ADAPTIVE ROUTING PROTOCOLS FOR VANET

by

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ABSTRACT

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A Vehicular Ad-hoc Network (VANET) is a wireless ad-hoc network that provides communications among vehicles with on-board units and between vehicles and nearby roadside units. The success of a VANET relies on the ability of a routing protocol to fulfill the throughput and delivery requirements of any applications operating on the network. Currently, most of the proposed VANET routing protocols focus on urban or highway environments. This dissertation addresses the need for an adaptive routing protocol in VANETs which is able to tolerate low and high-density network traffic with little throughput and delay variation.

This dissertation proposes three Geographic Ad-hoc On-Demand Distance Vector (GEOADV) protocols. These three GEOADV routing protocols are designed to address the lack of flexibility and adaptability in current VANET routing protocols. The first protocol, GEOADV, is a hybrid geographic routing protocol. The second protocol, GEOADV-P, enhances GEOADV by introducing predictive features. The third protocol, GEOADV-PF improves optimal route selection by utilizing fuzzy logic in addition to GEOADV-P's predictive capabilities.

To prove that GEOADV and GEOADV-P are adaptive their performance is demonstrated by both urban and highway simulations. When compared to existing routing protocols, GEOADV and GEOADV-P lead to less average delay and a higher average delivery ratio in various scenarios. These advantages allow GEOADV-P to outperform other routing protocols in low-density networks and prove itself to be an adaptive routing protocol in a VANET environment. GEOADV-PF is introduced to improve GEOADV and GEOADV-P performance in sparser networks. The introduction of fuzzy systems can help with the intrinsic demands for flexibility and adaptability necessary for VANETs.

An investigation into the impact adaptive beaconing has on the GEOADV protocol is conducted. GEOADV enhanced with an adaptive beacon method is compared against GEOADV with three fixed beacon rates. Our simulation results show that the adaptive beaconing scheme is able to reduce routing overhead, increase the average delivery ratio, and decrease the average delay.

I would like to dedicate this work to my understanding and supportive husband, Justin Skiles, who stood by me and encouraged me throughout my research. I also would like to dedicate this work to my mother, Linda Sirois, who pushed me to be better than my best.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

VANETs have emerged in response to an increasing demand regarding the variety of vehicular wireless devices [1,2,3]. VANETs are a subclass of mobile ad-hoc networks (MANETs) [4]. A MANET is an entirely mobile network built upon little to no required infrastructure. In a VANET, networks can differ in size, speed of the nodes (vehicles), geographic position of the node, and can have unreliable channel conditions causing intermittent connectivity between nodes [1, 2, 3, 4, 5]. Existing routing protocols built upon MANETs cannot be applied to VANETs due to these differences and challenges. [2,5,6,7,8,9,10,11,12]

A VANET is a wireless ad-hoc network that provides communications between vehicles with on-board units (OBUs) and nearby roadside units (RSUs) [5, 13]. VANETs propose is to supply:

1. Omnipresent connectivity to mobile users on the road. [5]
2. Vehicle to Vehicle (V2V) communications which is both efficient and able to enable the Intelligent Transportation Systems (ITS). [6]

In a VANET, RSUs are deployed along roadways, highways, interstates, sidewalks, and other transportation infrastructures to provide vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [13,14]. Figure 1.1 demonstrates the architecture of a VANET. Vehicles $V1$, $V2$, $V3$ and $V4$ have access to a RSU which has limited coverage (the green circle). Vehicles $V1$, $V2$, $V3$ and $V4$ can obtain information from the RSU, but $V5$ and $V6$ cannot. $V6$ would need to obtain information from $V5$, and $V5$ would obtain information from $V4$. Each vehicle communicates with nearby vehicles via V2V communications.

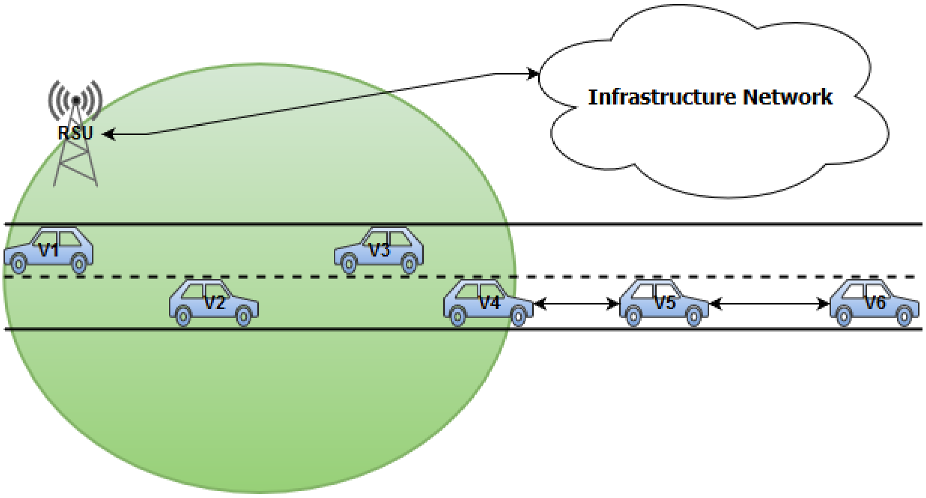


Figure 1.1: VANET Architecture

There are three possible types of communication that could be established within VANETs: Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I), and a hybrid combination of them [2, 5, 15, 16]. Figure 1.2 illustrates the three communication types [2, 15, 16].

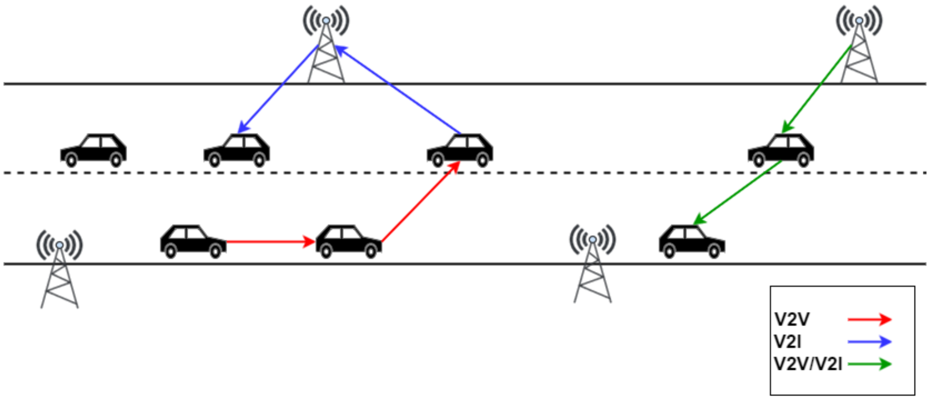


Figure 1.2: VANET Communication process

VANETs can take advantage of cellular networks and wireless local area networks (WLANs) to form a complete network topology [17]. A VANET can contain attributes of wireless, cellular, and ad-hoc network technologies to ultimately form an Intelligent Transport System (ITS) via V2V and V2I communications. [18].

A VANET's routing objective is to conduct packets through a path in the network to their final destinations. Routing protocols determine the process of information exchange between nodes by establishing a route, a packet forwarding algorithm, a maintenance action, and a failure recovery strategy. [14,19,20,21]. Traditional routing protocols are not suitable for efficient V2V communication as they were designed for MANETs and do not take advantage of the unique advantages of VANETs. Existing routing protocols which were originally designed for MANETs, do not utilize the unique characteristics of VANETs and therefore are not suitable for V2V\V2I communications over VANETs. [5]

Topology based routing and geographic routing make up the two main branches of VANET routing protocols [22, 23]. Topology based routing protocols use link-state information in the network in order to forward packets. Geographic routing uses the destination's locational information in order to forward packets [22, 24]. Topology based routing can be categorized as proactive, reactive, or hybrid [5,22,24,25,26,27,28, 29,30,31,32,32,33,34,35,36,37,38,39,40,41]. Proactive topology routing protocols use routing tables to determine the optimal propagation of message through the network. Reactive routing protocols build the route only when it is required. A reactive routing protocol will attempt to establish a route if a node wants to communicate with a node but does not have a route to that node [22, 24].

In order to select a suitable next-hop forwarding vehicle, geographic routing protocols rely on the positional information neighboring vehicles transmit. A Geographic routing protocol can be categorized as Delay Tolerant Network (DTN), non-DTN, or hybrid [12, 42, 43, 44, 45, 46, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63]. A Delay Tolerant Network (DTN) uses a carry and forward strategy to deal with frequent disconnection of nodes in the network [22, 23, 46]. A non-DTN protocol can be further categorized as beacon, non-beacon, and hybrid. Beaconing occurs when a protocol transmits a short message periodically. A non-beacon protocol does not send out a beacons. Hybrid beaconing involves mathematical calculations to determine when to send a message and a strategy related to geographical broadcast limits.

In this work, we will address the need for routing protocols which can be adaptive in both urban and highway environments to improve tolerance of low and high density network traffic with little performance variation.

1.2 PROBLEM STATEMENT

Routing protocols are considered to be an important contributor towards the performance, efficiency, and reliability of VANET communication systems. The success of a VANET relies on the ability of a routing protocol to fulfill the throughput and delivery requirements of any applications operating on the network. Due to the aforementioned importance, a variety of VANET routing protocols have been proposed and developed. Currently, most of the proposed VANET routing protocols focus on urban or highway environments.

An adaptive routing protocol in VANET is able to tolerate both low and high density network traffic with little throughput and delay variation. Designing an adaptive routing protocol for VANET involves a number of challenges due to the following factors:

- Communication links are very vulnerable due to the high mobility of vehicles
- Varying traffic (low, medium, or high density)
- Varying environments (urban vs. highway)

- Vehicle movement direction
- Link quality between vehicles

Topology based routing protocols are not ideal in a VANET environment. Proactive topology routing protocols use routing tables to determine the optimal propagation of messages through the network. In a VANET, nodes (vehicles) have elevated mobility speeds which contribute to failures in proactive routing protocols. Reactive topology routing protocols experience high initial route discovery delays because it only builds routes when necessary. [22, 24].

Existing VANET routing protocols do not adequately address the above challenges due to their focus on urban or high density networks and their lack of consideration regarding the dynamic nature of network traffic. AODV-VANET [5] combines VANET and the topology routing protocol Ad-hoc On-Demand Distance Vector (AODV) in order to improve the route discovery process but is designed primarily for urban environments. AODV-VANET also has stale entries in intermediate nodes, which can lead to inconsistent and incorrect routes. Protocols such as GeoDTN+Nav [62] are intended to be adaptive but experience significantly delayed packet delivery when operating under sparse network conditions. Some protocols need further evaluations such as Model Based Routing (MBR) [58] which has only been simulated over Dynamic Source Routing (DSR) [35, 36]. Greedy Perimeter Stateless Routing (GPSR) [42, 43] uses greedy forwarding to forward packets that are always more and more closer to the destination. Due to GPSR's stateless nature, local maxima can form in the network causing packets to route through the same path up to the local maximum position. Once the packets arrive at the local maxima, the packets is set to perimeter forwarding mode [42, 43].

This work addresses the need for adaptive routing protocols in urban and highway environments. The proposed hybrid Geographic Ad-hoc On-Demand Distance Vector (GEOADV) protocols utilize reactive and geographic attributes to adapt to inherent differences in various environments. By using vehicle information such as speed, direction, and density, GEOADV protocols address the demand for adaptive VANET routing protocols.

1.3 CONTRIBUTIONS

The contributions are as follows:

- Survey and classification of VANET Routing Protocols.
- Design and evaluation of the GEOADV routing protocol [64].
- Design and evaluation of the GEOADV-P routing protocol.
- Design and evaluation of the GEOADV-PF routing protocol.
- Investigated the impact adaptive beaconing has on GEOADV

1.4 ORGANIZATION

The remainder of this dissertation is structured as follows. First, Chapter 2 present a literature review of existing VANET routing protocols. Second, Chapter 3 gives an overview of the AODV, AODV-VANET, and GPSR, the main protocols the GEOADV protocols are based on. Third, Chapter 4 details the GEOADV and GEOADV-P protocols. Forth, Chapter 5 reviews GEOADV and GEOADV-P's performance results. Fifth, Chapter 6 presents a predictive fuzzy logic protocol and analyzes the protocol's performance. Sixth, Chapter 7 investigates the impact adaptive beaconing has on GEOADV. Finally, Chapter 8 summarizes this dissertation and presents future work.

CHAPTER 2

LITERATURE SURVEY

A routing protocol determines the way information is exchanged between two communicating entities. Included in a routing protocol is a process to build a route, a decision in forwarding scheme, and actions to be used to maintain the route or recover from routing failure. Routing protocols can be split into two subcategories: topology based routing and geographic routing [23]. Topology based routing protocols use link-state information, which exists in the network, to forward the packet. Geographic routing uses the destination's location information to forward the packet. Topology based routing can be categorized as reactive, proactive, or hybrid. A Geographic routing protocol can be categorized as non-DTN, DTN, or hybrid. [22, 23, 24, 46, 65]

Figure 2.1 shows the taxonomy of the surveyed routing protocols in VANETs. This section will survey developed routing protocols specific to VANETs and discussing their pros and cons, test scenario environments, and adaptability.

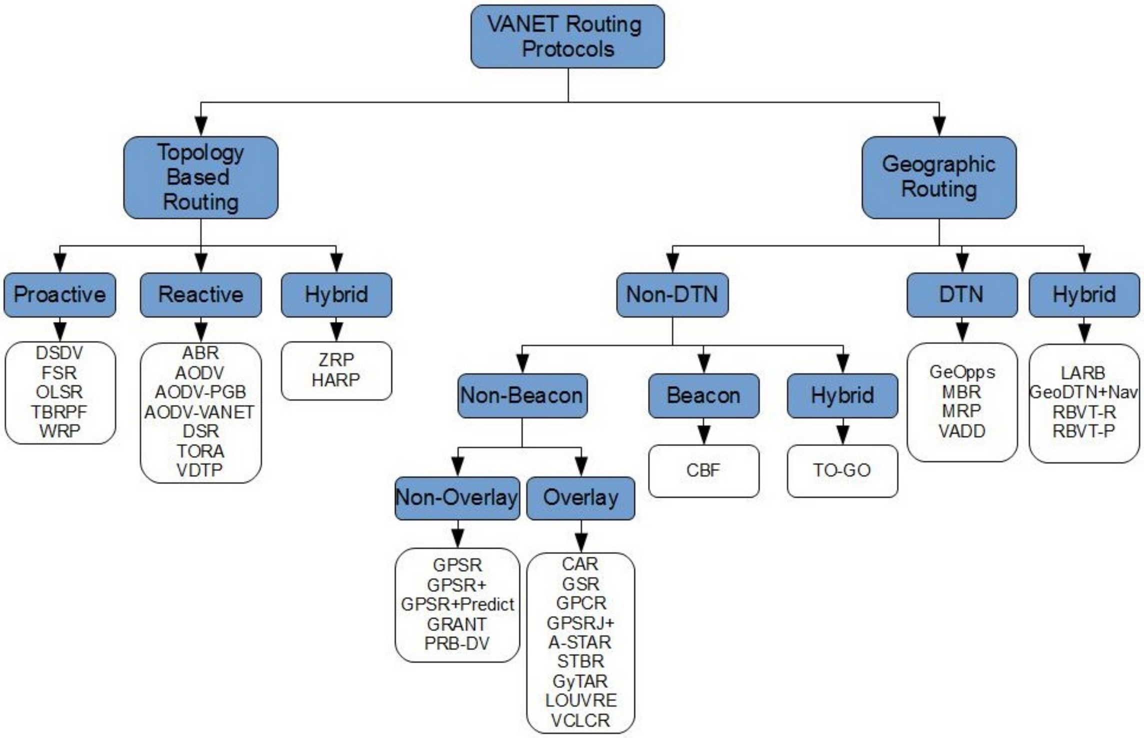


Figure 2.1: Taxonomy of Surveyed Routing Protocols in VANET

2.1 TOPOLOGY BASED ROUTING

2.1.1 Proactive Protocols

In order to propagate a message, proactive routing protocols use a routing table. Proactive routing protocols are not appropriate for VANET due to nodes (vehicles) moving at high speed and having high mobility. [22, 23, 24]

DSDV

The base of Destination-Sequenced Distance Vector (DSDV) [25] is the Bellman-Ford algorithm. In DSDV each node maintains the route to all know destinations, as a table. The topology changes are updated by immediate advertisements to the neighbors. In DSDV tables are can be updated completely if a node sends its entire information to other nodes or incrementally updated if a node sends only deltas to other nodes. Although DSDV is not used as much today, other protocols, such as AODV, use similar techniques. [22, 25]

Pros:

- Low complexity
- By using sequence numbers path is loop free
- Since the path is obtained from the routing table there is no latency

Cons:

- Overhead since some the information is never used
- Tables need to be updated regularly and therefore causes high bandwidth consumption

FSR

Fisheye State Routing (FSR) [26] is an enhancement of Global State Routing. FSR relies on a link state protocol as a base, therefore each node must maintains a topology map. Depending on how far the node is from the source, routing information is updated at different rates. If a node is closer to the source it updates more frequently than it does for a remote destination. [22, 26]

Initially, every node starts with an empty topology table and an empty neighbor list. The neighbor discovery mechanism is invoked in order to acquire neighbors and to maintain current neighbor relationships. After this the local variables are initialized. Then the distribution of Link State Packets (LSP) in the network is produced by using the information dissemination mechanism. In FSR, each node has a database consisting of the collection of LSPs. With the help of this database, the node is able to use route computation mechanism to create a routing table for the protocol. This procedure is repeated periodically. [22, 26]

Pros:

- Instead of flooding the entire network, uses periodic exchange of topology tables within the local neighbors only
- Reduce routing overhead

Cons:

- Does not activate a control message for link failure
- Poor performance in low density ad-hoc networks
- Routing tables grows linearly with network size
- Less knowledge about remote nodes
- Insufficient information for route establishing

OLSR

In Optimized Link State Routing (OLSR) is a classic link-state routing protocol designed for MANETs with low bandwidth and high mobility [28]. In OLSR, every node will periodically construct and maintain the set of neighbors that can be reached in one hop and two hops. Using this information the Multi-Point Relay (MPR) algorithm is able to minimize the number of active relays needed to cover all two hops neighbors. A node forwards a packet if and only if it has been selected as MPR by the sender node. OLSR periodically transmits link state information over the MPR backbone, in order to construct and maintain its routing tables. [27, 28, 29]

The main functions of OLSR are performed by HELLO messages, topology control (TC) messages, and multiple interface declaration (MID). [28].

HELLO messages are exchanged between neighboring nodes in a one hop distance. HELLO messages are periodically generated and contain information about the neighboring nodes and links between their network interfaces [27, 28, 29].

MPRs periodically send out TC messages to inform which nodes have selected it as their MPR. TC messages contain an MPR selector table and sequence number. Every node in the network maintains a topology table based on TC messages. In OLSR, routing tables are maintained by the node and are calculated based on these topology tables. If the topological table is updated, the routing table will be recalculated. OLSR's routing table contains the distance to the destination as well as addresses for the destination and next hop. [27, 28, 29]

Nodes send out MID messages in order to communicate information about their network interfaces participating in the network. This data is crucial as nodes can have multiple interfaces with distinct addresses actively communicating. [27, 28, 29]

Pros:

- Does not require a central administrative system to handle the routing process
- Periodically sent messages
- Sequential delivery is not required
- Works best in a dense network

Cons:

- Each host needs to periodically send messages in order to update the topology information throughout the network, which increases the protocols bandwidth
- Not suited for applications with long delay

TBRPF

Topology Broadcast based on Reverse-Path Forwarding (TBRPF) [30] uses a modified Dijkstra's algorithm in order to compute the source tree. In TBRPF, a source tree is computed for each node by using partial topology information received from the nodes topology table. This enables paths to all reachable nodes. In order to reduce overhead, only part of a node's source tree is reported to its neighbors. Periodic and differential updates are used in combination in order to keep all neighbors informed of the reportable parts of its source tree. In order to offer improved robustness in high mobility networks, there is the option to report additional topology information. [22, 30]

Pros:

- Routing messages are smaller this is due to TBRPF only transmitting the changes between the previous and current network state.

Cons:

- TBRPF's worst-case convergence time is twice that of the flooding time. Convergence time is a measure of how fast a group of nodes reaches the state where all nodes have the same topological information [66]

WRP

Wireless Routing Protocol (WRP) [31] uses an enhances DSDV by utilizing a set of tables, versus one table, to maintain more accurate information. WRP introduced processes to reduce route loops and secure reliable message exchange. In WRP, a node maintains four tables. These tables are a distance table, a routing table, a link cost table, and a message retransmission list. [31]

Pros:

- The use of sequence numbers allows for the path to be loop free
- Similarly to DSDV, since the path is obtained from the routing there is no latency
- Faster convergence
- Fewer table updates

Cons:

- Large bandwith consumpiton as tables need to be updated regularly
- Due to having to maintain multiple tables, WRP demands larger memory and greater processing power from nodes
- Not suitable for large MANETs as it suffers from limited scalability, this is due to WRP needing large memory storage and resources in maintaining its tables

2.1.2 Reactive Protocols

Reactive routing protocols builds routes only when necessary [22, 24]. Therefore, if a node needs to communicate with another node and it has no route, a reactive routing protocol will then try to establish a route. [22, 23, 24]

ABR

In Associativity-Based Routing (ABR) [32, 33] a route is selected based on associativity states of nodes. ABR introduces the concept of degree of association stability is calculated. The degree of association stability represents the consistency of the connection of one node with respect to another node. Node participate in exchanging beacons in order to calculate association stability between each other.

When a the beacon is received by a neighboring node the node updates its associativity tables. For every beacon received by a node, the nodes associativity is incremented with respect to the node from which it received the beacon. [22, 32, 33]

A high value of associativity in ABR implies a low node mobility and a low value implies a high node mobility. Associativity is reseted when one of the nodes moves out of proximity of the other. ABR's main objective is to find stable routes that stay active longer. There are three phases of ABR. These phases are route discovery, route reconstruction (RRC) and route deletion. [32, 33]

Pros:

- Stable routes have a higher preference compared to shorter route, there are fewer path breaks
- Due to fewer path breaks, there is a reduce extent of flooding in order to reconfigure the paths

Cons:

- Due to stable routes having a higher preference compared to shorter routes, the chosen path may be longer that the shortest path between the source and destination

AODV

Ad-hoc On-Demand Distance Vector (AODV) uses a hop-by-hop pattern in order to operate. AODV allows for a dynamic multi-hop routing between all participating nodes in the network. In AODV nodes can acquire routes rapidly for new destinations and nodes are not required maintain routes that are inactive. [23, 24]

Pros:

- Destination sequence numbers are used to identify the latest route, preventing routing loops
- Lower connection setup delay
- Possible to apply on large scale ad-hoc networks

Cons:

- Intermediate nodes can have inconsistent and stale routes. This occurs if the source sequence number is older than the current source sequence number and the intermediate node have a later source sequence number but not the latest
- High control overhead, due to multiple RREPs responding to a single RREQs
- High broadcast overhead
- Due to periodic beaconing there is excess bandwidth consumption

AODV+PGB

AODV+PGB uses preferred group broadcasting (PGB) [34] to reduce the broadcast overhead and provide a more stable route compared to AODV. In order to reduce the high broadcast overhead caused by AODV's route discovery process, receivers in PGB determine whether they are part of a preferred group and determine which node in the group to broadcast. The node is determined by the received signal of the broadcast. [34]

Pros:

- Same positives as AODV
- Reduces AODV's broadcast overhead

Cons:

- Only one node is allowed to broadcast, therefore route discovery can potentially take longer than AODV
- The identified preferred group may never be the group that makes the most progress towards the destination
- Broadcast can be discontinued if the group is found to be empty
- Two nodes in the same group can broadcast at the same time causing packet duplication

AODV-VANET

AODV-VANET is a proposed routing protocol from ”A Reliable Routing Protocol for VANET Communications” [5]. AODV-VANETs goal is to combine VANET features with the AODV routing protocol to improve the route discovery process. The AODV routing protocol was chosen as it is able to react quickly to network change and has an effective route discovery method. AODV-VANET introduces the Total Weight of the Route (TWR). [5]

Pros:

- TWR and expiration time estimation helps AODV-VANET achieve better routing performances
- Less bandwidth consumption than AODV
- Able to establish a stabler link compared to AODV
- Connection setup delay is lower
- Can be applied to a large scale ad-hoc network

Cons:

- Like AODV, intermediate nodes can have inconsistent and stale routes. This occurs if the source sequence number is older than the current source sequence number and the intermediate node have a later source sequence number but not the latest
- Can lead to heavy control overhead due to multiple RREPs responding to a single RREQs

DSR

Dynamic Source Routing (DSR) [35] routing packet overhead scales automatically as the protocol operates completely on demand. In order to operate entierly on-demand, DSR relies on the routing table to be maintained at each node. This means that a route can be formed on-demand whenever a sending node makes a request. [35, 36]. DSR is composed of the two main mechanisms: route discovery and route maintenance [36]. These two mechanisms work together in order to enable nodes to discover and maintain routes to destinations. [35, 36]

Pros:

- Beacon-less
- Small overload on the network because uses caching
- No periodical update is required

Cons:

- Can lead to byte overhead if there are too many nodes in the network
- Due to unnecessary flooding there is high bandwidth usage

- Not suited for applications with high mobility patterns
- Unable to repair broken links locally

TORA

Temporally Ordered Routing Algorithm (TORA) [32,37] is an enhance version of the link reversal algorithm. In TORA, the source node is the root of the tree and packets are broadcasted by the sending node. If a packet is received and the neighbor node is a downward link, the neighbor nodes rebroadcasts the packet based on the direct acyclic graph (DAG). [22,32,37]

Pros:

- Only creates a DAG when necessary
- Since not all intermediate nodes need to rebroadcast, TORA is able to reduce network overhead
- Performs well in a dense network.

Cons:

- Not scalable
- Worse performer than AODV and DSR

VDTP

Vehicular Data Transfer Protocol (VDTP) [38] operates on top of DSR. TORA consists of two different phases. The first phase is the information requesting phase. The second phase is the data requesting phase. The communication process is accomplished by downloading and saving a shared file via a file petitioner and a file owner respectively. [38]

Pros:

- Low packet loss

Cons:

- Limited testing

2.1.3 Hybrid Protocols

Hybrid protocols where implemented to help decrease control overhead caused by proactive routing protocols and decrease the initial route discovery delay caused by reactive routing protocols, hybrid routing protocols were introduced. [22, 24]

ZRP

Zone routing protocol (ZRP) [39, 40] uses concept of zones in order to create and maintain routes. ZRP maintains a topological map of a zone centered on each node, therefore combining both of proactive and reactive topology based protocols. If a destination is within the zone, the route is immediately available. ZRP uses a route discovery procedure if a destination is outside the zone. [39, 40]

Pros:

- Reduces the traffic amount compared to pure proactive or reactive routing
- Performs well in large networks.

Cons:

- Increasing complexity

HARP

Hybrid Ad Hoc Routing Protocol (HARP) [41] sections the entire network into zones, that do not overlap, to produce a stable route from a source node to a destination node. HARP does the aforementioned process in order to improve delay. Depending on the position of destination, HARP uses intra-zone or inter-zone routing. Intra-zone uses proactive protocols and inter-zone uses reactive protocols. [41]

Pros:

- In order limit flooding in the network, route discovery applied in zones
- Stronger routes due to routes being chosen on stability criteria

Cons:

- It is not applicable in high mobility ad-hoc networks.

Table 2.1: Review of Topology VANET routing protocols presented

Routing Protocol	**Type**	**Forwarding Strategy**	**Recovery Strategy**	**Digital Map Required**	**Scenario**
DSDV	Proactive	Multi hop	Multi hop	No	Urban
FSR	Proactive	Multi hop	Multi hop	No	Urban
OLSR	Proactive	Multi hop	Multi hop	No	Urban
TBRPF	Proactive	Multi hop	Multi hop	No	Urban
WRP	Proactive	Multi hop	Multi hop	No	Urban
ABR	Reactive	Multi hop	Store and Forward	No	Urban
AODV	Reactive	Multi hop	Store and Forward	No	Urban
AODV+PGB	Reactive	Multi hop	Store and Forward	No	Urban
AODV-VANET	Reactive	Multi hop	Store and Forward	No	Urban
DSR	Reactive	Multi hop	Store and Forward	No	Urban
TORA	Reactive	Multi hop	Store and Forward	No	Urban
VDTP	Reactive	Multi hop	Store and Forward	No	Urban
ZRP	Hybrid	Multi hop	Store and Forward	No	Urban
HARP	Hybrid	Multi hop	Store and Forward	No	Urban

2.2 GEOGRAPHIC ROUTING

Geographic routing is a when each node knows its own and neighbor nodes geographic position. This information can be known by a location determining services, such as a GPS. A geographical routing protocol doesn not maintain routing tables or interchange link state information with neighboring nodes. [22,24,46]

In Geographical Routing Protocols can be categorized as a Delay Tolerant Network (DTN), non-DTN, or Hybrid. A Delay Tolerant Network (DTN) uses carry and forward strategy to deal with frequent disconnections of nodes in the network. In carry and forward strategies, when a node cannot communicate with the other nodes the node will store the packet and then forward the packet based on the neighboring node metrics. [22,46]

A non-DTN protocol can be further sub categorized as beacon, non-beacon, and hybrid. Beaconing occurs when a protocol transmits a short message periodically. Beaconing makes the presence and position of a node available. In beaconing a neighbor node will be removed from the neighbors table if the node fails to receive a beacon after a period of time from the neighbor node. A non-beacon protocol does not send out a beacons. Hybrid beaconing involves mathematical calculations to determine when to send a message and a strategy related to geographical broadcast limits. [22,46]

Non-DTN beacon protocols can be categorized as Non-Overlay or Overlay. Overlay is a network where all nodes are associated by links, virtual or logical, that are built on top of an existing network. [22,46]

2.2.1 Non-DTN Beacon Non-Overlay

GPSR

Greedy Perimeter Stateless Routing (GPSR) protocol uses greedy forwarding to constantly forward packets closer to the destination. GPSR assumes vehicles are equipped with a location service devices, such as a GPS, so that nodes can access their own geographical information. In GPSR, intermittent hello packets are exchanged amongst nearby vehicles to learn the locations their neighbors in a one-hop distance. This information is kept in the header of the transmitted packet. Therefore, the forwarding process can follow the greedy forwarding process when selecting the next forwarding node [42, 43].

Pros:

- Stateless
- A node only needs to know the neighbors in one-hop to forward a packet
- Decisions for packet forwarding are made dynamically

Cons:

- In high mobility networks stale information about the neighbors position are often in the sending nodes neighbor table [22]
- Issues can arise if the destination node is moving, as the destination nodes information for intermediate node is not updated
- Due to GPSR being stateless if a local maxima is formed in the network, packets will continue to follow the same path to the local maxima. Once the packets arrive at the local maxima, each packet is set to perimeter forwarding mode.

GPSR+PRedict

GPSR+PRedict [44] is based on GPSR and estimates the future position of all participating nodes. In GPSR+PRedict the predicted future position is attached in the hello message. The future position is also stored in the neighbors list of each node and included in the best next hop calculation. In order to not weigh down the protocol, the information of the future position is only added to the hello packet and in list of neighbors. [44]

Pros:

- Stateless
- Decrease in cost of routing compared to basic GPSR

Cons:

- Only compared against GPSR
- Local maxima can still form in the network

GRANT

In "Position-based Unicast Routing for City Scenarios" [45] Greedy Routing with Abstract Neighbor Table (GRANT) is proposed. GRANT is an enhancement of the GSPR algorithm and its goal is to avoid a local maximum. GRANT sections the plane and choses a representative for each area. This process helps reduce the overhead from exchanging neighbor information. [45]

Pros:

- Performs better than GPSR in city scenarios

- Lower amount of times the packet is recovered per route compared to traditional greedy routing, the

Cons:

- No performance metrics to confirm its performance

PRB-DV

Position-Based Routing with Distance Vector (PRB-DV) [46] makes use of the AODV route recovery process when a packets arrives at a local maximum. In PRB-DV, a node will broadcast a request packet if the node is at a local maximum. If a node receives a request packet, the node will determine if it is closer to the destination than the broadcasting node. If not, the node will record the broadcasting node and then rebroadcasts the request. If the node is closer to the destination the node will send a reply to broadcasting node. [46]

Pros:

- Handles local maximum issue

Cons:

- In order to discover the non-greedy part of the route additional flooding is necessary
- Performance in packet delivery and overhead is uncertain because no assessment has been done comparing PRB-DV to GPSR or AODV

2.2.2 Non-DTN Beacon Overlay

A-STAR

In Anchor-Based Street and Traffic Aware Routing (A-STAR) [47] a street map is used to compute the sequence of anchors (road junctions). These anchors are computed with traffic awareness and a packet must pass through an anchor in order to reach its destination. All packets in A-STAR are routed through anchor points. [47]

Pros:

- Packet delivery ratio is lower compared to GSR and GPSR

Cons:

- High complexity

CAR

Connectivity-Aware Routing (CAR) [48] protocol consists of four major functions: destination location and path discovery, data packet forwarding, path maintenance, and error recovery. In CAR the local maximum problem is handled. CAR uses preferred group broadcast (PGB) to reduce the broadcast overhead from AODV route discovery. CAR also utilizes advanced greedy forwarding (AGF) to make informed decisions dealing with node mobility. [48]

Pros:

- Does not require a digital map
- No local maximum problem
- Higher packet delivery ratio than GPSR

Cons:

- If traffic environment changes, cannot adjust with a different sub path

GSR

GSR [12] routing was proposed for VANETs in city environments. GSR combines position-based routing (greedy forwarding) with topological knowledge (previously selected shortest path). GSR uses Dijkstra algorithm to calculate the shortest path. [12]

Pros:

- High packet delivery ratio compared to AODV and DSR
- More scalable than AODV and DSR

Cons:

- Does not handle low density networks where there is a lack of nodes to forward packets
- Due to the use of hello messages as control messages, GSR has a higher routing overhead
- Does not consider connectivity between two junctions

GPCR

Greedy Perimeter Coordinator Routing (GPCR) [49] makes the assumption a planar graph is formed naturally by streets and junctions. This assumption helps GPCR avoid using a static street map or another type of external information. GPCR is made up of a restricted greedy forwarding procedure as well as a repair strategy.

GPCR's repair strategy, is based on the real-world streets and junctions topology and therefore eliminates the need of a graph planarization algorithm. [49]

Pros:

- Eliminates planarization by routing along roads

Cons:

- Can lead routing loops. This is due tot the fact that GPCR will forward packets "cross" junctions when there is no node at a junction. Forwarding across "empty" junctions is likely to lead to a non-planar graph. [54]
- Inefficiency in routing as packet stops at junction nodes
- Does not apply on city map that are not grids

GPSRJ+

GPSRJ+ [50] is based off GPCR. GPSRJ+ removes the stops at a junction GPCR introduced, and is able to keep an efficient planarity of topological maps. In order to anticipate the next road segment a neighboring junction node will take, GPSRJ+ uses two-hop neighbor beaconing. If the GPSRJ+ predicts that the neighboring junction will forward the packet on a road with a different direction, the packet will be forwarded to the junction node. If GPSRJ+ does not predict this, the junction will be bypassed and the packet will be forwarded to the furthest neighboring node. [50]

Pros:

- Removes the stop at a junction GPCR introduced
- Packet delivery ratio of GPCR was increased
- The number of hops in the recovery mode is reduced

Cons:

- Not a good solution for the delay sensitive applications
- Like GPCR, it does not apply on city map that are not grids

GyTAR

Greedy Traffic Aware Routing (GyTAR) [51] is a geographic routing protocol based on intersections. GyTAR uses junctions(intersections) selection in order to discover robust routes in urban environments. GyTar is made up of two modules: selection and forwarding data between two junctions. [51]

Pros:

- Efficiently handles high mobility topology changes and network fragmentation
- Better throughput, delay, and routing overhead than GSR

Cons:

- Assumes that the number of cars in the road will be provided by RSUs
- Cannot avoid voids

LOUVRE

Landmark Overlays for Urban Vehicular Routing Environments (LOUVRE) [52] builds a landmark overlay network over an urban topology. Every landmark in LOUVRE is placed at an intersection and vehicular traffic density between these landmarks are distributively estimated. Another feature in LOURVE is that overlay network between landmarks are built with the acknowledgment of traffic density-based overlay links. LOURVE determines the best paths to and from any landmark located on the same grid and maintains these paths for local routing. Packets are routed for remote routing to the best neighboring grid. When a vehicle analyzes its routing table to determine the best path, it will follow the landmarked paths connected by intersections to the destination. [52]

Pros:

- Has a higher packet delivery and achieves lower hop count than compared protocols
- Allows for an obstacle free geographic routing [52]

Cons:

- Not scalable

STBR

Street Topology-Based Routing(STBR) [53] makes use of a provided street map such as a planar graph and utilizes three states in order to create a route. These states are master, slave, and forwarder. On a junction, only one node acts as a master and all other nodes act as slaves. Intermediate nodes between junctions are set in the forwarder state. [53]

Pros:

- Unicast communication
- Able to traverse the least spanning multiple junctions for the longest distance

Cons:

- Not appropriate for mixed scenarios (i.e mixed urban highway environments)
- Complexity increases because of special cases

VCLCR

VANET cross link corrected routing protocol (VCLCR) [54] removes cross links, introduced by GPCR's perimeter traversal, dynamically in order to avoid routing loops. When VCLCR is in perimeter forwarding mode, the route information is recorded in the packet and is used to check if there is a loop or cross link. The natural planar feature of urban maps is used to avoid planarization strategy. [54]

Pros:

- Suitable for highly mobile VANETs because the salient features of dynamic loop detection and statelessness
- Consistently higher packet delivery ratio compared to GPSR and GPCR
- Stateless

Cons:

- Not very scalable

2.2.3 Non-DTN Non-Beacon

CBF

Contention-Based Forwarding (CBF) [55] is base on a greedy position-based forwarding algorithm. Data packets are broadcasted to every direct neighbors and the neighboring nodes make the decision to forward the packet. In CBF beacon messages transmitted proactively are not required. [55]

Pros:

- Uses less bandwidth because it eliminates the use of beacon messages

- Performs better that beacon-based greedy forwarding in general two-dimensional scenarios using random way-point mobility

Cons:

- In city environments local maximum frequently occurs

2.2.4 Non-DTN Hybrid

TO-GO

Topology-assist Geo-Opportunistic Routing (TO-GO) [56] is a geo-routing protocol that uses topology knowledge. By using two-hop beaconing, TO-GO is able to acquire its topology information in order to select the best target forwarder and utilizes opportunistic forwarding to determine what node has the highest probability of reaching the aforementioned forwarder. As the forwarder selection is determined using wireless channel quality, TO-GO is classified as a Non-DTN hybrid. [56]

Pros:

- By knowing a junction node's furthest nodes on different road segments to determine the best forwarding node, TO-GO is able to reduce the overhead of two-hop beaconing

Cons:

- End-to-End latency is higher than GPCR, GPSR, GPSRJ+.

2.2.5 DTN

GeOpps

Geographical Opportunistic Routing (GeOpps) [57] is a geographical delay tolerant routing algorithm. By using a vehicle's navigation system GeOpps is able to route messages to a specific location. In GeOpps, a packet will be forwarded to a node if it has a minimum arrival time.

In GeOpps vehicles periodically broadcast the destinations of the packets that they have stored currently. Neighbors within one-hop calculates the Minimum Estimated Time Of Delivery for the packet(METD) required to deliver a packet, this value is then sent to the vehicle. If the vehicle has the lowest METD it keeps the packet other wise the packet is forwarded to the node which has the lowest METD. This is repeated until the packet reaches expires or reaches the destination. [57]

Pros:

- Has high delivery ratio
- Delivery ratio relies on the mobility patterns and road topology but not reliant on the density of the network.

Cons:

- Navigation information is disclosed to the network, causing security concerns

MBR

Model Based Routing(MBR) [58] is a routing algorithm that takes advantage of the predictable node moments along a highway.

Pros:

- Improved end-to-end transmission delay
- Verified that vehicular motion on a highway can advance the success of message delivery

Cons:

- Delays measured at only low vehicle densities

MRP

Mobile Relay Protocol(MRP) [59] is designed to be layered on top of an existing ad-hoc routing protocol. MRP is responsible for forwarding, storage, and delivery of relay packets. In MRP if a route to a destination is unavailable, a node performs a relay to its immediate neighbors. A relay is a controlled local broadcast. MRP makes the assumption that one of the relay nodes will encounter a node that has a valid route to the destination, therefore increasing the probability that the message will be successfully delivered.

Pros:

- Improved DSR protocol

Cons:

- High number of duplicate packets sent to final destination
- Only tested over one protocol

VADD

Vehicle-Assisted Data Delivery (VAAD) [60] uses predicable vehicle mobility to help determine its carry and forward strategy. Amongst the proposed VAAD protocols in [60] H-VAAD was shown to have one of the best performance.

VADD follows three basic principles. The first principle is to transmit through wireless channels as much as possible. Second principle is if the packet has to be carried through multiple roads, the road with higher speed should be chosen. The third principle is dynamic path selection should be executed throughout the packet forwarding process continuously. [60]

Pros:

- High delivery ratio
- Desirable for multi-hop data delivery

Cons:

- Situations like sparse networks are neglected
- Causes large delay due to change of topology and traffic density

2.2.6 Hybrid

LARB

Location-Aware Reliable Broadcasting protocol (LARB) [61] uses an adaptive hop counter scheme for urban environment. LARB uses a reliable broadcasting mechanism from DECA, reviewed in [61], and enhances the ability to limit the area of broadcasting messages. Using neighbor density information, LARB is able to calculate the maximum number of hops in order to limit the area of message dissemination.

LARB can limit the area of rebroadcasting. In order to do this LARB only uses neighbor information within one hop in order to select the next rebroadcasting node. The node with the highest number of one hop neighbors is determined to be the most efficient and desirable rebroadcasting node.

Pros

- Limits the area of rebroadcasting by using the number of hops
- Outperform the simple flooding method with GPS and hop counter scheme

Cons

- Limited testing, the protocol was compared only against simple flooding method with GPS and hop counter scheme.
- Delivery outside region higher in low density environments

GeoDTN+Nav

Geographic DTN Routing with Navigator (GeoDTN+Nav) [62] considers node movements when computing the next forwarding node in the DTN mode. GeoDTN+Nav is an extension of VANET Cross Link Corrected Routing (VCLCR) [54]. GeoDTN+Nav improves VCLCR by using the vehicular mobility and a location determining services, such as a GPS. [62].

In GeoDTN+Nav each vehicle is to be equipped with virtual navigation interface (VNI). VNI is a lightweight package interactive interface which has vehicle components. VNI's underlying vehicle components find adjacent vehicles and provide the navigation information in a consistent format. [62]

Pros

- Improved graph reachability by use of delay tolerant store-carry-forward

Cons

- High number of duplicate packets sent to final destination
- Only tested over one protocol
- Increased delivery delay

RBVT-R

Road-Based using Vehicular Traffic information (RBVT) [63] uses real time information to route traffic. RBVT-R is a hybrid reactive routing protocol which uses reactive elements to form a path. By using connected road segments RBVT-R can create routes on demand. A connected road segment is defined as a segment between two adjacent intersections with adequate traffic to guarantees network connectivity. Intermediate nodes to forward packets between intersections, by using the routes defined in the data packet header [63]. In RBVT-R's improved flooding is used to reduces issues with broadcasting. RBVT-R is able to improves it's flooding by follow the following rules when broadcasting an RD packet:

- The RD packet is discarded if the node has already received a RD packet with the same source address and sequence number.
- When a node receives as RD packet that doesn't match the above criteria, the packet will be held for a period of time. Once this time pasts, a node will rebroadcasts the RD packet if the packet was not rebroadcasted by other nodes located further along on the same road segment.

Using this method RBVT-R is able to insure that the nodes furthest along the road segment rebroadcasts the request first, thus guaranteeing a faster progress and less overhead for the network. [63]

Pros

- Outperforms AODV, OLSR, GPSR and GSR in average delivery ratio
- When selecting the next neighbor node, RBVT-R provides an advantage to link quality over forward progress
- Uses improved flooding is used to reduces issues with broadcasting

- Faster route creation
- Less overhead for the network

Cons

- The amount of intersections that can be attached to a route is limited by the size of the IP packet header options as well as the number of bytes available to identify each road intersection [63]

RBVT-P

RBVT-P is a proactive routing algorithm, proposed in "VANET Routing on City Roads Using Real-Time Vehicular Traffic Information" [63]. RBVT-P proactively discovers and distributes the road-based network topology, This is done in order to maintain a relatively consistent view of the network connectivity at each node. It is assumed in RBVT-P, a source can determine the position of the destination node by querying a location service. [63]

By capturing the real time view of the traffic, RBVT-P is able to limit flooding. This helps with connectivity since as long as that road segment remains connected, changes between certain nodes on a road segments over time does not matter as much. [63]

In RBVT-P road-based network topology is constructed using connectivity packets (CPs). CP are unicast in the network to traverse road segments and store their endpoints (intersections) in the packet. The network topology information in the CP is extracted and stored in an RU packet. The RU packets is is disseminated to all nodes in the region covered by the CP. The RU is marked with a time-stamp to indicate the freshness of its information. [63]

Pros

- Consistently selected the shortest connected path in simulations
- Limited network flooding
- Uses timestamps to handle consistency issues

Cons

- Does not perform well in sparse networks

Table 2.2: Review of Geographic VANET routing protocols presented

Routing Protocol	Type	Forwarding Strategy	Recovery Strategy	Digital Map Required	Scenario
GPSR	Non-DTN, Beacon, NON-Overlay	Greedy forwarding	Store and Forward	Yes	Urban
GPSR	Non-DTN, Beacon, NON-Overlay	Greedy forwarding	Store and Forward	Yes	Highway
GRANT	Non-DTN, Beacon, NON-Overlay	Multi hop	Multi hop	Yes	Urban
PRB-DV	Non-DTN, Beacon, NON-Overlay	Multi hop	Multi hop	Yes	Urban
A-STAR	Non-DTN, Beacon, Overlay	Multi hop	Multi hop	Yes	Urban
CAR	Non-DTN, Beacon, Overlay	Multi hop	Multi hop	No	Urban
GSR	Non-DTN, Beacon, Overlay	Multi hop	Multi hop	Yes	Urban
GPCR	Non-DTN, Beacon, Overlay	Greedy forwarding	Store and Forward	Yes	Urban
GPSRJ+	Non-DTN, Beacon, Overlay	Multi hop	Multi hop	Yes	Urban
STBR	Non-DTN, Beacon, Overlay	Multi hop	Multi hop	Yes	Urban
GYTAR	Non-DTN, Beacon, Overlay	Greedy forwarding	Store and Forward	Yes	Urban
LOUVRE	Non-DTN, Beacon, Overlay	Multi hop	Multi hop	Yes	Urban
VCLCR	Non-DTN, Beacon, Overlay	Multi hop	Multi hop	Yes	Urban
CBF	Non-DTN, Non-Beacon	Multi hop	Multi hop	Yes	Highway
TO-GO	Non-DTN, Hybrid	Multi hop	Multi hop	Yes	Urban
GeOpps	DTN	Multi hop	Multi hop	No	Urban
VADD	DTN	Multi hop	Multi hop	No	Urban
MBR	DTN	Multi hop	Multi hop	No	Highway
MRP	DTN	Multi hop	None	No	Urban
LARB	Hybrid	Multi hop	Multi hop	No	Urban
GeoDTN+Nav	Hybrid	Multi hop	Multi hop	No	Urban
RBVT-R	Hybrid	Multi hop	Multi hop	No	Urban
RBVT-P	Hybrid	Multi hop	Multi hop	No	Urban

2.3 SUMMARY

In this section, a literature review of VANET protocols currently proposed was classified and the pros and cons of each protocol were present. In Table 2.1 each topology protocol is categorized. Table 2.2 each geographic protocol is categorized. These tables break down each protocol discussed above by type, forwarding strategy, recovery strategy, whether a digital map is required, and the scenario it has been tested/developed to be used in. As previously discussed, routing protocols can be split into topology based routing or geographic routing [23]. Topology based routing can be categorized as reactive, proactive, or hybrid. Geographic routing protocol can be categorized as non-DTN, DTN, or hybrid, with many more subtypes. Each protocol has a forwarding strategy and a recovery strategy. Forwarding strategies are either multi-hop or greedy forwarding. Recovery strategies are either multi-hop or store and forward

By studying these protocols it can see that, currently, most of the proposed VANET routing protocols focus on urban or highway environments. Some protocols such as GeoDTN+Nav are intended to adaptive but when in a sparse network packet delivery slows significantly. Some protocols need further evaluations such as MBR which has only been simulated DSR. AODV-VANET [5] combines VANET and the topology routing protocol Ad-hoc On-Demand Distance Vector (AODV) in order to improve the route discovery process but is designed primarily for urban environments. AODV-VANET also has stale entries in intermediate nodes, which can lead to inconsistent and incorrect routes. Greedy Perimeter Stateless Routing (GPSR) [42, 43] protocol uses greedy forwarding to constantly forward packets closer to the destination. Due to GPSR being stateless if a local maxima is formed in the network, packets will continue to follow the same path to the local maxima. Once the packets arrive at the local maxima, each packet is set to perimeter forwarding mode. Moving forward the goal is to produce a more adaptive protocol in the VANET environment, which is what the GEOADV protocols will address.

CHAPTER 3

OVERVIEW OF CLOSELY RELATED PROTOCOLS

In this chapter, we will focus on the routing protocols we used for our foundation of the GEOADV protocols.

3.1 AODV

Ad-hoc On-Demand Distance Vector (AODV) is a MANET reactive routing protocol, which operates by a hop-by-hop pattern. AODV allows for a dynamic, self-starting, multi-hop routing between all participating nodes in the network. In AODV, nodes can acquire routes rapidly for new destinations and nodes are not required maintain routes that are inactive. [23, 24, 27, 65]

In AODV, there are three message types: Route Requests (RREQs), Route Replies (RREPs) and Route Errors (RERRs). RREQ and RREP messages are used for route discovery. When and RREQ receives a broadcast query, the RREQ will record the address of the node sending the query in their routing table. This procedure is called backward learning as it records its previous hop. When the RREQ arrives at the destination, a RREP is sent back along the completed path. This is provides the source obtain route information. AODV takes part in ”backwards learning”, at each stop the node records its previous hop, therefore establishing the forward path from the source. This entire process (flooding RREQs and returning RREPs) establishes a full bidirectional path. This path will be maintained as long as the source continues using it. If the route is broken, a link failure will be reported to the source. This will trigger another RREQ in order to find a new route. [23, 24, 27, 65]

The basic protocol is shown below:

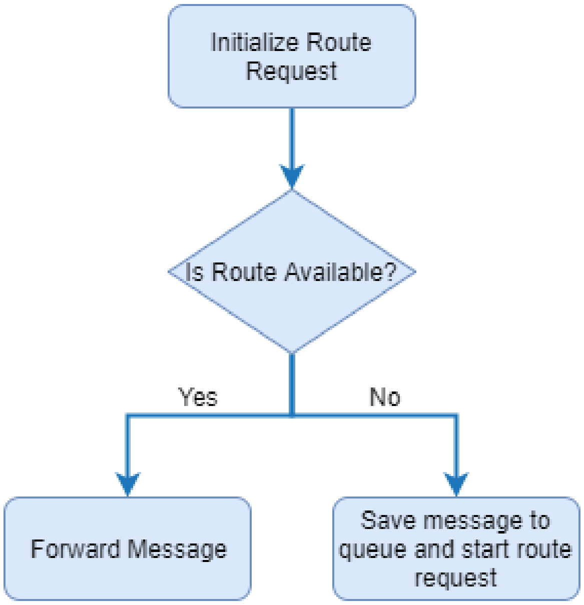


Figure 3.1: Flowchart illustrating the basic AODV Protocol

Upon receiving routing information, a node updates its routing table and sends out queued messages.

Routing table management is needed in AODV in order to avoid entries of nodes that do not exist in the route from source to destination. Destination sequence numbers are used to handle routing table information, and helps AODV maintains loop free routes, and identify the latest route to the destination. Destination sequence numbers can be applied to large networks. When a node in the network detects that a route is no longer valid for communication it will delete all the related entries from the routing table for that node. After deleting all related entries from the routing that it then sends the RREP to current active neighboring nodes that route is not valid anymore for communication. [23, 23, 24, 32]

In AODV intermediate nodes can lead to inconsistent and stale routes if the source sequence number is older and the intermediate node has a higher but not the latest destination sequence number. Also in AODV multiple RREPs in response to a single RREQs can lead to heavy control overhead. AODV is a MANET protocol and therefore does not utilize VANET features fully. [23, 23, 24, 32]

3.2 AODV-VANET

AODV-VANET is a proposed routing protocol from A Reliable Routing Protocol for VANET Communications [5]. AODV-VANET incorporates VANET features into AODV in order to improve the route discovery process. AODV was chosen as it is able to react quickly to network changes and has an effective route discovery method. AODV-VANET introduces the Total Weight of the Route (TWR) and exipiration time.

TWR is defined between the source node and destination node. [5] TWR is calculated in order to determine the best route for data packets to travel [5]. This is done by analyzing the VANET characteristics that determine whether a node will stay within communication for enough time to send all necessary data packets. VANET characteristics that affect TWR are:

- Vehicle Speed and Acceleration
- Vehicle Movement Direction
- Link Quality Between Vehicles

TWR is greatly affected the speed and acceleration of the vehicle. The greater the speed and acceleration differences between two vehicles, the greater the TWR is between the two vehicles. This is because, unlike vehicles moving at a similar speed and acceleration, they do not stay in communication range as for as long. Vehicles that move at relatively the same speed are preferable and therefore are assigned a lower TWR. [5]

The direction of the vehicle is crucial in calculating the TWR as vehicles stay in radio communication range longer if they are moving in a similar direction. [5]

The link quality factor is part of TWR's calculation as neighboring vehicles, buildings, and obstructions directly influence the link quality between vehicles. [5]

Keeping these characteristics in mind TWR can be defined by the following equation [5]:

$$TWR = \sum_{i=1}^{N} \{ f_s \times |S_{i-1} - S_i| + f_a \times |A_{i-1} - A_i| + f_d \times |D_{i-1} - D_i| + [f_q \times \frac{1}{LQ})] \}, \quad (3.1)$$

Where,

N: Number of nodes in the route.
S: Speed of the vehicle.
f_s: Speed weight factor.
A: Acceleration of the vehicle.
f_a: Acceleration weight factor.
D: Direction vector of the vehicle.
f_d: Direction weight factor.
f_q: Link quality weight factor.
LQ: Link quality between the two adjacent vehicles.

Expiration time was introduced in order to avoid link ruptures. After the route discovery process, the best route (from the source to destination) is chosen. Despite the strong connection due to using TWR a link breakage may still occurs. This can happen due to an vehicles leaving the radio communication range. In order to handle this scenario expiration time is calculated and a new route discovery process will be initiated at ΔT. [5]

AODV-VANET's route discovery is similar to AODV's. When RREQ message is initialized, the requesting node will attach its movement details into the RREQ message. TWR is initialized to zero and expiration time is set to a large number. The created RREQ is then flooded to its neighbors. If a intermediate node receives a RREQ message, the node will extract the sender's movement details to calculate the

TWR and expiration time. If the expiration time is less than the expiration time in the RREQ it will be updated. In order to calculate the new TWR, the node will query its stored memory for the link quality between the two nodes. The newly calculated TWR and expiration time is then attached to the RREQ message, as well as the nodes movement details. If the intermediate node lacks a route to the destination, it will flood its own neighboring nodes with the new RREQ message. This process will be repeated until a route is found to the destination or no such destination can be found. [5]

When a node responds to an RREQ message and has a route to the destination or the RREQ received is the destination itself, a RREP message is generated. When creating the RREP message, the TWR and expiration time is attached in the RREP message. The node will then search its routing table to find the TWR and expiration time to the destination and update the information in the RREP message. Then the RREP message will be sent to the source and the destination nodes. Thereby causing both the source and the destination nodes to receive the TWR and the expiration time of the route. [5]

In AODV-VANET has the similar negatives to AODV. In AODV-VANET intermediate nodes can lead to inconsistent and stale routes if the source sequence number is older and the intermediate node has a higher but not the latest destination sequence number. Also in AODV-VANET multiple RREPs in response to a single RREQs can lead to heavy control overhead. [5]

3.3 GPSR

Greedy Perimeter Stateless Routing (GPSR) is a geographic MANET protocol which uses greedy forwarding to constantly forward packets closer to the destination. GPSR, assumes vehicles are equipped with a Global Positioning System (GPS) device or other location services to get their own geographical information. Intermittent

Hello Packets are exchanged between nearby vehicles to learn locations of their one-hop neighbors. This information is kept in the header of the transmitted packet. Therefore, the forwarding process can follow a greedy scheme to select the next forwarding node that is closer to the destination than any other neighbor [42, 43]. A flowchart for GPSR routing protocol is shown in Figure 3.2.

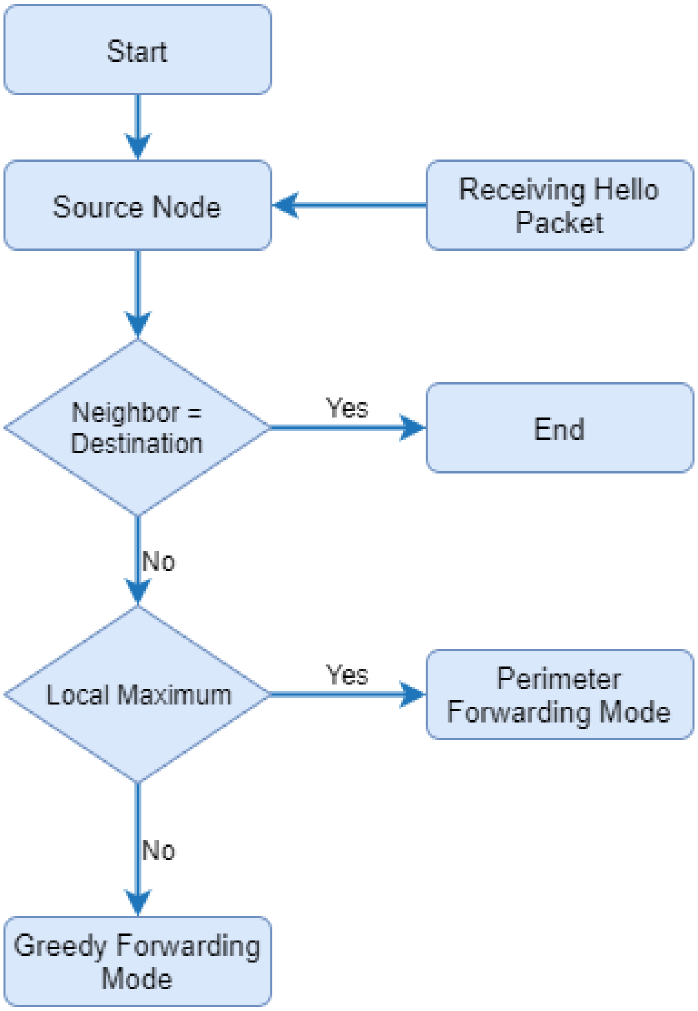


Figure 3.2: Flowchart illustrating the basic GPSR Protocol

GPSR is stateless and this normally provides several advantages. In order to forward the packet, the node only needs to remember one hop neighbor location. Forwarding packet decisions are made dynamically. [42, 43]

For high mobility characteristics of the node, stale information of neighbors position are often in the sending node's neighbor table. The destination nodes information in the packet header of the intermediate node is never updated, which causes issues if the destination node is moving. Due to GPSR being stateless if a local maxima is formed in the network, packets will continue to follow the same path to the local maxima. Once the packets arrive at the local maxima, each packet is set to perimeter forwarding mode. In the perimeter forwarding mode, once the packet arrives at a location closer than where greedy forwarding failed, the packet will switch back to greedy forwarding mode and continue routing to the destination [43].

3.4 SUMMARY

A detailed review of AODV, AODV-VANET, and GPSR was conducted in this Chapter. These routing protocols were reviewed as they are the base of our GEOADV protocols to be reviewed in later chapters. AODV is a MANET reactive routing protocol, which operates by a hop-by-hop pattern. AODV allows for a dynamic, self-starting, multi hop routing between participating mobile nodes [23,24,27,65]. AODV-VANET incorporates VANET features into AODV's route discovery process [5]. GPSR is a MANET protocol which uses greedy forwarding in order to forward packets progressively closer to the destination [42, 43]. These protocols have many positives but are not adaptive in both urban and highway environments. AODV and GPSR are routing protocols designed for MANET, and therefore do not utilize VANET features. AODV-VANET [5] is design only for urban environments and intermediate nodes can lead to inconsistent routes due to stale entries. Due to GPSR's stateless nature, which generally provides many advantages, local maxima can forms in the network. If a local maxima is formed in the network, packets will continue to follow the same path to the local maxima. Once the packets arrive at the local maxima, the forwarding mode of each packet is set to perimeter forwarding. By incorporating the positives of these protocols a more adaptive protocol for VANET can be produced.

CHAPTER 4

GEOADV AND GEOADV-P ROUTING PROTOCOLS

Although routing protocols, such as GPSR and AODV-VANET, work well in city environments they are not adaptive in sparse, rural, or highway environments. AODV-VANET [5] incorporates VANET features into AODV's route discovery process but is design only for urban environments and intermediate nodes can lead to inconsistent routes due to stale entries. Due to GPSR being stateless if a local maxima is formed in the network, packets will continue to follow the same path to the local maxima. Once the packets arrive at the local maxima, the forwarding mode of each packet is set to perimeter forwarding [42,43]. GEOADV and GEOADV-P are hybrid protocols, which combine both geographic and reactive routing in order to be adaptive in varying environments.

4.1 GEOADV ROUTING PROTOCOL

Geographic Ad-hoc On-Demand Distance Vector (GEOADV) combines our modified AODV protocol, AODV-WR, with our modified GPSR protocol, GPSR-WR. AODV-WR is the base AODV protocol augmented with the calculation of total weight of the route (TWR). AODV-WR is based off of AODV-VANET [5] however instead of just reporting broken routes, intermediate nodes can repair broken routes.

4.1.1 Total Weight of the Route

In GEOADV, the total weight of the route (TWR) is determined between the source and destination nodes. TWR, based on [5], is calculated in order to determine the best route for data packets to travel [5, 64]. This is done by analyzing the VANET characteristics that determine whether a node will stay in communication for enough time to send all necessary data packets. The VANET characteristics that affect TWR are:

- Vehicle Speed and Acceleration
- Vehicle Movement Direction
- Link Quality Between Vehicles

TWR is greatly affected by the vehicle speed and acceleration. The greater the difference in speed and acceleration between two vehicles, the greater the TWR will be. This is because the vehicles will not stay in communication as long as vehicles that are moving at comparatively the same speed and acceleration. Vehicles that move at relatively the same speed and acceleration are desired more and are assigned a lower TWR. IN GEOADV the best route is the route with the least TWR. This route will consist of vehicles choosing next-hop nodes that have closest speed and acceleration. [5,64]

The vehicle movement direction is crucial in calculating the TWR as vehicles stay in radio communication range longer if they are moving in a similar direction. [5,64]

Link quality between vehicles in the route to the destination, is another parameter to be considered in calculating the TWR. Numerous factors such as neighboring vehicles, buildings, and obstructions can influence link quality. The full TWR equation is illustrated in Equation 4.1 [5,64].

$$TWR = \sum_{i=1}^{N}\{f_s \times |S_{i-1} - S_i| + f_a \times |A_{i-1} - A_i| + f_d \times |D_{i-1} - D_i| + f_q \times \frac{1}{LQ}\}, \tag{4.1}$$

Where,

N: Number of nodes in the route.

S: Speed of the vehicle.

f_s: Speed weight factor.

A: Acceleration of the vehicle.

f_a: Acceleration weight factor.

D: Direction vector of the vehicle.

f_d: Direction weight factor.

f_q: Link quality weight factor.

LQ: Link quality between the two adjacent vehicles.

4.1.2 Expiration Time

The expiration time T is calculated the help avoid link breakage and establish a more reliable route. T does this by determining when to initiating the route discovery process at ΔT. The calculate of expiration time is illustrated in Equation 4.2 [64,67]. In Equation 4.2, v_i and v_j represent the velocities of the current and previous nodes respectively. θ_i and θ_j are the angles of the current and previous nodes. $(x_i,\, y_i)$ and $(y_j,\, y_j)$ are the coordinates of both nodes.

$$T = \frac{-(ab+cd)+\sqrt{(a^2+c^2)R^2-(ad-bc)^2}}{a^2+c^2}, \tag{4.2}$$

Where,

$a = v_i \cos\theta_i - v_j \cos\theta_j$

$b = x_i - x_j$

$c = v_i \sin\theta_i - v_j \sin\theta_j$

$d = y_i - y_j$

The expiration time is set in the header by the source node and is updated each time a node contains a lower expiration time. By doing this we are able to avoid unnecessary flooding of the whole network. [64, 67]

4.1.3 Greedy Forwarding

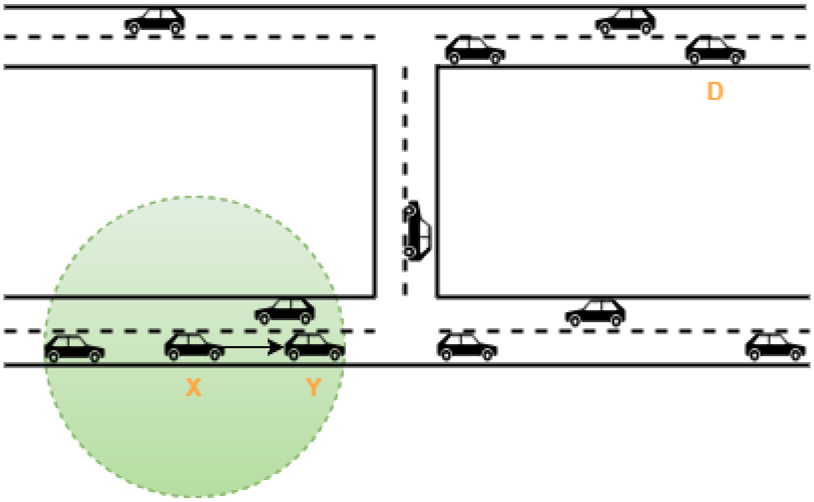


Figure 4.1: GEOADV-P Greedy forwarding example

GEOADV uses greedy forwarding when passing a message. An example of GEOADV greedy forward is shown in Figure 4.1.3. In this example X receives a packet bound for D. X's radio range is shown as then green circle around X. In greedy forwarding, X will forward the packet to Y. This is because the distance between Y and D is less than any of X's other neighbors.

4.1.4 Route Discovery

```
if Source has no route to Destination then
    TWR = 0;
    Expiration time = 10000;
    Create RREQ;
    if Has node in one hop range then
        Forward Node;
    else
        Flood neighbors with RREQ;
    end
else
    Forward Data;
end
```

Figure 4.2: GEOADV Initial Route Request (RREQ) Handling

```
if Node is destination then
    if First Received then
        Respond with RREP;
    else
        if Contains higher source sequence then
            Respond with RREP;
        else
            if TWR less than current TWR then
                Respond with RREP;
            end
        end
    end
else
    Update Expiration Time;
    Update TWR;
    if Has node in one hop range then
        Forward Node;
    else
        Flood neighbors with RREQ;
    end
end
```

Figure 4.3: GEOADV Route Request (RREQ) Handling

GEOADV initiates the route discovery process similar to a greedy forwarding process. If the source node does not have a route to the destination node a RREQ is created. This algorithm is shown in Figure 4.2. Initially, when the RREQ message is created, the requesting node will place its details (position, speed, acceleration, and direction) in the RREQ message. The TWR is initialized to zero and the expiration time is set to a large number. Also in the RREQ is the the coordinates of the destination node. After the RREQ is created it searches the neighbors table within its one hop communication range to find the node which is nearest to the destination node. Then the GEOADV protocol takes this node as the next forwarding node and the RREQ packet is forwarded to that node. If, within the one hop range, there are no neighboring nodes that are closer to the destination node than the source node, AODV-WR will be switched on and the RREQ packet will be flooded to all neighboring nodes. This process will be repeated until the RREQ reaches the destination node. Thereupon, the destination node will reply with a route-reply (RREP) packet to the source node. This algorithm is shown in Figure 21. [64]

4.1.5 Route Reply

In GEOADV, when a RREQ packet arrives at the destination node, the destination node only responds with a RREP packet in three cases:

1. This is the first time the destination node has received a RREQ packet from the identified source node.
2. The destination node has received a RREQ packet from the identified source node, but the RREQ has a higher source sequence number.
3. The destination node has received a RREQ packet from the identified source node, and the RREQ has the same source sequence number, but the RREQ has a better (lower) TWR.

4.1.6 Route Repair

In GEOADV, intermediate nodes participate in transferring data in order to repair routes locally. When a broken link is recognized by a node, the node will buffer the received data packets for the destination, and then look up its neighbor node table to attempt to find a neighbors closer to the destination node. If a closer neighbor node exist, the routing table will be updated and the data packets will be forwarded to that node. If there is not a closer neighbor node, a route repair packet (RRP) will be created by the node and the network will be flooded. If a neighboring nodes receives a RRP packet the node will look in its routing table, to see if it has a route to the destination node. If a neighboring node has a route,it will reply with a route repair reply packet (RRRP) to the intermediate node. If a neighboring node does not have a route, it investigates in its own neighbor node table for a node closer to the destination. If there is a node closer to the destination, the neighboring node will reply with a RRRP packet to the intermediate node. Otherwise, the neighboring node will flood the RRP packet to all its neighboring nodes.

Since request are flooded in the network, the intermediate node can receive more than one RRRP packet. The node will first use the route given by the first received RRRP packet until a route with a lower (better) TWR is received. If the route fails to be repaired location, the intermediate now will send a Route Error (RERR) packet to the source node.

4.2 GEOADV-P ROUTING PROTOCOL

GEOADV-P is an enhancement of the GEOADV protocol. GEOADV-P uses predictive elements with its already existing is a hybrid routing. In GEOADV-P, the calculation of the predicted total weight of the route (PTWR) is used. The GEOADV-P flowchart can be seen in Figure 4.2.

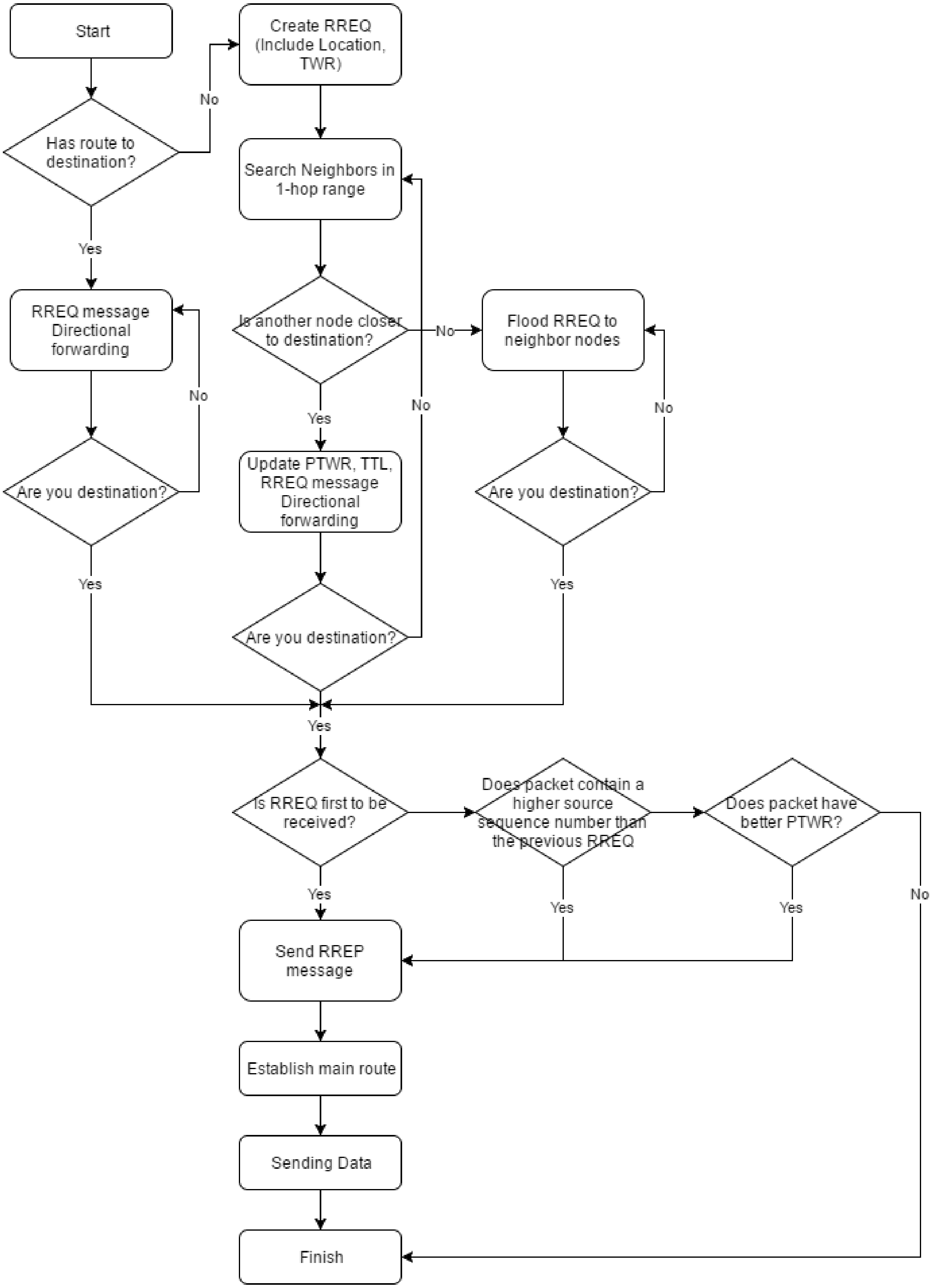


Figure 4.4: GEOADV-P Flow Chart

4.2.1 Predicted Total Weight of the Route

In GEOADV-P, predicted total weight of the route (PTWR) is determined between the source and destination nodes, and is based on TWR [5,64]. PTWR is calculated in order to determine the best route for data packets to travel. This is done by analyzing the VANET characteristics that determine whether a node will stay in communication for enough time to send all necessary data packets. The VANET characteristics that affect PTWR are:

- Vehicle Speed and Acceleration
- Predicted Vehicle Speed
- Vehicle Movement Direction
- Link Quality Between Vehicles

PTWR, based on [5], is greatly affected by the vehicle speed and acceleration. The greater the difference in speed and acceleration between two vehicles accounts for a greater PTWR between the two vehicles. This is because they do not stay in communication range as long as vehicles that are move at comparatively the same velocity and acceleration. Vehicles that move at relatively the same speed and acceleration are desired more and are assigned a lower PTWR. IN GEOADV-P the best route is the route with the least PTWR. This route will consist of vehicles choosing next-hop nodes that have closest speed and acceleration [5, 64]. Therefore predicted speed of the vehicle is an important factor for PTWR. The predicted speed is based off of the current vehicles speed and acceleration, the equation to calculate it can be seen in (4.3).

$$S_p = S + t \times A \tag{4.3}$$

Where,

S: Speed of the vehicle.
S_p: Predicted speed of the vehicle.
A: Acceleration of the vehicle.
t: Period of Time

TWR is greatly affected by the vehicle speed and acceleration. The greater the difference in speed and acceleration between two vehicles, the greater the TWR will be. This is because the vehicles will not stay in communication as long as vehicles that are moving at comparatively the same speed and acceleration. Vehicles that move at relatively the same speed and acceleration are desired more and are assigned a lower TWR. In GEOADV-P the best route is the route with the least TWR. This route will consist of vehicles choosing next-hop nodes that have closest speed and acceleration. [5, 64]

The vehicle movement direction is crucial in calculating the TWR as vehicles stay in radio communication range longer if they are moving in a similar direction. [5, 64]

Link quality between vehicles in the route to the destination, is another parameter to be considered in calculating the PTWR. Numerous factors such as neighboring vehicles, buildings, and obstructions can influence link quality. [5, 64].

The full PTWR equation is illustrated in (4.4) [5, 64].

$$PTWR = \sum_{i=1}^{N} \{ f_s \times |(S_{p-1} - S_p)| + f_a \times |A_{i-1} - A_i| + f_d \times |D_{i-1} - D_i| + f_q \times \frac{1}{LQ} \},$$

Where,

N: Number of nodes in the route.

S: Speed of the vehicle.

S_p: Predicted speed of the vehicle.

f_s: Speed weight factor.

A: Acceleration of the vehicle.

f_a: Acceleration weight factor.

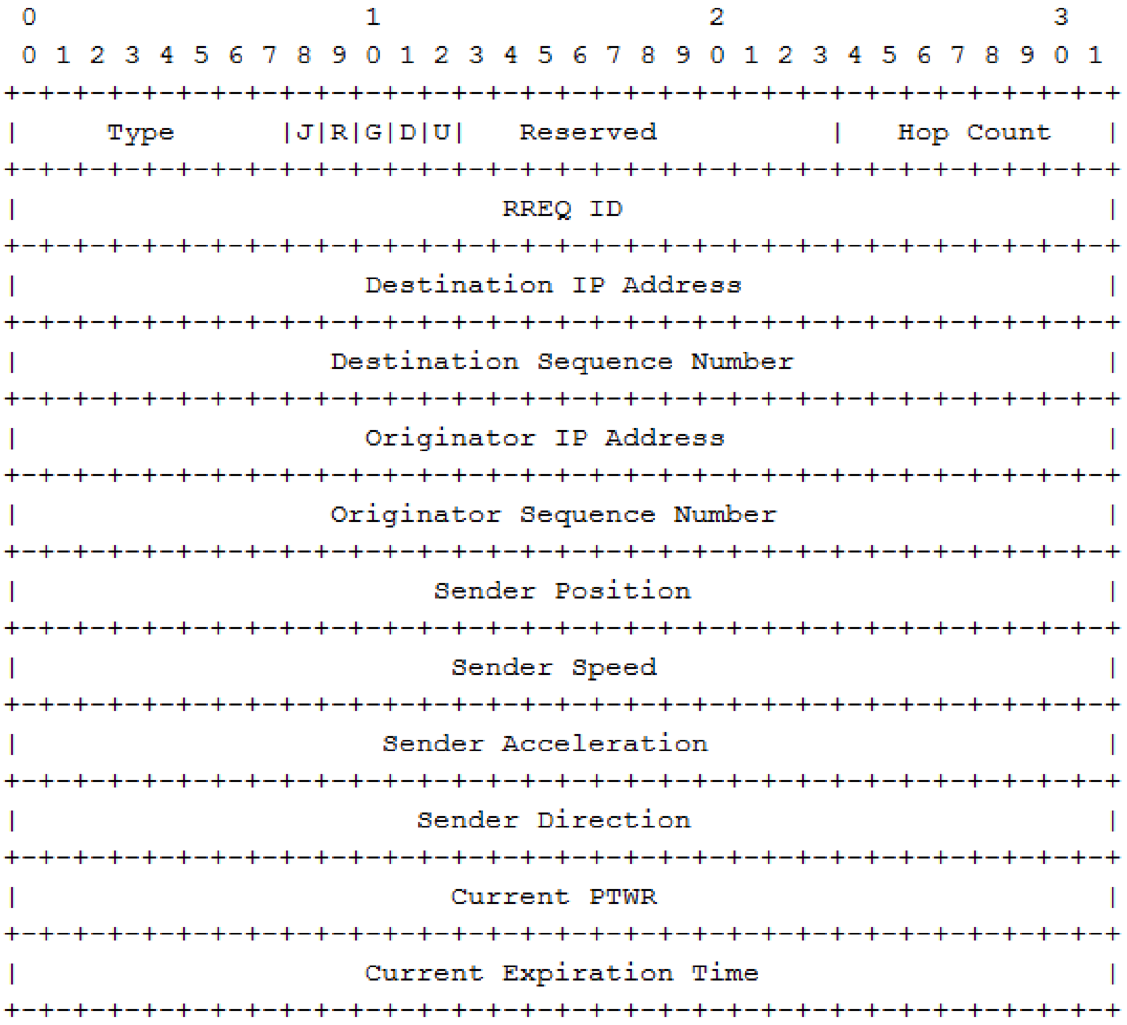
D: Direction vector of the vehicle.

f_d: Direction weight factor.

f_q: Link quality weight factor.

LQ: Link quality between the two adjacent vehicles.

4.2.2 Route Discovery



```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |J|R|G|D|U|   Reserved          |   Hop Count   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                            RREQ ID                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Destination IP Address                     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Destination Sequence Number                  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Originator IP Address                      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Originator Sequence Number                   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Sender Position                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         Sender Speed                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      Sender Acceleration                      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Sender Direction                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         Current PTWR                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Current Expiration Time                    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 4.5: RREQ Message Contents

GEOADV-P initiates the route discovery process similarly to greedy forwarding and GEOADV, described in Section 4.1.3 and Section 4.1.4 respectively. In GEOADV-P if the source node does not have a route to the destination node a RREQ is created. The contents of the RREQ packet is shown in Figure 4.5. RREQ packet contains: the source nodes movement detail (position, speed, acceleration, and direction), the PTWR initialized to zero and the expiration time is set to a large number, the location and coordinates of both the source node and the destination node. After the RREQ is created it searches the neighbors table within its one hop communication range to find the node which is nearest to the destination node. If within the one hop range there are no neighboring nodes closer to the destination node, AODV-WR will be switched on and the RREQ packet is flooded to all neighboring nodes. This process will be repeated until the RREQ reaches the destination node. Thereupon, the destination node will reply with a route-reply (RREP) packet to the source node.

4.2.3 Route Reply

GEOADV-P route reply logic is similar to GEOADV's, see Section 4.1.5. In GEOADV-P, when a RREQ packet arrives at the destination node, the destination node only responds to a RREP packet in three cases:

1. This is the first time the destination node has received a RREQ packet from the identified source node.
2. The destination node has received a RREQ packet from the identified source node, but the RREQ has a higher source sequence number.
3. The destination node has received a RREQ packet from the identified source node, and the RREQ has the same source sequence number, but the RREQ has a better (lower) PTWR.

4.2.4 Route Repair

Like GEOADV's, GEOADV-P's intermediate nodes participate in transferring data in order to repair routes locally. When a broken link is recognized by a node, the node will buffer the received data packets for the destination, and then look up its neighbor node table to attempt to find a neighbors closer to the destination node. If a closer neighbor node exist, the routing table will be updated and the data packets will be forwarded to that node. If there is not a closer neighbor node, a route repair packet (RRP) will be created by the node and the network will be flooded. If a neighboring nodes receives a RRP packet the node will look in its routing table, to see if it has a route to the destination node. If a neighboring node has a route,it will reply with a route repair reply packet (RRRP) to the intermediate node. If a neighboring node does not have a route, it investigates in its own neighbor node table for a node closer to the destination. If there is a node closer to the destination, the neighboring node will reply with a RRRP packet to the intermediate node. Otherwise, the neighboring node will flood the RRP packet to all its neighboring nodes.

Since request are flooded in the network, the intermediate node can receive more than one RRRP packet. The node will first use the route given by the first received RRRP packet until a route with a lower (better) PTWR is received. If the route fails to be repaired location, the intermediate now will send a RERR packet to the source node.

4.3 SUMMARY

In this chapter the proposed protocols GEOADV and GEOADV-P were reviewed. Although routing protocols like GPSR and AODV-VANET work well in city environments they are not adaptive in sparse, rural, or highway environments. GEOADV is a hybrid geographic routing protocol, was proposed to address the concern how protocols are not adaptive for different VANET environments. GEOADV-P, and enhancement of GEOADV, is a predictive hybrid protocol which was also introduced to address the lack of adaptability in current protocols. GEOADV and GEOADV-P combine both geographic and reactive routing. In chapter 5 the performance of both GEOADV and GEOADV-P protocols will be analyzed.

CHAPTER 5

GEOADV AND GEOADV-P PERFORMANCE RESULTS

In this chapter, GEOADV and GEOADV-P performances will be demonstrated. These protocols will address the need for an adaptive routing protocol in VANET environments. GEOADV and GEOADV-P's adaptive performance will be demonstrated in a highway environment, and an urban environment. GEOADV and GEOADV-P has the smallest consistent average delays and outperforms all other protocols in average delivery ratio. GEOADV-P is showing to be an adaptive protocol in the VANET environment. It was observed that GEOADV-P's average delay remains less than one second, and even in increased density is more stable, GEOADV-P outperforms AODV, GSPR, AODV-WR, GSPR-WR, AODV-PWR, and GSPR-PWR.

5.1 PERFORMANCE EVALUATION

5.1.1 Tools and Techniques Used

All simulations were done using OMNET++, SUMO and Veins. OMNeT++ [68] is an open source, C++ based event simulator. OMNET++ can be used to simulate communication networks and parallel systems [68]. SUMO (Simulation of Urban Mobility) [69] handles large road networks and simulates micro and macroscopic mobility models. SUMO can import and edit street maps from OpenStreetMap [70] database. SUMO uses a collision-free car-following model in order to determine positions and speed levels of the vehicles [69]. Veins [71, 72] is an open source simulation framework for Inter-Vehicular Communication (IVC). Veins is composed of an event-based network simulator and a road traffic microsimulation model [71,72].

5.1.2 Evaluation Methodology

The performances of GEOADV and GEOADV-P are compared against representatives from the main classes of routing protocols and proposed VANET protocols.

- AODV [24] a MANET reactive routing protocol
- GPSR [42] a MANET geographical routing protocol
- AODV-WR our AODV based protocol that uses VANET movements and the calculation of TWR
- GPSR-WR our GPSR based protocol that uses VANET movements and the calculation of TWR

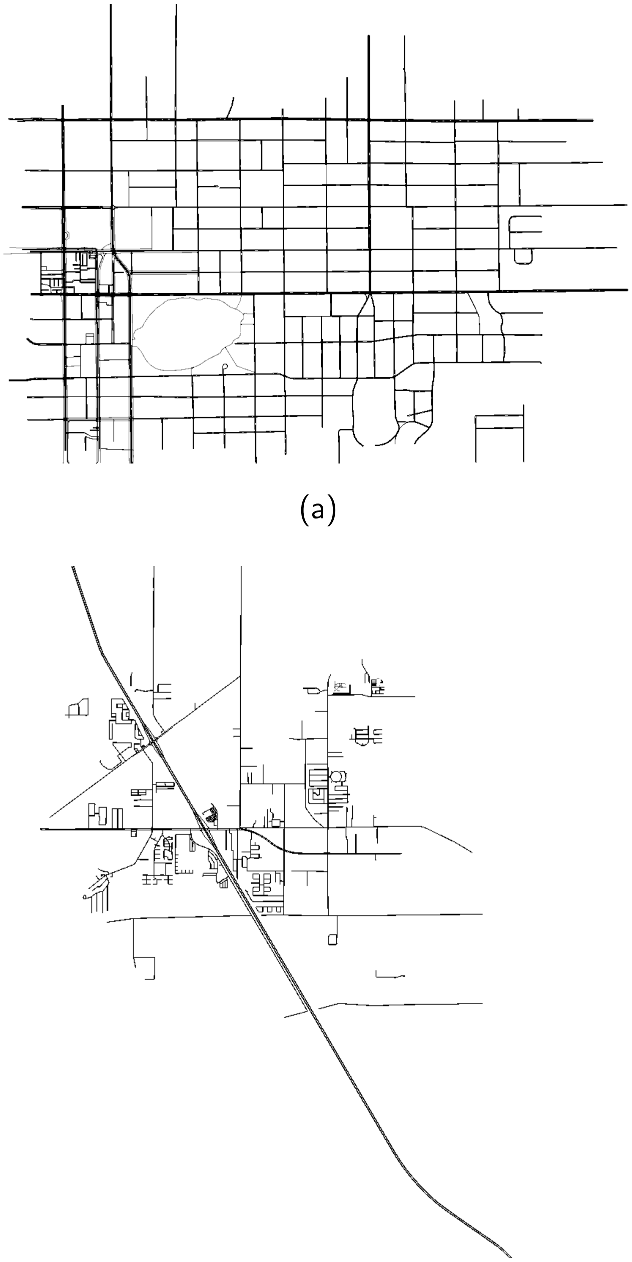
5.1.3 Metrics

The performance of the GEOADV and GEOADV-P routing protocols was evaluated by varying constant bit rate (CBR), data rates, network densities, and concurrent UDP flows. The metrics used to evaluate the performance are as follows:

- Average delivery ratio
- Average delay

5.2 SIMULATION RESULTS

Urban and highway simulations were performed to compare the GEOADV-P against, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV. Figures 5.1a and 5.1b show the maps used for the urban and highway simulations. Figure 5.1a which is the map for the urban scenario, this is a portion of downtown Orlando, Florida. Figure 5.1b is the map of the highway scenario, this is a portion of I95 in Florida.



(a)

(b)

Figure 5.1: Simulation Maps for urban and highway scenarios (a) Part of Downtown Orlando, FL (b) Stretch of Highway on I95 in Florida

For both urban and highway simulations the map was extracted from OpenStreetMap [70] database. SUMO [69] was used to generate the movements of the vehicle nodes. Maps extracted from OpenStreetMap were inputted into SUMO and the particulars where set for speeds limits and the number of lanes for the roads in the extracted map. Traffic-light-operated intersections and priority intersections for the extracted maps were specified. The first 1000 seconds of the SUMO output were discarded in order to obtain more accurate information on vehicular movements. The resulting output from SUMO, was then converted into input files for the OMNeT++ Simulation.

For the wireless configuration, IEEE 802.11p with DCF standard at the MAC layer was used. IEEE 802.11p and IEEE 1609.x are called wireless access in vehicular environments (WAVE) standards because their goal is to facilitate the provision of wireless access in vehicle environments [73, 74, 75, 76, 77]. At the physical layer, in order to characterize physical dissemination a shadowing propagation model was used. The communication range was set at 400m and had 80% probability of success for transmissions. These values were based off of Nzouonta's [63] simulation which used studies that reported real-life measurements between moving vehicles in the range 450-550m [78].

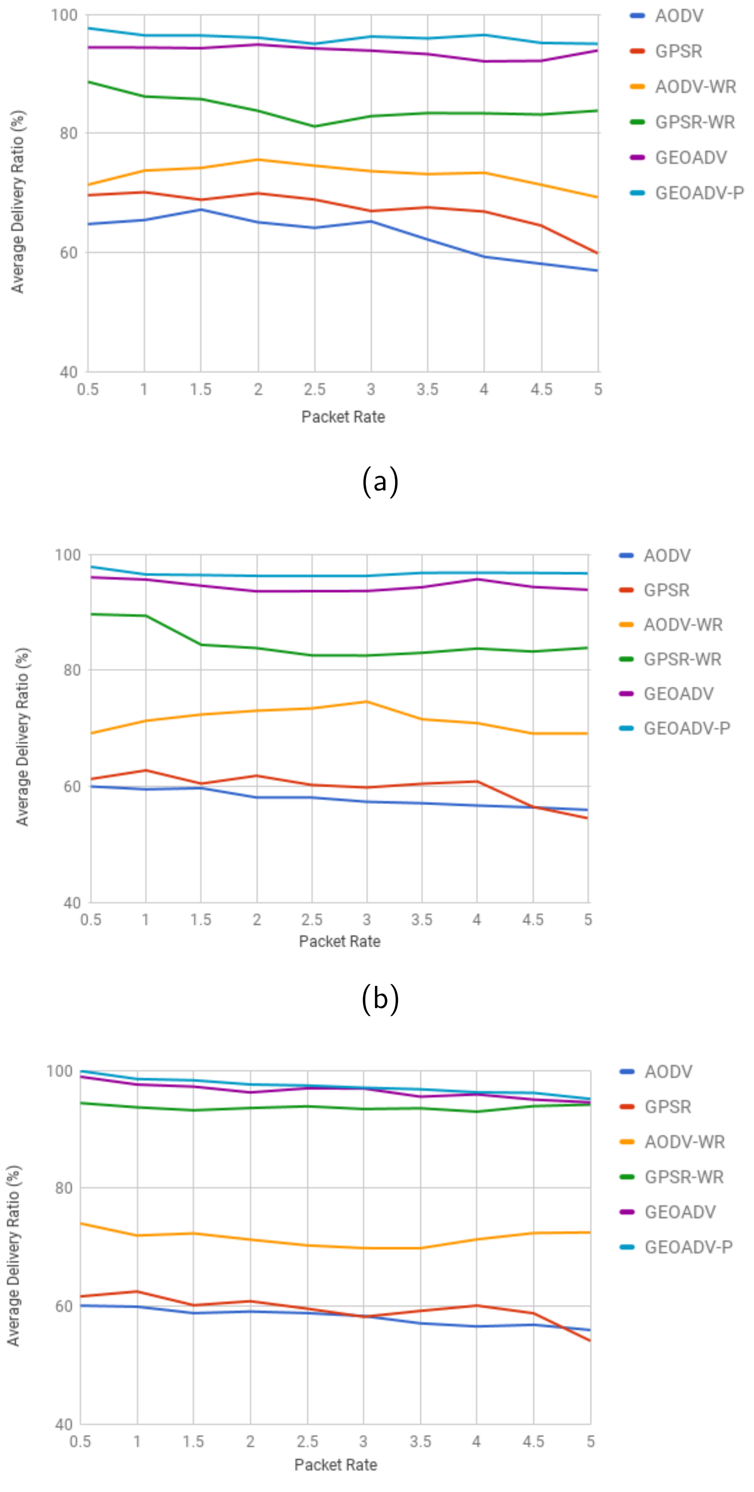
The simulation time for each protocol simulation was 600 seconds. Three simulations for each protocol were done, one with 200 vehicles (low density), another with 400 vehicles (medium density), and the last one with 600 vehicles (high density). This is to illustrate how traffic effects each protocol, and how the protocol is able to adapt. The simulation parameters are summarized in Table 5.1.

Table 5.1: GEOADV-P Simulation Setup

Parameters	**Values**
Number of Vehicles	200, 400, 600
Transmission Range	400m
Simulation Time	600s
Bitrate	18 mbps
MAC Protocol	IEEE 802.11p
Data Packet Size	512 bytes

5.2.1 Average delivery ratio

The average delivery ratio represents number of data packets successfully received over the total number of data packets sent. All duplicate packets which were generated by the loss of acknowledgments at the MAC layer were excluded. The average delivery ratio illustrates a routing protocol's ability to transfer data successfully end-to-end. In Figures 5.2 and 5.3 GEOADV-P and GEOADV are shown to have the most stable performances amongst all the protocols simulated throughout all densities, having the highest average delivery ratio.

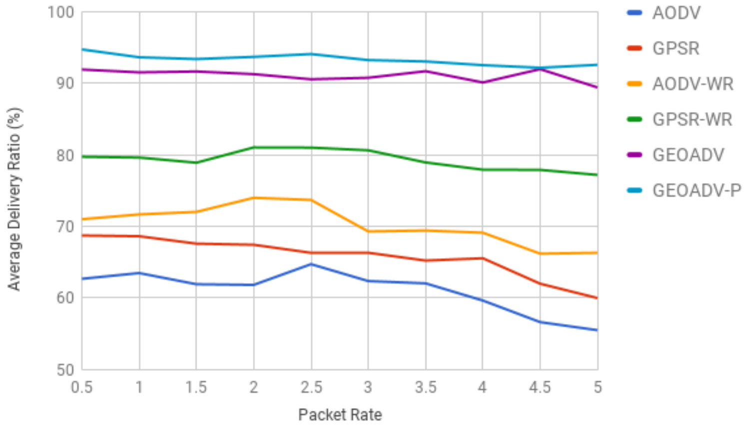


(a)

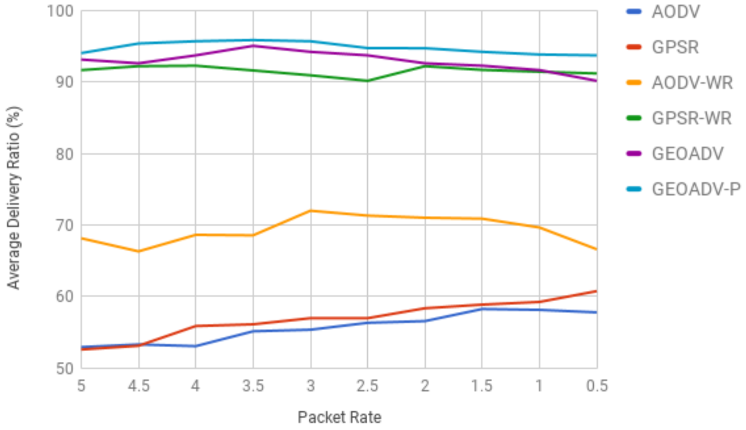
(b)

(c)

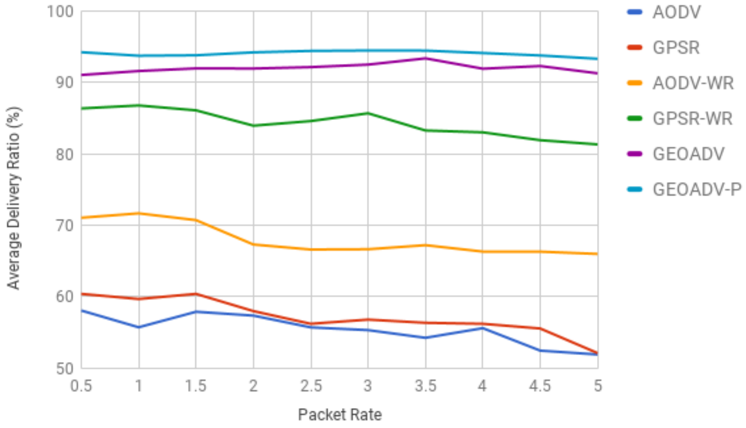
Figure 5.2: Urban Simulation Average Delivery Ratio for GEOADV-P, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV with (a) 200 vehicles, (b) 400 vehicles, (c) 600 vehicles



(a)



(b)



(c)

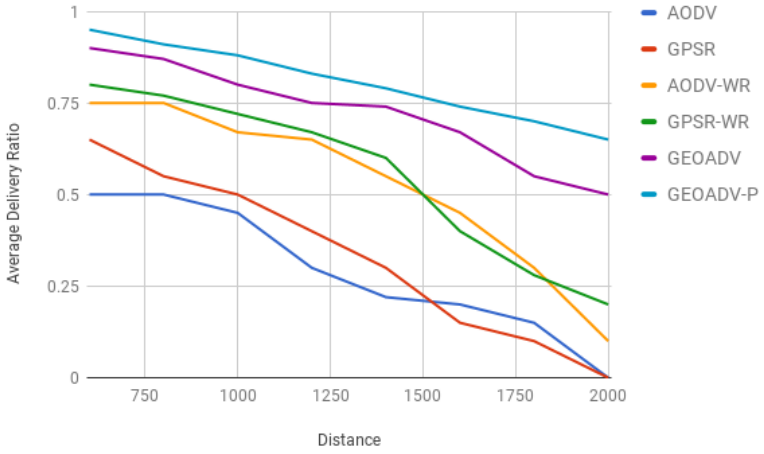
Figure 5.3: Highway Simulation Average Delivery Ratio for GEOADV-P, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV with (a) 200 vehicles, (a) 400 vehicles, (a) 600 vehicles

In the urban simulations, shown in Figure 5.2, GEOADV-P and GEOADV outperforms the other protocols. GEOADV-P's average delivery ratio is about 40% higher compared to AODV's. GEOADV shows to perform with a high average delivery ratio in denser networks than in sparser networks where as in GEOADV-P network density is insignificant, which can be seen in Figures 5.2a (low density) and 5.2c (high density).

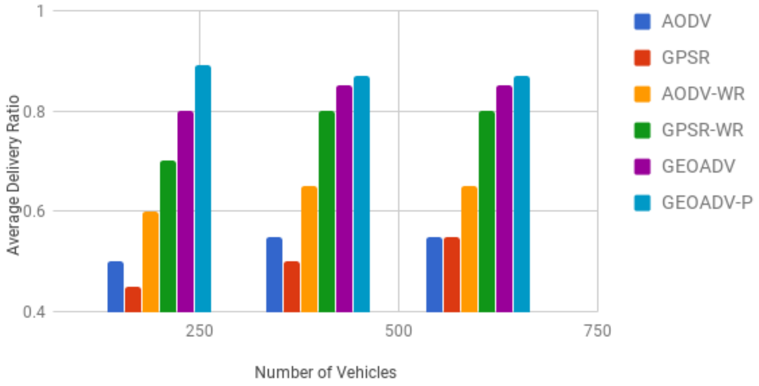
In the highway simulations, shown in Figure 5.3, GEOADV-P and GEOADV outperforms the other protocols as well. It can be observed like in the urban simulation that GEOADV performs better in dense networks than in sparse networks where as in GEOADV-P network density is insignificant, this can be seen in Figures 5.2a (low density) and 5.2c (high density). Other cases will need to be performed in order to access what has been observed.

Across the network densities, it can be observed that the delivery ratio of GPSR-WR, GEOADV, GEOADV-P increases as the network becomes denser. This is because these protocols integrate road layouts. AODV-WR stabilizes as the networks become denser. GEOADV-P, GEOADV, GPSR-WR, and AODV-WR uses real-time knowledge of the vehicular traffic on the roads which helps them perform more efficiently. GPSR-WR performs better in medium and dense networks than in sparser networks. This is caused by network partitions preventing full coverage of the map and therefore there is a limited amount of information gathered by the protocol's beacons. This does not show to be as much as an issue with GEOADV or GEOADV-P because of both the route repair and when items are not within a one-hop range AODV-WR is initiated. This helps GEOADV and GEOADV-P be more adaptive than GPSR-WR in sparser networks. The addition of the predictive elements causes GEOADV-P route repair to be even more accurate.

GPSR's poor performance in the urban scenarios is because city roads have irregularities such as dead-end streets and therefore the shortest Euclidean distance is not always equivalent to the shortest path. Another contributing factor to GPSR performance is because the protocol is stateless. Although the has many advantages one negative is if a local maxima forms in the network, because of the stateless nature of GPSR, stale entries. Due to GPSR being stateless if a local maxima is formed in the network, packets will continue to follow the same path to the local maxima. Once the packets arrive at the local maxima, the forwarding mode of each packet is set to perimeter forwarding [42, 43]. This does not happen with AODV and AODV-WR were both protocols can perform local repair or send a route error notification to the source node.



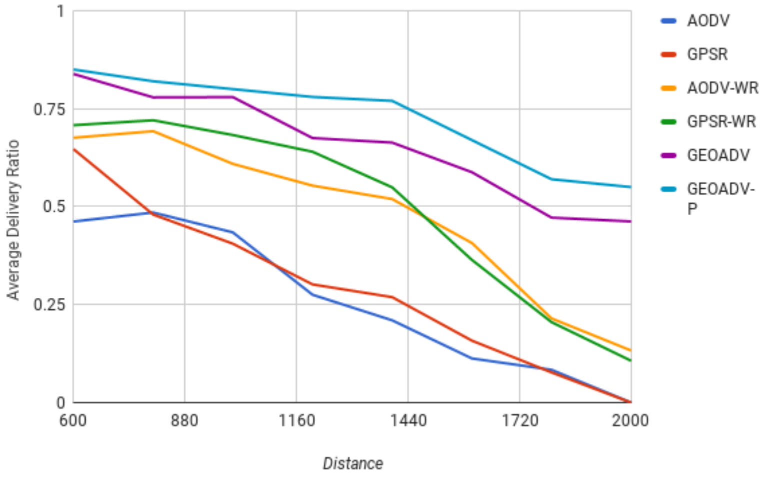
(a)



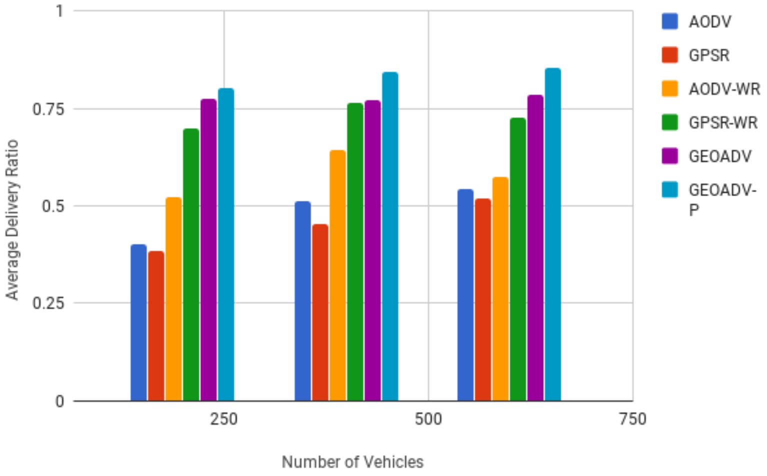
(b)

Figure 5.4: Urban Simulation for GEOADV-P, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV (a) shows average delivery ratio by Vehicle Distance, (b) shows average delivery ratio by Number of Vehicles (Density)

The average delivery ratio over distance is shown in Figure 5.4a. It can be seen that GEOADV-P degrade in the average delivery ratio over distance is significantly less than other protocols, and the average delivery ratio stays above 0.65 for long distance and at density the average delivery ratio above 0.87. Figure 5.4b shows the average delivery ratio in low density (200 vehicles), medium density (400 vehicles), and high density (600 vehicles) networks. GEOADV-P performs almost consistently in all types of networks (low densities being its worst performance).



(a)



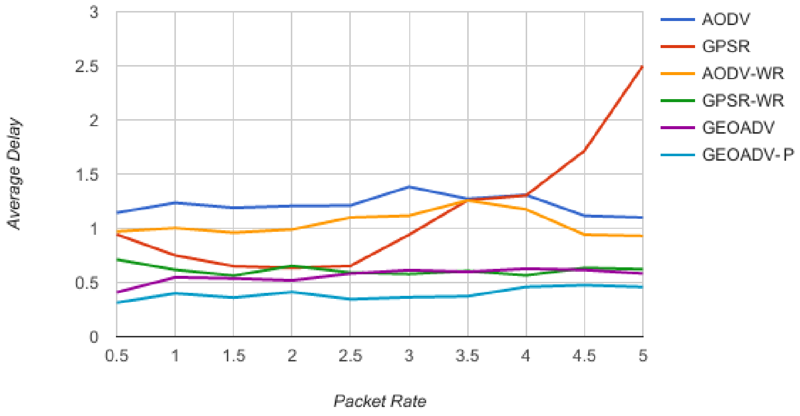
(b)

Figure 5.5: Highway Simulation for GEOADV-P, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV (a) shows average delivery ratio by Vehicle Distance, (b) shows average delivery ratio by Number of Vehicles (Density)

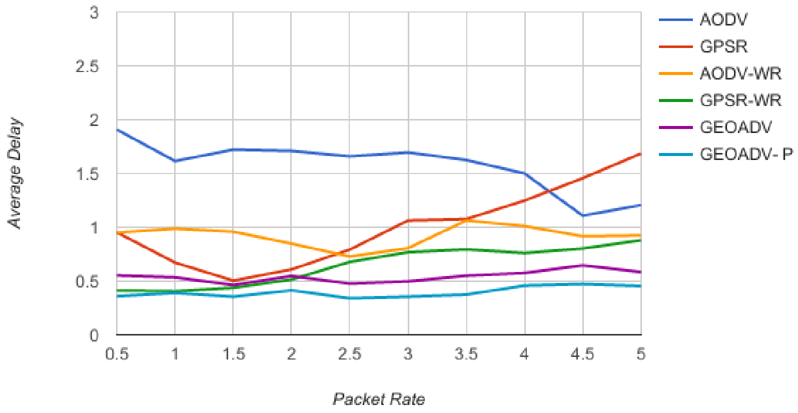
In Figure 5.5a it can be seen that GEOADV-P degrade in average delivery ratio over distance for highway environments is significantly less than other protocols, and the average delivery ratio stays above 0.55 for long distance and at density the average delivery ratio stays above 0.80. Figure 5.5b shows the average delivery ratio in low density (200 vehicles), medium density (400 vehicles), and high density (600 vehicles) networks. GEOADV and GEOADV-P perform almost consistently in all types of networks (low densities being its worst performance). GEOADV performs worst than GEOADV-P in lower density networks showing GEOADV-P to be more stable in lower density networks than GEOADV.

5.2.2 Average delay

The above figures show GEOADV and GEOADV-P have the smallest consistent average delay amongst the protocols in the urban and highway scenarios. Average delay shows the latency created by the routing protocol. Average delay is the computed by acquiring transmissions of all data packets delivered successfully.



(a)



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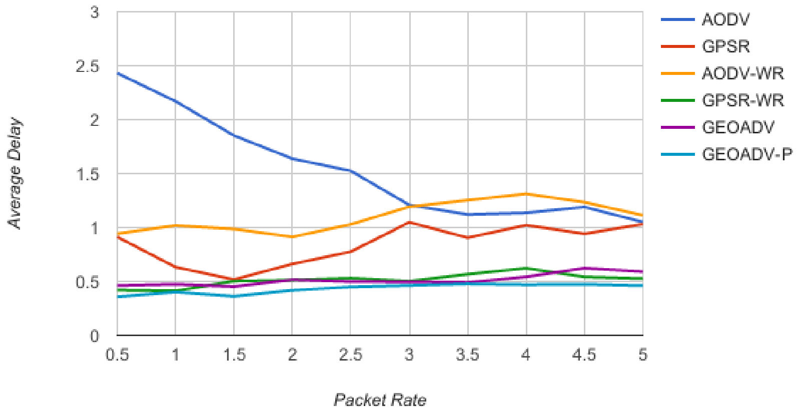
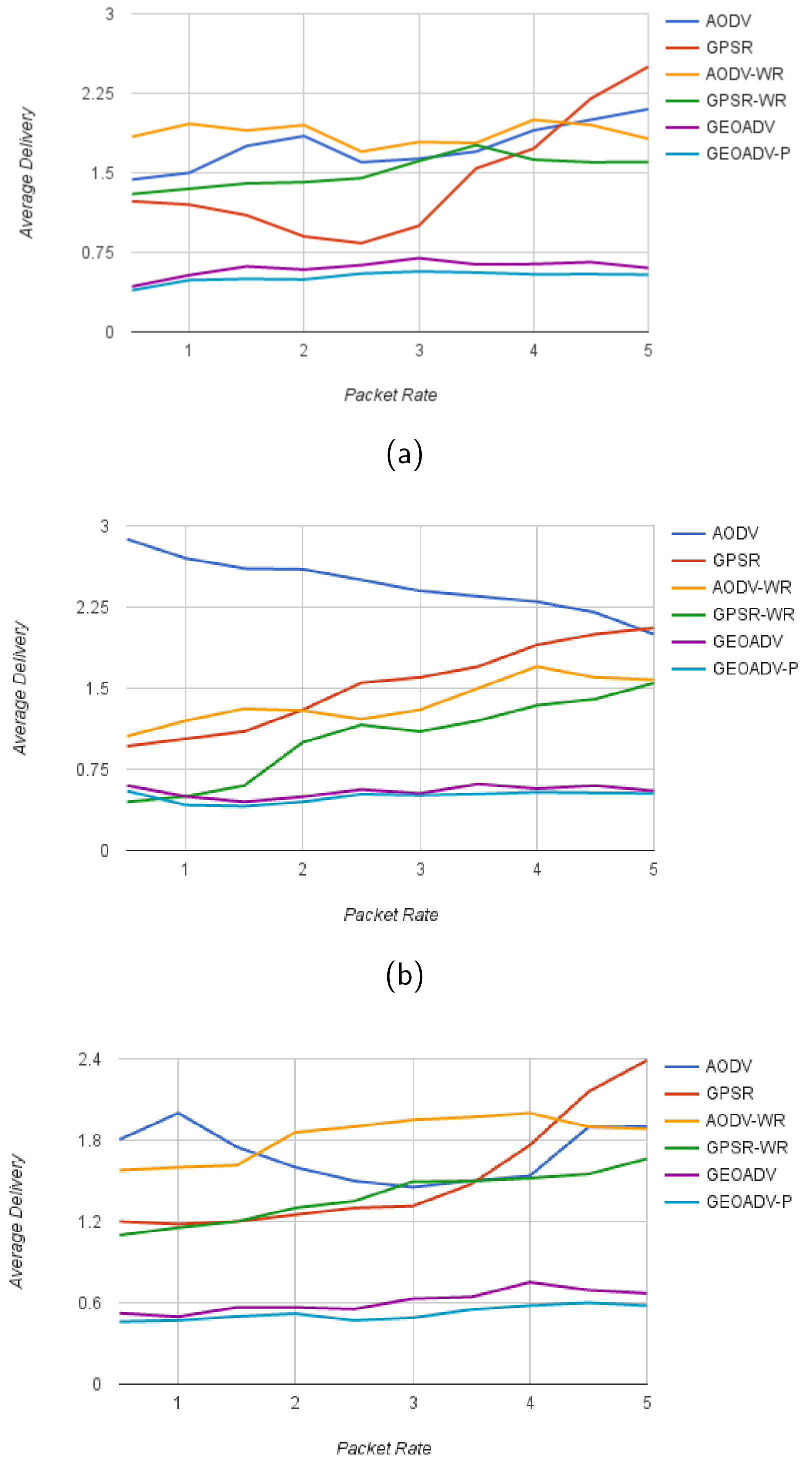


(c)

Figure 5.6: Urban Simulation Average Delay for GEOADV-P, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV with (a) 200 vehicles, (b) 400 vehicles, (c) 600 vehicles



(a)

(b)

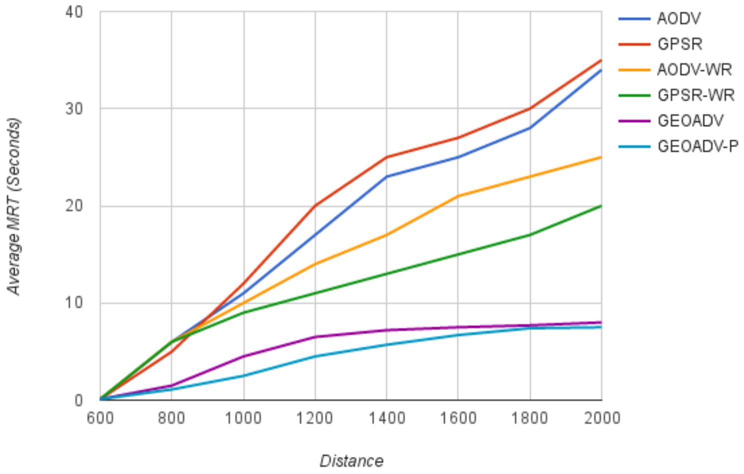
(c)

Figure 5.7: Highway Simulation Average Delay for GEOADV-P, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV with (a) 200 vehicles, (b) 400 vehicles, (c) 600 vehicles

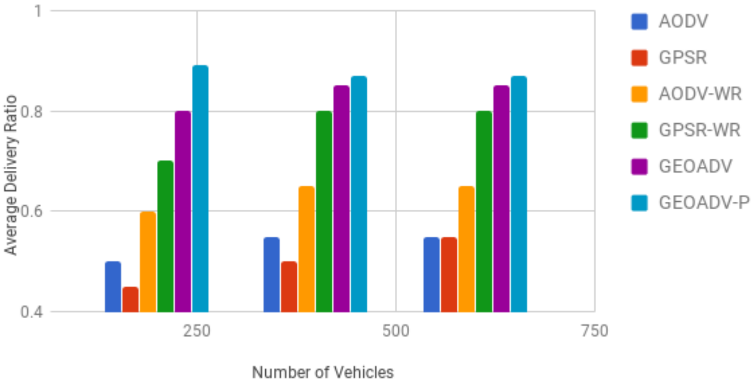
In the urban simulations, GEOADV-P's average delay consistently remains less than 0.5 seconds, and unlike GEOADV it is consistently stable in all densities. GEOADV is more stable in higher densities, where as GEOADV-P is stable in medium and high densities. This is because GEOADV-P's routes remain active for longer periods of time causing fewer packets needing to be buffered. The average delay of GPSR-WR decreases with the increase in density. The average delay in GPSR increases in the urban scenario as the density increases.

In the highway simulations, it can be observed the average delay for GEOADV-P consistently remains less than 0.65 seconds, whereas the average delay of GEOADV remains below 1 second. GPSR-WR decreases with the increase in density only being consistently less than one second in high density scenarios (Figure 5.7c). The average delay of GPSR continually increases as the density increases in the highway simulation.

GEOADV-P performs better than all other protocols in both urban and highway scenarios, and remains consistently less than .65 seconds average delay. GEOADV and GEOADV-P's average delay remains below 1 second. GPSR-WR performs better than AODV-WR in both scenarios. In case of AODV-WR as the density of vehicle increases its delay is also increases. As stated previously, GPSR's poor performance in the urban scenarios is because city roads have irregularities such as dead-end streets and therefore the shortest Euclidean distance is not always equivalent to the shortest path.



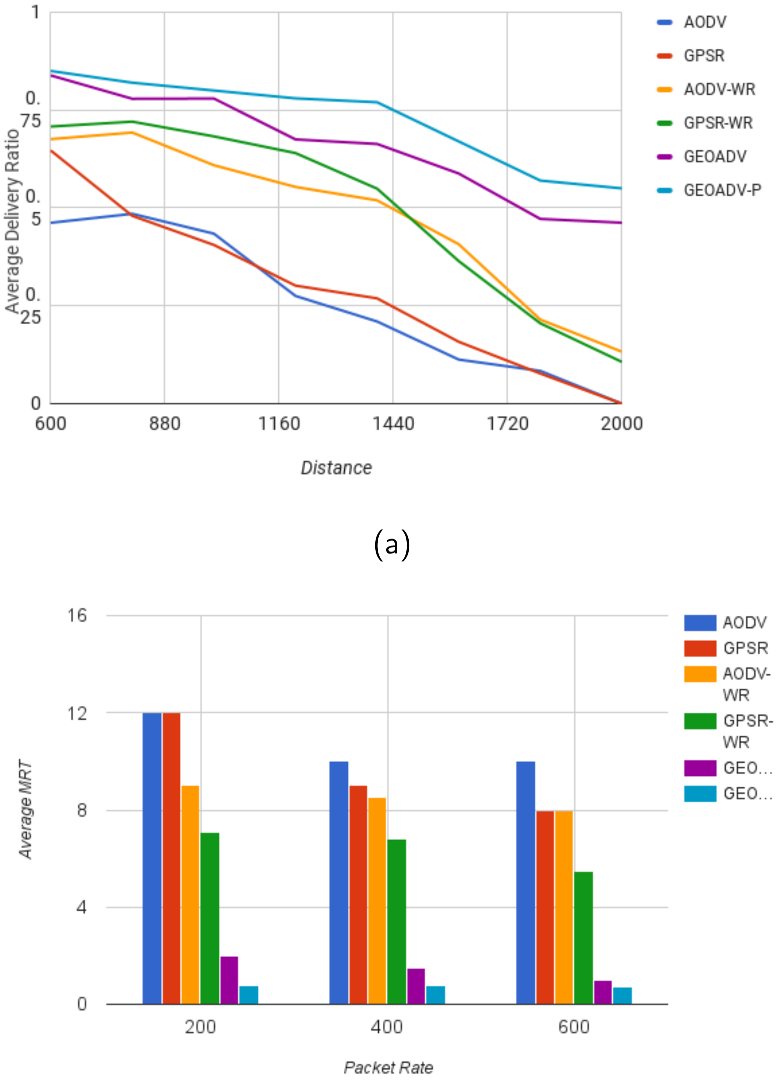
(a)



(b)

Figure 5.8: Urban Simulation for GEOADV-P, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV(a) shows average delay by Vehicle Distance, (b) shows average delay by Number of Vehicles (Density)

In Figure 5.8a it can be seen that GEOADV-P and GEOADV stay below 8 seconds for long distance and is significantly less than other protocols, in urban environments. The average delay stays below 7.5 seconds for GEOADV-P for long distance. Figure 5.8b shows the average delay in low density (200 vehicles), medium density (400 vehicles), and high density (600 vehicles) networks. GEOADV-P performs almost consistently in all types of networks.



(a)

(b)

Figure 5.9: Highway Simulation for GEOADV-P, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV(a) shows average delay by Vehicle Distance, (b) shows average delay by Number of Vehicles (Density)

For highway environments, GEOADV-P and GEOADV stay below 8 seconds for long distance and is significantly less than other protocols, shown in Figure 5.9a. The average delay stays below 7 seconds for GEOADV-P for long distance. Figure 5.9b shows the Average delay in low density (200 vehicles), medium density (400 vehicles), and high density (600 vehicles) networks. GEOADV-P performs almost consistently in all types of networks.

5.3 SUMMARY

In this chapter the performance of GEOADV and GEOADV-P, the two proposed protocols, where reviewed. GEOADV-P is an enhancement of GEOADV protocol which was introduced to solve the problem of a lack of adaptive protocols for urban and highway environments. Although routing protocols like GPSR, GPSR-WR, and AODV-VANET work well in city environments they are not adaptive in sparse, rural, or highway environments. GEOADV-P is a predictive hybrid protocol, combining both geographic and reactive routing. GEOADV-P is augmented with the calculation of the predicted total weight of the route (PTWR). In the urban and highway simulations it was shown that GEOADV-P has the smallest consistent average delay and outperforms all other protocols in average delivery ratio. GEOADV-P is showing to be an adaptive protocol in the VANET environment. GEOADV-P is able to perform better in low density networks than GPSR-WR. This is because when GPSR-WR is in a low density network, network partitions prevents full coverage of large sections of the map, thus limiting the information gathered by the protocols beacons. This does not show to be an issue with GEOADV-P because of both the route repair and when items are not within a one hop range AODV-WR is initiated. This helps GEOADV-P be more adaptive than GPSR-WR in sparser networks GEOADV-P as is able to be more stable in highway environments than GPSR-WR. Despite these successes GEOADV and GEOADV-P still show some inconsistencies in sparser networks.

CHAPTER 6

GEOADV-PF ROUTING PROTOCOL

GEOADV-PF is an enhancement of GEOADV-P protocol which uses predictive elements and fuzzy logic with its already existing hybrid routing. In GEOADV-PF routing protocol fuzzy logic is used in order to help determine route selection. Due to the mobility of vehicles in VANET, communication links are very vulnerable. The selection of an optimal route depends on the networks environment and solutions for optimal route selection are complex and inflexible. Introducing fuzzy systems to VANET can help with the flexibility.

6.1 FUZZY LOGIC

Fuzzy logic accepts a range of values and returns estimated results [79, 80, 81]. Each fuzzy logic system generally has three main components. First the fuzzifier, the fuzzifier maps the input into a fuzzy set. Second the inference engine, the inference engine is implemented by the fuzzy logic rule-based processor to obtain the solution based on IF-THEN sets of rules Finally the defuzzifier, the defuzzifier is used to transform the solution to the output.

Fuzzy Logic [82, 83, 84, 85, 86] is based on natural language with a tolerance to imprecise data. Fuzzy logic is capable of modeling complex real-life scenarios. The essence of Fuzzy logic is its fuzzy decision engine which can be described as follows:

- The Input-Output system
- The Rule-Base and Fuzzy Table
- Membership functions

- Fuzzification, Fuzzy Inference and Defuzzification

In VANET environments because of the mobility of vehicles, communication links are very vulnerable. The selection of an optimal route depends on the networks environment and solutions for optimal route selection are complex and inflexible. Introducing fuzzy systems to VANET can help with the flexibility of the routing protocol. The flexibility of a routing protocol and be improved by changing membership functions and fuzzy rule sets. By using fuzzy logic a routing protocol can be improved in varying scenarios.

6.1.1 Fuzzifier

In the proposed routing protocol, the number of neighbors in a one-hop distance, speed of the vehicles, and distance of the current vehicle to destination are considered as the inputs of the fuzzy system for route evaluation. The output of the fuzzy system returns the probability of route selection. Figure 6.1 shows the fuzzy control system used for the protocol.

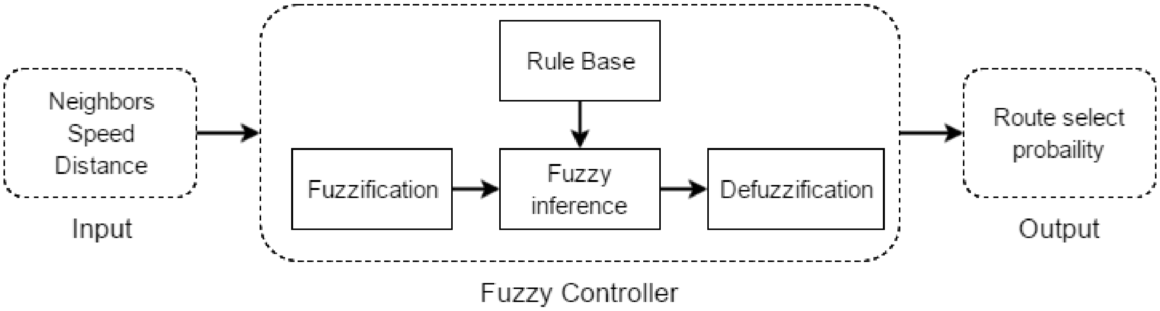


Figure 6.1: Fuzzy Control System

Membership functions for the number of neighbors in a one-hop distance, speed of the vehicles, and distance of the current vehicle to destination. The membership functions are trapezoidal functions, the inputs are low, medium, and high. Output membership function that specifies the probability of route selection.

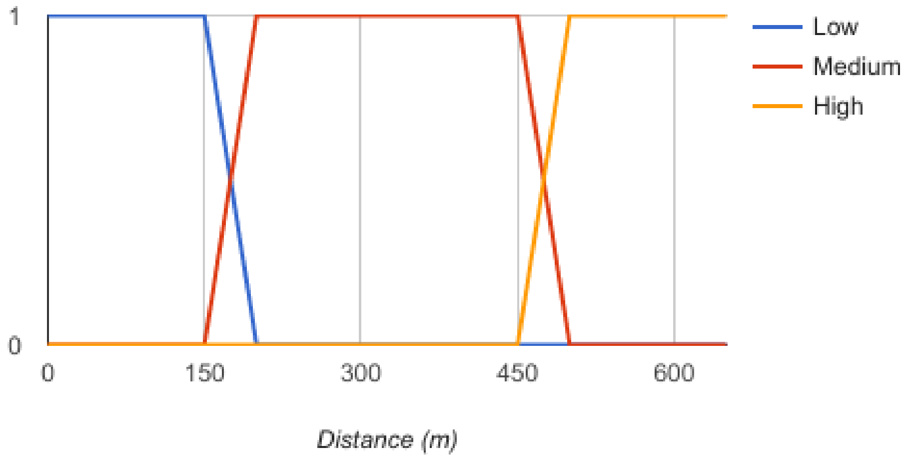


Figure 6.2: Membership distance function

As displayed in Figure 6.1.1 membership functions Low, Medium, and High correspond to the input Distance. The distance between the current node and destination is obtained using the equation in Equation 6.1, (x_1, y_1) shows coordinate of the destination node and (x_2, y_2) is the coordinates of the current node.

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{6.1}$$

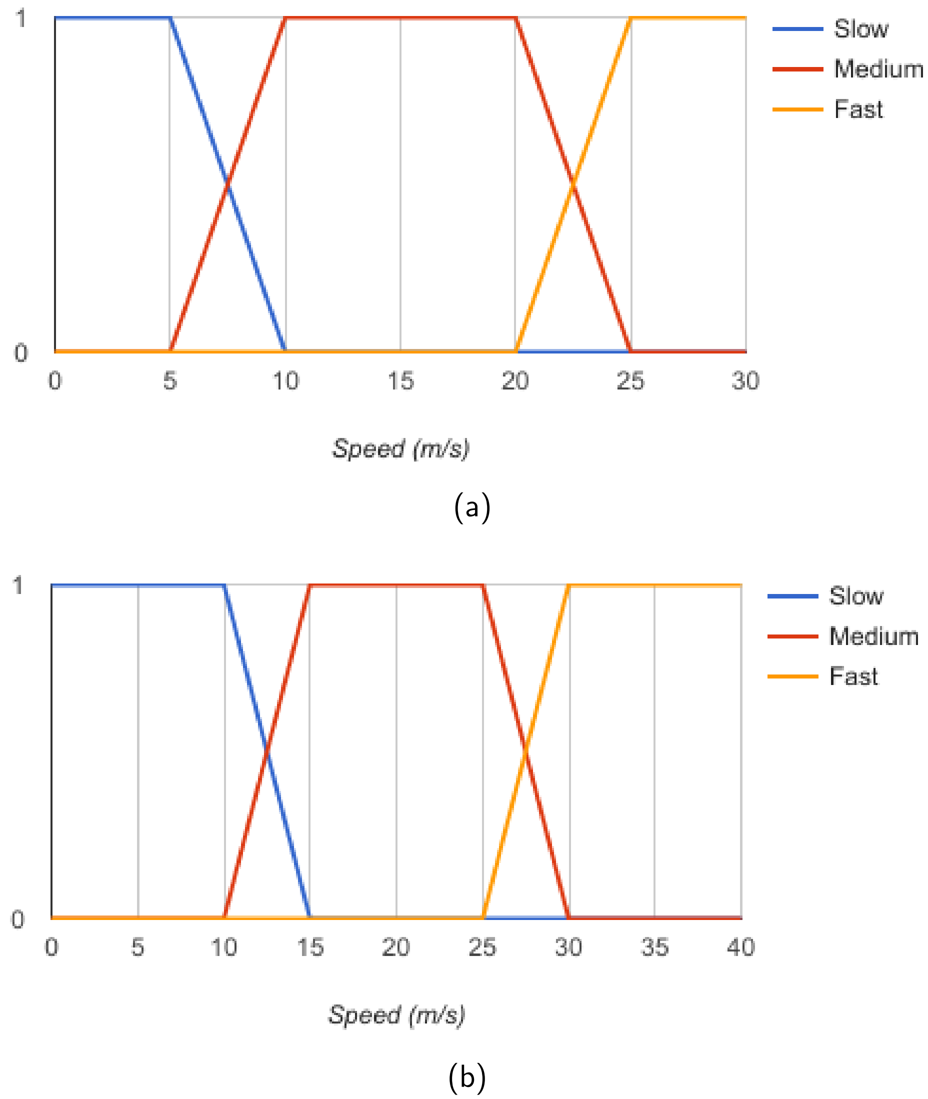


Figure 6.3: Membership functions for speed

As displayed in Figure 6.3 membership functions Low, Medium, and High. These memberships functions represent the input Speed. Figure 6.3a represents the membership function for an urban environment while Figure 6.3b represents the membership function for an highway environment.

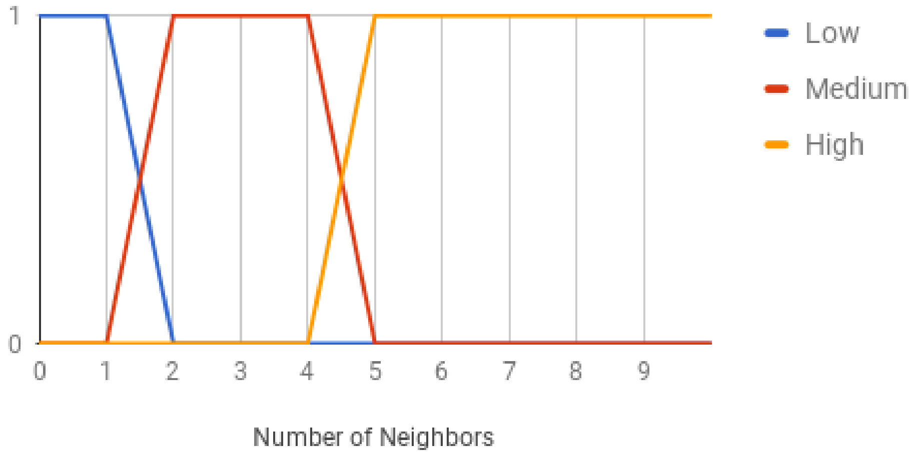


Figure 6.4: Membership function for number of neighbors

As displayed in Figure 6.1.1 membership functions Low, Medium, and High are used to represent the input Neighbors. Figure 6.5 illustrates how the number of neighbors is determined in a one-hop range. Vehicles V1 to V6 are neighbors in a one-hop range to the current forwarded (CF). However, for the input, only V1, V2, and V3 are counted as neighbors to CF as they move in the same direction. Vehicles stay in communication longer if they are moving in a similar direction of each other compared to vehicles moving in the opposite direction of each other. Hence, the vehicle movement direction (or vector) is crucial when determining neighbors in a one-hop range.

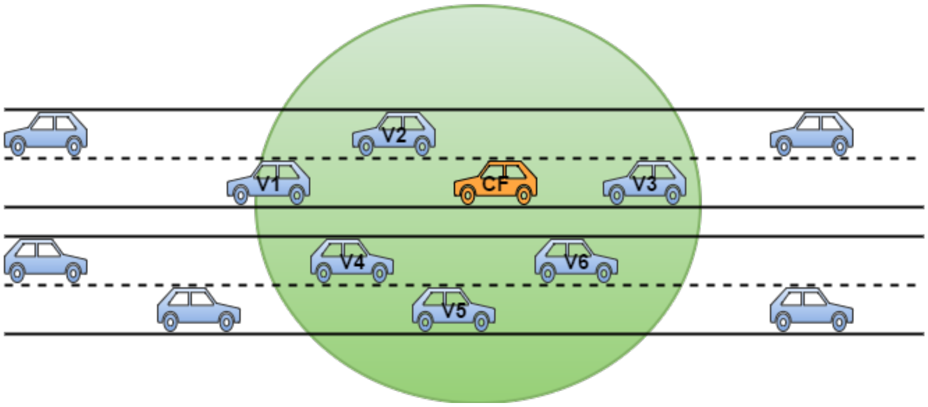


Figure 6.5: Neighbors in one hop range

Table 6.1: Main Rules for GEOADV-PF Fuzzy Inference Engine

	IF			**THEN**
Rule	**Distance**	**Speed**	**Neighbors**	**Output**
1	Low	Low	Low	Bad
2	Low	Low	Medium	Normal
3	Low	Low	High	Best
4	Low	Medium	Low	Bad
5	Low	Medium	Medium	Normal
6	Low	Medium	High	Best
7	Low	High	Low	Bad
8	Low	High	Medium	Normal
9	Low	High	High	Good
10	Medium	Low	Low	Bad
11	Medium	Low	Medium	Normal
12	Medium	Low	High	Best
13	Medium	Medium	Low	Bad
14	Medium	Medium	Medium	Normal
15	Medium	Medium	High	Good
16	Medium	High	Low	Bad
17	Medium	High	Medium	Normal
18	Medium	High	High	Normal
19	High	Low	Low	Bad
20	High	Low	Medium	Bad
21	High	Low	High	Good
22	High	Medium	Low	Bad
23	High	Medium	Medium	Bad
24	High	Medium	High	Normal
25	High	High	Low	Bad
26	High	High	Medium	Bad
27	High	High	High	Normal

6.1.2 Fuzzy Inference Engine

Knowledge base is the chief component of the fuzzy inference engine, this made up of a group of rules that associate the fuzzy inputs to the output [83]. This group of rules is based on the main rules that determine the condition of a vehicular network. The main rules are shown in Table 6.1.

Referring to Table 6.1, Main Rule 1 is describes a sparse network in an urban area where the node to the destination distance is low; the vehicle would move with low speed; and the number of neighbors is small with a possibility that a node has no neighbor. Main Rules 2 and 10 also describes a sparse urban network.

Any route with low amount of neighbors (0-1) is considered bad as the probability of link breakage is extremely high. If link breakage where to occur in this scenario there is a probability the route will not be able to repair itself is high. This covers rules 1, 4, 7, 10, 13, 16, 19, 22, and 25.

Most rules with a medium amount of neighbors (2-4) are considered normal. This covers rules 2, 5, 8, 11, 14, and 17. The probability of link breakage is much lower than rules with a low amount of neighbors but in urban scenarios nodes can change directions easily so the chances or link breakage still exist. If link breakage where to occur in this scenario there is a probability the route will not be able to repair itself. Rule 20, 23 and 26 are considered bad despite having medium neighbors as these have a high distance to carry the package from node to destination and a medium-high speed. These could represent a possible highway scenario or a low density urban simulation. When nodes are moving at a high speed or the packet has a further distance to go there is a higher probability of link breakage.

Most rules with a high amount of neighbors (5+) are considered good. This covers rules 9, 12, and 21. Due to the large amount of vehicles moving in the same direction the chance of link breakage is low, also if link breakage did occur the route repair will most likely be able to repair itself in these scenarios. Rules 24 and 27 are considered normal despite having a high amount of neighbors due to the distance the packet has to travel to the destination and the high speed. As vehicles are moving at a higher speed and the distance is further away therefore there is a higher probability of link breakage.

Rules 3, 6, and 12 are considered best as the distance is low/medium and the speed is low/medium and the amount of neighbors moving in the same direction is high. Smaller distance and lower speeds are less likely to have link breakage. If link breakage did occur the route repair will most likely be able to repair itself in these scenarios.

6.1.3 Defuzzifier

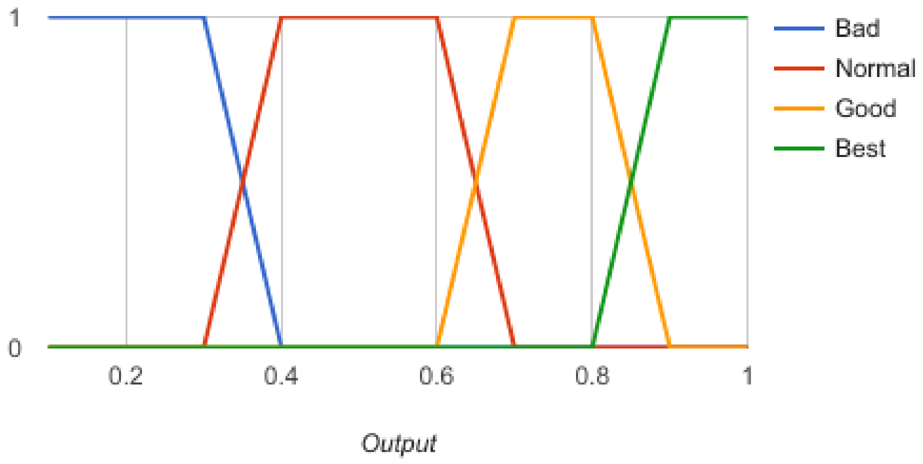


Figure 6.6: Membership output functions

The output includes 4 membership functions as shown in Figure 6.6, these are categorized as bad, normal, good, and best. The output value is compared with the value stored in the RREQ. If the probability of route selection is less than what is in the destination node, the route will be replaced. At last, intermediate nodes update their information with the information stored in the RREQ. This is done until the receiving node is the destination node. This guarantees that the route with the highest probability is chosen.

6.2 ROUTE REQUEST

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |J|R|G|D|U|   Reserved          |   Hop Count   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                            RREQ ID                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Destination IP Address                     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Destination Sequence Number                  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Originator IP Address                      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Originator Sequence Number                   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                        Sender Position                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         Sender Speed                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                     Sender Acceleration                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Sender Direction                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                         Current PTWR                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      Current Fuzzy Output                     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Current Expiration Time                    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 6.7: RREQ Message Contents

```
Data:
PTWR: Predicted total weight of the route
T: Expiration Time
N_d: Destination node
if Source has no route to Destination then
    $PTWR = 0$;
    $T = 10000$;
    Update Fuzzy Output;
    Create RREQ;
    if Has node in one hop closer to $N_d$ then
        Forward Node;
    else
        Broadcast RREQ;
    end
else
    Forward Data;
end
```

Figure 6.8: Initial Route Request (RREQ) Handling

GEOADV-PF initiates the route discovery process similar to a greedy forwarding process, the greedy forwarding process is reviewed in Chapter 4 Section 4.1.3. If the source node has no route to the destination node a RREQ is created. This algorithm is shown in Figure 6.8. The node will initially create a RREQ message by its placing the source node details (position, speed, acceleration and direction) in the RREQ message. The PTWR and expiration time, reviewed in Chapter 4 are set to zero and a large number respectively. The RREQ will also contain the coordinates of the destination node. The RREQ contents are shown in Figure 6.7. After the RREQ is created, the neighboring tables within a one hop communication range are searched in order to find the node nearest to the destination node. This node is then identified as the next forwarding node and the RREQ packet is forwarded to that node. If, within the one hop range, there are no neighboring nodes that are closer to the destination node than the source node is (i.e. void region or neighboring nodes have no location information), AODV-WR will be switched on and the RREQ packet will be flooded to all neighboring nodes. This process will be repeated until the RREQ reaches the destination node. Thereupon, the destination node will reply with a route-reply

(RREP) packet to the source node. This is shown in Figure 6.9.

```
Data:
$PTWR_j$: RREQ's Predicted total weight of the route
$T_j$: RREQ's Expiration Time
$PTWR_i$: $PTWR$ calculated by current node
$T_i$: $T$ calculated by current node
$N_i$: Current Node
$N_d$: Destination node
if $N_i \neq N_d$ then
    // Is an intermediate node
    Update $T$;
    $PTWR = PTWR_i + PTWR_j$;
    Update Fuzzy Output;
    if Has node in one hop closer to $N_d$ then
        Forward Node;
    else
        Broadcast RREQ;
    end
else
    // Node is destination
    if First Received then
        Respond with RREP;
    else
        if Contains higher source sequence then
            Respond with RREP;
        else
            if $T >$ Last $T$ then
                if $PTWR <$ Last PTWR && Higher Fuzzy Output then
                    Respond with RREP;
                else
                    if Higher Fuzzy Output then
                        Respond with RREP;
                    end
                end
            end
        end
    end
end
```

Figure 6.9: Route Request (RREQ) Handling

6.3 ROUTE REPLY

In GEOADV-PF, when a RREQ packet arrives at the destination node, the destination node only responds to a RREP packet four three cases:

1. This is the first time the destination node has received a RREQ packet from the identified source node.
2. The destination node has received a RREQ packet from the identified source node, but the RREQ has a higher source sequence number.
3. The destination node has received a RREQ packet from the identified source node, and the RREQ has the same source sequence number, but the RREQ has a greater T, better (lower) PTWR, and higher fuzzy probability output.
4. The destination node has received a RREQ packet from the identified source node, and the RREQ has the same source sequence number, but the RREQ has a greater T, and higher fuzzy probability output.

6.4 ROUTE REPAIR

Like GEOADV and GEOADV-P, GEOADV-PF's intermediate nodes participate in transferring data in order to repair routes locally. When a broken link is recognized by a node, the node will buffer the received data packets for the destination, and then look up its neighbor node table to attempt to find a neighbors closer to the destination node. If a closer neighbor node exist, the routing table will be updated and the data packets will be forwarded to that node. If there is not a closer neighbor node, a route repair packet (RRP) will be created by the node and the network will be flooded. If a neighboring nodes receives a RRP packet the node will look in its routing table, to see if it has a route to the destination node. If a neighboring node has a route,it will reply with a route repair reply packet (RRRP) to the intermediate node. If a neighboring node does not have a route, it investigates in its own neighbor node table for a node closer to the destination. If there is a node closer to the destination, the neighboring node will reply with a RRRP packet to the intermediate node. Otherwise, the neighboring node will flood the RRP packet to all its neighboring nodes.

Since request are flooded in the network, the intermediate node can receive more than one RRRP packet. The node will first use the route given by the first received RRRP packet until a route with a lower (better) PTWR is received. If the route fails to be repaired location, the intermediate now will send a RERR packet to the source node.

6.5 PROTOCOL PERFORMANCE

6.5.1 Tools and Techniques Used

All simulations were done using OMNET++, SUMO and VEINS. A review of these tools can been seen in Section 5.1.1.

6.5.2 Evaluation Methodology

The performance of the GEOADV-PF is evaluated and compared against representatives from the main classes of routing protocols and currently proposed VANET protocol. GEOADV-PF is evaluated and compared against: AODV [24] a MANET reactive routing protocol; GPSR [42] a MANET geographical routing protocol; AODV-WR which is AODV based protocol that uses VANET movements and the calculation of TWR; GPSR-WR which is GPSR based protocol that uses VANET movements and the calculation of TWR; GEOADV our original hybrid protocol.

6.5.3 Metrics

The performance of the GEOADV and GEOADV-P routing protocols was evaluated by varying constant bit rate (CBR), data rates, network densities, and concurrent UDP flows. The metrics used to evaluate the performance are as follows:

- Average delivery ratio
- Average Delay
- Routing overhead

6.5.4 Simulation Set Up

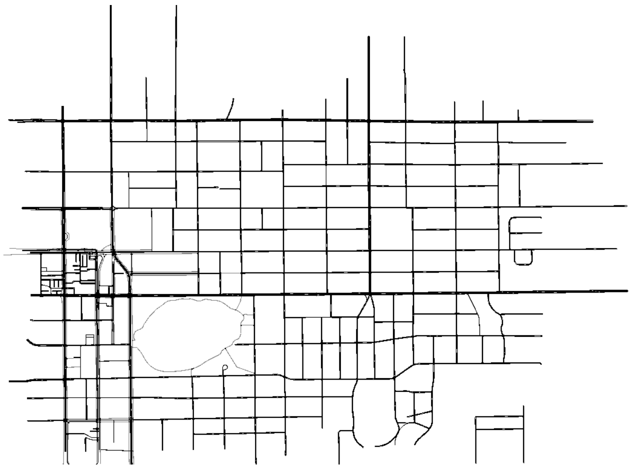


Figure 6.10: Simulation Maps for urban scenario

Urban simulations were performed to compare the GEOADV-PF against, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV. Figure 6.5.4 shows the map used for the urban simulation, this is a portion of downtown Orlando, Florida.

For our urban simulation the map used was extracted from OpenStreetMap [70] database. SUMO [69] was used to generate the movements of the vehicle nodes. The map extracted from OpenStreetMap was inputted into SUMO and the particulars where set for speeds limits and the number of lanes for the roads in the extracted map. Traffic-light-operated intersections and priority intersections for the extracted map was specified. The first 1000 seconds of the SUMO output were discarded in order to obtain more accurate information on vehicular movements. The resulting output from SUMO, was then converted into input files for the OMNeT++ Simulation.

For the wireless configuration, IEEE 802.11p with DCF standard at the MAC layer was used. IEEE 802.11p and IEEE 1609.x are called wireless access in vehicular environments (WAVE) standards because their goal is to facilitate the provision of wireless access in vehicle environments [73, 74, 75, 76, 77]. At the physical layer, in order to characterize physical dissemination a shadowing propagation model was used. The communication range was set at 400m and had 80% probability of success for transmissions. These values were based off of Nzouonta's [63] simulation which used studies that reported real-life measurements between moving vehicles in the range 450-550m [78].

The simulation time for each protocol simulation was 600 seconds. Three simulations for each protocol were done, one with 200 vehicles (low density), another with 400 vehicles (medium density), and the last one with 600 vehicles (high density). This is to illustrate how traffic effects each protocol, and how the protocol is able to adapt. The simulation parameters are summarized in Table 6.2.

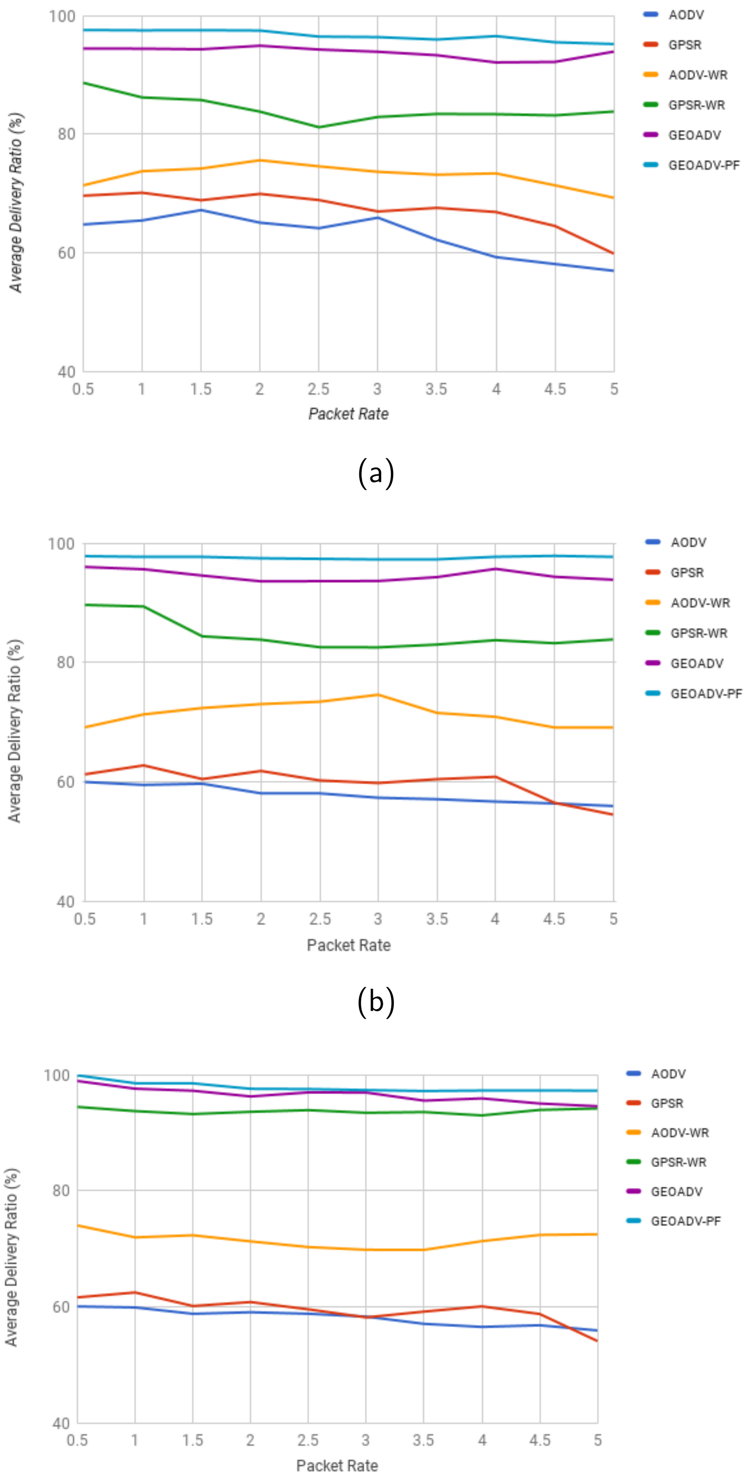
Table 6.2: GEOADV-PF Simulation Setup

Parameters	**Values**
Number of Vehicles	200, 400, 600
Speed (m/s)	Between 5 to 20 m/s
Transmission Range	400m
Simulation Time	600s
Bitrate	18 mbps
MAC Protocol	IEEE 802.11p
Data Packet Size	512 bytes

6.5.5 Simulation Results

Average delivery ratio

The average delivery ratio represents number of data packets successfully received over the total number of data packets sent. All duplicate packets which were generated by the loss of acknowledgments at the MAC layer were excluded. The average delivery ratio illustrates a routing protocol's ability to transfer data successfully end-to-end. Figure 6.11 shows GEOADV-PF and GEOADV have the most stable performances amongst all the protocols simulated throughout all densities, having the highest average delivery ratio.



(a)

(b)

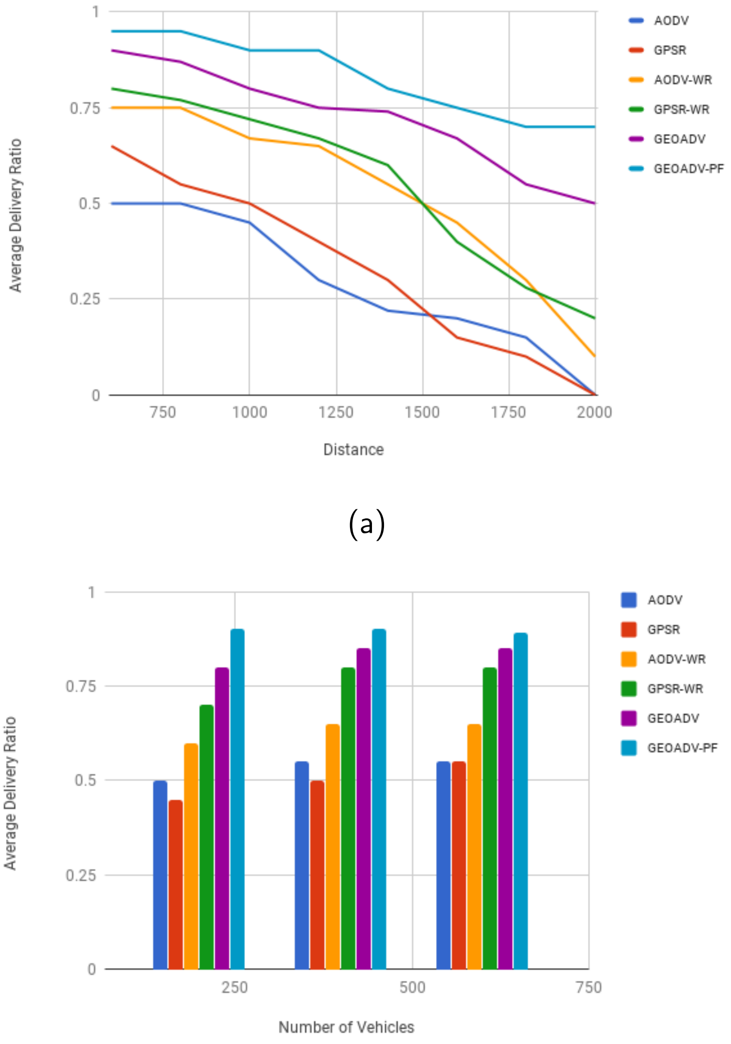
(c)

Figure 6.11: Urban Simulation Average Delivery Ratio for GEOADV-PF, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV with (a) 200 vehicles, (b) 400 vehicles, (c) 600 vehicles

In our urban simulations, GEOADV-PF and GEOADV outperform the other compared protocols. GEOADV-PF's average delivery ratio is about 40% higher compared to AODV's. GEOADV shows to perform better in denser networks compared to sparser networks. As for GEOADV-PF network density is insignificant, which can be seen in Figures 6.11a (low density) and 6.11c (high density).

Across the network densities, it can be observed that the delivery ratio of GPSR-WR, GEOADV, GEOADV-PF increases as the network becomes denser. This is because these protocols integrate road layouts. AODV-WR stabilizes as the networks become denser. GEOADV-P, GEOADV, GPSR-WR, and AODV-WR uses real-time knowledge of the vehicular traffic on the roads which helps them perform more efficiently. GPSR-WR performance increases in medium and dense networks, due to network partitions preventing a full coverage of large sections of the map in low density networks. This limits the information gathered by the protocols beacons. This does not show to be as much as an issue with GEOADV or GEOADV-PF because of both our route repair and when items are not within a one hop range AODV-WR is initiated. This helps GEOADV and GEOADV-PF be more adaptive than GPSR-WR in sparser networks. The addition of our predictive elements causes GEOADV-PF route repair to be even more accurate.

GPSR poor performance in the urban scenarios is because city roads have irregularities such as dead-end streets and therefore the shortest Euclidean distance is not always equivalent to the shortest path. Another contributing factor to GPSR performance is because the protocol is stateless. Although the has many advantages one negative is if a local maxima forms in the network, because of the stateless nature of GPSR, stale entries. Due to GPSR being stateless if a local maxima is formed in the network, packets will continue to follow the same path to the local maxima. Once the packets arrive at the local maxima, the forwarding mode of each packet is set to perimeter forwarding [42, 43]. This does not happen with AODV and AODV-WR were both protocols can perform local repair or send a route error notification to the source node.



(a)

(b)

Figure 6.12: Urban Simulation Average Delivery Ratio for GEOADV-P, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV (a) shows average delivery ratio by Vehicle Distance, (b) shows average delivery ratio by Number of Vehicles (Density)

Figure 5.4a, shows average delivery ratio compared to the distance between vehicles. GEOADV-PF and GEOADV outperform all the other protocols. GEOADV-PF degrades significantly less than other protocols when distance increases between the node, and the average delivery ratio stays above 0.7 for long distances.

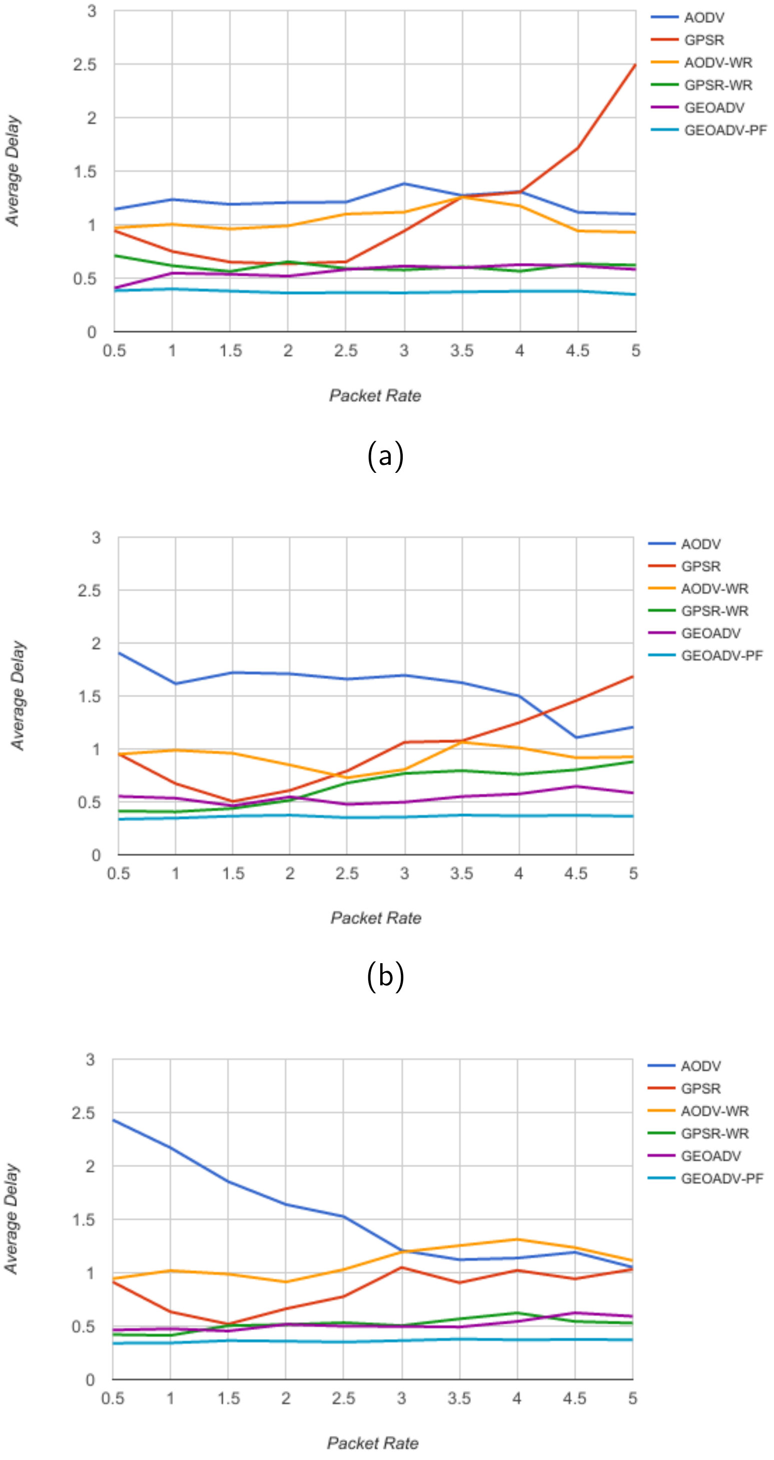
Figure 6.12b shows the average delivery ratio in low density (200 vehicles), medium density (400 vehicles), and high density (600 vehicles) networks. GEOADV-PF performs almost consistently in all types of networks and stays above .89.

Average delay

Average delay shows the latency created by the routing protocol. Average delay is the computed by acquiring transmissions of all data packets delivered successfully. In Figure 6.13 and 6.14 shows GEOADV and GEOADV-PF have the smallest consistent average delay amongst the protocols in the urban scenarios.

In our urban simulations, GEOADV-PF's average delay consistently remains less than 0.4 seconds, and unlike GEOADV it is consistently stable in all densities. Compared to GEOADV, which performs best in higher densities, GEOADV-PF is stable in all densities. This is because GEOADV-PF's routes remain active for a longer period of time causing fewer packets needing to be buffered. The average delay of GPSR-WR decreases with the increase in density. The average delay in GPSR increases in the urban scenario as the density increases.

GEOADV-PF performs better than all other protocols in urban scenarios, and remains consistently less than 0.4 seconds average delay. GEOADV average delay remains below 1 second. GPSR-WR performs better than AODV-WR in both scenarios. In case of AODV-WR as the density of vehicle increases its delay is also increases. As stated previously, GPSR's poor performance in the urban scenarios is because city roads have irregularities such as dead-end streets and therefore the shortest Euclidean distance is not always equivalent to the shortest path.

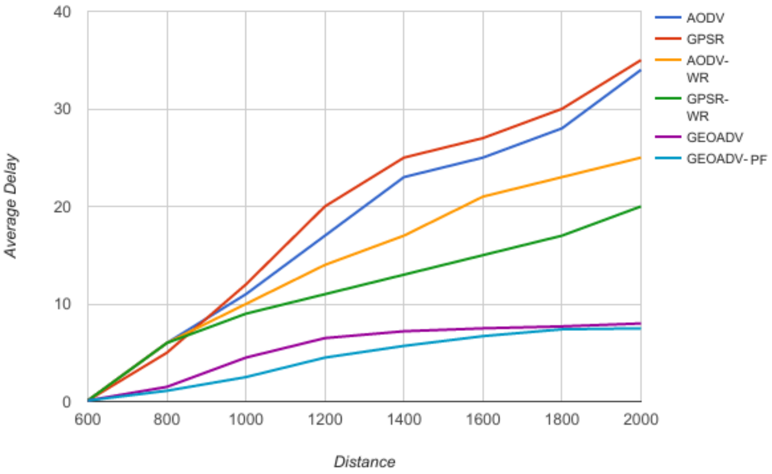


(a)

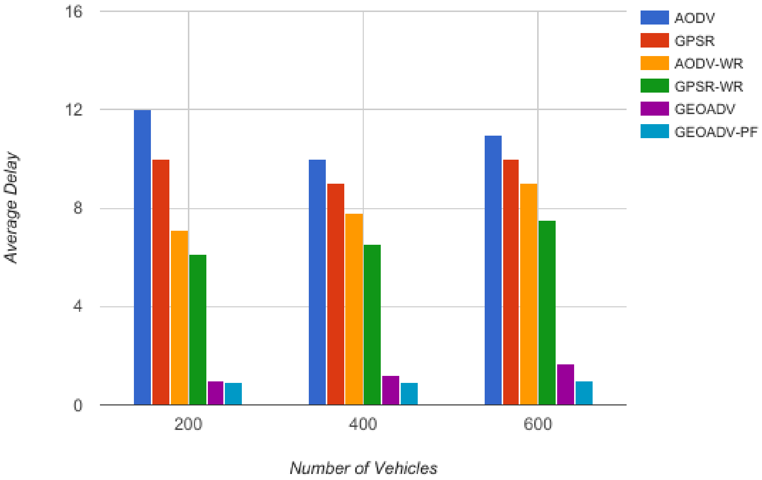
(b)

(c)

Figure 6.13: Urban Simulation Average Delay for GEOADV-PF, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV with (a) 200 vehicles, (b) 400 vehicles, (c) 600 vehicles



(a)



(b)

Figure 6.14: Urban Simulation Average Delay for GEOADV-P, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV(a) shows average delay by Vehicle Distance, (b) shows average delay by Number of Vehicles (Density)

Figure 6.14a, shows the average delay compared to distance traveled. It can be seen that GEOADV-PF and GEOADV stay below 8 seconds for long distances and is significantly less than other protocols. The average delay stays below 7.5 seconds for GEOADV-PF for long distance.

Figure 6.14b shows the average delay in low density (200 vehicles), medium density

(400 vehicles), and high density (600 vehicles) networks. GEOADV-PF performs almost consistently in all types of networks.

Overhead

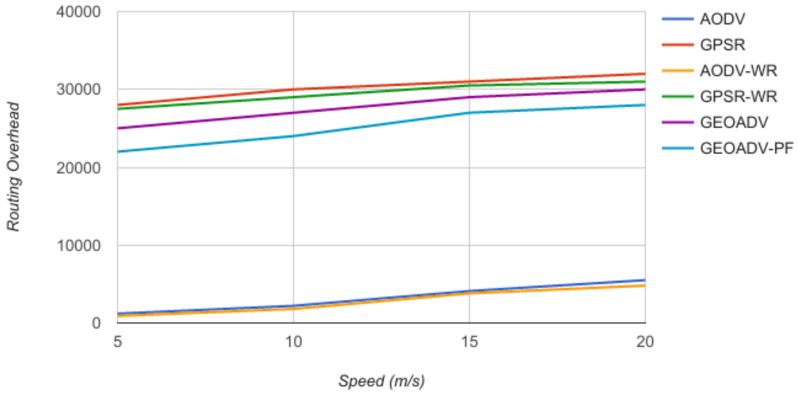


Figure 6.15: Urban Simulation Overhead for GEOADV-PF, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV

Routing overhead refers to network informations sent by the protocol. This uses a portion of the available bandwidth for communication protocols. The routing overhead represented Figure 6.15 is total number of routing bytes for control packets sent in the network over the speed of the node. Figure 6.15 shows the overhead by speed for GEOADV-PF, GEOADV, GPSR-WR, AODV-WR, GPSR, and AODV. AODV and AODV-WR routing overhead is less than other protocols because they do not send packets when there is no communication in the network. GPSR, GEOADV, and GEOADV-PF periodically send a beacon packet. GEOADV and GEOADV-PF have less overhead than GPSR as they are hybrids of AODV-WR. GEOADV-PF has less overhead than GEOADV due to its strong links and less breakage.

6.6 SUMMARY

In this chapter the GEOADV-PF routing protocol was introduced. GEOADV-PF is an enhancement of GEOADV protocol which was introduced to solve the problem of a lack of adaptive protocols for urban and highway environments. GEOADV-PF uses predictive elements and fuzzy logic with its already existing hybrid routing. Although routing protocols like GPSR, GPSR-WR, and AODV-VANET work well in city environments they are not adaptive in sparse, rural, or highway environments.

GEOADV-PF is augmented with the calculation of the predicted total weight of the route (PTWR). In the proposed routing protocol, the number of neighbors in a one-hop distance, speed of the vehicles, and distance of the current vehicle to destination are considered as the inputs of the fuzzy system for route evaluation. The output of the fuzzy system returns the probability of route selection.

In the urban simulations it was shown that GEOADV-PF has the smallest consistent average delay and outperforms all other protocols in average delivery ratio. Despite GEOADV-PF success, it can be seen in these simulations that the overhead of GEOADV-PF is higher than AODV, but less than GPSR and GEOADV. GEOADV-PF is showing to be an adaptive protocol in the VANET environment. GEOADV-PF is able to perform better in low density networks than GPSR-WR. This is because when GPSR-WR is in a low density network, network partitions prevents full coverage of large sections of the map, thus limiting the information gathered by the protocols beacons. This does not show to be an issue with GEOADV-PF because of both the route repair and when items are not within a one hop range AODV-WR is initiated. This helps GEOADV-PF be more adaptive in varying networks densities.

CHAPTER 7

INVESTIGATING THE IMPACT OF ADAPTIVE BEACONING ON GEOADV PERFORMANCE

In geographic routing, nodes are able to maintain up-to-date information on their neighbors by using beaconing. Beaconing is successful in VANET environments but causes a large amount of routing overhead. In this chapter the impact adaptive beaconing has on GEOADV's performance will be investigated.

7.1 UNDERLYING ADAPTIVE BEACONING SCHEME

For the underlying beaconing scheme an adaptive scheme called Fuzzy Logic Beacon (FB) is proposed. FB is a variation of [83], [87] and [82]. In FB each vehicle starts with the same broadcast interval. After the first broadcast, the next beacon interval is then determined by supplying the fuzzy inference engine with three inputs. These inputs are the number of neighbors in a one-hop distance, the speed of the vehicles, and the link quality of the network. The output of the fuzzy system returns the beaconing rate. FB's fuzzy inference engine is based on Mamdani's [88] fuzzy inference method which uses IF-THEN rules in order to construct the engine. Figure 7.1 shows the fuzzy control system used for FB.

Optimal route selection is entirely dependent on the operating conditions of the networks in use. This is problematic because VANETs consist of unpredictable vehicles in motion, inefficient communications, and unreliable network connections. To alleviate and avoid these hindrances, the introduction of fuzzy systems can help with the intrinsic demands for flexibility and adaptability. Fuzzy logic accepts a range

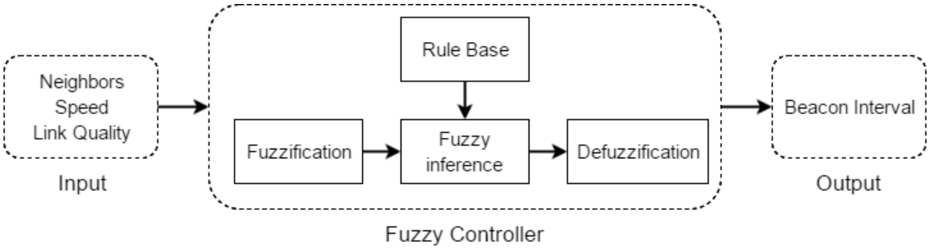


Figure 7.1: Fuzzy Control System

of values and returns estimated results [79, 80, 81]. Each fuzzy logic system generally has three main components:

- Fuzzifier: This maps the input into a fuzzy set
- Fuzzy Inference Engine: Implemented by the fuzzy logic rule-based processor to obtain the solution based on IF-THEN sets of rules
- Defuzzifier: Used to transform the solution to the output.

Fuzzifier

Membership functions for the number of neighbors in a one-hop distance, the speed of the vehicles, and link quality of the current vehicle to the previous vehicle are illustrated in the below figures. The membership functions are trapezoidal functions, the inputs are low, medium, and high. Output membership function that specifies the beacon rate to be used.

Figure 7.2 shows the membership functions for number of neighbors in a one hop distance. Low, Medium, and High are used to represent the input. Figure 7.3a illustrates how the number of neighbors is determined in a one-hop range. Vehicles V1 to V6 are neighbors in a one-hop range to the current forwarder (CF). However, for the input, only V1, V2, and V3 are counted as neighbors to CF as they move in the same direction. Vehicles stay in communication longer if they are moving in a similar direction of each other compared to vehicles moving in the opposite direction of each other. Hence, the vehicle movement direction (or vector) is crucial when determining neighbors in a one-hop range.

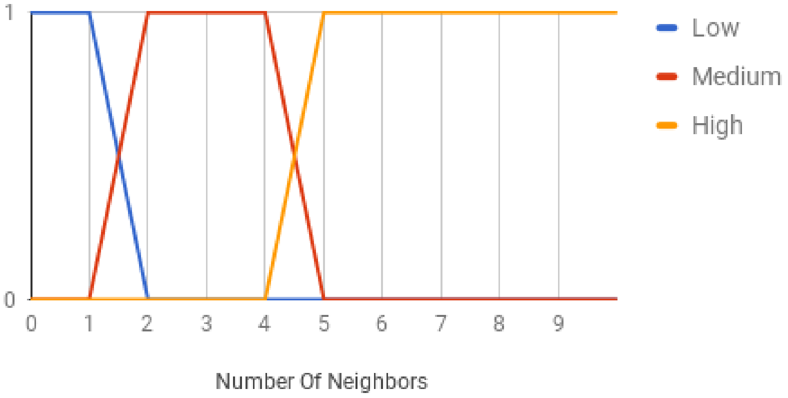


Figure 7.2: Membership function for number of neighbors

There are four main direction types showing in Figure 7.3b, vehicles determined to be moving in a similar direction have at most a 45-degree variation. This variation accounts for road way anomalies.

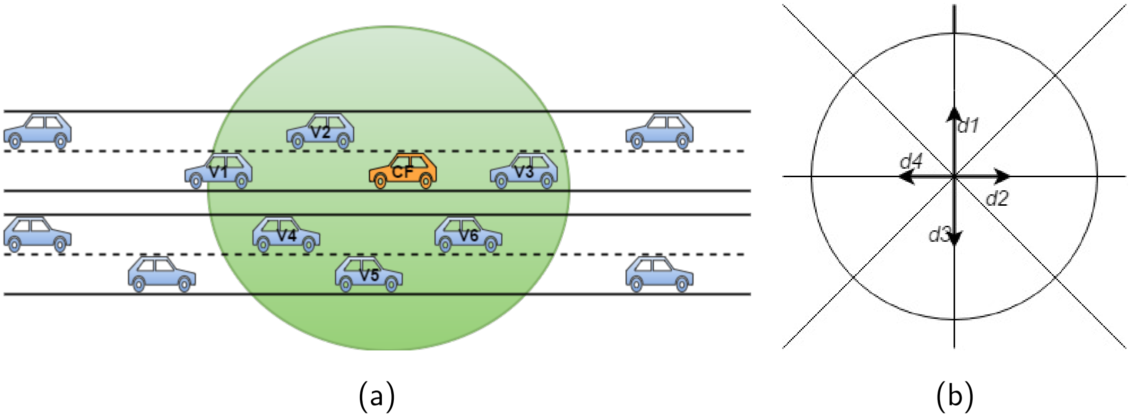
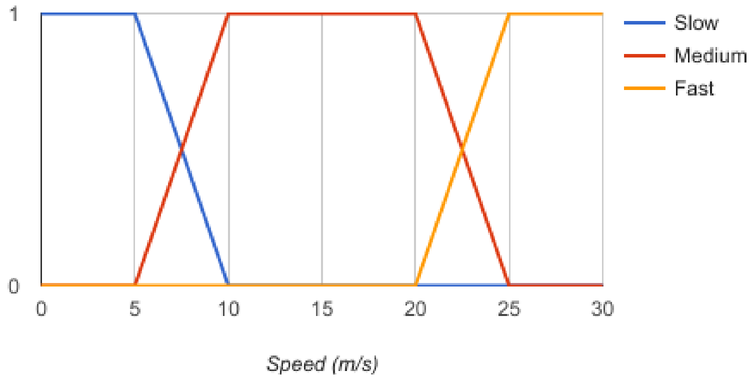
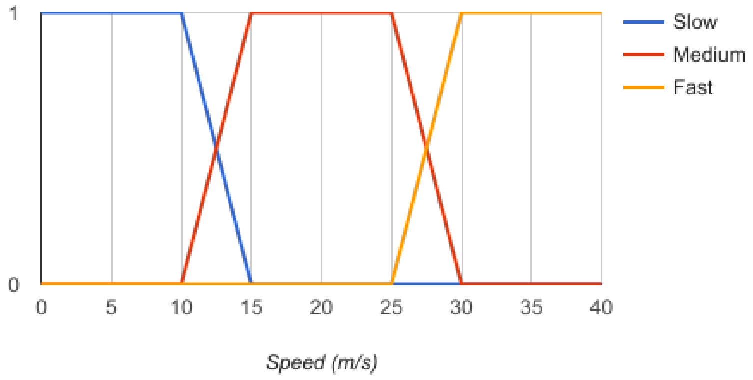


Figure 7.3: (a) Neighbors in one hop range (b) Node direction types

As displayed in Figure 7.4 membership functions Low, Medium, and High are used to represent the input Speed. Figure 7.4a represents the membership function in an urban environment while Figure 7.4b represents the membership function in an highway environment.



(a)



(b)

Figure 7.4: Membership functions for speed

Figure 7.5 shows the membership functions for link quality. Low, Medium, and High are used to represent the input Link Quality. The link quality between the nodes is the ratio of beacons received over the total beacons sent.

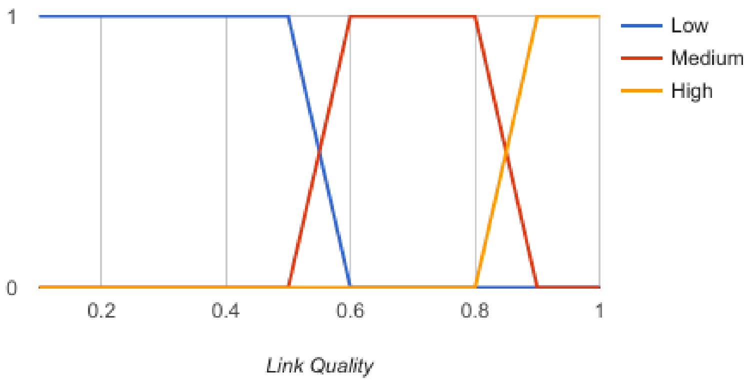


Figure 7.5: Membership function for link quality

Fuzzy Inference Engine

Knowledge base is the chief component of the fuzzy inference engine, this made up of a group of rules that associate the fuzzy inputs to the output [83]. This group of rules is based on the main rules that determine the condition of a vehicular network. The main rules are shown in Table 7.1.

Referring to Table 7.1, Main Rule 1 is used to describe a sparse network in an urban area where the link quality amongst vehicles is low; the vehicle would move with low speed; the number of neighbors is small with a possibility that a node has no neighbor. Main Rules 2 and 10 also describes a sparse network in an urban area.

Any route with a low amount of neighbors will have a medium to very high beaconing rate. This is because the network is not stable due to the low number of neighbors. As the number of neighbors increases in the network beaconing can significantly go down and speed and link quality play a more important factor in determining the beacon interval.

Table 7.1: Main Rules for FB's Fuzzy Inference Engine

	IF			**THEN**
Main Rule	**Neighbors**	**Speed**	**Link Quality**	**Output**
1	Low	Low	Low	High
2	Low	Low	Medium	Medium High
3	Low	Low	High	Medium High
4	Low	Medium	Low	High
5	Low	Medium	Medium	Medium High
6	Low	Medium	High	Medium
7	Low	High	Low	Very High
8	Low	High	Medium	High
9	Low	High	High	Medium High
10	Medium	Low	Low	Medium High
11	Medium	Low	Medium	Medium
12	Medium	Low	High	Medium Low
13	Medium	Medium	Low	Medium High
14	Medium	Medium	Medium	Medium
15	Medium	Medium	High	Medium Low
16	Medium	High	Low	Medium High
17	Medium	High	Medium	Medium
18	Medium	High	High	Medium Low
19	High	Low	Low	Medium
20	High	Low	Medium	Medium Low
21	High	Low	High	Low
22	High	Medium	Low	Medium Low
23	High	Medium	Medium	Low
24	High	Medium	High	Low
25	High	High	Low	Medium Low
26	High	High	Medium	Medium Low
27	High	High	High	Medium Low

Defuzzifier

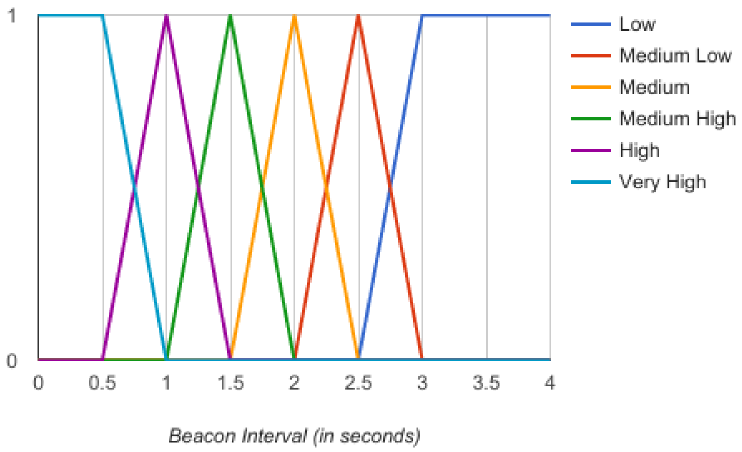
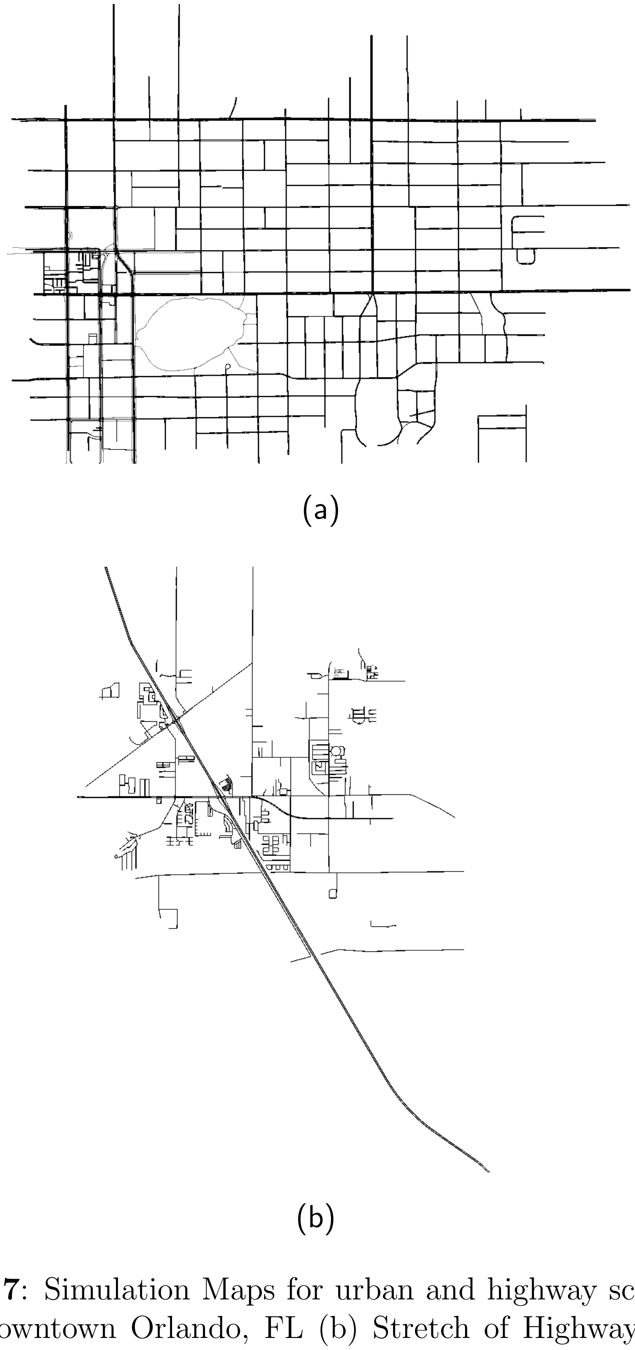


Figure 7.6: Output membership functions

The output includes 6 membership functions as shown in Figure 7.6, these are categorized as low, medium low, medium, medium high, high, and very high. The output value is used to determine the beacon interval in seconds. After determining the beacon interval a timer is set until the interval is hit and then the beacon is broadcasted. After the beacon is broadcasted the process for determining the beacon interval is repeated.


(a)

(b)

Figure 7.7: Simulation Maps for urban and highway scenarios (a) Part of Downtown Orlando, FL (b) Stretch of Highway on I95 in Florida

7.2.1 Tools and Techniques Used

All simulations were done using OMNET++, SUMO and VEINS. A review of these tools can been seen in Section 5.1.1.

7.2.2 Simulation Set Up

Table 7.2: Simulation Setup for Adaptive Beaconing

Parameters	**Values**
Number of Vehicles	50, 100, 150, 200, 250
Speed (m/s)	Between 5 to 40 m/s
Transmission Range	250m
Simulation Time	1200s
Bitrate	18 mbps
MAC Protocol	IEEE 802.11p
Data Packet Size	512 bytes

Figures 7.7a and 7.7b show the maps used for the urban and highway simulations. Figure 7.7a shows the map for the urban scenario, which is a portion of downtown Orlando, Florida. Figure 7.7b is the map of the highway scenario, which is a portion of I95 in Florida. The impact of the adaptive fuzzy logic beacon (FB) on GEOADV is compared against three different fixed beacon interval (FBI) rates. The FBI rates are 0.05, 0.5, and 2.5 seconds. The base routing protocols for all implementations is GEOADV.

For urban and highway simulations the map was extracted from OpenStreetMap [70] database. SUMO [69] was used to generate the movements of the vehicle nodes.

The first 1000 seconds of the SUMO output were discarded in order to obtain more accurate information on vehicular movements. The resulting output from SUMO, was then converted into input files for the OMNeT++ Simulation.

For the wireless configuration, IEEE 802.11p with DCF standard at the MAC layer was used. IEEE 802.11p and IEEE 1609.x are called wireless access in vehicular environments (WAVE) standards because their goal is to facilitate the provision of wireless access in vehicle environments [73, 74, 75, 76, 77]. At the physical layer, in order to characterize physical dissemination a shadowing propagation model was used. The communication range was set at 400m and had 80% probability of success for transmissions. These values were based off of Nzouonta's [63] simulation which used studies that reported real-life measurements between moving vehicles in the range 450-550m [78].

The simulation time for each protocol simulation was 1200 seconds. Six simulations for each beacon rate were done to illustrate how traffic effects each beaconing rate. The simulation parameters are summarized in Table 7.2.

7.2.3 Metrics

The performance of the GEOADV routing protocol enhance with FB, was assessed using the following metrics:

- Average delivery ratio
- Average delay
- Routing overhead ratio

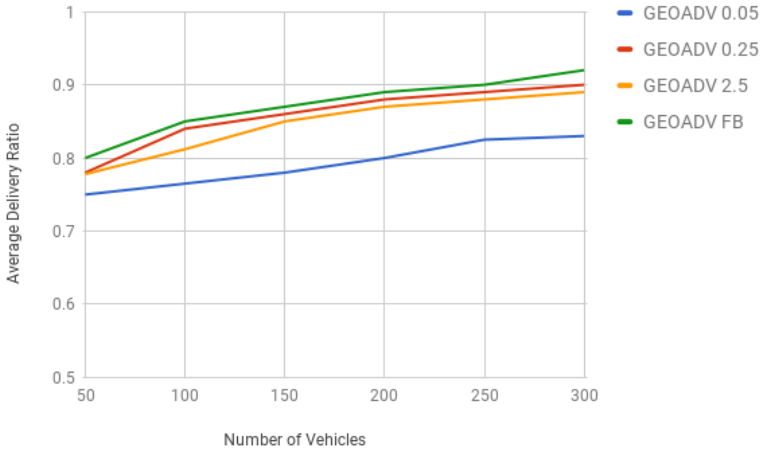
7.2.4 Simulation Results

Average delivery ratio

The average delivery ratio represents number of data packets successfully received over the total number of data packets sent. All duplicate packets which were generated by the loss of acknowledgments at the MAC layer were excluded. The average delivery ratio illustrates a routing protocol's ability to transfer data successfully end-to-end.

Across the network densities, it can be observed that the average delivery ratio of GEOADV increases as the network becomes denser. This is because the GEOADV protocol integrates road layouts with its route discovery system and higher density networks are able to create a more integrated path than lower density networks.

Figure 7.8a and Figure 7.8b show that both FB and the fixed beacon interval achieve similar average delivery ratio. GEOADV FB's average delivery ratio is increased between 0.01 and 0.09 for urban simulations and 0.023 to 0.12 for highway simulations. GEOADV 0.25 have an increased performance compared to FBI 0.05 due to the fact that GEOADV 0.05 has a high routing overhead. FB is able to perform at a better rate than the fixed beacon intervals due to its reduced routing overhead



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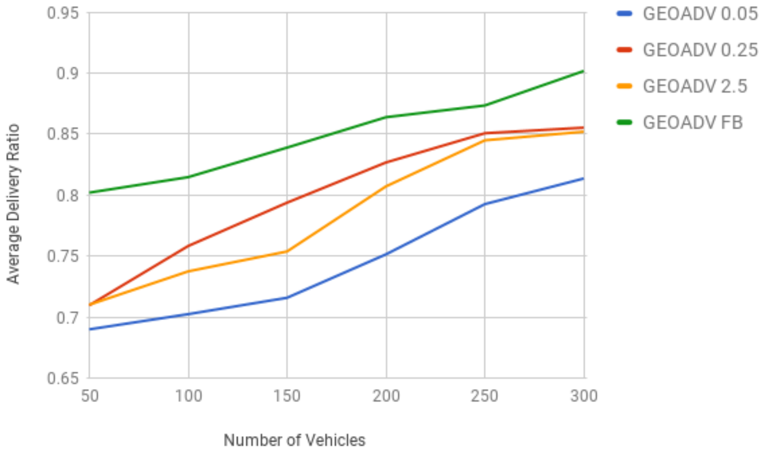

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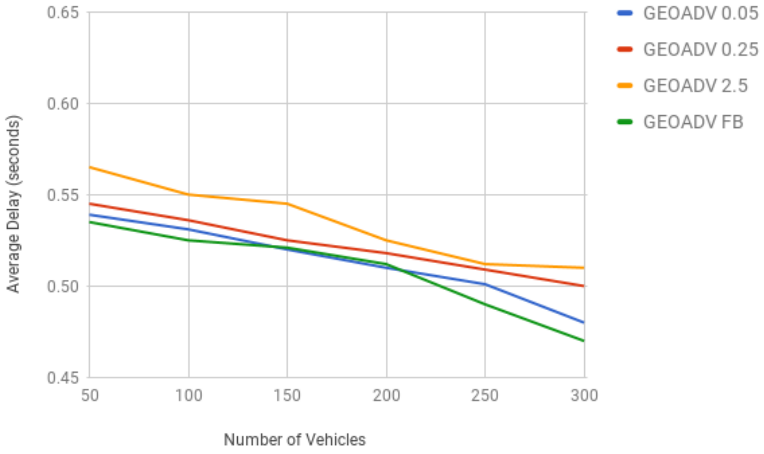
Figure 7.8: Average Delivery Ratio (a) urban environment simulation results, (b) highway environment simulation results

Average delay

Average delay shows the latency created by the routing protocol. Average delay is the computed by acquiring transmissions of all data packets delivered successfully.

Across the network densities, it can be observed that the average delay of GEOADV decreases as the network becomes denser. This is because the GEOADV protocol integrates road layouts with its route discovery system and higher density networks are able to create a more integrated path than lower density networks.

GEOADV FB has the lowest average delay, and that fixed beacons rates incur a higher average delay, in the urban and highway simulations, as can be seen in Figures 7.9a and 7.9b. GEOADV FB's lower average delay compared to the fixed rate beacons is due to the channel not being frequently used to broadcast messages and therefore nodes are able to forward data packets. GEOADV 2.5 has the highest average delay in both urban and highway simulations, showing that by reducing beacon frequency the information accuracy is degraded and packets which are forwarded are less suitable or become dropped due to the route becoming stale.



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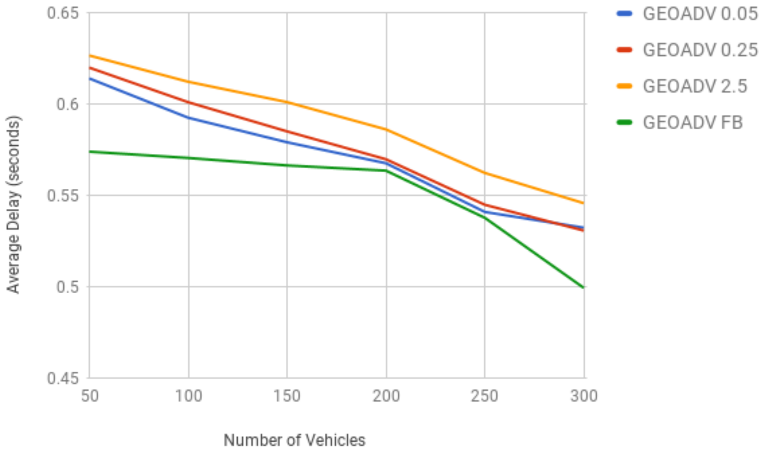


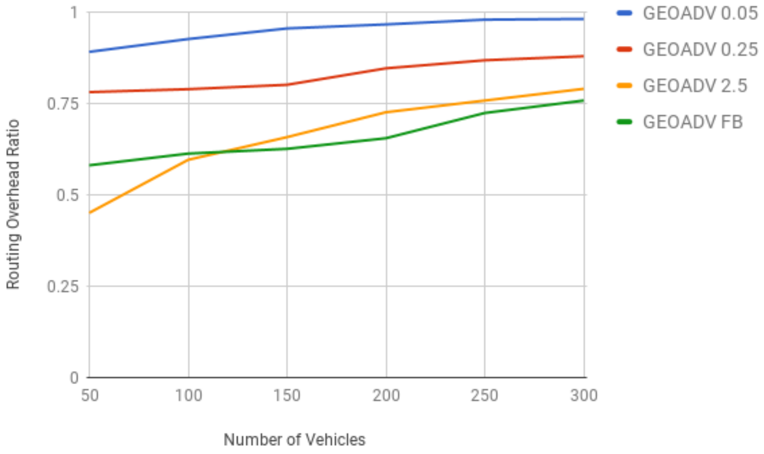
(b)

Figure 7.9: Average Delay (a) urban environment simulation results, (b) highway environment simulation results

Overhead

Routing overhead refers to network information sent by the protocol. This uses a portion of the available bandwidth for communication protocols. The routing overhead ratio shown in Figure **??** is determined by the total beacon packets emitted over the total transmitted number of packets in the network [83].

Figure 7.10a shows GEOADV FB reduces the routing overhead by up to 25.5% to 32.9% compared to the shortest fixed interval (0.05 seconds) in the urban simulation. In the highway simulation, shown in Figure 7.10b, GEOADV FB reduces the routing overhead by approximately 26.7% to 36%. This reduction in overhead is why the average delivery ratio and average delay for GEOADV FB was improved in both urban and highway environments. FB's has an increased routing overhead compared to GEOADV 2.5 for lower density networks. This is because beaconing rates based on the fuzzy logic method were determined to be higher than 2.5 seconds. By having an increased beacon frequency FB's average delivery ratio and average delay are improved. This shows that by reducing beacon frequency the information accuracy is degraded and packets which are forwarded are less suitable or get dropped due to the route becoming stale.



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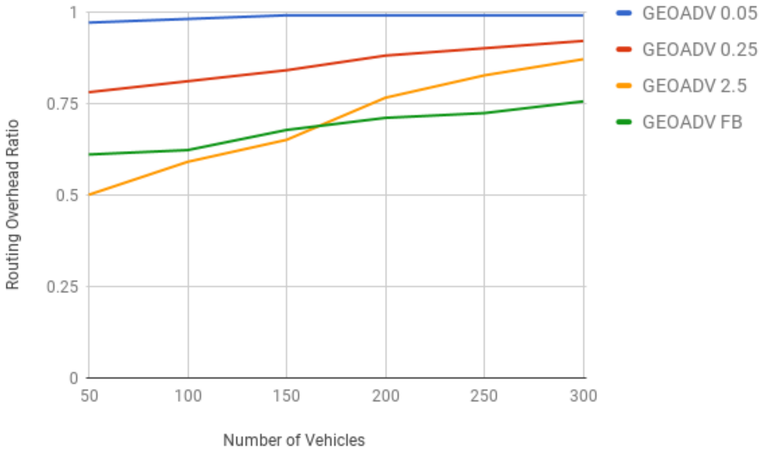

(b)

Figure 7.10: Routing Overhead (a) urban environment simulation results, (b) highway environment simulation results

7.3 SUMMARY

In geographic routing, nodes are able to maintain up-to-date information on their neighbors by using beaconing. Beaconing is successful in VANET environments but causes a large amount of routing overhead. This chapter investigated the impact adaptive beaconing has on the GEOADV protocol. GEOADV is a hybrid protocol, which combines both geographic and reactive routing. The GEOADV protocol is enhanced with an adaptive beaconing method, FB, which is based on fuzzy logic. Fuzzy Logic is based on natural language with a tolerance to imprecise data. Fuzzy logic is capable of modeling complex real-life scenarios. In the FB method, each vehicle starts with an initial broadcast interval. After the first broadcast, the next beacon interval is then determined by supplying the fuzzy inference engine with three inputs. These inputs are the number of neighbors in a one-hop distance, the speed of the vehicles, and the link quality of the network. GEOADV enhanced with FB was compared against GEOADV with three fixed beacon intervals (0.05, 0.25, 2.5) and demonstrated that GEOADV FB and the fixed beacon intervals achieved approximately similar average delivery ratio. FB experienced the lowest average delay, and fixed interval beacons incurred a higher average delay. FB reduced the routing overhead by approximately 25.5% to 32.9% in the urban simulation and 26.7% to 36% in the highway simulation. GEOADV FB's incurred an increased routing overhead compared to GEOADV 2.5 for lower density networks. By having an increased beacon frequency GEOADV FB's average delivery ratio and average delay were improved. This shows that by reducing beacon frequency the information accuracy is degraded and packets which are forwarded are less suitable or get dropped due to the route becoming stale. These results show that enhancing GEOADV with adaptive beaconing reduces the routing overhead significantly compared to fixed beacon rates.

CHAPTER 8

CONCLUSION

VANETs consist of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connections in which network nodes self-organize their communications via wireless channels without the need for a central access point. This dissertation focused on the need for adaptive routing protocols in Vehicular Ad-hoc Networks (VANETs) to assist with tolerance in low and high density network traffic, reduced throughput, and delay variation. The main contributions of this work are: GEOADV routing protocol, GEOADV-P routing protocol, GEOADV-PF routing protocol, and an investigation on the impact adaptive beaconing has on the GEOADV protocol.

The GEOADV routing protocols were introduced to solve the lack of adaptive routing protocols in urban and highway environments. Existing routing protocols like GPSR, GPSR-WR, and AODV-VANET work well in city environments, but do not perform adequately in sparse, rural, and highway environments.

GEOADV uses greedy forwarding to pass a message and combines our modified AODV protocol, AODV-WR, with our modified GPSR protocol, GPSR-WR, in order to create a hybrid routing protocol. GEOADV uses the calculation of the total weight of the route (TWR) to determine if an intermediate vehicle should be chosen to route data packets by examining the vehicle's sustained time spent within the radio range.

GEOADV-P is an enhancement of GEOADV, combining both geographic and reactive routing. GEOADV-P is augmented with calculations of the predicted total weight of the route (PTWR). The predicted speed, based on the vehicular speed and acceleration, is used in the calculation of PTWR.

Based on GEOADV-P, GEOADV-PF uses fuzzy logic to help determine an optimal route. Route evaluation in GEOADV-PF requires inputs related to the number of neighbors in one-hop, speeds of vehicles, and distances of vehicles to the destination. The output of the fuzzy system returns the probability of route selection. Introducing fuzzy systems to VANET can help with the flexibility of the routing protocol. The flexibility of a routing protocol can be improved by changing membership functions and fuzzy rule sets.

In the urban simulations, it was shown that GEOADV-PF maintains the smallest consistent average delay and outperforms AODV, GPSR, AODV-WR, GPSR-WR, and GEOADV in average delivery ratio. Despite GEOADV-PFs success, these simulations demonstrate that GEOADV-PFs overhead exceeds that of AODV but remains below that of GPSR and GEOADV. AODV and AODV-WR routing overhead are less than other protocols because they do not send packets when there is no communication in the network. GEOADV-PF has shown itself to be an adaptive VANET protocol by outperforming GPSR-WR in low density networks. GPSR-WR performs poorly in low density networks because network partitions prevent full coverage of large sections of the map and limit the information gathered by the protocols beacons. GEOADV-PF does not exhibit this poor behavior because of route repair features and the initiation of AODV-WR when items are not within a one-hop range. These advantages help GEOADV-PF be more adaptive than GPSR-WR in sparser networks.

In geographic routing, nodes are able to maintain up-to-date information on their neighbors by using beaconing. Beaconing is successful in VANET environments but causes a large amount of routing overhead. The GEOADV protocol was enhanced with an adaptive beaconing method, FB, which was based on fuzzy logic. In the FB method, each vehicle starts with the same initial broadcast interval. After the first broadcast, the next beacon interval is then determined by supplying the fuzzy inference engine with three inputs. These inputs are the number of neighbors in a one-hop distance, the speed of the vehicles, and the link quality of the network. GEOADV enhanced with FB was compared against GEOADV with three fixed beacon intervals (0.05, 0.25, 2.5) and demonstrated that GEOADV FB and the fixed beacon intervals achieved approximately similar average delivery ratio. FB experienced the lowest average delay, and fixed interval beacons incurred a higher average delay. FB reduced the routing overhead in both urban simulation and highway simulation. These results show that by enhancing GEOADV with adaptive beaconing the routing overhead was significantly reduced compared to fixed beacon rates.

8.1 FUTURE WORK

Several potential research topics and extensions can enhance the work. Consider the following:

- Predictive: By improving TWR and other calculations in routing protocols to using more predictive elements routing can be significantly enhanced. TWR can be enhanced to use predicted angular directions or future link quality estimates.
- Machine Learning: Machine learning gives us an opportunity of learning the most probable route to be taken. By reviewing traffic patterns of a map, most probable routes can be determined and used to determine connectivity between vehicles.

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