.2 A-STAR Forwarding Strategy

4.3.2.1 Anchor Computation

A-STAR adopts the anchor-based routing approach. Firstly, the source gets the location information about the destination from the location service. Using the underlying street map, the source node computes an anchor path (a sequence of junctions) through which a packet must pass to reach the destination. In GSR [36], the anchor path is the shortest path from source to destination. However, there may not be enough node density along the shortest path to provide a stable path for the data packet.

In A-STAR, the node density along a street is one of the factors considered when computing an anchor path. An anchor path with high node density usually means good connectivity along the path, thus higher probability of packet delivery. To get the anchor path, each street is assigned a weight. The weight is inversely related to the vehicular traffic condition on that street, meaning that less weight is assigned to a street with high node density. The anchor path is computed as the least weight path from the source to the

destination instead of the shortest path. Thus it is more likely to get the anchor path along streets with high node density. There may be many ways to perform the weight assignment considering the traffic condition of a street, two simple methods are proposed. A map of the street traffic can be static or dynamically generated.

Weight Assignment

Statistically Rated Map

It is observed that in a metropolitan area, some streets are wider and can accommodate more vehicular traffic than others. These are usually the main streets, served by regular fleets of city buses. Connectivity on such streets should be higher due to higher density of vehicular nodes and more stable due to regular presence of city buses. With this observation, weight can be assigned to each street based on the number of bus lines serving, i.e. the more bus lines serving a street, the less weight is assigned. A simple Reciprocal function is used in the current simulation such that when a street has n bus lines going through it, it is assigned with the weight of $1/n$. For a street without any bus, it is assigned with normal weight of 1. The street map used by the vehicle is assumed to be loaded with bus route information. For our M-Grid model, each street is marked with the number of bus routes going through it, and all vehicles are loaded with the same street map information. For such a map with static pre-configured information, it is called a *statistically rated map*.

Dynamically Rated Map

While bus route information can provide a reasonable estimate of the expected vehicular traffic on each street, the traffic conditions in a city area can be quite dynamic.

A better weight assignment scheme is therefore one that continuously monitors and assigns weight to a street based on its traffic condition. It could be envisaged that future IVCS would be able to monitor the city traffic condition, summarize and distribute such information to every vehicle connected to the IVCS network. This information could then be used to re-compute the weight of each street on the map, e.g. more vehicles, less weight assigned, and vice-versa. Such a map is called a *dynamically rated map*. A reciprocal function is again used to relate weight assignment with node density such that when a street has m nodes on it, its weight will be $1/m$. In the simulation, ideal mechanism is implemented to monitor, summarize and distribute traffic condition without any overhead. Thus, this algorithm is included to show the performance that A-STAR may achieve when we have accurate traffic information.

Number of Turns

Number of turns refers to the number of direction changes along an anchor path, which always happens at the junction of the street. It is observed that when routing along an anchor path with many turns, a packet is more likely to reach a local maximum because there is no node near the junction at the turn. Packets traveling through anchor path with more turns are more likely to have longer route length in number of hops, because small distance (usually one hop with small distance) is needed to reach the junction before turning to the next street. Thus, the number of turns along the anchor path is introduced as the secondary metric for the route selection. If two anchor paths happen to have the same weight, the one with less number of turns is selected.

4.3.2.2 Local Recovery

It has been shown that the local recovery algorithm of GPSR using perimeter-mode is quite inefficient in city area. Other recovery algorithms that rely on “right hand rule” such as face-1 or face-2 [38] also face a similar problem. GSR adopts a “switch back to greedy” approach for local recovery: when a packet reaches a local maximum along its anchor path, it switches back to greedy mode. This is not efficient as it has been shown that greedy forwarding does not perform well in a city environment.

Thus, a more efficient recovery strategy is proposed for A-STAR: a new anchor path is computed from the local maximum to which the packet is routed. The packet is salvaged by traversing through the new anchor path. To prevent other packets from traversing through the same void area, the street at which a local maximum occurred is temporarily marked as “out of service”, and this information is distributed to other part of the network by piggybacking them onto the packets to be recovered. Nodes receiving these packets update their local map with the “out of service” information prior to making their forwarding decision. The “out of service” streets are not used for anchor computation or re-computation during the “out of service” duration. The “out of service” duration should be chosen so that the connection along the street may be established after that duration because of vehicular movement. In the current simulation, this value is set to 2 seconds. In 2 seconds, on average the vehicle will move around 20 meters, which implies a good possibility that the void will disappear. A maximum threshold value ($LR_{max}=3$) is also defined to limit the number of times a packet can be recovered to prevent the perpetual sending of outdated data and bandwidth wastage.

Figure 11 presents the pseudo code of the A-STAR algorithm.

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```

Let  $R$  be a node receiving a packet  $p$  for destination  $D$ 
Let  $N$  be the set of one-hop neighbors of  $R$ 
Let  $AP$  represent the anchor path in the header of  $p$ 
Let  $L$  represent the number of hops  $p$  has traversed
Let  $L_{max}$  represent the maximum hops  $p$  is allowed to traverse
Let  $LR$  represent the number of times  $p$  has been recovered
Let  $LR_{max}$  represent the maximum number of times  $p$  is allowed to be recovered
If ( $R = \text{source } S \text{ of } p$ )
    Initialize  $AP = \text{null}$ 
Else If ( $L \geq L_{max}$ ) or ( $LR > LR_{max}$ )
    Discard  $p$ 
    Return
If “out of service” information present in the header of  $p$ 
    Update local map with the “out-of-service” information
Forward:
If ( $AP = \text{null}$ )
    //anchor path initialization
    Set  $AP = \text{least weight path from } R \text{ to } D \text{ with Dijkstra algorithm}$ 
    If ( $AP = \text{null}$ )
        // no anchor path exists, drop the packet
        Discard  $p$ 
        Return
    //compute the next hop  $n$  along the anchor path
    If ( $\exists n \in N$ :  $n$  resides on  $AP$  and has shortest distance along  $AP$  to  $D$ )
        Forward  $p$  to  $n$ 
    Else // local maximum occurs
        Mark the street where  $n$  resides as “out of service” for time period  $T$ 
        Record the “out of service” information in the header of  $p$ 
        Set  $AP = \text{null}$ 
        Goto Forward

```

Figure 11: Pseudo code of A-STAR algorithm

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Figure 12 illustrates the operation of the A-STAR algorithm. In this example all the street are assumed to have the same weight of 1. Source s is trying to send a packet to destination d . Following the A-STAR algorithm as described in Figure 11, it computes the least weighted anchor path, which is path A . The packet is forwarded along path A and reaches local maximum at intermediate node i . Following the local recovery algorithm of A-STAR, the current street is marked as “out of service” with a time out value and a new anchor path is computed, path B . The packet is delivered successfully following path B . In the case of GSR, the packet will be dropped at node i . In the case of GPSR, the packet will traverse path C from node i resulting in delivery of the packet. However, path C is a much longer than path B .

Figure 12: Local Recovery of A-STAR

4.4 Simulation Environment and Parameters

4.4.1 Simulation Environment

The simulation environment is the same as the one described in section 3.4.1. Four position-based routing protocols are implemented, namely:

- i) GPSR
- ii) GSR
- iii) A-STAR-SR (A-STAR with statistically rated map)
- iv) A-STAR-DR (A-STAR with dynamically rated map)

4.4.2 Mobility Model

In section 3.4.2, the well-know Random Way Point mobility model is described. To better describe the behavior and environment of IVCS, a new mobility model Metropolitan Grid (M-Grid) [62] is proposed.

The proposed M-Grid is a variant of the Manhattan model in [54]. It models a typical metropolitan environment that consists of roads and junctions made up of square grids. Nodes, which are vehicles, must travel along the grid lines, which represent the roads, at constant speeds. Each grid intersection is treated as a junction where the vehicle would stop for fix period, junction pause time, before it proceeds in a new direction at a new randomly chosen speed. The M-Grid model is shown in Figure 13. The number of grids can be changed to simulate maps of different sizes. Some special features, which distinguish our M-Grid model from the Manhattan model, are:

- In this M-Grid model, two types of nodes with different mobility characteristic are introduced: bus and car. Bus, which always travels along the bus route, shows high

regularity and low mobility. In Figure 13, the light gray color rectangles represent circular bus route over the metropolitan area. In the simulation, some nodes are marked as bus and constantly moving along bus routes at low speed. Buses are likely to be evenly distributed along the bus routes with certain distance between them. The bus routes are bi-directional indicating that there are buses running clockwise and anti-clockwise. The bus routes can be changed to simulate different scenario with different coverage.

Another type of node is to represents cars. Initially cars are randomly distributed along the streets. There is no special requirement for the movement of a car. As long as a car travels along the streets, it can choose any direction. Thus on reaching a junction, it stops for the duration of pause time. It then randomly chooses the new direction. Compared with buses, cars show high degree of randomness when traveling in the M-Grid model.

- Another aspect special to M-Grid is the ability to simulate the non-uniform distribution of vehicle density. It is always true that, in real life, there are more vehicles on some main roads, especially the bus routes. In M-Grid, higher preference is assigned to the bus route. When a car chooses its next direction to go, it will exhibit preference to choose bus routes to other routes. Thus, the vehicular traffic on bus routes is higher than other parts of the city. The car preference to move along bus routes compared to the normal routes can be manipulated to simulate different kind of environment.
- In the metropolitan scenario, buildings beside the road always result in blocking of signal transmission. In M-Grid, a simple model of signal blocking is supported by

placing obstacles inside the grid area. As illustrated in Figure 14, the width of the street is 40 meters, and the gray block represents the obstacles placed. It is assumed that the obstacles fully block the signal transmission. Thus two nodes can only communicate directly with each other when they are in their respective transmission ranges and obey the “line-of-sight” criterion. The GSR [36], the real world tests with vehicles show that transmission range of 250 meters results a network with too sparse connectivity for real world applications. It is further shown that transmission range of 500 ~ 800 meters are feasible with external antennas and 500 meters is chosen for the simulation. Considering our street length is 400 meter, the transmission range used of 350 meters is chosen to achieve an acceptable performance level while minimizing the problem of performance degradation.

In this project, the M-Grid model combined with ns-2 is used to simulate the ad hoc network in an IVCS environment. Streets are identified by the junctions at both ends and arrays are used to store the junction position information. A bus route is stored as a series of junctions.

Figure 13: M-Grid

Figure 14: M-Grid with obstacles

4.4.3 Simulation Parameters

The M-Grid mobility pattern in Figure 15 is used for experiments in section 4.5. It shows three loop lines (or service numbers), plying the streets in various parts of the city. Each line is bi-directional with buses running clockwise and anti-clockwise. Note that the number of vehicles (nodes) is varied to reflect different vehicle densities. Throughout the evaluation, the number of buses is kept constant, while only the car density is varied. Inter-bus distance is approximately 1 kilometer for each line in the same direction. With three bus lines for the M-Grid shown in Figure 15, a total of 37 buses will be running in the city: two (route *a*, *c*) with 12 buses, one (route *b*) with 13 buses. Moreover, cars at the junction would select to move into a street which is on a bus route with a probability of 0.75 (to show the preferential movements in M-Grid). The speed limit of buses and cars are 50 and 70 km/h respectively. Table 2 summarizes the parameter values used in our simulation.

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Table 2: Simulation Setting

Parameter	Settings
Mobility model	M-Grid
Traffic model	20, 40, 60 CBR connections
CBR packet sending rate	4 packets / second
Data payload	64 bytes
Map size	2800x2400 m ² (7x6 grid)
Node number	200, 250, 300, 350, 400, 450, 500
Simulation time	500 seconds

Figure 15: M-Grid with bus routes

4.4.4 Performance metrics

For the performance comparison of this chapter, the following performance metrics defined in section 3.4.4 are used:

- Data Delivery Percentage

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- Routing Protocol Control Overheads
- Average End-to-End Delay
- Average Route Length

Besides these, 2 new metrics are used:

- Route Length Distribution: This shows the distribution of the route length of successfully delivered data packet.
- Data Forwarding Overhead: In [64], the author suggests that the routing protocol control overhead only presents one part of the efficiency of a routing protocol. He proposes a new metric: average number of data bits transmitted per data bit delivered.

$$= \frac{\text{Total Data Transmitted by All Nodes}}{\text{Total Data Delivered to All Destinations}}$$

There are two types of data for the “Total Data Transmitted by All Nodes”: those data transmitted by intermediate nodes and successfully reached destination; those data transmitted by intermediate nodes but dropped half way. This can be thought as the total effort the network spends to deliver per unit of data. It measures the efficiency of delivering data within the network. If this metric is very high, it means the routing protocol consumes very high bandwidth to deliver each bit of data and thus not efficient.

This metric is especially important for comparison of different position-based routing protocols with local recovery. An inefficient local recovery algorithm can route a packet through a very long route while an efficient local recovery algorithm is usually able to find a shorter recovery route. In the following sections

this new metric will be used to compare the internal forwarding efficiency of different position-based routing protocol.

4.5 Performance Results and Analysis

4.5.1 Position-Based Forwarding Strategies

This section is used to compare the performance of different position-based forwarding strategies. The presence of an ideal omniscient location service is assumed to supply location information to each protocol under study. Results on the control overhead is not presented here because the overhead messages are predominantly beacon messages transmitted periodically by nodes to build up their neighbors' location information, therefore the amount of control overhead is the same for all position-based routing protocols considered in this study. However, the Data Forwarding Overheads are computed to compare the efficiency of different protocols.

4.5.1.1 Performance Comparison under Single Traffic Scenario

In this section, the performance of the 4 protocols is compared using single traffic scenario with 20 CBR pairs. Recall that A-STAR differs from GSR and GPSR in two main aspects. Firstly, A-STAR incorporates traffic awareness with anchor path forwarding by using statistically rated or dynamically rated maps. Secondly, A-STAR employs a new local recovery mechanism that is more suitable for a city environment than the greedy approach of GSR, or the perimeter-mode of GPSR. To investigate the impacts of each mechanism on the routing performance, the protocols are initially evaluated without local recovery, and later with local recovery. Without local recovery, a packet is simply dropped when it encounters a local maximum. Figure 16 and 17 show

the protocols performance (with 95% confidence intervals) with and without local recovery respectively.

In Figure 16(a), it is observed that packets delivery ratio increases as node number increases. This is to be as expected as the probability of connectivity increases with increasing node density, which in turn reduces the number of packets dropped due to local maximum. It is also observed that GPSR's performance is comparable to GSR, possibly because the grid layout of streets did not pose as much problem to GPSR as it did with fork junctions in [37]. A-STAR, with traffic awareness, shows the best performance because it can select paths with higher connectivity for packet delivery. As much as 40% more packets are delivered by A-STAR, compared to GSR. Between A-STAR-SR and A-STAR-DR, the latter performs better by using current vehicular traffic information. Figure 16(b) shows the end-to-end delay. Generally, no significant difference is observed between the protocols. A-STAR, however, shows slightly higher delay. This is due to A-STAR route selection metrics where connectivity rather than shortest distance is the major consideration resulting longer route and longer delay.

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(a) Packet Delivery Ratio

(b) End-to-End Delay

Figure 16: Performance without local recovery

With local recovery, packets that encounter local maximum can be rerouted and delivered instead of being dropped. Thus, more packets are delivered by each protocol as shown in Figure 17(a). The improvement ratio of the delivery ratio for each protocol with local recovery is shown in Table 3. The improvement ratio is calculated as:

$$= \frac{(\text{delivery ratio with local recovery} - \text{delivery ratio without local recovery})}{\text{delivery ratio without local recovery}} \times 100\%$$

From Table 3, it can be seen that local recovery schemes are most effective in improving the delivery ratio at medium node density, especially when node number is between 250 and 350. At low node density, especially when node number = 200, the network connectivity is too sparse. At high node density, especially when node number = 500, the delivery ratio is already quite high and thus there is not much room for improvement. The delivery ratio improvement of A-STAR with local recovery is the highest among all the protocols. With the fact the A-STAR without local recovery already achieves better delivery ratio than others, A-STAR with local recovery further widen the performance gap as shown in Figure 17(a). It is also observed that local recovery allows A-STAR-SR to narrow its performance gap with A-STAR-DR as shown in Figure 17(a) especially at high node density.

Figure 17(b) shows the corresponding result for end-to-end delay. A key observation is that GPSR with local recovery incurs significantly higher end-to-end delay. This is because of frequent attempts by GPSR to salvage packets from local maximum via perimeter-mode, which is generally inefficient and causes congestion especially at lower node density. Delay of A-STAR is lower than GPSR, but it is almost twice the delay of GSR, once again at lower node number. A close analysis of its route length distribution in

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Figure 18 suggests that the higher delay is partly an artifact of local recovery mechanism in A-STAR where packets that would otherwise be dropped are successfully delivered.. These packets usually have long route length and contribute to a higher average end-to-end delay. Another reason for the longer delay is because more traffic is being routed via bus routes and consequently higher contention at the medium access control (MAC) layer, thus longer delay incurred in forwarding the packets.

(a) Packet Delivery Ratio

Figure 17: Performance with local recovery

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(b) End-to-End Delay

Figure 17: Performance with local recovery (Continued)**Table 3: Delivery Ratio Improvement with Local Recovery**

Number of Nodes	GPSR	GSR	A-STAR-SR	A-STAR-DW
200	0.096	0.120	0.188	0.146
250	0.133	0.136	0.336	0.220
300	0.146	0.124	0.290	0.189
350	0.169	0.127	0.281	0.197
400	0.144	0.108	0.173	0.108
450	0.148	0.111	0.171	0.104
500	0.157	0.086	0.117	0.074

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Figure 18: Route length distribution (for 200 nodes)

As mentioned earlier, for the convenience of performance comparison among the four protocols, the presence of an ideal omniscient location service is assumed. The main protocol control packet overhead is caused by the beacon messages which are same for all four protocols. Thus, the control packet overhead will not be compared.

The four protocols use different forwarding schemes and local recovery schemes consuming different level of bandwidth. The Data Forwarding Overhead metric is used to compare the data packet forwarding efficiency. This metric measures the internal efficiency of a routing protocol by measuring the amount of data transmitted for each bit of data delivered.

The comparison of Data Forwarding Overhead is shown in Figure 19. GPSR is the most inefficient and its Data Forwarding Overhead is 5-8 times higher than other protocols.

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This is because many packets entering the perimeter mode of GPSR consume a lot of bandwidth but still fail to reach the destination. For GSR and A-STAR, generally their Data Forwarding Overhead is comparable. At low node density, e.g. 200 nodes, A-STAR is slightly less efficient than GSR. This is because the local recovery success rate of A-STAR is not high in a sparse network. When the node number increases, especially when node number equals 500, A-STAR is more efficient than GSR. This is because with the dense network A-STAR can successfully deliver more data packets using the local recovery scheme. For the two schemes of A-STAR, A-STAR-SR is generally less efficient than A-STAR-DR because it uses static map information while the latter uses the current traffic information.

Figure 19: Data Forwarding Overhead

4.5.1.2 *Performance Comparison under Increasing Traffic Scenarios*

In this section, we will compare the performance of 4 different position-based routing protocols with local recovery under increasing data traffic load. The objective is to test the efficiency of A-STAR under different data traffic condition. Increasing data traffic is simulated by increasing the number of CBR traffic pairs: 20, 40 and 60. The performance comparison of different routing protocols for 250 nodes is shown in Figure 20, and the comparison for 400 nodes is shown in Figure 21. The following trends are observed:

Firstly, with increased data traffic, the performance of all protocols starts to degrade because the network becomes congested with heavy data traffic. When the number of CBR pairs increases from 20 to 60, GPSR suffers the most from the network congestion and GSR suffers the least. The delivery ratio of GPSR decreases by 30% for both 250 nodes and 400 nodes and the end-to-end delay increases by 600%. GSR experiences 7% decrease in its delivery ratio and 50% increase in the end to end delay for 250 nodes, and it experiences 5% decrease in the delivery ratio and 100% increase in the end-to-end delay for 400 nodes. The performance degradation of the two A-STAR schemes is similar. For 250 nodes, A-STAR experiences 18% decrease in the delivery ratio and 400% increase in the end-to-end delay. For 400 nodes, A-STAR experiences a 7% decrease in the delivery ratio and 500% increase in end-to-end delay. There are two reasons for the dramatic increase in the end-to-end delay. First, A-STAR does have higher congestion level than GSR because it delivers more data packets using local recovery scheme and thus consumes more bandwidth. Secondly, the bus routes get highly congested when there is too much traffic traveling through it. Generally the data forwarding overhead of A-STAR and GSR is comparable. This shows that A-STAR

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under heavy traffic condition still performs efficiently as the effort spent to deliver the same amount of data is similar as GSR.

Second observation is that under the same traffic condition, especially same number of CBR pairs, A-STAR performs better than GPSR and GSR in term of delivery ratio. Although A-STAR is experiencing higher congestion than GSR under heavy traffic, its delivery ratio is still much better than GSR while its end-to-end delay is longer than GSR.

To summarize, all the position-based protocols simulated experience performance degradation under heavy data traffic. GPSR deteriorates the most and GSR deteriorates the least. A-STAR experiences dramatic increase in the end-to-end delay. This indicates that the network congestion level of A-STAR is much higher than GSR under heavy data traffic. There are two reasons for the high congestion level of A-STAR. Firstly, the local recovery scheme of A-STAR has caused more data packets forwarded in the network. Secondly, the bus routes which are preferred forwarding anchor path become congested.

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(a) Delivery Ratio

(b) End-to-End Delay

(c) Data Forwarding Overhead

Figure 20: Performance Comparison for increasing Data Traffic for 250 nodes

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(a) Delivery Ratio

(b) End-to-End Delay

(c) Data Forwarding Overhead

Figure 21: Performance Comparison for increasing Data Traffic for 400 nodes

4.5.2 Position-based Routing and Topology-based Routing

In this section, the performance of A-STAR is further compared with a typical topology-based reactive routing protocol. AODV is chosen as it is shown in [63] that AODV outperforms DSR. Our scenario is considered as stressful because of the large number of nodes, large map size and high mobility. The location service of RLS in section 4.3.1 is implemented with A-STAR. This is to compare the efficiency of the whole A-STAR routing protocol to the efficiency of reactive routing protocols. The AODV implementation is optimized with expanding ring search and local repair. The simulation results (with 95% confidence intervals) are presented in Figure 22.

From Figure 22(a), it is observed that A-STAR delivery ratio is slightly less than AODV at low node density, but has a higher delivery ratio at high node density. This is because at low density, AODV's flooding based route discovery can find nearly all the available routes. As the node density increases, the flooding based approach consumes more bandwidth causing network congestion as shown in Figure 22(c). So at high node density, although the connectivity of the network is high, packet drop ratio increases because of network congestion. A-STAR, however, relies on flooding based location service mainly at the beginning of a data transmission. The majority of A-STAR's control packets are 1-hop beacons used to exchange position information. The overall control overhead is successfully maintained at a low level as shown in Figure 22(c). From Figure 22(b), it is observed that A-STAR constantly achieves a lower end-to-end delay compared to AODV. It is because the high congestion level of AODV caused by high control overhead increases the data packet delivery delay and route discovery delay.

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Another reason is because A-STAR benefited from the greedy position-based forwarding, the average route length of A-STAR is less than AODV as shown in Figure 22(d).

(a) Delivery Ratio

(b) End-to-End Delay

Figure 22: Performance comparison between A-STAR and AODV

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(c) Control Overhead

(d) Average Route Length

Figure 22: Performance comparison between A-STAR and AODV (Continued)

4.6 Summary

In this chapter, a new position-based routing protocol A-STAR is proposed for metropolis vehicular communications. A-STAR features a novel use of city bus route information to identify anchor paths of higher connectivity so that more packets can be delivered to their destinations successfully. Under light traffic condition, A-STAR demonstrates improvement in packet delivery ratio while maintaining reasonable end-to-end delay. Under heavy traffic conditions, A-STAR still shows very good performance in terms of packet delivery compared to other protocols. Although the average end-to-end delay of A-STAR is longer than GSR under heavy traffic scenarios, A-STAR takes similar effort to deliver same unit of data as GSR.

It is shown that A-STAR experiences higher network congestion level than GSR because more packets are forwarded by the local recovery scheme and the preferred bus route chosen as anchor path becomes congested under heavy data traffic condition. A load-balancing algorithm to distribute the traffic other parts of the network when the bus route is congested would improve the performance of A-STAR under heavy traffic. This will be an area for future research.

With a simple reactive location service, A-STAR also shows performance advantage over typical topology-based reactive routing protocol. A performance comparison was carried out against AODV. The results show that the A-STAR can achieve higher delivery ratio in dense network and has much lower control overhead than AODV.

Chapter 5

Conclusion and future work

5.1 Conclusion

IVCS presents different challenges in the routing protocol design using a MANET approach. The goal of this project is to investigate the effect of constrained mobility in city environment and utilizing bus route regularity in the design of the routing protocol for IVCS.

Random waypoint is the mobility pattern that has been widely used in MANET research. Considering the characteristics of IVCS, the M-Grid mobility pattern is proposed to realistically model the IVCS operating environment. Initial work has been carried out to investigate the characteristics of M-Grid, and the performance of MANET protocol in the M-Grid.

No single protocol can satisfy the requirements of IVCS under different topology size. Thus, the approach of combining existing reactive protocols with the proposed local recovery mechanism is proposed for small town IVCS environment. However, in the case of metropolitan city, position-based routing protocol is adopted and a new protocol, A-STAR is proposed.

A local recovery mechanism designed to suit an IVCS scenario, PATCH, is proposed to improve the scalability of existing reactive routing protocols. When a route breakage occurs, instead of end-to-end route re-discovery, PATCH tries to repair the route locally

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by restricted local broadcasting of the repair packet. Thus, PATCH reduces the control overhead and increases the performance of the reactive routing protocols. A reactive routing protocol with the PATCH mechanism is a good candidate to efficiently serve the IVCS in a small town area.

Position-based routing is the most promising routing strategy used to solve the topographic scalability problem in MANET. However, there are some problems when applying the position-based forwarding approach in IVCS environment. The anchor-based Street and Traffic Aware routing protocol, A-STAR, was proposed for the large scale IVCS. Supported by a digital map, the proposed protocol considers the underlying topology information in determining the packet routes. This is realized by computing an anchor path, a series of junctions, which the packets need to traverse. A-STAR helps to route the packets around obstacles in IVCS thus improving the performance. Furthermore, the proposed protocol takes vehicular traffic condition into consideration when determining the path i.e. by assigning weight to the street according to the traffic condition of that street. Two ways of assigning the weight are proposed: statistically and dynamically rated. A-STAR with dynamically rated scheme simulates the ideal condition where a node always has the latest traffic condition when determining the path. The performance of A-STAR is compared with other similar protocols: GPSR and GSR under different data traffic and topology size. It is shown that A-STAR outperforms the other protocols in majority of the cases especially in delivery ratio. Equipped with a simple reactive location service (RLS), A-STAR also shows performance advantage over the typical reactive routing protocol AODV.

5.2 Recommendations for Future Research

Currently, the M-Grid mobility model is used to simulate the IVCS environment. M-Grid is still a simple mobility model that does not simulate all the characteristics of the individual vehicular behavior and the real vehicular traffic model. There are many possible improvements that can be done on M-Grid, e.g. traffic lights can be introduced in M-Grid so that cars will not crash with each other at the junctions. More complex mobility model to use realistic map and realistic bus routes will also be one possible area to be implemented.

The current design of A-STAR assumes that every node has a map. In practice, only some vehicles have map information. For example, in BUSNet, only buses have the whole map information while cars do not store any map information. In such scenario, a car will not have the ability to do anchor computation. Some modifications are needed to make A-STAR adapt to this scenario. A possible solution is to allow a car to request for assistance from buses: it can request a bus to compute an anchor path to facilitate the packet forwarding; or it hand over its data packets to a bus which will in turn deliver these data packets.

Currently, the dynamically rated scheme of A-STAR assumes ideal traffic monitoring and distribution mechanism and is only used as the performance benchmark for A-STAR. In the future, a system is expected to be developed that can summarize the vehicular traffic information and distribute the information to the network. This could lead to realistic inter-vehicular communication system.

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A-STAR is designed to route the data traffic through the path with high node density with the hope that high node density results in high connectivity and high possibility of data delivery. However, if too much data traffic goes through the high node density area, congestion may occur. Thus, a load balancing scheme is needed to distribute the data traffic to other areas when one area is congested. One possible way is to modify the current local recovery scheme. Instead of redirecting packets from a void area in the local recovery scheme, the new scheme should be able to detect congested areas and redirect packets before they enter a congested area.

We have described a system that can connect all vehicles in a city environment as nodes in an ad hoc network. The next step is to design useful network services for our system. For example, our system can improve service quality of a bus company by providing commuters or staff at central bus station with information like bus's location, occupancy and other data; or benefit drivers and passengers by providing the street conditions (accidents, slippery roads and obstacles).

The provisioning of Internet access in the IVCS network is one of the main objectives, considering the prosperous services supported by Internet. Currently, the BUSNet is still an isolated ad-hoc network. Gateways are required to connect the BUSNet to the Internet, which can be installed at bus stops or road junctions. Another possible solution is to connect the BUSNet to the current WLAN hotspots, which are currently available at shopping centers, restaurants, or cafes. In order to guarantee Internet connectivity, all vehicles can install GPRS or UMTS network card so that they can switch to the GPRS connection automatically in case the multi-hop wireless ad-hoc connection to its gateway is disrupted.

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There are still many other issues when trying to connect BUSNet to Internet, such as gateway discovery, service discovery, mobility management and routing between wired and wireless network. All these remain as the future research areas for this project.

Publication List

Main Publications

1. Genping Liu, Boon Chong Seet, Bu Sung Lee, Chuan Heng Foh and Kai Juan Wong, “*A-STAR: A Mobile Ad Hoc Routing Strategy for Metropolis Vehicular Communications*”, In Proc. the ICOIN 2004, Busan, Korea, February 2004.
2. Genping Liu, Kai Juan Wong, Bu Sung Lee, Boon Chong Seet, Chuan Heng Foh and Lijuan Zhu, “*PATCH: A Novel Local Recovery Mechanism for Mobile Ad-Hoc Networks*”, In Proc. the IEEE VTC 2003 Fall, Orlando, Florida, USA, October 2003.
3. Boon Chong Seet, Genping Liu, Bu Sung Lee, Chuan Heng Foh and Kai Juan Wong, “*A Mobile Ad-Hoc Routing Strategy for Metropolis Vehicular Communications*”, In Proc. the Networking 2004, Greece, Athens, May 2004.

Other Related Publications

1. Lijuan Zhu, Bu Sung Lee, Boon Chong Seet, Kai Juan Wong, Genping Liu, Shell Ying Huang and Keok Kee Lee, “*Performance of New Broadcast Forwarding Criteria in MANET*”, In Proc. the ICOIN 2004, Busan, Korea, February 2004.
2. Kai Juan Wong, Bu Sung Lee, Boon Chong Seet, Genping Liu and Lijuan Zhu, “*BUSNet: Model and Usage of Regular Traffic Patterns in Mobile Ad Hoc Networks for Inter-vehicular Communications*”, In Proc. the ICT 2003, Thailand, April 2003.
3. Bu Sung Lee, Kai Juan Wong, Boon Chong Seet, Lijuan Zhu and Genping Liu, “*Performance of Mobile Ad Hoc Network in Constrained Mobility Pattern*”, In Proc. the 2003 International Conference on Wireless Networks, Las Vegas, Nevada, USA, June 2003.

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