Winter 2009

Supporting Protocols for Structuring and Intelligent Information Dissemination in Vehicular Ad Hoc Networks

Filip Cuckov
Old Dominion University

Recommended Citation

Cuckov, Filip. "Supporting Protocols for Structuring and Intelligent Information Dissemination in Vehicular Ad Hoc Networks" (2009). Doctor of Philosophy (PhD), dissertation, Engineering and Technology, Old Dominion University, DOI: 10.25777/pyjz-tw44
https://digitalcommons.odu.edu/ece_etds/54

SUPPORTING PROTOCOLS FOR STRUCTURING AND INTELLIGENT INFORMATION DISSEMINATION IN VEHICULAR AD HOC NETWORKS

by

Filip Cuckov
B.S. May 2003, Old Dominion University
M.S. May 2005, Old Dominion University

A Dissertation Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirement for the Degree of

DOCTOR OF PHILOSOPHY

ELECTRICAL AND COMPUTER ENGINEERING

OLD DOMINION UNIVERSITY
December 2009

Approved by:

Min Song (Director)

Linda L. Vahala (Member)

Frederic D. McKenzie (Member)

Michele C. Weigle (Member)

ABSTRACT

SUPPORTING PROTOCOLS FOR STRUCTURING AND INTELLIGENT INFORMATION DISSEMINATION IN VEHICULAR AD HOC NETWORKS

Filip Cuckov
Old Dominion University, 2009
Director: Dr. Min Song

The goal of this dissertation is the presentation of supporting protocols for structuring and intelligent data dissemination in vehicular ad hoc networks (VANETs). The protocols are intended to first introduce a structure in VANETs, and thus promote the spatial reuse of network resources. Segmenting a flat VANET in multiple cluster structures allows for more efficient use of the available bandwidth, which can effectively increase the capacity of the network. The cluster structures can also improve the scalability of the underlying communication protocols. The structuring and maintenance of the network introduces additional overhead. The aim is to provide a mechanism for creating stable cluster structures in VANETs, and to minimize this associated overhead. Further a hybrid overlay-based geocast protocol for VANETs is presented. The protocol utilizes a backbone overlay virtual infrastructure on top of the physical network to provide geocast support, which is crucial for intervehicle communications since many applications provide group-oriented and location-oriented services. The final contribution is a structureless information dissemination scheme which creates a layered view of road conditions with a diminishing resolution as the viewing distance increases. Namely, the scheme first provides a high-detail local view of a given vehicle's neighbors and its immediate neighbors, which is further extended when information dissemination is employed. Each vehicle gets aggregated information for road conditions beyond this extended local view. The scheme allows for the preservation of unique reports within aggregated frames, such that safety critical notifications are kept in high detail, all for the benefit of the driver's improved decision making during emergency scenarios.

This work is dedicated to my family:

To my father, Dragan Čučkov, for instilling in me the spirit of embracing technology;

To my mother, Teuta Krašnica Čučkova, for always encouraging me to be persistent in my endeavors;

To my sister, Nataša Nikčevska, for all the bestowed wisdom at the crossroads in my life.

ACKNOWLEDGEMENTS

The work presented in this dissertation is a result from many years of dedicated research, persistence in times of difficulty, and good fortune delivered in moments of need. However, it would not be complete without the help, support, and guidance from many people.

I would like to first thank my advisor Dr. Min Song for all his invaluable advice, direction, and patience extended to me in the past several years. His professionalism and attention to detail in every aspect is reflected throughout this dissertation.

I am especially grateful to my dissertation committee members Dr. Linda Vahala, Dr. Rick McKenzie, and Dr. Michele Weigle, for their help, comments, and suggestions during my research.

The Department of Electrical and Computer Engineering has provided an excellent environment for my academic growth, and I am forever grateful for all the knowledge obtained in my studies, and for the extended opportunity to be a part of it. I would like to thank Deborah Kinney, Linda Marshall, and Romina Samson for their help throughout the years.

My American family, Jim and Claire Carbone, have been my pillar of support throughout my adult life, and I can never thank them enough for all their love and care. I would also like to thank Mihail Cutitaru for being a wonderful younger brother to me.

I would like to thank Ana Samolov for all her love and patience. Her wisdom and cheering on have been a driving force during my studies. Without her I would not be complete.

Last, but not least, I would like to thank my friends and roommates Milka Nikolić and Marija Ćitić for creating a loving and nurturing atmosphere in our home away from home.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLES

Page

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Intelligent Transportation Systems (ITS) is an area of research that has become of increased interest to the transportation industry, governments, and the academic community in recent years. Vehicular Ad-Hoc Networks (VANETs), wireless networks comprised of intelligent vehicles with on-board sensors of various types, a GPS digital-map system, and some computing capability, can directly facilitate the development of ITS, because they incorporate safety, comfort, and entertainment applications for vehicles.

VANETs may be considered a subset of Mobile Ad-Hoc Networks (MANETs), where the difference between the two is mostly in the average characteristics of the nodes within the network. MANET nodes are generally considered to be more diverse, in terms of mobility, computational ability, and battery life, and can range from laptops, PDAs, and even newer generation cell phones, all with drastically different characteristics and mobility patterns. Most communication protocols developed for MANETs have been evaluated using a random walk algorithm for the movement of the nodes in the network and their focus is set on minimizing the communication for the purpose of extending the lifetime of the nodes. The battery life of VANET nodes is a non-issue as it is generally accepted that the power is provided by the vehicles themselves, while the computational ability is generally considered to be equivalent to that of a modern personal computer. Additionally, VANET nodes most commonly would have access to a GPS device, and the mobility pattern exhibited by the nodes cannot be said to follow the traditional way-point model most

---

This dissertation follows the style of *IEEE Transactions.*

commonly used in MANET analysis and simulations. The mobility of nodes within a VANET is restricted to a highway/road infrastructure and their speeds are generally faster than in MANET, and the directionality of the moving nodes also plays an important role in communication. The application scope of MANETs is more general, where protocols do not necessarily focus on time-critical information dissemination. VANETs have been designed to support, first and foremost, safety applications, which require robust and efficient communication protocols that aim to provide prompt delivery of emergency data. Therefore, communication solutions developed for MANETs do not necessarily translate well in the VANET domain because of the extremely dynamic network topology defined by the very nature of VANETs and the behavior of the nodes within.

I.1 VANET CLUSTERING

Clustering is an important area of research for Vehicular Ad-Hoc Networks which has received much attention from the academic community in recent years ([1],[2],[3]-[5],[6],[7]). Unlike a non-clustered network, its counterpart can guarantee scalability and some basic levels of performance in the presence of high mobility and large number of nodes. Clustering is an effective tool for topology control because it can introduce structure in a flat network, and thus effectively increase the network capacity by the spatial reuse of network resources. Additionally, by the introduction of cluster heads, routing of information is simplified both in the intra-cluster and inter-cluster domain, and within the network as a whole. The cluster heads form a backbone of the network and act as local managers to cluster members, as illustrated in Figure 1. This means that clustering

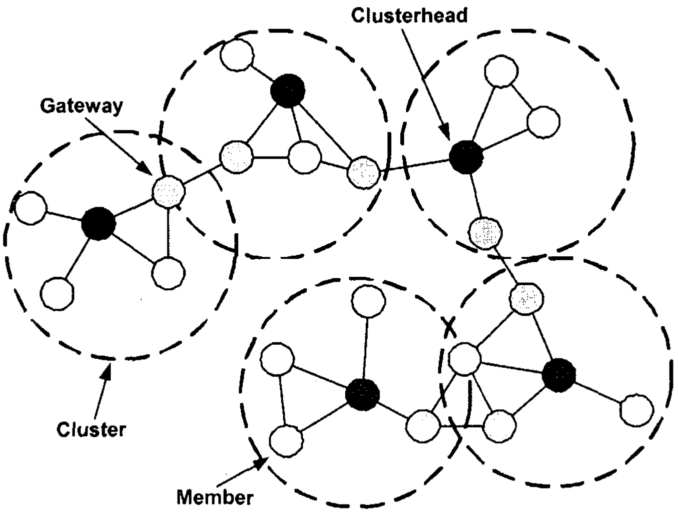


Fig. 1: Cluster structure illustration.

provides a superior structure for data dissemination [8], where information is propagated through the cluster heads, which in turn decide the relevance of that specific information for the local area in question. Finally, a regular node in a cluster structure needs to know high-resolution information only about its co-members, thus reducing the overall information stored locally at that node, compared to any node in a flat network.

The communication overhead of a proactive routing protocol in a flat network with n nodes is $O(n^2)$ [9]. For large-scale networks, such as VANETs where the number of nodes in a local urban area could range from tens of thousands to hundreds of thousands, such an overhead would render the network useless. Therefore, the introduction of a hierarchical structure is of great importance to the performance of VANETs, and clustering proves to be one such effective method of topology control. Clustering, however, is not overhead-free and creating and maintaining cluster structures within an ad-hoc network comes with additional communication and computational costs. Furthermore, some clustering schemes suffer from a ripple effect of re-clustering ([5],[7],[8]), which happens when clusters are re-built over the entire network due to a single cluster failure. Most clustering schemes employ an explicit message exchange between nodes, and in the case of high mobility (as in VANETs) cluster related information is exchanged more rapidly, causing higher bandwidth consumption and reduced network performance.

Many established protocols exist for MANETs (such as AODV, DSR, etc.) that provide routing support either in on-demand or in a table-driven fashion. These protocols provide basic communication mechanisms which can effectively manage the MANET's absence of firm topology. Table-driven routing protocols are more stable than their on-demand counterpart, but require more communication in order to maintain an up-to-date view of the network topology, and thus are prone to higher overhead. On-demand routing protocols aim to avoid this overhead, but in doing so, they become more sensitive to topology changes due to high node mobility. When the size of the network increases, the communication overhead for maintaining fresh routing information also increases which drastically affects the scalability of the protocols. An average MANET may contain anywhere from tens to hundreds of nodes, while a VANET may contain thousands, at the very least. Thus, there is a need for a structure that can support these routing protocols, so that they can scale well. One method of topology control is clustering, where the network is segmented in smaller groups of geographically adjacent nodes. This way the routing information can be reduced for all the nodes within the network, and the spatial reuse of network resources is promoted. Cluster heads can act as managers of their adjacent nodes and form a backbone for inter-cluster routing which can support long distance communication and data dissemination.

I.2 GEOCAST ROUTING IN VANETS

Plenty of unicast routing protocols have been developed for the MANET domain since its conception. Most unicast routing protocols are based on either table-driven or on-demand techniques and are created to facilitate end-to-end delivery between mobile hosts. In cases where a single mobile host may need to send the same exact message to multiple selected receiving hosts, the existing unicast protocols would reproduce the same message for each host, while specifying the unique destination, and would send them individually. This is clearly an inefficient method of data forwarding to groups of hosts that need to receive the same information. The more logical way to do this is to send the message only once, while specifying the multiple intended destinations. The transmission of messages to a group of hosts identified by a single destination address is referred to as multicasting, depicted in Figure 2. Multicasting can improve the efficiency of wireless links, by exploiting the inherent broadcast property of the medium. Since many applications for MANETs, and consequently VANETs, involve group-oriented communication, multicasting support is crucial for increased network performance and scalability. Multicasting support could be provided through simple flooding techniques, however this may introduce extremely high overhead and delays to the underlying network. Instead, most multicasting protocols focus on organizing participating nodes into a structure that can be easily managed under the highly dynamic MANET/VANET environment. VANET groups, or clusters, possess a spatial commonality that can be furthermore exploited by employing a variant of multicasting: geocast.

Traditionally a multicast group is defined as a collection of arbitrarily positioned hosts

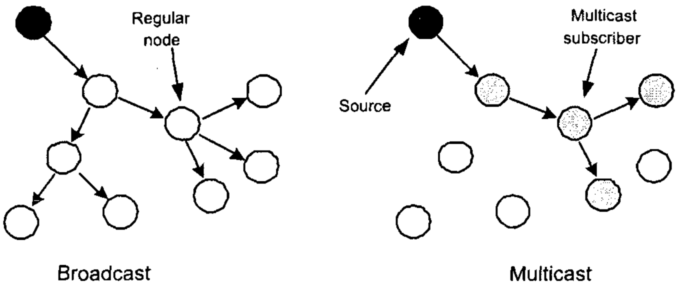


Fig. 2: Broadcast versus multicast.

subscribed to a service of common interest. In contrast, a geocast group is a set of hosts temporally coupled in a specific area, where the problem is how to efficiently deliver a message to such a dynamic group. The common approach of solving this problem is for the geocast protocol to provide a distributed message delivery mechanism, in which each node bases its next-hop decision solely on its location, the location of its neighbors, and the destination's location. This stateless approach is the simplest variant of geocast, where multicast support is provided through unicast flooding techniques by exploiting the inherent broadcast property of the wireless medium. Stateless geocast protocols avoid creating a structure and place the computational burden on the sending hosts, which maintain and specify the list of destinations in the packet header.

Overlay-based protocols build a virtual infrastructure on top of the network most commonly in a form of a tree or a mesh, or a combination of both. These structures then become the backbone for multicast support. The advantage of overlay protocols is that the virtual topology is a stable structure which can remain unchanged even if the physical topology changes. Consequently this state change concealment may result in increased management to hide the physical topology changes, eventually resulting in longer delays and lower efficiency in packet delivery. Relaxing the rigidness constraint of the overlay backbone can result in a geocast protocol which can intelligently organize participating nodes into a set of superimposed structures which can be easily managed under the highly dynamic VANET environment.

Geocast protocols that need to define an explicit route towards the zone of relevance require an underlying structure from which a route can be constructed. Protocols that favor the initial construction of a route are more balanced and efficient in the geocast forwarding phase. The on-demand structures created for geocast support by this category of protocols are transversely-grown, destination-biased, unbalanced trees and meshes. Currently, to the author's best knowledge, there are no existing geocast protocols for VANETs which attempt to merge the stateless and overlay-network based approaches. A hybrid approach can exploit the performance benefit provided by the earlier and the robustness of the latter approach. The fusion of these methods, especially in the presence of a structured overlay network backbone, can be used to introduce a performance benefit in geocast communications for VANETs.

I.3 INFORMATION DISSEMINATION IN VANETS

Communication protocols employed in VANETs must manage the large number of highly dynamic nodes present in the network and must aim to provide efficient service while minimizing overhead and delays for time-critical applications. Emergency applications, which can be classified as time-critical, require rapid and efficient data delivery services, so that all vehicles that need to get informed about an emergency or road hazards receive the information promptly. Comfort applications, non-critical information services aimed to improve driver comfort and awareness, can also benefit from these mechanisms. The goal of information dissemination in VANETs is to provide efficient service for emergency notifications while aiming to minimize the associated overhead.

To illustrate the need for intelligent information dissemination schemes in VANETs, consider the following scenario where a collision on a segment of a highway has slowed down or even stalled traffic in one direction. If vehicles near the accident independently begin to create and broadcast this information that may need to reach other vehicles which are kilometers away, there would be a series of redundant reports which, through flooding techniques, may cause a large broadcast storm that will propagate along the direction of the flood, creating excessive congestion and delays in the network. The end result could be that the report is not delivered in a timely manner (or not at all) so that drivers approaching the accident site will fail to react quickly and intelligently to this event. One obvious solution to this problem is to reduce collisions by eliminating redundant re-broadcasts of the same information. Data aggregation can be also employed to combine reports and reduce the amount of data forwarded throughout the network, thus reducing overhead. Furthermore, utilizing a communication technique other than flooding, which will minimize channel contention and delays, will bring about faster data delivery.

Most data aggregation and dissemination approaches for VANETs attempt to create and utilize a structure for collecting information. The structures vary and can be categorized as either node-centric, as in a tree, mesh, or a cluster, or road-centric, as in highway segmentation. Tree-based data aggregation is centered on a parent node that is responsible for collecting, filtering, and aggregating information from a set of child nodes, where the key challenge is how to construct and maintain an efficient aggregation tree. The problem with tree-based approaches is that often global knowledge of the network topology is required to construct and maintain an efficient tree, which is a very large problem for large and dynamic networks like VANETs. Cluster-based aggregation of data revolves around a cluster-head node, which controls a group of regular nodes, that send data up to the head where it is aggregated. The dissemination in this approach is done mainly through the cluster-heads, which in a sense create a backbone of master nodes. As with any master node, cluster-heads present a single point of failure, and the efficiency of any dissemination scheme largely depends on the stability of the clusters. Segment-based approaches attempt to pre-divide highways in equidistant static segments. At any given time vehicles belonging to a given segment could aggregate information about that segment and disseminate the information through temporary segment master nodes (usually ones closest to the segment center). The problem with this approach is that the management of the short-lived segment membership and role selection introduces overhead from too many and frequent segment updates.

I.4 CONTRIBUTIONS

The goal of this dissertation is the presentation of supporting protocols for structuring and intelligent information dissemination in vehicular *ad hoc* networks. The protocols are intended to first introduce a structure in VANETs, and thus promote the spatial reuse of network resources. Segmenting a flat VANET in multiple cluster structures allows for more efficient use of the available bandwidth, which can effectively increase the capacity of the network. The cluster structures can also improve the scalability of the underlying communication protocols. The structuring and maintenance of the network introduces additional overhead. The aim of this researcg is to provide a mechanism for creating stable cluster structures in VANETs, and to minimize the associated overhead. The clustering scheme is then utilized to provide support for more efficient large distance routing and data dissemination by formulating a geocast protocol that creates a dedicated multicast cluster head backbone overlay virtual infrastructure on top of the physical network. This backbone provides support for group-oriented communication in VANETs, which is utilized in the information dissemination scheme to create a detailed local view and layered extended view of traffic conditions for each vehicle. The intent is for these supporting protocols to increase the performance and scalability of VANETs. The unique contributions of this dissertation are the following protocols for structuring and intelligent information dissemination:

- A Mobility-Aware General-Purpose VANET Clustering Scheme,
- A Hybrid Overlay-Network Geocast Protocol for VANETs, and
- A Geocast Driven Structureless Information Dissemination Scheme for VANETs.

The clustering schemes reviewed in the following chapter focus on providing stable clusters with low overhead, and some of these also aim to address mobility as a factor for cluster creation and maintenance. However, not many of those address the type of mobility that VANET nodes exhibit. The reviewed related works that focus on MANET clustering generally form a cluster structure as depicted in Figure 1. These MANET clusters can

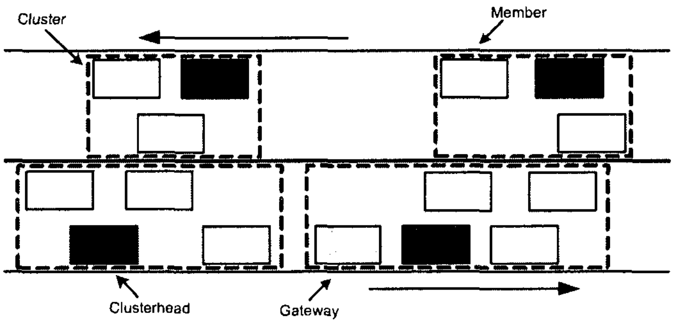


Fig. 3: Traditional depiction of directional VANET clusters.

effectively increase the scalability of the underlying routing protocols, assuming that the nodes exhibit a random-walk movement at relatively low speeds. Since VANET nodes exhibit more directed movements at much higher speeds, it makes little sense to employ the same clustering mechanisms. For instance, if the directionality of the nodes was ignored in a small VANET placed on an interstate, the average lifetime of the clusters would decrease rapidly since nodes moving in opposite directions would attempt to form clusters that would last for a short amount of time, thus decreasing their stability and increasing the overhead associated with re-clustering. In this dissertation, a clustering scheme designed specifically for VANETs is presented that creates stable cluster structures by exploiting the directionality factor of the moving nodes. The clusters created by this scheme resemble the ones depicted in Figure 3, where clusters are only formed between vehicles moving in the same direction on the same roadway.

Building on the developed clustering scheme, a VANET backbone can then be created by the interconnection of all the cluster heads, which can be utilized for providing a method for efficient data dissemination. The cluster heads can act as local managers of their subordinate nodes, and gather information on the average characteristics of the cluster. This data can then be forwarded to other cluster heads, which can then form a detailed picture of the state of the network, or at the very least, their immediate surroundings. One way the data can be sent between cluster heads is by a direct pair wise communication. Since the clustering scheme assigns a special gateway role to nodes that are in communication with other clusters, the data would logically propagate through those nodes. In a scenario of a densely populated network where the cluster backbone is large, this pair wise communication is performed between a given cluster and every other cluster in the backbone. This method introduces redundant communication and makes little sense, since the same exact data will possibly propagate many times through intermediate cluster heads to reach the edge of the backbone. A more efficient way to do this is to send the same data only once while specifying a list of receivers, which can improve the overall efficiency of the wireless links. Since the clustering scheme provides an existing structure, this structure is utilized to form a dedicated multicast cluster head backbone that could be used for efficient data dissemination. This dissertation presents a hybrid overlay-based geocast protocol, which utilizes a backbone overlay virtual infrastructure on top of the physical network to provide geocast support, which is crucial for group and location-oriented communication in VANETs. The presented protocol is a hybrid approach which uniquely utilizes an intrinsic structure to simplify the routing computation and provides persistent support for location-based communication in VANETs.

The final contribution of this dissertation is a structureless information dissemination scheme which creates a layered view of road conditions with a diminishing resolution as the viewing distance increases. Namely, the scheme first provides a high-detail local view of a given vehicle's neighbors and their immediate neighbors, which is further extended when information dissemination is employed. Each vehicle gets aggregated information for road conditions beyond this extended local view. The scheme allows for the preservation of unique reports within aggregated frames, such that safety-critical notifications are kept in high detail, all for the benefit of the driver's improved decision making during emergency scenarios.

I.5 OUTLINE

The remainder of this dissertation follows a traditional format. Chapter II discusses the background of MANET and VANET clustering schemes, multicast and geocast protocols, and data aggregation and information dissemination schemes. This chapter also presents related work in the mentioned fields of research as well as their unique contributions and limitations. Chapter III presents the first contribution of this dissertation, a mobility-aware general-purpose clustering scheme for VANETs. This chapter provides the details of the scheme, as well its analysis and simulations of its operation. In Chapter IV a hybrid overlay-network geocast protocol for VANETs is presented. This protocol is analyzed for both structured and unstructured VANETs. Chapter V presents a geocast-driven structureless information dissemination scheme, that utilizes the geocast protocol presented in Chapter IV. Chapter VI concludes this dissertation by discussing the unique contributions.

CHAPTER II

BACKGROUND AND RELATED WORK

II.1 CLUSTERING

Depending on the approach taken for cluster formation/maintenance, clustering schemes are categorized as low-maintenance or high-maintenance, mobility-aware, energy-efficient, load-balancing, or a combination-metrics-based, where any of the previous methods are combined. It is desireable for robust clustering schemes designed for VANETs to be low-cost and to employ mobility-awareness, while conforming to the properties of the network. Additionally, the schemes must not make an assumption of a stationary period for cluster formation, and they must address cluster stability and the high-mobility exhibited by the nodes, while reducing communication and computational costs.

VANETs inherently possess a mobility element that is very different from any other type of network, which may present an obstacle or advantage in the design of protocols and communication schemes. A traditional view of the VANET cluster structure that takes the directionality of vehicles as a factor is shown in Figure 3.

II.1.1 Mobility-Based Clustering Schemes for MANETs

Some clustering schemes that take node mobility into consideration are the Distributed Dynamic Clustering Algorithm (DDCA) [11], and the Mobility Based Metric for Clustering in MANETs (MOBIC) [5].

DDCA satisfies the non-stationarity property by exhibiting the ability for clusters to be formed in dynamic scenarios where mobile nodes utilizing DDCA can obtain complete and accurate information of a local area. Each node runs the clustering scheme independently, continuously, and asynchronously, and, furthermore, nodes desiring to be cluster heads (CH) need not to have any special attributes. The cluster size can be adaptively adjusted in DDCA, which causes the scheme to form large clusters in networks with low mobility and small clusters in highly-dynamic networks. Routing is table-driven within the clusters and inter-cluster routing is on-demand. DDCA can adaptively select the routing mechanisms, but the way this is done is not specified in detail. Some unique features of DDCA are that it requires no periodic re-clustering, and that CHs and cluster members do not require a direct connection. As long as members can reach their CHs they will stay within the same cluster. This last property of DDCA may make sense for MANETs, but for VANETs it makes little sense.

MOBIC is a scheme which addresses node mobility more suitably for VANETs. It is designed with somewhat uniform group mobility in mind, where nodes are expected to move with low relative speeds to each other, similarly to vehicles on a highway. The cluster creation and joining methods in MOBIC are similar to those of DDCA. The difference is that any nodes that possesses a low relative speed to its neighbors, calculated by taking into account the signal strength of a pair of messages from each neighbor, has the ability to become a CH. A node becomes a CH if it has the lowest relative speed to all the nodes interested in being cluster members. This operation requires a lot of pairwise communication before the decision is made which to be the CH. A unique feature of MOBIC that avoids unnecessary cluster merging is that merging occurs only when a CH is within 1-hop communicating range of another CH that is only moving in the same direction. The

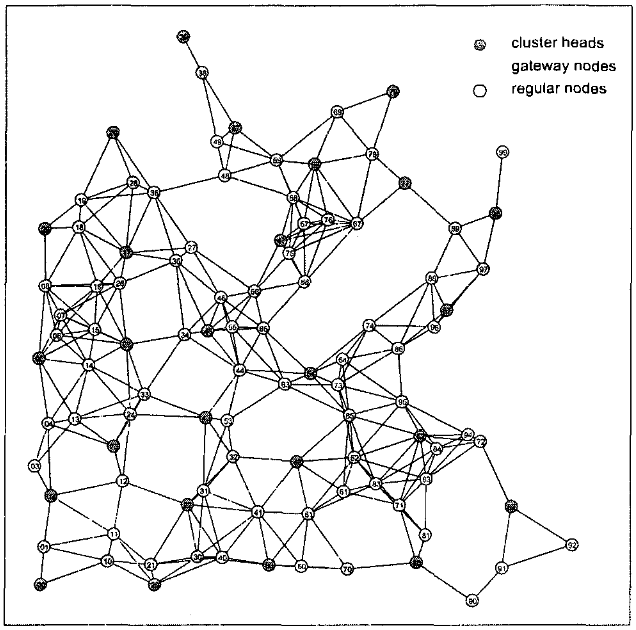


Fig. 4: LCC Clustering among 100 nodes.

performance of MOBIC can decrease rapidly in the event of random node movement and highly-variable node speeds. In cases such as these cluster stability is not guaranteed by MOBIC, but could be enhanced by modifying its 1-hop cluster size property.

Both MOBIC and DDCA are based on low-cost cluster creation and maintenance principles defined by the Least Cluster Change (LCC) [7], Adaptive Clustering for Mobile Wireless Networks (ACMN) [6], and the Passive Clustering (PC) [8] scheme. LCC and ACMN require an initial stationary period for cluster construction. LCC is a pioneer in building robust cluster structures based on looser rules than its predecessors, where it is preferred to execute re-clustering procedures periodically to maintain cluster stability.

LCC forms initial clusters by simply choosing CHs to be the nodes with the lowest identifier (ID) in the neighborhood. This property of LCC increases the overall clusters' stability and their lifetimes. A sample result of LCC clustering on one hundred nodes is shown in Figure 4. Re-clustering in LCC is done only in two possible cases: when two CHs are within 1-hop communication range (causing a cluster merge), and when a node can not access a CH (forcing it to create a lone cluster). The latter case of re-clustering in LCC may be a cause of large communication overhead in the network in the event that there are frequent CH disconnects in the cluster architecture. ACMN is unique in the sense that clusters are formed without any nodes being assigned any special role in the network. Cluster formation in ACMN is the same as in LCC, except that once clusters are formed, CHs and gateways revert to being ordinary nodes. ACMN requires that the distance between any two nodes in the cluster to be at most two hops, and if this property of the cluster is violated at any time, a cluster re-structuring process is invoked.

The Passive Clustering scheme (PC) does not require a stationary period for initial cluster formation and nodes do not exchange cluster control messages explicitly. Cluster control messages in PC are piggybacked on ordinary messages that are exchanged only when nodes have something to send. Not every node that can be a gateway becomes one in PC. The number of gateways in the network is limited by a rule which states that the distance between gateways and CHs must be above/below some (unspecified) threshold value. This decision requires a global knowledge of the cluster structure within the network and may be the cause of unnecessary delays and/or overhead.

II.1.2 Clustering for VANETs

Several papers that provide some thought on how clustering may be beneficial specifically for VANETs are the: Cluster-Based Multi-Channel Communication Protocols in VANETs (CBMCCP) [10], Efficient Secure Aggregation in VANETs (ESAV) [14], and the Application-based Clustering in VANET (ACV) [15]. These works cover three different aspects of clustering for VANETs, but none of them dwell on the topic of clustering specifically. The first focuses on the division and usage of Direct Short Radio Communication (DSRC) dedicated channels for inter-ckuster and intra-cluster purposes, the second centers on security through data aggregation achieved by network segregation into geographical clusters, and the third discusses a possible application of clustering in VANETs.

CBMCCP focuses on the channel communication mechanisms, assuming a simplified clustering scheme. It consist of three protocols: cluster configuration, inter-cluster communication, and coordination and communication protocols. The scheme allots two of the seven available DSRC channels for inter-cluster control and data, respectively. One channel is alloted for intra-cluster control and the remaining four channels are alloted for intra-cluster data communication. CBMCCP does not discuss the methods of creating clusters, rather it assumes clusters already exist and a vehicle that enters the highway initiates a *Join* cluster routine. Cluster head selection is initiated in the event of a failure of a CH. The intra-cluster coordination and communication protocol focuses on dividing intra-cluster resources using a TDMA based scheme. Inter-cluster communication is done via different channels and differing priorities depending on if the type of traffic is real-time or non-real-time.

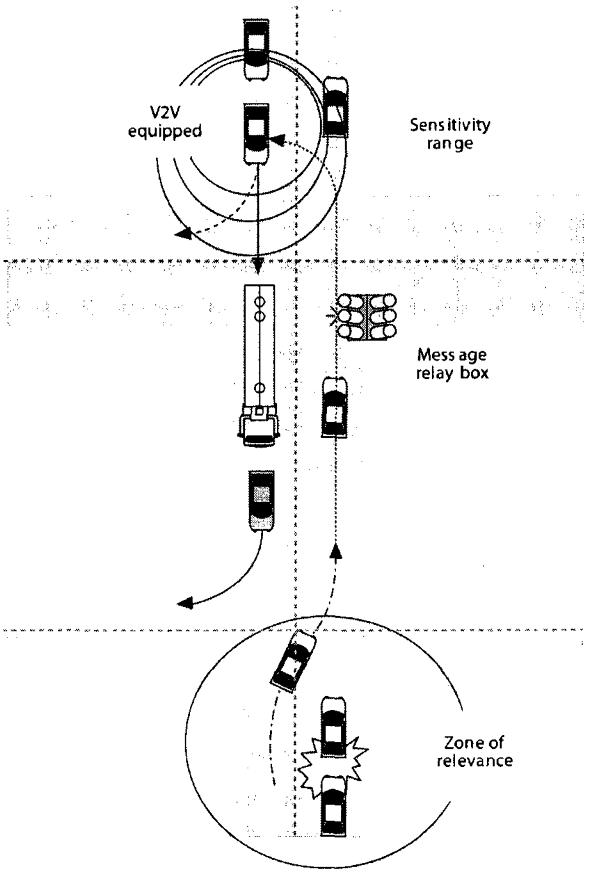


Fig. 5: ACV Danger warning system utilizing relay boxes.

ESAV and ACV explore different aspects of the application of clustering within VANETs. ESAV focuses on providing a secure framework for VANET through data aggregation, but additionally explores the topic of group management. In ESAV highways are divided in predefined segments of certain size. Vehicles are expected to be equipped with a digital map that contains the segmenting information. ESAV employs on-the-fly group formation based on the segment in which a vehicle is located. Once a vehicle enters a segment it becomes a member of that group. If a vehicle is on the edge of a group, being closest to the border between two segments, it is assigned a gateway status. Using this segmented highway grouping concept, ESAV provides a framework for secure communication in VANETs. The idea of using a predefined segmented map information for data aggregation has been explored previously (in [16]), but not from the security standpoint. ACV proposes clustering at the application level where multiple orthogonal clusters may be formed between vehicles based on the application at hand. The advantage of having clusters organized by the application layer is that every application can apply different rules to its clustering algorithm. ACV does not propose a specific clustering scheme, just some sample applications mostly utilizing relay-boxes (additional infrastructure) for the local-area propagation of warning messages, such as in intersections and highway ramps, as shown in Figure 5.

The stable clustering in pseudo-linear highly mobile ad hoc networks [12] presents several solutions such as the Dynamic Doppler Velocity Clustering (DDVC) and the Dynamic Link Duration Clustering (DLDC). They consider only 1-hop clusters, aiming to privide a stable clustering scheme for highly mobile nodes with a pseudo-linear directionality, such as vehicles on a highway, trains, commercial air traffic, etc. DDVC provides a mobility metric which could be utilized for cluster creation in cases when GPS data is unavailable for positioning information. The algorithm specifies a metric derived from the relative velocity between nodes, by examining the Doppler shift of the control packets exchanged. From this metric DDVC determines, similarly to MOBIC, the directionality of moving nodes, and creates clusters based on the information. DLDC is an additional clustering scheme which creates clusters based on the estimated link expiration time between nodes. When position and velocity are taken into consideration, the link duration time between

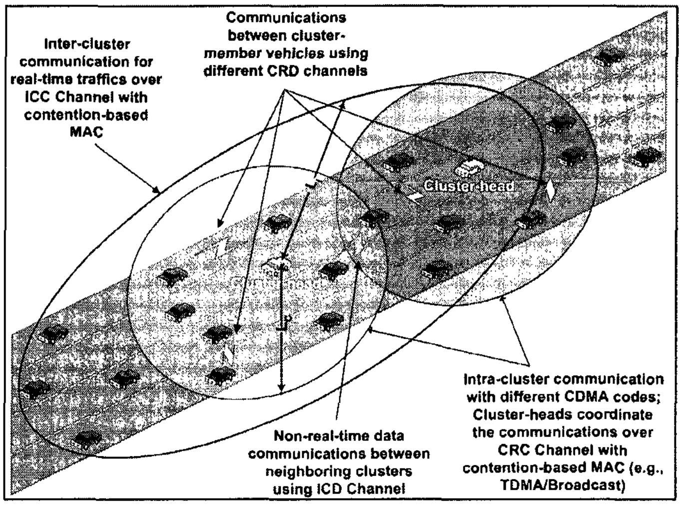


Fig. 6: CMCS Operation illustration.

two nodes can be more precisely estimated, and this estimation is utilized by DLDC to create clusters that are more stable.

The Cluster-Based Multichannel MAC Protocols (CMCS) defined in [13] are suited for QoS provisioning over VANETs. Even though CMCS focuses on the MAC specifics and methods for providing QoS, it defines a clustering scheme based on three different protocols: the Cluster Configuration Protocol, the Intercluster Communication Protocol, and the Intracluster Coordination and Communication Protocol. The communication of CMCS clusters is illustrated in Figure 6. The scheme effectively manages cluster-membership, real-time traffic delivery and non-real-time data communications.

II.2 MULTICAST AND GEOCAST

Most protocols for multicasting support in MANETs can be categorized as either overlay-based or stateless. Overlay-based approaches build a multicasting structure on top of the

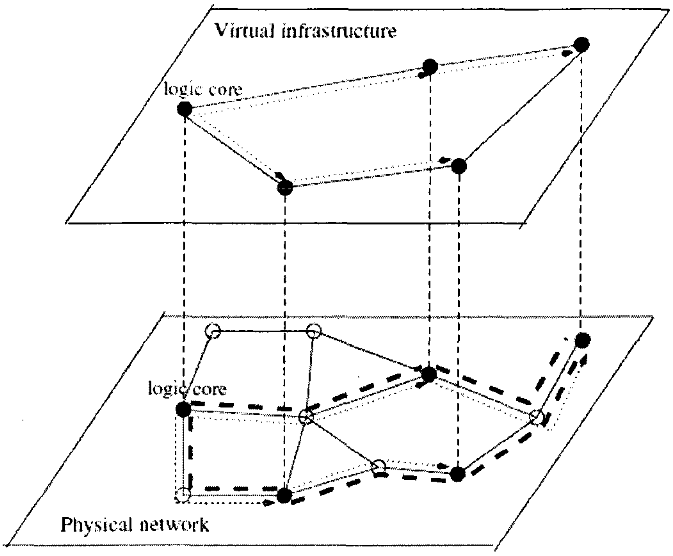


Fig. 7: Overlay virtual infrastructure.

network most commonly in a form of a tree or a mesh, where the combination of both is considered to be a hybrid approach. Since overlay-based approaches seem to introduce an overhead for the creation and maintenance of the multicasting structures, stateless multicasting avoids any structure and puts the computational burden on the sending hosts, which maintain and specify the list of destinations in the packet header.

II.2.1 Overlay Multicasting

Overlay multicasting builds a virtual infrastructure to form an overlay network on top of the physical network, as shown in Figure 7, where each link represents a unicast tunnel. The overlay network is responsible for implementing multicast functionalities such as routing, packet duplication, and dynamic membership maintenance. The advantage in

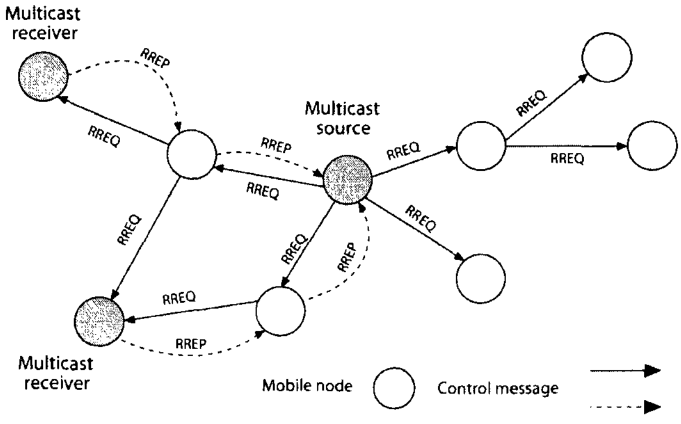


Fig. 8: MAODV Route discovery.

this approach is that the virtual topology can remain unchanged even if the physical topology changes. Consequently, this may involve increased management to hide the physical topology changes, resulting in long delays and lower efficiency in packet delivery.

The Multicast Operation of the AODV protocol (MAODV) [24], is an extension to the well-known AODV protocol that includes an additional routing table for multicasting purposes. MAODV discovers multicast routes in an on-demand fashion using the same route discovery defined in AODV, as illustrated by Figure 8. When a source node wishes to create a multicast tree, or simply has data to send, it initiates a route request procedure that propagates throughout the network. Intermediate nodes receiving the route request message save the path in the AODV table, and the shortest reverse path to the source, which is then later used for more efficient reverse data delivery. Only nodes that are designated as the multicast target by the source, or wishing to participate in the multicast, may respond to the propagating request. This response to join the multicast tree is done once the request message reaches its destination and a reply message is sent back to the source by the destination node through all intermediate nodes. Once the source node receives the replies, it creates a logical tree including all participating nodes and the destinations. The structure of the tree is kept alive through periodic *Hello* messages. When the tree structure changes, the protocol informs all participating nodes of the change and resumes its operation. If a multicast tree can not be reconnected then the nodes that are on the edges of the connection failure become leaders for a new tree construction that aims to reach the source through new links.

The Ad-hoc Multicast Routing protocol (AMRoute) [27], is an ad-hoc multicasting protocol that uses the overlay method for multicasting. AMRoute creates bidirectional shared trees and meshes (it could be considered to be a hybrid approach) utilizing only nodes that are interested in participating within a multicast group as the nodes of the tree. The tree links between the multicast tree members are unicast tunnels, which are point-to-point links between two multicast routers located anywhere within the network. This means that AMRoute does not need to be supported by any nonparticipating nodes, and also, because the underlying unicast routing protocol is responsible for packet delivery, the multicast tree structure does not need to change in cases when the underlying network topology changes.

Another protocol for overlay multicasting is the Progressively Adapted Sub-Tree in Dynamic Mesh (PAST-DM) [19]. The main difference between PAST-DM and other source-based overlay multicasting protocols is that in PAST-DM each source constructs its own data delivery tree. The tree construction, based on a modified source-based Steiner tree algorithm, introduces no additional overhead of control messages for the tree creation by utilizing each node's local link state table. A Steiner tree is a fully connected tree in a minimal manner with $N-2$ connection points, where a connection point must have a degree of three, and N is the number of nodes. The local link state table is periodically refreshed by a local neighbor discovery flood. The tree construction process begins at the source, which designates all of its immediate neighbors to be its first-level children. These children then repeat the algorithm to establish their own subtrees. Once all the multicast-participating nodes have been reached and included in the Steiner tree, the source forwards the data packet to the subtrees. The virtual topology progressively adapts to the changes of the underlying network topology, through periodic updates obtained from the neighbor discovery flood. Simulation results show that PAST-DM is robust and efficient, introduces low overhead, and it outperforms AMRoute, especially when the periodic updates are conducted less frequently.

The Application Layer Multicasting Algorithm (ALMA) [18] is a flexible receiver-driven overlay multicasting protocol which creates a logical tree between multicast members. The construction of the tree begins at the receiver-end. When a node wishes to subscribe to a multicast group, it finds the first node on the logical path from itself to the root of the multicast tree. The node may choose if it wishes to be a permanent child node, or to host other children. Each child node is responsible for maintaining the connection to its parent, and needs not notify its parent if it finds a better logical connection to the multicast tree. Parent nodes, which may also be children to other nodes, are responsible for notifying all immediate multicast group nodes of any changes in connectivity. The protocol contains mechanisms that facilitate the reconfiguration of the logical multicast tree high mobility and congestion scenarios, such as loop detection and avoidance, and continuity

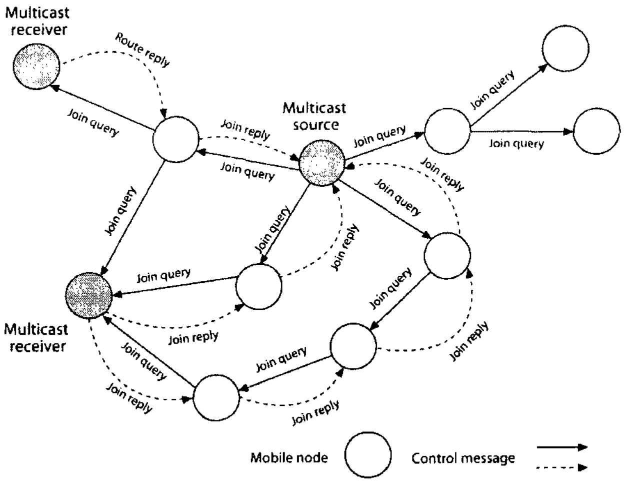


Fig. 9: ODMRP Mesh creation.

insurance after a tree reconfiguration. These mechanisms show to increase the performance of ALMA, which is greatly suited for small group sizes, however its performance seems to greatly degrade once the multicast groups exceed a threshold. Therefore, ALMA is a suitable overlay multicasting protocol for small group sizes, and its application-layer placement seems to ease its potential implementation.

The On-Demand Multicast Routing Protocol (ODMRP) [20] is a mesh-based on-demand multicast routing protocol for MANETs. In ODMRP group formation is initiated by a sending node, as shown in Figure 9, where if no route exists to the multicast group of receiving nodes, a query is started by the means of a local flood. The join query is processed only once by each node and then forwarded until it reaches the destination nodes, which then in turn send a reply packet to the source. Once the source receives the reply packets it chooses the best (shortest) path to forward the multicast packets to the destinations. Intermediate forwarding nodes only forward if the packets are not duplicates (according to their local view) or if the multicast group timer has not expired. The join query is periodically re-broadcast by the source in order to refresh the multicast group membership information and to update the routes. If a forwarding node's status is not fresh after a periodic join query, then that node is eliminated by the source. Nodes that no longer wish to subscribe to the multicast group simply need not reply. If the source node no longer wishes to be in the group, it simply stops sending join queries throughout the network. ODMRP proves to be an efficient, scalable, and effective multicasting protocol for dynamic MANETs. The protocol also introduces low overhead and provides robust operation by exploiting the mesh overlay topology where multiple redundant paths are available to the source for the purpose of data forwarding. Its simplicity of operation makes it the benchmark against which other, newer multicasting protocols are compared.

The Multicast Core Extraction Distributed Ad hoc Routing algorithm (MCEDAR) [22] applies a distributed minimum dominating set algorithm to select a backbone of core nodes. This connected set then forms a framework that can be used for both unicasting and multicasting support. The set of core nodes must provide full interconnectivity of all nodes within the network. Additionally the core nodes are expected to exhibit greater stability than other nodes. A core node and the subset of nodes to which it has a unique connection may be thought of as a cluster. The core nodes are responsible for maintaining the link table to their children. The MCEDAR backbone is in fact a mesh which provides high-level multicasting support, while any low-level multicasting is done via source-based on-demand minimum height tree structuring. The resulting multicasting tree may share links with the backbone, but it is generally seen as a shorter-lived structure. The problem with MCEDAR is that it assumes that core nodes are more stable (less mobile) than other nodes. A failure of a core node demands a restructuring of the backbone, which in highly dynamic MANETs may result in excessive overhead. Core nodes are also potential hot-spots of network traffic. All these factors, including the fact that the backbone spans the entire network, pose a limit on the scalability of the approach.

II.2.2 Stateless Multicasting

Most multicasting applications only require relatively short-lived communication sessions. Therefore, the overhead associated with the creation, maintenance, and control of overlay multicast structures, may prove to be too costly for the benefit obtained. The Differential Destination Multicast protocol (DDM) [28] recognizes this fact and creates a framework for source-based multicasting, where the source encodes the multicast receiver addresses in a DDM header and the packets are routed by the underlying unicast protocol (DSR) to the destinations. The fact that the source has to specify the full multicast routing path may result in large packet headers for large multicast group scenarios, which may affect its performance. Thus, DDM is designed for small multicast groups, and proves to be efficient when operating in highly dynamic networks. DDM supports stateless and soft state operational modes. In the stateless mode, intermediate nodes along the forwarding path do not need to maintain any information about the multicast route, they simply look at the header and allow the underlying unicast protocol to figure out the next hop on route. In the soft state mode, the intermediate forwarding nodes save a cache of any previous paths to destinations and their associated next hops on the route. If any changes of path information occur, a forwarding node will inform the source node of the relevant change in the multicasting path. In cases of large groups and high node mobility, this state change

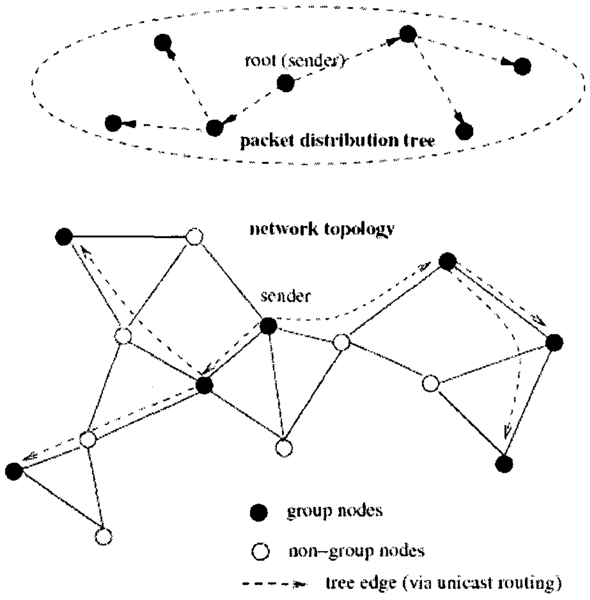


Fig. 10: LGT Overlay packet distribution tree and the underlying topology.

information exchange may become frequent and reduce the performance of DDM.

The Effective Location-Guided Tree construction algorithms for small group multicast in MANET (LGT) [25] are algorithms based on multicasting encapsulated in unicast packets, similar to DDM's. The difference between the two is that in DDM the source-created multicast tree can not be controlled by the upper networking layers, while in LGT the forwarding tree is created with an upper layer support in mind. LGT uses two source-based tree construction algorithms that utilize the geometric locations of destination nodes to construct an efficient overlay tree structure for multicast support, as shown in Figure 10. The algorithms include a hybrid location update mechanism for dissemination of location information between groups of nodes. The first algorithm is lower in complexity and constructs packed distribution trees of a given degree based on geometric proximity of the subtrees, or clusters. The second algorithm is also location-based and creates a Steiner tree structure, which is more suited for dynamic scenarios. The trees created by the this algorithm need to be more frequently maintained since they are susceptible to changes in the network topology. LGT adopts an optimization technique which is mostly utilized by more stable nodes, and is based on route caching to reduce the overhead associated with multicast packet forwarding.

II.2.3 Geocast in VANETs

Vehicles in VANETs, as well as forwarding zones, tend to follow a well established road infrastructure, and furthermore there is an inherent directional element to proceedings that can be exploited to induce an added performance benefit. Many VANET protocols use vehicles travelling in the opposite direction of the message propagation as physical carriers to restore connectivity in a partitioned network. In contrast, the schemes developed by Agarwal, et al. [40] and Yu and Heijenk [58] are an example of how a faster delivery of messages can be achieved in the upstream direction by using clusters of vehicles in the opposite direction as alternate routes. This study's protocol implements both features in order to restore connectivity and accelerate message delivery.

Depending on the approach taken to deliver the location-sensitive messages, geocast protocols can be categorized as structureless and explicit route setup based. Structureless protocols, which include directed flooding and greedy forwarding, focus only on providing a mechanism for determining the next hop(s) towards the geographic zone of relevance. Directed flooding protocols, such as DREAM [50] and LAR [51], provide brute-force methods of pushing the message towards the destination sub-area, by employing a subset of hosts within a two-dimensional field, and, as such, are suited specifically for MANETs. Directed flooding does not address the directional topology of VANETs and the specific requirements imposed by the network, therefore most structureless geocast protocols suited for vehicular communications prefer to employ greedy forwarding mechanisms, as does this study's protocol.

Greedy forwarding aims to minimize the traffic associated with broadcast storms while attempting to maximize the between-hops range covered by the message toward the destination. These goals can be achieved by using either persistent or probabilistic forwarding. Protocols that use persistent forwarding ([41, 45, 55, 54]) generally include a procedure that either explicitly designates a specific node as the message relay, or blindly forwards the message along the geocast path. Maihöfer and Eberhardt introduced a cached approach to geocast [54], where blind re-forwarding is prevented in cases of low connectivity. In cases when a forwarding node has no available connections in the forwarding direction, their greedy protocol uses a cache to temporarily store the message until a vehicle appears within radio range, at which time the message is removed from the cache and broadcasted along. The protocol in this dissertation uses this approach and expands on it by introducing a more opportunistic method.

The Inter-Vehicle Geocast (IVG) protocol [41] defines geocast groups as regions on a given road where a message of interest needs to dwell. IVG utilizes reverse directional flooding by vehicles ahead of the zone of relevance, and opposite lane message propagation to ensure coverage even in sparse scenarios, however its service is non-persistent.

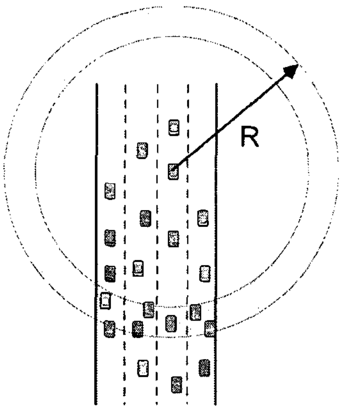


Fig. 11: p-IVG Forwarding contention zone.

Abiding geocast [58], a time-stable geocast protocol for VANETs, undertakes IVG's problem of non-persistence by introducing a dynamic wait time, that saves unnecessary re-broadcasts and extends the lifetime of messages. Message re-broadcasting intervals in IVG are based on the distance between the sender and recipient, therefore farther nodes tend to re-broadcast earlier. Ibrahim and Weigle developed p-IVG [49], an extension to IVG, a protocol that recognizes the potential for channel contention in an intermediate forwarding zone, as shown in Figure 11. Such a contention may occur when several vehicles along the edge of the communication radius have near equivalent re-broadcast probabilities. p-IVG introduces a probabilistic re-broadcasting wait time based on the vehicle density in the zone of relevance, and thus effectively reduces local broadcast storms. Protocols such as OPbG [42], GeoMobCast [56], and DDB [48] investigate the same problem and introduce a different scheme for p-persistent retransmissions. Farnoud and Valee [45] present a unique solution which improves robustness and lowers delays in VANETs better than p-persistent schemes, by using positive orthogonal codes to define re-transmission patterns.

Unlike the previously mentioned protocols, which provide solutions and optimizations solely for unidirectional geocast support in VANETs, CAR [55] and VADD [59] also consider static and dynamic geocast zones. VADD includes protocols that operate in straightway, intersection, and destination modes, and, as such, provide vehicle-assisted data delivery to the best route with the lowest delay. The CAR protocol provides a more comprehensive solution, since it includes routing support for static and dynamic geocast regions in VANETs. The protocol also provides a destination location discovery service, maintains a cache of successful routes to destinations, and introduces an adaptive beaconing service to reduce network congestion. Even though this study's protocol does not utilize adaptive beaconing because the beaconing application and its associated overhead is deemed by the research community to be an independent background utility, it is similar to the CAR protocol in the sense that it provides support for unidirectional (reverse and forward), static, and dynamic geocast in VANETs.

The subject of overlay multicast for MANETs [47], as well as wireline networks [44], is a well studied one, where most solutions create either tree-based or mesh-based overlay structures for multicast support. Multicast trees present a fitting structure for directional networks such as VANETs, because they can easily embrace segmented hierarchical structures such as clusters. Their construction can be on-demand driven through the periodic exchange of *Hello* messages and based on existing unicast routing protocols. Optimization techniques for tree creation and maintenance, such as source-based Steiner tree algorithms, as well as algorithms for loop detection and avoidance, and continuity insurance after a tree reconfiguration, aim to provide a more robust tree structure under highly dynamic environments. Mesh-based overlay multicast protocols can be efficient and robust since the resulting structure includes multiple redundant links available to the source for the purpose of data forwarding. Most mesh-based protocols create a multicast tree within the mesh structure for more efficient message delivery. The resulting multicasting tree may share links with the backbone, but it is generally seen as a shorter-lived structure. The requirement that the set of core nodes must provide full interconnectivity may present a drawback in large dynamic and segmented networks, especially in cases of low penetration ratios. Fortunately this requirement can be adjusted to suit networks such as VANETs, where the mesh-based method can prove to be an efficient approach to multicasting.

II.3 DATA AGGREGATION AND DISSEMINATION

Recent research on information dissemination and data aggregation for VANETs has produced approaches and methods which vary widely yet bring about unique solutions of overhead reduction, duplicate report avoidance and elimination, accurate aggregation, and efficient communication of relevant data in the network.

The Spatially-Aware Congestion Elimination (SPACE) [60] algorithm takes a directed weighted graph, where a digital road map is decomposed into a set of edges with an assigned weight of the travel time on a given edge. The algorithm then produces and impact vector for each edge, a quantity used by vehicles in their route creation phase. Normally, without any events such as accidents on any edge, routes are constructed by selecting the edges with the highest impact factors (e.g. shortest traveling time). In the case of an event on a given road which may negatively affect the travel time for vehicles, the vehicles will disseminate this information only on segments which are affected by the event.

Wu, et al. [61] present a mobility-centric algorithm (MDDV) that combines opportunistic forwarding, geographical forwarding, and trajectory-based forwarding for the support of data dissemination in VANETs. The algorithm defines a dissemination road length quantity for each link in a digital road map which is assigned as a weight and used to define a forwarding trajectory. The forwarding trajectory is the smallest sum of the weights from the source to the destination region on the weighted road graph. Vehicles along the path must buffer and forward messages depending on the local connectivity. The active propagation of messages in MDDV is limited to an area near the message destination, such that the information is kept alive where it matters most.

Leontiadis and Mascolo [62] present a subscriber-based approach for geographic-based message dissemination in VANETs. Vehicles may subscribe to a service (event updates, notifications, etc.) advertised by a publisher. The publisher indicates the area and time validity of the information to be disseminated. The number of messages broadcast by the publisher depends on the density in the area of interest, yet the message propagation is ensured by the communication between vehicles. The authors examine mobility patterns of vehicles as well as dissemination strategies to define the forwarder selection algorithm and the number of generated broadcasts in order for the message to stay alive.

In their paper, Hu and Chen [63] have proposed an Adaptive Multi-channel Data-dissemination (AMD) mechanism, which supports multi-channel traffic awareness and deterministic balance search techniques, to pursue the fairness and robustness for a hybrid data delivery in multichannel data-dissemination environments. The multi-channel

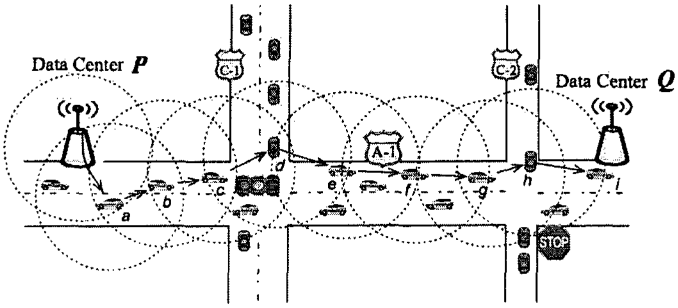


Fig. 12: Directional broadcast and intersection dissemination in DPB.

traffic awareness technique is able to periodically estimate the access frequencies of all items disseminated in the push channels in response to dynamic traffic. Their technique assumes a broadcast approach to data dissemination.

The study presented by Zhao, et. al. [64] studies the dissemination capacity of a VANET as well as providing several schemes which aim to provide efficient data dissemination while maximizing this capacity. The vehicles periodically broadcast information that is propagated throughout the network for as long as the message is valid. The authors examine the problem of keeping messages alive in intersection areas, as shown in Figure 12. Instead of simply propagating the message along the intended path, their push-data intersection mode scheme forces the propagation of the message along all directions of a given intersection. This way the message is delivered to more nodes needing the information, and the life of the message is prolonged.

The authors of Catch-Up [65] present a data aggregation scheme for VANETs, which provides mechanisms for merging several reports by controlling the wait time between broadcasts. The data aggregation is executed on segments, where the roadways are predivided in pieces of a predefined size. The aggregated data is then disseminated throughout the network in individual reports for each segment. The forwarding decision of multiple reports is defined through a future reward model. The model defines the benefits of different delay-control policies, which are chosen from a decision tree.

Ibrahim and Weigle [66] present a cluster-based accurate syntactic compression of aggregated data (CASCADE) where each vehicle's specifics are represented as an offset from the cluster's average characteristics, such as position and speed. For information dissemination, CASCADE uses p-IVG, a probabilistic-based geocast which aims to maximize the per-hop reach and minimize contention in a forwarding zone. The data aggregation is lossless and is coded using differential coding for each cluster.

Dietzel et al. [67] present a structure-free aggregation scheme which employs fuzzy logic reasoning for making a decision when to aggregate data. This scheme's decision criteria allow for a flexible aggregation decision with multiple-membership degree-based fuzzy logic functions. Aggregated reports are not automatically disseminated, rather a selection is made to single out reports which are current and accurate. Their evaluation clearly shows that structure-free aggregation and dissemination is better in accuracy when compared to segmented aggregation, and that the dissemination speed is roughly the same for both approaches.

CHAPTER III

MOBILITY-AWARE GENERAL-PURPOSE CLUSTERING

Here the GVC scheme is defined by first stating the network model and assumptions that are taken into consideration for its design. A detailed description is then provided of the mode of operation of the scheme as well as a mathematical model. Simulation results are then provided and analyzed, as well as are performance comparisons with related works.

III.1 NETWORK MODEL

It is assumed that all the nodes in the network are vehicles equipped with an on-board communication system based on the Direct Short Range Communications (DSRC) service standard, with a transmission range between 300 m and 1,000 m. The MAC protocol is assumed to be 802.11a-based, as per ITS industry standards, with a Carrier Sense Multiple Access (CSMA) capability allowing for the avoidance of collisions, and the wireless channel is assumed to be error free. The GVC scheme is not dependent on GPS, because it could extract vehicle directionality similarly to MOBIC, however the communication system in each vehicle may coordinate with a GPS device, which can provide positioning, velocity, and global time information.

The network comprises N homogeneous vehicle nodes that are uniformly distributed in a two-dimensional Euclidean space, with vehicle positioning and mobility constrained to predefined highway paths. The network dynamics are bounded by a realistic VANET mobility algorithm. The model assumes that the flow of traffic is continuous without

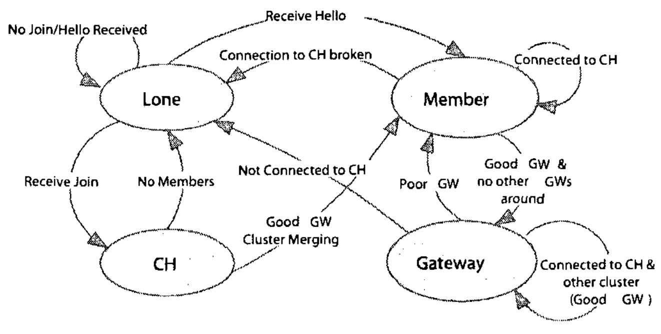


Fig. 13: GVC Finite state machine.

impedance due to collisions and other obstacles. Individual vehicles' speeds exhibit low variance compared to the speed limit of the highway being travelled. Additionally, it is assumed that cluster formation is not for any specific application, such as platooning, for example, rather that clusters are created for general-purpose support, such as data aggregation and forwarding, and enhanced large distance routing.

III.2 GVC MODUS OPERANDI

The GVC scheme operation is next described in four distinct phases of operation: starting with the initial cluster formation, where all nodes within the network are assumed to have just powered on; the cluster maintenance phase, where clusters are in a stable state; cluster merging, where two or more clusters satisfy the merging requirement set by GVC; and the CH handoff phase, which happens when a CH intends to leave its cluster.

III.2.1 Initial Cluster Formation

Figure 13 depicts the finite state machine dictating the state of any GVC node. GVC does not assume a stationary period for initial cluster creation. Nodes that power up immediately enter the *Lone* state, in which they periodically broadcast *Hello* messages. The DSRC standard states that periodic safety messages are broadcasted by nodes at least every 100 ms and at most every 300 ms via the DSRC control channel [18]. Furthermore, non-safety periodic messages in DSRC can occur at a minimum of 50 ms, depending on the types of applications that are running in a given VANET. This means that GVC can treat any of the DSRC periodic messages as *Hello* messages, where any given node can learn about its immediate one-hop neighborhood within a maximum time-frame of 300 ms. The GVC clustering related information can be piggybacked onto these DSRC periodic messages, thus avoiding the explicit forwarding of GVC messages. If a given node does not hear from any other nodes, it will remain in the Lone state. If it receives at least one *Hello* message that has a time-stamp lower than its own last sent *Hello* message, and it is from a node moving in the same direction, the node in question will switch its state to being a Member of a cluster in the process of formation. Then, that node will send a *Join* message to the node which sent the lowest time-stamped *Hello* (the potential CH), informing it that it wishes to become a member of the cluster. Once the potential CH receives the *Join* message it will then switch its state to CH. This sequencing of events guarantees that the node which is first to broadcast a *Hello* message eventually becomes a CH.

To clarify that this decision-making covers the hidden terminal problem, consider the following while referring to Figure 14 (a). If node C is the first to broadcast a *Hello*

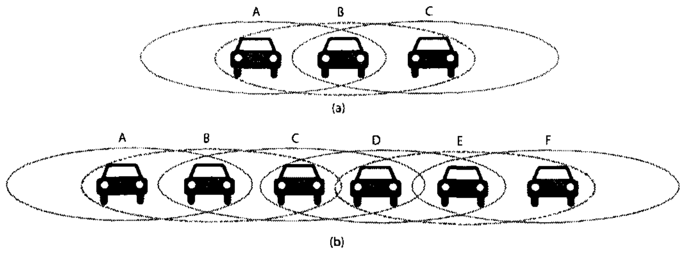


Fig. 14: GVC Hidden terminal discovery.

message, followed by node A, then node B will send a *Join* message to node C, which will also be heard by node A. Since the message sent by B contains C's address as its destination, node A can learn that there is a node (B) within its communicating range that is joining another cluster. Node B already knows about A, but since it first received a *Hello* from C, it chose to ignore node A. Then node A can send a *Join* request through B to join C's cluster, depending on the number of maximum hops requirement for the cluster, which is a variable global parameter in GVC which is true for all clusters. Expanding on the idea, consider the scenario presented in Figure 14 (b), let us assume that the maximum hop count between a CH and its members is defined to be equal to two, which means a member can reach its CH through another node. In a case where the first nodes to transmit a *Hello* message are C, A, and F, in that order, B will be again in the same situation as described previously. Node D will hear only from C, and E will hear only from F, which means that they will send a *Join* request to C and F accordingly. It is easy to see that intermediate results of this initial exchange of messages will cause C and F to become CHs, with B and D, and E as their members accordingly. Due to the chosen two hop criterion, A will send a *Join* message to C through B, and the cluster structure will be complete.

III.2.2 Gateway Criteria

The question is what happens to nodes D and E, which can communicate directly in the previously presented scenario, where two clusters are formed, one with node C as the CH and A, B, and D as members, and the other with node F as a CH and E as a member. Depending on the directionality of the moving nodes, E and D have the potential to become Gateways(GW) for the two existing clusters. In a flat MANET, the criterion for a node becoming a GW is not usually related to a directionality factor. For VANETs the idea is that if two clusters are moving in opposite directions on the same highway, and if the frontmost nodes of the clusters can hear each others, then those two nodes do not satisfy the criterion to be a GW, since as time passes by eventually every node within the cluster will get to hear every node of the other cluster. In this case, if every potential GW node reported to its CH that it is in direct communication with another CH, the intra-cluster overhead would increase drastically. Therefore, a good gateway is defined to be one that is in direct communication range with other nodes from another cluster that is moving in the same direction on the same highway. This does not mean that two oppositely moving clusters can not exchange information, rather the assignment of quasi-permanent GWs is dismissed for the cause of better inter-cluster performance. Safety messages, for example, that are sent by other clusters will propagate throughout the clusters via these potential GWs anyway, because they are broadcast with 1-*p* persistence.

A potential GW node becomes a GW in a similar fashion as the CH is elected in the initiation phase. Assuming that several nodes satisfy the good GW criterion, the one which is the first to broadcast the information intended for its CH will become the GW. Under the network assumptions stated earlier, this will result in each cluster having exactly two GWs, one in the front and one in the back. In a flat MANET, it could be possible that a cluster can have two gateways for any other cluster within its range. In fact, for a fully connected MANET with X clusters, the number of GWs pairs (*Grange*) could range from: $X-1 \leqslant G_{range} \leqslant \begin{pmatrix} X \\ \\ 2 \end{pmatrix}$,while in GVC, under normal conditions the number of GWs is fixed to $X-1$ pairs per direction of a highway.

III.2.3 Cluster Maintenance

The cluster structure is kept firm through the periodic messages propagating throughout the group. In multi-hop clusters, each node will forward the periodic *Hello* from the CH to the edges of the cluster, informing the members that they are still connected to their CH. The reverse operation is done also through periodic messages, where the information is aggregated from the edges of the cluster towards the center.

Gateway Role Relinquishing

A Gateway could possibly move out of range of the node(s) it is connected to from the neighboring cluster, or it could lose connectivity with its own CH. In the first case, the GW will send a message to the CH informing it that it is no longer fit to be a GW and the node will revert back to the *Member* state. In the second case, no explicit messages are sent to the CH. The cluster head will find out that the connectivity with its GW has been broken through the periodically aggregated reverse messages.

Merging of Clusters

In the case of two CHs being in direct communication range (relative to the number of hops requirement) a merging procedure is executed, where explicit merging messages are exchanged between the CHs. In a VANET this would occur when the two clusters are asymmetrical and happen to collide with each other. GVC employs absorption merging, where the cluster with more members will take-in the smaller cluster's members. One explicit message from each CH is required to be sent to the other CH informing it of its size, and when the smaller one has been determined, it sends the details of its member population to the new CH. The members of the absorbed cluster will learn of the absorption through the next round of periodic *Hello* messages sent by the new CH. The nodes on the outer edge of the absorbed cluster that no longer satisfy the hop requirement to be members of the new cluster will revert to the *Lone* state.

Cluster Head Handoff

There are two possible actions in the event when a CH learns that the connection to its members has been broken. The first is if there is still a connection to any of its members through another node, the CH will handoff the responsibility to the most connected node within the cluster head. The second is if there are two or more possibilities with equal connectivity, it will make a random decision of which node will be the new CH. The new CH will keep the cluster ID and the cluster members will be informed of the handoff in the next periodic update. If the CH has no way of communicating with its members, they will again learn about the disconnection in the following update period, and all (including the departing CH) will revert to the *Lone* state, forcing a cluster initialization, or join another nearby cluster.

III.3 GVC PERFORMANCE ANALYSIS

At the initial time $t = 0$, there are N nodes in the network. At any given time t, the distribution function describing the number of nodes that emit a periodic *Hello* message is represented by

$$f(t-t_i) = \begin{cases} 1 & \text{if } t-t_i = \frac{t}{\Delta t}t_p; \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

where t_i is a random initial time it takes for a node to transmit a *Hello* message, t_p is the time of periodic message broadcasts, and Δt is the smallest increment in time. Thus, at time t, the number of nodes sending a periodic message is M, where $M \leqslant N$, and M_s is defined as the total number of messages sent by the M nodes, where $M_s = M$, and $M = \sum_{i=1}^{N} f(t-t_i)$. The probability, as a function of distance, that M nodes receive a *Join* message from the remaining set of $N-M$ nodes at a future time is:

$$f(r-d_{ij}) = \begin{cases} 1 & \text{if } r-d_{ij} > 0; \\ 0 & \text{if } r-d_{ij} \leq 0 \end{cases} \equiv H(r-d_{ij}). \tag{2}$$

where $H(r-d_{ij})$ is the Heaviside step function, d_{ij} is the distance between the i^{th} and j^{th} node, and r is the communication radius. Therefore, the total number of received *Join* messages by M nodes is: $M_r = \sum_{i=1}^{M} \sum_{j=1}^{N-M} H(r-d_{ij})$. and the total number of exchanged messages, such that M nodes can either form or join a cluster is

$$M_{total} = M_s + M_r = \sum_{i=1}^{N} f(t-t_i) + \sum_{i=1}^{M} \sum_{j=1}^{N-M} H(r-d_{ij}) \tag{3}$$

From this, the number of messages exchanged per node for the purpose of creating or joining a cluster is

$$M_n(d_{ij},t) = \frac{M_{total}}{M} = 1 + \frac{\sum_{i=1}^{M}\sum_{j=1}^{N-M} H(r-d_{ij})}{\sum_{i=1}^{N} f(t-t_i)}. \tag{4}$$

Given that the arrival rate of *Hello* messages is Poisson-distributed,

$$f(M,\lambda t) = \frac{e^{-\lambda t}(\lambda t)^M}{M!} \tag{5}$$

where M is the number of nodes sending a *Hello* message (and therefore the number of messages sent), λ is the vehicle arrival rate, $N = \lambda t$ the total number of nodes, and $0 \leqslant t \leqslant t_{total}$. Now, the number of nodes sending a *Hello* message is:

$$M(t) = Nf(M,\lambda t) = \lambda t \frac{e^{-\lambda t}(\lambda t)^M}{M!} = \frac{e^{-\lambda t}(\lambda t)^{M+1}}{M!}. \tag{6}$$

According to (2) the number of received *Join* messages by M nodes is: $M_r = \sum_{i=1}^{M(t)}\sum_{j=1}^{\lambda t - M(t)} H(r-d_{ij})$, and also the total number of relevant exchanged messages, such that M nodes can either form or join a cluster is:

$$M_{total} = M(t) + M_r = \frac{e^{-\lambda t}(\lambda t)^{M+1}}{M!} + \sum_{i=1}^{M(t)}\sum_{j=1}^{\lambda t - M(t)} H(r-d_{ij}) \tag{7}$$

Finally, the number of messages exchanged per node for the purpose of creating or joining a cluster is:

$$M_n(d_{ij},t) = \frac{M_{total}}{M(t)} = 1 + \frac{Me^{\lambda t}}{(\lambda t)^{M+1}} \sum_{i=1}^{M}\sum_{j=1}^{\lambda t - M(t)} H(r-d_{ij}). \tag{8}$$

The total number of messages exchanged for the formation of GVC clusters could be estimated based on the values of the system parameters, such as the communication radius of nodes, r, and the vehicle density, ρ. If it is assumed that the initial time t_i is the same for all the nodes, then according to (1), the total number of sent *Hello* messages M would be equal to the total number of nodes N, or in the case of a Poisson distibution $M = \lambda t f(M, \lambda t)$.

The number of nodes in communication range of the potential clusterhead node, i.e., the number of nodes per cluster, according to (2), can be estimated as a product of the vehicle density and communication radius, $N_{cluster} = \rho r + 1$. This implies that the expected number of clusters is

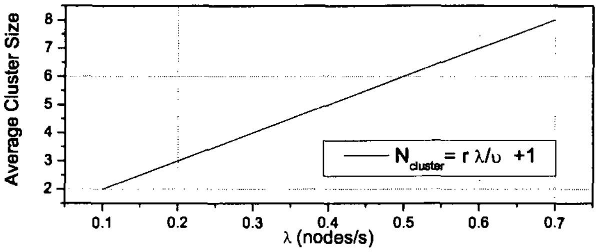
$$C = \frac{M}{N_{cluster}} = \frac{M}{\rho r + 1}. \tag{9}$$

Therefore, the estimated number of the join request messages is the number of clusters multiplied by number of nodes per cluster minus the clusterhead node

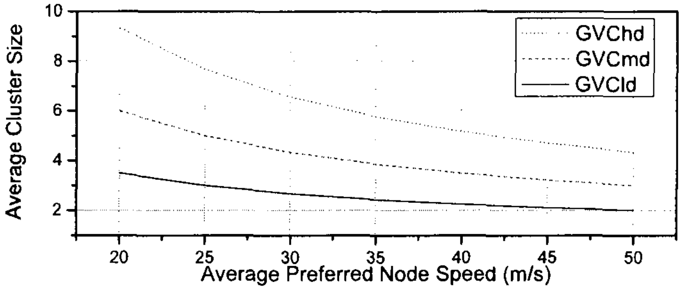
$$M_{jrq} = \frac{M}{\rho r}(\rho r - 1). \tag{10}$$

This equation can give us an estimate of the average cluster size, as a function of the density, as shown in Figure 15(a), or if the density is expressed in terms of the vehicle arrival rate $\rho = \frac{\lambda}{2V}$, where V is the average preferred node speed. The model shows that as the density increases, the expected size of the clusters increases in a linear manner. Figure 15(b) shows the expected cluster size of the model as a function of the preferred node speed V, in low (GVCld), medium (GVCmd), and high density (GVChd) scenarios. The average cluster size drops off rapidly as the preferred speed of the nodes increases, which is due to the fact that the system is more dynamic in the sense that nodes have the tendency to travel their path faster and therefore spend less time participating in a single cluster formation.

From all this, the total number of exchanged messages for forming the clusters, as a



(a) Cluster Size as a function of the node density.



(b) Cluster Size as a function of the node preferred speed.

Fig. 15: The model of the average cluster size.

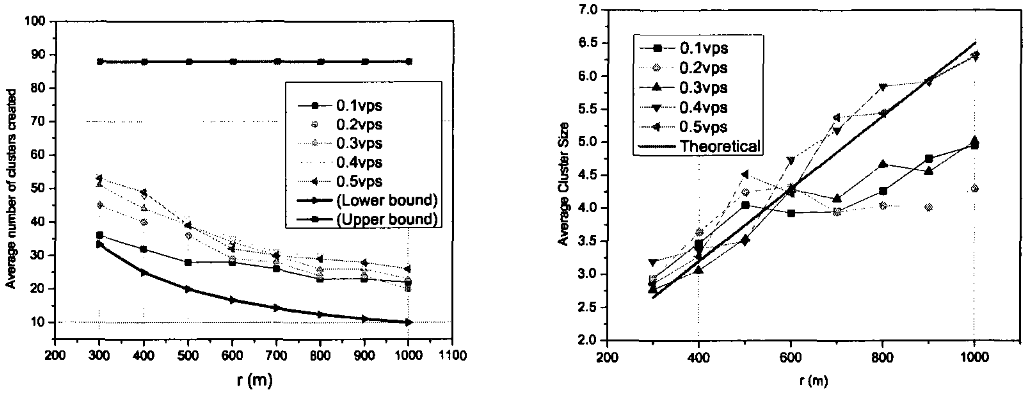
function of *r*, is defined as:

$$M_{total} = M + \frac{M}{\rho r}(\rho r - 1) = 2M - \frac{M}{\rho r} = \frac{2M\rho r}{\rho r + 1} \tag{11}$$

In the next section the presented model will be compared to the results obtained from simulating the operation of the GVC scheme.

III.4 SIMULATION RESULTS AND ANALYSIS

A VANET was simulated according to the previously stated network model and assumptions. For each simulation the first 300 s of simulation time were examined. The communication radius of nodes was varied in increments of 100 m starting from 300 m up to 1,000 m. Vehicles were simulated to travel on a 5,000 m long four-lane road, with an



(a) Average number of clusters created.

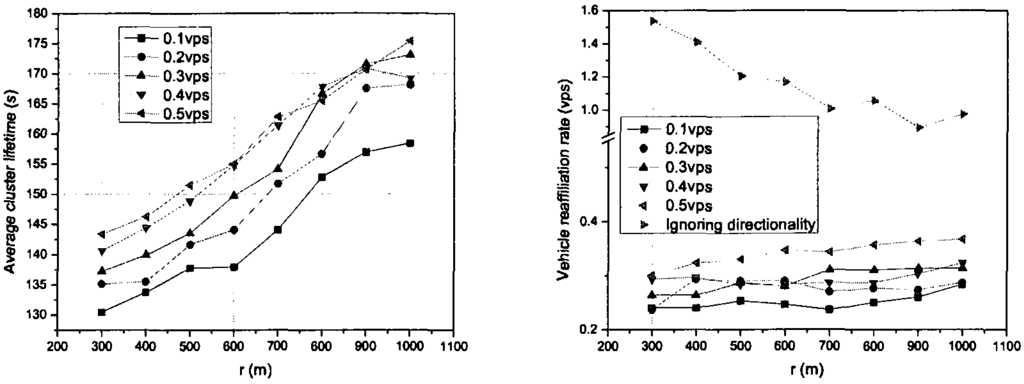
(b) Average cluster size.

Fig. 16: GVC Characteristics.

initial speed between 18 m/s to 22 m/s. The vehicle density was represented as a function of the vehicle generation rate λ (where $\rho = \frac{\lambda}{v}$), which was varied from 0.1 vehicles/s (vps) to 0.5 vps in increments of 0.1 vps.

Figure 16(a) shows that the average number of clusters created by GVC conforms to the theoretically predicted pattern, calculated by plugging in the simulation parameters in (9), and that it follows the lower bound very closely. As the communication radius (r) increases it can be seen that the number of clusters created, per each of the five densities investigated, falls off and converges quickly. This result was expected, since as r grows, the more vehicles should be within communication range of existing clusters, and the need to create new ones diminishes.

The average cluster size, depicted in Figure 16(b), shows that as r increases the number of members per cluster increases also. The simulation results of GVC exhibit a positive trend in following the theoretical model, especially in the cases of higher vehicle densities, when $\lambda = 0.4$ and $\lambda = 0.5$. In the lower density ranges, the cluster size seems to taper off



(a) Average GVC cluster lifetime.

(b) Vehicle reaffiliation rate.

Fig. 17: GVC Cluster stability.

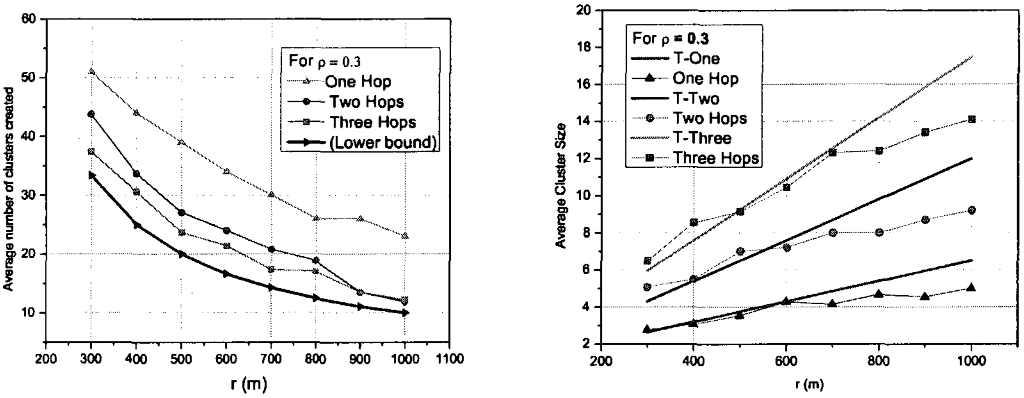
at some point even as *r* increases. This result is due to the relatively sparser distribution of vehicles, which results in lower overall connectivity, and lower probability for GVC to form larger clusters.

Figure 17(a) illustrates that the average lifetime of GVC clusters is proportionally dependent both on *r* and λ. GVC clusters exhibit a relatively high longevity even in the lowest density and communication range, especially considering that this average includes short-lived clusters created due to the distribution and mobility of the nodes within the simulation. There is a significant lifetime gain as *r* increases, which is in the range of 30*s*. Vehicle density seems to also positively affect the average lifetime, but not as drastically as the communication range.

The vehicle reaffiliation rate, shown in Figure 17(b), an indicator of cluster stability, is a measure that shows the number of nodes per second that had to reaffiliate with another cluster due to cluster merges or failures. In GVC, this number increases slowly as *r* and λ increase, which is expected because when *r* and λ are large, the average cluster size is larger, and when a merge or failure occurs more nodes are affected. The Figure also shows the effect of ignoring the directionality factor of moving nodes for cluster creation and maintenance. The vehicle reaffiliation rate in the sample of ignoring directionality, where $\lambda = 0.3$ vps, is much (3 to 5 times) higher than the average reaffiliation rate exhibited by GVC. This also shows that GVC increases the stability of clusters while reducing communication for the purposes of cluster creation and maintenance.

The effects of varying the hop-limit are shown in Figure 18. Figure 18(a) shows the positive effects of increasing the cluster hop-limit, where it can be seen that as the the hop-limit is increased, the average number of clusters created rapidly approaches the theoretically defined lower bound,.but, with a diminishing return. This result is expected, since as the hop-limit is increased, the size of the clusters also increases. Therefore, there is a lower probability for new clusters to be formed, resulting in decreased overall cluster creation messages in the network. As expected, Figure 18(b) shows that the average members per cluster increases as the hop-limit is increased, thus increasing the inter-cluster maintenance communication and consequently the potential overhead. The results again follow the theoretical model closely and follow a similar pattern as observed in Figure 16(b).

The following figures compare this study's GVC scheme with related work. First, in Figure 19(a), the average cluster size is compared as a function of the average preferred node speed of GVC and CMCS. Figure 15(b) shows the expected behavior of GVC and Figure 19(a) shows the actual behavior of GVC as well as the behavior of CMCS. From this Figure, it can be seen that GVC follows the theoretical model closely, yet the actual cluster size is a bit smaller than the expected. This is because the model can not account for the stochastic process of the dynamics of the network. Figure 19(a) also shows that,



(a) Average number of clusters.

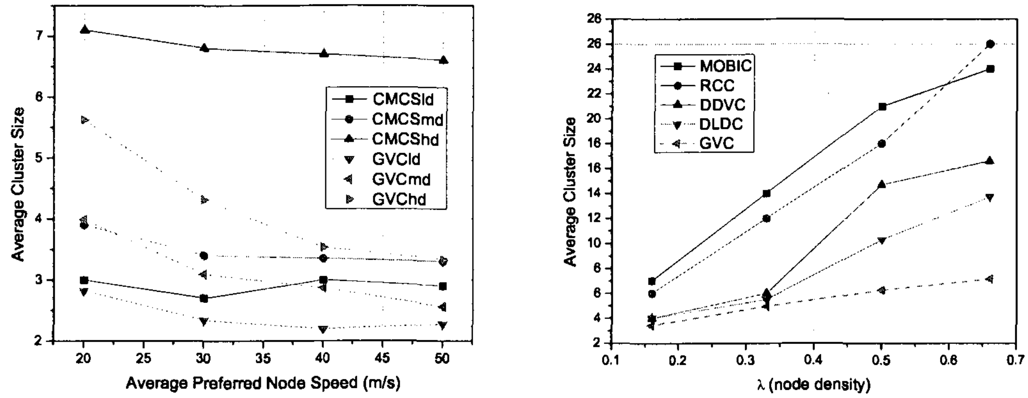
(b) Average cluster size.

Fig. 18: The effects of varying the hop-limit.

in general, GVC forms clusters of relatively smaller size than CMCS, which consequently results in smaller and more compact clusters which exhibit a better lifetime than those of CMCS, as shown in Figure 20(a).

Figure 19(b) shows the performance of GVC in terms of the average cluster size as a function of the node density compared to MOBIC, RCC, DDVC and DLDC. From this Figure it can be seen that the GVC cluster size follows the theoretical model's predicted cluster size very closely (referring back to Figure 15(a)). Also when compared to the other clustering schemes, GVC seems to be relatively unresponsive to the fluctuations in node density. This means that GVC clusters are smaller and more stable because of the way clusters are created in GVC, where the increase in density does not neccessarily steeply affect the increase in cluster size.

Figure 20(a) illustrates the effect of the previously observed smaller GVC cluster size on the lifetime of the clusters. From this Figure it can be seen that as the preferred speed of the nodes increases, the lifetime of both GVC and CMCS clusters degrades, yet GVC



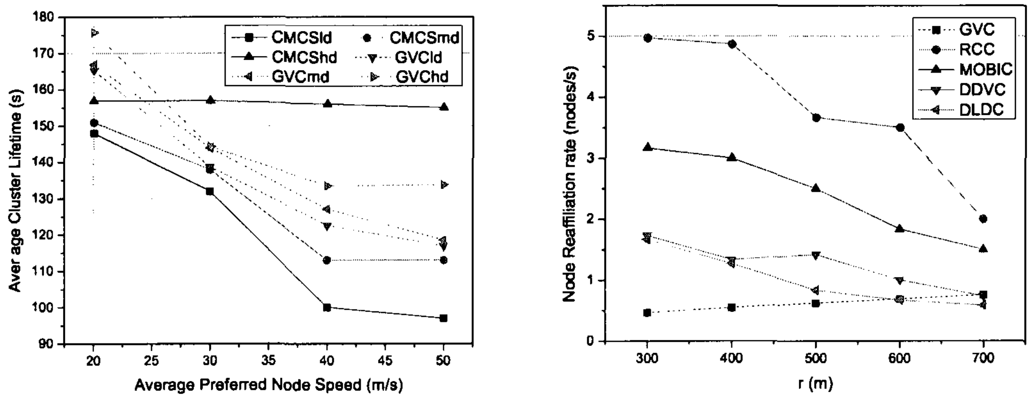
(a) Average cluster size as a function of the preferred node speed.

(b) Average cluster size as a function of the node density.

Fig. 19: GVC Performance comparison.

exhibits a longer lifetime, except in the case of a high density of vehicles. This is due to an anomaly in the way CMCS results have been obtained. Namely, in the simulation of CMCS, the nodes move on a circular road that is pre-populated to a certain density, and nodes exit the road at a same interval as new nodes are entering, thus keeping the density constant. In the high density case, this results in an effect where it seems that no vehicles entering or leaving can affect any given cluster, and thus their corresponding lifetimes.

Finally, Figure 20(b) shows the stability of GVC clusters as a function of the communication radius compared to MOBIC, RCC, DDVC, and DLDC. The Figure shows that the node reafilliation rate for GVC is far lower than those of the competition. The rest of the schemes have a tendency to reduce their reafilliation rate as the communication radius increases, which is due to the fact that clusters contain more and more members. The end effect is that their cluster stability is relatively increased. GVC outperforms the competition by maintaining a relatively low reafilliation rate, and consequently a high cluster



(a) Average cluster lifetime as a function of the preferred node speed.

(b) Node reaffiliation rate.

Fig. 20: GVC Stability comparison.

stability, in all of the examined communication ranges.

III.5 CONCLUSIONS ON THE GVC SCHEME

A novel mobility-aware, general-purpose clustering scheme designed for VANETs was presented, which takes the directionality of moving vehicles into consideration during the cluster creation and maintenance phases. The simulation results show that the GVC scheme creates robust cluster structures, which adhere closely to the lower-bound limits calculated by this study's theoretical performance model. GVC clusters exhibit a relatively long lifetime, even in scenarios with low vehicle densities and reduced communication radius. The GVC cluster structure is also very stable, especially if compared to when directionality is ignored. Due to this property the overhead associated with the clustering scheme is greatly reduced. Additionally, if all GVC-related data was to be piggybacked onto DSRC periodic safety messages, then the only cost associated with the operation of the scheme would be computational.

CHAPTER IV

HYBRID OVERLAY-NETWORK GEOCAST

Here a novel Hybrid Overlay-network Geocast (HOG) protocol designed for VANETs is presented. The protocol is hybrid in the sense that it aims to create a virtual backbone for geocast support on top of the physical network, while providing persistent service by incorporating greedy stateless methods. This protocol operates in a distributed manner both in unstructured and structured VANETs, and, furthermore, it can be easily adapted to utilize existing structures in a given VANET (i.e. clusters), such that it can operate more efficiently.

IV.1 SYSTEM MODEL AND ASSUMPTIONS

A given stretch of highway can be modeled effectively by a two lane, bidirectional road, since the average vehicle length and lane spacing are very small (on the order of several meters) when compared to the typical DSRC transmission range (up to 1 km). This model accounts for N vehicles, each equipped with a wireless transceiver and a positioning device (i.e. GPS). The wireless radio is assumed to operate at the same power level on each node, such that the communication radius R is common for all nodes N. The MAC protocol is assumed to be 802.11-based, with CSMA capability, allowing for the avoidance of collisions, and the wireless channel is assumed to be error free. The positioning device is additionally assumed to provide the global time, from which each vehicle can compute its current speed and general heading. The vehicles travel independently in each direction on the highway segment while complying with the well known car following model, such that the average speed Vx and inter-arrival time λ of the vehicles in direction x are exponentially distributed. The network runs a beaconing service application, where each node periodically transmits its location and velocity information to its neighbors that are within its communication radius R.

IV.2 VANET GEOCAST

The type of geocast that can be utilized within a VANET is highly dependent on the application at hand. The forward or reverse propagation of messages may be sufficient for most emergency applications, yet comfort applications may require additional approaches to geocast message forwarding. The following are the elementary types of geocast, which in any combination and permutation can satisfy the requirements of most simple and complex VANET geocast operations.

IV.2.1 Unidirectional End-Point Bounded

The simplest form of geocast in VANETs is the unidirectional forwarding of messages that are bounded by an endpoint and/or a time to live (TTL) parameter. For example, consider a scenario where an emergency (ambulance, police car, fire truck, etc.) vehicle needs to send a warning message to inform all other vehicles along its path to make room. The endpoint for the message could be an intersection where the emergency vehicle will change its direction, or it could be terminated after its TTL expires. In this case, the geocast protocol needs to employ a greedy forwarding mechanism, such that the message dissemination executes as fast as possible while extending the per-hop range of the message.

IV.2.2 Static-Absolute

Another type of geocast is to a static geographic area, where all vehicles need to be informed of a service or an emergency particular to a given region. Some examples could include an accident on a two-way road, where a crashed vehicle emits a warning message to all approaching vehicles within a given radius to slow down, or a gas station wishing to advertise its service to all approaching vehicles. The message reach in this case is bounded by geographic coordinates, and possibly by a TTL parameter. The definition of the coordinate endpoints demarcating the message dwell area could be complex, described by a finite set of vertices or a point and dwell radius, or as simple as a pair of points on a given road defining a road segment. Here both road segments and dwell areas defined by a center point and dwell radius are considered, since most applications' requirements can be satisfied by utilizing these two types of static-absolute geocast. In this type of geocast, regular greedy forwarding is not an efficient approach. The aim of the geocast protocol in this case would be to keep the message alive in the given area as efficiently as possible, while minimizing unnecessary re-broadcasts.

IV.2.3 Dynamic-Relative

Dynamic-relative geocast is bound by a velocity vector and/or a relative dwell area. Its aim is to provide services for information dissemination between organized clusters of vehicles in VANETs. Consider an application where each cluster head periodically collects information about its members, extracting data such as average velocity, density, size, and length of the cluster. This type of geocast can then be used by cluster heads to inform other nearby clusters about the average characteristics of their own cluster. Furthermore, these types of data can be aggregated, such that vehicles can have a view of traffic conditions with a diminishing resolution as the distance increases. The dynamic message dwell area for this type of geocast could be defined similarly to static-absolute geocast, but with an additional velocity component. This velocity vector could be independent (delayed forwarding) or connected to a set of endpoints (moving segment). Delayed forwarding is the simpler variant, where each node employs a greedy forwarding protocol with an additional impeding method, aiming to produce an effect where messages on average travel with a given predefined speed. A moving segment could be either a sweeping area, or a relatively static area to the moving source node. This depends on the value of the velocity vector, such that if it is defined to be about the same value as the average speed of vehicles in a given area, then the moving segment appears to be relatively static to the source node. Otherwise, the segment will appear as a sweeping one, again relative to the source node.

IV.3 UNIQUE PROTOCOL FEATURES

The following are sapient features of this study's HOG protocol, common to both unstructured and structured VANETs, which aim to reduce collisions, as well as redundant broadcasts and re-broadcasts in all the previously-mentioned types of geocast for VANETs.

IV.3.1 Beacon-Driven Cached Forwarding

Sparse VANETs may contain large gaps between groups of vehicles, in which case a forwarding scheme can employ a store-wait-resend procedure in order to ensure the forward propagation of messages. This simple procedure can be the source of many unnecessary collisions due to blind periodic re-broadcasts. This study's protocol employs an on-demand cached forwarding method which aims to minimize these collisions. The cache is driven by the beaconing service, such that if a forwarding vehicle is on the edge of a given group and no vehicles are (or are soon going to be) within reach in the forwarding direction, it will then store the message until the next beaconing update. The forwarding vehicle will pass on the message if a vehicle appears in the forwarding direction, or another vehicle in its immediate vicinity is moving with a greater speed towards the forwarding area.

IV.3.2 Reverse-Direction Temporal Message Propagation

Reverse-direction message propagation can alleviate the connectivity problem between groups of physically separated vehicles in sparsely populated VANETs. It is intuitive that a vehicle traveling in the opposite direction of a forwarding node can almost certainly provide temporary connectivity to disconnected vehicles behind it. Yet, the opposite way traveling nodes can be also used for forward message propagation. This study's protocol utilizes both techniques to provide a persistent best-effort service for mitigating this connectivity problem. While these techniques provide a best-effort service, they do not guarantee restored connectivity between segmented groups of vehicles. Therefore this protocol, while using these techniques, will also store the message until a beaconing update reports on a vehicle in the forwarding direction, at which time the message will be re-broadcast. If the received message proves to be a duplicate, then it will be discarded, otherwise the receiving node will accept the forwarding responsibility.

IV.3.3 Stable Geocast Router Selection

This study's protocol aims to both extend the longevity of links between geocast router nodes, and avoid redundant re-broadcasts by employing an inert-neighbor selection method. Given that the greedy protocol, in the unidirectional end-point bounded mode, provides a best effort on selecting the furthest possible forwarding node in the direction of the geocast propagation, a beaconing update may still provide several equivalent choices (in terms of positioning) to the current forwarding node. This could be due to the current precision of GPS devices, which is in the range of several meters. Therefore, given several choices, the protocol will select the most inert vehicle when compared to its own velocity, and if that fails to single out a node, then it will randomly choose one out of the remaining set. Furthermore, if a given node is bound to exit the reach of the source node by the next beaconing update, that node will be eliminated from the selection, unless it is the only one, in which case it will be selected as a router anyway and an attempt will be made to forward a geocast packet if one exists.

IV.4 HOG PROTOCOL OPERATION

Next the operation of this study's protocol is described in both unstructured and structured VANETs.

IV.4.1 Unstructured Overlay

The HOG protocol aims to create a virtual overlay backbone for geocast support in VANETs. This problem is more difficult for an unstructured VANET, where there is no

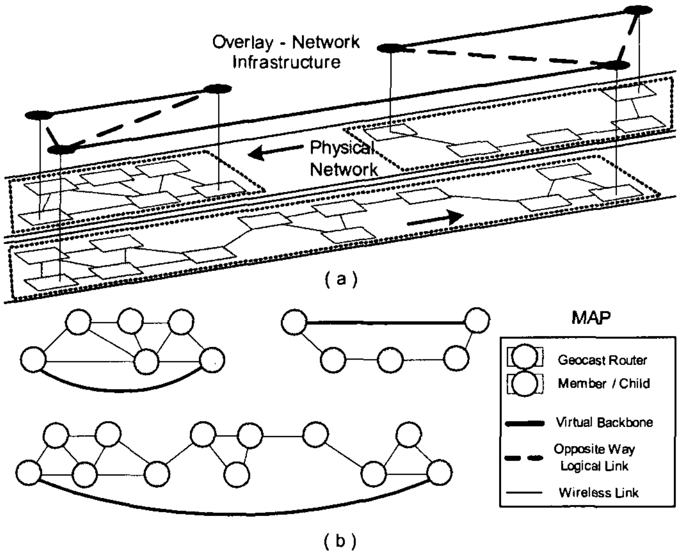


Fig. 21: Unstructured VANET: (a) Overlay infrastructure on top of the physical network. (b) Logical link representation.

central control. Therefore the protocol needs to operate in a fully distributed fashion, while striving to reduce overhead associated with the creation and maintenance of the overlay backbone. In the sample scenario depicted by Fig. 21 (a), several groups of vehicles are moving on a bi-directional road. The wireless links between groups of vehicles are based on the communication radius R which in this case, for the sake of simplicity and illustration, is chosen to be very small. Nonetheless, the Figure illustrates the directional element of the VANET, as well as the disconnection between groups of vehicles (or clusters).

The logical overlay backbone, shown in Fig. 21 (a) and (b), is created by a set of geocast router nodes which maximize the per-hop reach in the unidirectional geocast mode. The creation process is carried out by the beaconing service, where all necessary information is piggybacked onto beacon messages. The pseudo-code for the virtual backbone geocast router selection is provided in Fig. 22, where A, P, S, D are the address, position, speed, and direction of the sending node, T is the message timestamp, V is the vehicle neighbour list, FL is the set of possible forwarding nodes, and EG, GR, RN (Edge Router, Geocast Router, Regular Node) describe the geocast status and address (GS, GA) of a node X in the network. The protocol builds this backbone beginning with the outermost nodes of a given cluster of vehicles moving in one direction and building the route inwards. This building process is initiated by a node which is on an outer edge, a decision made based on its own position and the information gathered from the beaconing updates (Fig. 22, (17-19)). Due to the precision of GPS devices, several nodes may claim to be on the edge of a given cluster. In this case, the node which is the first to react, or begin the backbone building process, will become an outer geocast router. This node will then query its list of neighboring vehicles and select the furthest one to be the next router in the backbone, according to the stable geocast router selection procedure described previously (Fig. 22, (6-15)). The process will continue until an edge node in the opposite end of the cluster has been reached, thus completing the backbone.

Note that each router in the virtual backbone sequence knows and actively determines only its next hop, therefore the edge router(s) need not know nor confirm the full backbone path. The backbone structure may change frequently due to the very dynamic nature of VANETs. The protocol eliminates unnecessary overhead associated with keeping the backbone firm, while providing a deterministic structure for geocast support. Also, since the backbone building process is started by two edge nodes, and carried out in opposing directions by the inner group nodes, there will be two, possibly distinct, backbones in each direction for a given group of vehicles. This result introduces robustness to the protocol in cases of a geocast router failure. In fact, after each beaconing update, all nodes regardless

```
X receives beacon(A, P, S, D, T)($GA_1$, $GS_1$ ... $GA_n$, $GS_n$)
if $\exists\ i : V[i].A == A$            //if neighbor already in table
    V[i].P,S,D,T := P,S,D,T; // update neighbor info
else if X.D == D         // if moving in the same direction
    V.add_new(A,P,S,D,T); // add as new neighbor
for $\forall\ k \in V$                // check all neighbors
{ if $\exists j : V[j].P == \min(V[k].P)$
    if $\exists! j : V[j].P == \min(V[k].P)$
      FL.add(V[j]);        //add the farthest in FL
    else if $\exists! j : | V[j].S - X.S | == \min(| V[k].S - X.S |)$
      FL.add(V[j]);     //or pick most inert
    else                  //if all else fails, pick random
      FL.add(rand(V[j] | V[j].P == min(V[k].P)));
  else if $\exists j : V[j].P == \max(V[k].P)$
      // same algorithm as above, except
      // min() → max() and "-" → "+"  }
if FL $\neq \varnothing$               // if the current node is not alone
  if $\exists!\ l : l \in$ FL    // if it is an edge node
    X.GS := EG;  // change state to edge geocast router
    X.append_beacon(l.A, GR); // l becomes GR
else if X.A == GA && X.GS == GR
  X.GS := GR; // X becomes GR
  for $\forall\ m \in$ FL : m.A $\neq$ A  //inform all nodes in FL to
    X.append_beacon(m.A, GR);  //become GRs
else if X.A == GA && X.GS == RN
  X.GS := RN; //X becomes RN
  for $\forall\ n \in$ FL : n.A $\neq$ A  //inform all nodes in FL
    X.append_beacon(n.A, RN);  //to become RNs
else
  X.GS := RN;
```

Fig. 22: Pseudo-code for the HOG backbone router selection.

of their status will silently select a set of nodes which meet the criteria described by the router selection method. This is beneficial in cases of highly dense VANETs, where there may be no segmentation between groups of vehicles and an outer node cannot be singled out. In such extreme cases, the virtual backbone will be determined at the time when geocast communication is initiated, therefore an "edge" node will become the one which responds the fastest, and the rest of the process will be the same as described before.

The message forwarding phase of the HOG protocol is dependent on the type of geocast employed. In a unidirectional mode, the message forwarding follows the established backbone geocast routers, such that maximum per-hop reach is achieved in the forwarding direction. The protocol employs both beacon-driven cached forwarding, in cases where large segmentation may occur between groups of vehicles, and reverse-direction temporal message propagation, to restore connectivity. The same methods are executed by the HOG protocol when geocasting to a static area, but with a slight modification. Static-absolute geocast requires a message to dwell in a given area, and since the virtual backbone is moving relative to the static area, there is a delay mechanism which allows for the message to stay alive within its bounds. This delay mechanism utilizes the beacon-driven cached forwarding method. While still utilizing the backbone for greedy forwarding, the mechanism reduces unnecessary broadcasts by waiting for vehicles that have the potential to enter the zone of relevance before the packet is forwarded. This way, only vehicles that enter the static zone receive the geocast message. When geocasting to a dynamic group, the protocol manages the message forwarding similarly to the way static geocast is managed, except that the delay mechanism is controlled by the velocity vector. Each forwarding node examines the time the message was received, the physical distance it has travelled, and the requirement imposed by the velocity vector to calculate a delay until the next re-broadcast.

IV.4.2 Structured Overlay

A structured VANET is one where groups of vehicles organize themselves in a hierarchical structure (i.e. cluster) where a central node serves the purpose of a manager for the group.

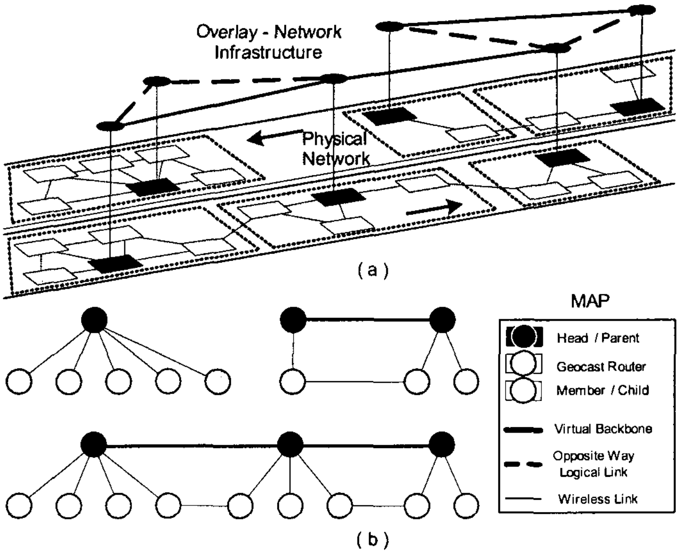


Fig. 23: Structured VANET: (a) Overlay infrastructure on top of the physical network. (b) Logical link representation.

These parent nodes are referred to as cluster heads, and their role is to manage the membership of nodes within the cluster they control. The size, in terms of members, of a given cluster can vary depending on the clustering protocol being used to create the hierarchy. Most clustering protocols for VANETs create one-hop clusters, such that the cluster head is in direct communicating range with all its members. Multi-hop clusters require a higher volume of message exchanges in order to create and maintain the cluster structure. Since the DSRC communication radius is on the order of hundreds of meters, a single hop cluster's length can reach up to several kilometers (assuming a symmetrical cluster in a high density scenario), possibly containing hundreds of member nodes. A sample one-hop, directionally clustered VANET is depicted in Fig. 23 (a). Clusters are structures that can be very useful for gathering, processing, and disseminating local data within a VANET. They are logically organized as trees, as shown in Fig. 23 (b), with the cluster head as the parent node to all tree members, and nodes in direct communicating range with other clusters as gateways. Since a structure is already in place, the geocast protocol exploits this fact and creates a virtual backbone from the set of cluster heads connected via gateways.

Gateways are nodes on the outer edge of a given cluster, selected as such by the cluster head, which maintains up-to-date information on all its children. As such, when used by this study's protocols, they already define the edge of the virtual backbone. Depending on the type of clustering scheme employed, the intra-cluster routing can either be centralized, always going through the cluster head, or not. However, inter-cluster routing almost always goes through the gateway nodes. In a structured VANET, the HOG protocol begins the virtual backbone building process from the cluster heads. The cluster heads designate themselves and the outer gateway nodes as geocast routers, which pass on the information to gateways of other clusters, and so on until a disconnection occurs. In segmented VANETs, the virtual backbone in a given direction may consist of lone clusterheads, therefore this protocol employs the same features as described in the previous section to restore connectivity in such cases. Even though the message forwarding phase is the same, the creation and maintenance of the overlay infrastructure in this case is much simpler when compared to an unstructured VANET, which is due to the fact that cluster heads and the underlying clustering algorithm assume the computational and communication load.

IV.5 PERFORMANCE ANALYSIS

In this section a performance analysis of the HOG protocol is presented. The following performance model builds on the previously stated system model and assumptions.

IV.5.1 Preliminary

Considering a two-directional road with length L and vehicle arrival rates λ_1 and λ_2 for each direction accordingly, it is observed that the expected end-to-end delay of the protocol and forwarders per packet are inversely proportional to the expected vehicle group length including the expected spacing between groups (where a group is a set of contiguously connected vehicles), and directly proportional to the vehicle arrival rate(s). First the average traffic characteristics are derived in order to form a delay analysis. τ is defined as the vehicle inter-arrival time, a quantity which is closely related to the vehicle arrival rate which is most commonly used in VANET simulations to define vehicle densities. The most commonly used distribution to define τ, which closely describes real-world traffic patterns, is the Poisson distribution:

$$f(\tau) = C\lambda e^{-\lambda\tau}$$

where λ is the vehicle arrival rate, v is the average speed, and C is a normalization constant. C is used to calculate the average values of τ when the inter-arrival time difference between two vehicles is such that the distance between them is either within or outside their communication radius R. This means that if $\tau v \leq R$ the two vehicles in question are connected (C_c) and if $\tau v > R$ then they are disconnected (C_d). If the vehicles are within communicating range, then the normalization constant is found from the following equation:

$$\int_0^{\frac{R}{v}} C_c \lambda e^{-\lambda\tau} d\tau = 1,$$

or after solving for C_c:

$$C_c = \frac{1}{1-e^{-\lambda R v}} \; and \; f_c(\tau) = \frac{\lambda e^{-\lambda\tau}}{1-e^{-\lambda R v}}. \tag{12}$$

Similarly, C_d is calculated from:

$$\int_{\frac{R}{v}}^{\infty} C_d \lambda e^{-\lambda\tau} d\tau = 1 \; C_d = e^{\frac{\lambda R}{v}} \; and \; f_d(\tau) = e^{\frac{\lambda R}{v}} \lambda e^{-\lambda\tau}. \tag{13}$$

From this C_c is used to calculate T_σ, the expected inter-arrival time such that vehicles are within communicating range, which is found from the partial integration of the following quantity:

$$\begin{gathered} < \tau_\sigma > = \int_0^{\frac{R}{v}} \frac{\lambda\tau}{1-e^{\frac{-\lambda R}{v}}} e^{-\lambda\tau} d\tau = \\ T_\sigma = \frac{1}{\lambda} - \frac{R}{v} \frac{e^{\frac{-\lambda R}{v}}}{1-e^{\frac{-\lambda R}{v}}} \end{gathered} \tag{14}$$

T_γ, the expected inter-arrival time such that vehicles are disconnected, is calculated analogous to the calculation of T_σ:

$$\begin{gathered} < \tau_\gamma > = \int_{\frac{R}{v}}^{\infty} e^{\frac{\lambda R}{v}} \lambda\tau e^{-\lambda\tau} d\tau = \\ T_\gamma = \frac{1}{\lambda} + \frac{R}{v} \end{gathered} \tag{15}$$

T_σ and T_γ are next used to define most of the quantities shown in Fig. 24, such as the average distance between any two connected and disconnected vehicles L_σ and L_γ accordingly, the average length of a group of contiguously connected vehicles L_g, and the realistic total length of the same group L_G. L_σ and L_γ are simply given by:

$$L_\sigma = vT_\sigma = \frac{v}{\lambda} - R\frac{e^{\frac{-\lambda R}{v}}}{1-e^{\frac{-\lambda R}{v}}}, \; and \tag{16}$$

$$L_\gamma = vT_\gamma = \frac{v}{\lambda} + R \tag{17}$$

The average length of a group of connected vehicles is defined to be simply the sum of the distances between the vehicles (L_σ) until a disconnection occurs, which is the total number of vehicles (λt) multiplied by the probability that they are separated by a distance larger than R ($f_d(t)$):

$$\begin{aligned} L_\sigma\left(\int_0^\infty \lambda t\, f_d(t)\,dt - 1\right) &= \left(\frac{v}{\lambda} - R\frac{e^{\frac{-\lambda R}{v}}}{1-e^{\frac{-\lambda R}{v}}}\right)(e^{\frac{\lambda R}{v}} - 1) \\ &= \frac{ve^{\frac{\lambda R}{v}} - v}{\lambda} - R = L_g\,. \end{aligned} \tag{18}$$

IV.5.2 HOG-Unidirectional End-Point Bounded

First a model is developed for the end-to-end delay introduced by the HOG protocol in the unidirectional end-point bounded mode. The delay model is largely dependent on the vehicle density or, in actuality, the market penetration ratio, where the largest delays in a sparsely connected network are incurred from the physical separation of vehicles. The time it takes for two disconnected groups to establish a temporal link is dependent on their relative velocities $v1$ and $v2$ and the communication radius R.

It was established earlier that opposite direction forwarding is a best-effort approach that the HOG protocol uses to reduce the reconnection time between disconnected groups of vehicles travelling in the same direction. The time it would take for any two given groups that are separated by a distance L_γ to communicate using opposite direction forwarding is relative to the average velocities in each direction of the roadway. Therefore, if the density in the opposite lane is sufficient, such that a vehicle on the edge of a group in the forwarding direction does not have to wait for another vehicle to arrive in the opposite direction for the message to be relayed, then the average delay associated with the

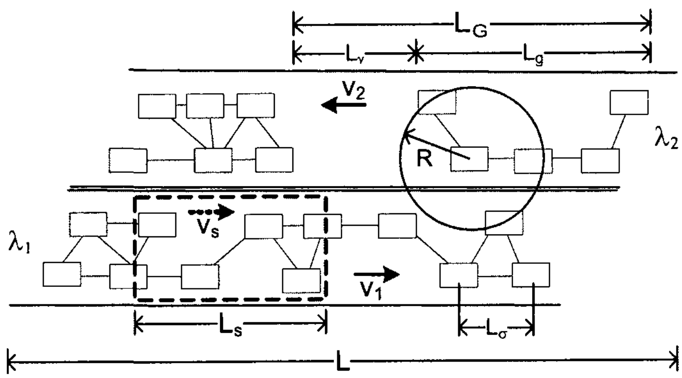


Fig. 24: HOG Variables.

break in connectivity in this type of forwarding is: $t_\delta = \frac{L_\gamma}{|\vec{v_1}|+|\vec{v_2}|}$, where $\vec{v_1}$ and $\vec{v_2}$ are the average velocities in each direction. In contrast, if a forwarding vehicle on the edge of a group has to wait for a relaying vehicle in the opposite lane to appear, which would take on average $\frac{1}{\lambda_2}$, then t_δ would be increased by that quantity. Therefore, the average delay in re-establishing a connection between two separated groups in one direction by using opposite lane forwarding is:

$$T_\delta = < t_\delta > = \frac{\frac{v_1}{\lambda_1}+R}{v_1+v_2} + \frac{1}{2\lambda_2} \tag{19}$$

Considering that the HOG protocol builds an overlay backbone of geocast router nodes which begin at the edge of a given group and are separated by the maximum distance (Fig. 22 (6-15)), then the end-to-end delay of the protocol in the unidirectional end-point bounded mode is equal to the time it takes for each node to forward a message along the path plus T_δ for each group pairing along the length of the geocast path. First the latter quantity is considered, which is based on the expected group length L_g, and the average separation between a given pair of groups L_γ.

The actual group length, L_G, is defined as the combination of the average group length and spacing, a quantity used to define the number of disconnections in the length of the geocast path.

$$L_G = L_g + L_\gamma = \frac{v e^{\frac{\lambda R}{v}}}{\lambda} \tag{20}$$

Consequently, the largest delay factor of the protocol's unidirectional forwarding due to group separation is defined as:

$$\begin{aligned} D_u = \frac{L T_\delta}{L_G} = \\ = L \frac{\lambda_1}{v_1} e^{-\frac{\lambda_1 R}{v_1}} \cdot \left(\frac{\frac{v_1}{\lambda_1} + R}{v_1 + v_2} + \frac{1}{2\lambda_2} \right) \end{aligned} \tag{21}$$

The delay model is further expanded by calculating the number of forwarders per packet (N_{Fu}) and including the delay associated with per-hop packet forwarding (D_c) in the total delay for the HOG protocol's unidirectional geocast operation. The calculation of the per-hop packet delay has been examined in many other works ([43, 53]) and it is beyond the scope of this paper, thus it can be assumed for D_c to be a constant value within the delay model. The forwarders per packet for the HOG protocol can be estimated by singling out the number of forwarders per group, which is inversely proportional to the communication radius R, and averaging the value over the number of disconnected groups along the length of the geocast path L, where:

$$N_{Fu} = \frac{L_g}{R} \cdot \frac{L}{L_G} = \frac{L}{R} \left[1 - e^{\frac{-\lambda R}{v}} \cdot \left(\frac{1 + R\lambda}{v} \right) \right], \tag{22}$$

or if the geocast message does not define L, but rather a time to live (T_{tl}) value, then the quantity can be also expressed as:

$$N_{Fu} = \frac{v T_{tl}}{R} \left[1 - e^{\frac{-\lambda R}{v}} \cdot \left(\frac{1 + R\lambda}{v} \right) \right]. \tag{23}$$

Finally, the total delay for the HOG protocol's unidirectional geocast operation is given by:

$$D_U = D_u + N_{Fu} \cdot D_c. \tag{24}$$

IV.5.3 HOG-Static and Dynamic Segments

For the operation of the HOG protocol when geocasting to a static or dynamic segments, a good scenario is if $T_\delta \leq \frac{L_s}{v_1}$, meaning that the time to reconnect two separated groups through opposite direction forwarding is less than the time it takes on average for a forwarding vehicle to travel the whole length of a given segment. The delay then can be expressed as previously calculated in (21): $\frac{L_s T_\delta}{L_G}$. In the case when $T_\delta > \frac{L_s}{v_1}$, or the reconnection time is greater than the time it takes on average for a vehicle to travel the whole length of the segment, there will then be an extra time in which a vehicle spends outside the segment, defined as $T_{\varepsilon 1} = T_\delta - \frac{L_s}{v_1}$ where $T_{\varepsilon 1} v_1 = d_{\varepsilon 1}$, therefore $T_{\varepsilon 2} = \frac{d_{\varepsilon 1}}{v_2}$ is the time it takes for the message to come back to the segment via opposite direction carry. The total time that the message is not in the segment is then given by: $T_{\varepsilon 1} + T_{\varepsilon 2}$. The associated delay in geocasting to a static segment due to group separation is then:

$$D_s = T_\delta - \frac{L_s}{v_1} + \frac{T_\delta v_1 - L_s}{v_2} = \frac{v_1 + v_2}{v_2} \cdot \left(T_\delta - \frac{L_s}{v_1} \right). \tag{25}$$

The same delay factor for geocasting within a dynamic segment is slightly different, since the segment is moving with a velocity vector $\vec{v_s}$, and is given by:

$$\begin{aligned} D_d &= T_\delta - \frac{L_s}{|\vec{v_1} - \vec{v_s}|} + \frac{T_R \, |\vec{v_1} - \vec{v_s}| - L_s}{|\vec{v_2} + \vec{v_s}|} = \\ &= \frac{|\vec{v_1} - \vec{v_s}| + |\vec{v_2} + \vec{v_s}|}{|\vec{v_2} + \vec{v_s}|} \cdot \left(T_\delta - \frac{L_s}{|\vec{v_1} - \vec{v_s}|} \right) \end{aligned} \tag{26}$$

The forwarders per packet within a segment is calculated similarly as is done in equation (22), where the length of the segment L_s is substituted for L. The difference is that the total number of forwarders during the lifetime of the message is included which, due to group separation, can not forward the message while they are within the segment. These forwarding nodes in effect will spend $\frac{L_s}{v}$ amount of time within the segment before they exit the area, at which time they will utilize an opposite direction message forwarding, taking T_δ time, to restore the connectivity to a segment. Thus, during the lifetime of the message there will be: $\frac{T_{tl}}{T_\delta + \frac{L_s}{v}}$ forwarders which will restore segment connectivity, and the total number of forwarders per packet for the static segment geocast of the HOG protocol is given by:

$$N_{Fs} = \frac{v T_{tl}}{R} \left[1 - e^{\frac{-\lambda R}{v}} \cdot \left(\frac{1 + R\lambda}{v} \right) \right] + \frac{T_{tl}}{T_R + \frac{L_s}{v}} \tag{27}$$

Similarly, the same quantity for dynamic segments is:

$$N_{Fd} = \frac{|\vec{v} - \vec{v}_s| \, T_{tl}}{R} \left[1 - e^{\frac{-\lambda R}{|\vec{v} - \vec{v}_s|}} \cdot \left(\frac{1 + R\lambda}{|\vec{v} - \vec{v}_s|} \right) \right] + \frac{T_{tl}}{T_R + \frac{L_s}{|\vec{v} - \vec{v}_s|}}. \tag{28}$$

Finally, the total delay of the HOG protocol's geocast to static segments will fall between the best case of no segment disconnects, and the worst case where the delay will be the sum of the average time spent by a forwarding vehicle within a segment, the time to reconnect, and the time wasted due to collisions:

$$\frac{L_s T_\delta}{L_G} < D_S < D_s + \frac{L_s}{v} + N_{Fs} \cdot D_c. \tag{29}$$

Following the same logic, the total delay for the dynamic geocast of the HOG protocol will be:

$$\frac{L_s T_\delta}{L_G} < D_D < D_d + \frac{L_s}{|\vec{v} - \vec{v}_s|} + N_{Fd} \cdot D_c. \tag{30}$$

In the following section the HOG protocol is evaluated and examined based on the performance analysis just presented.

IV.6 EVALUATION

Table 1: HOG Simulation parameters.

Parameter	Value
Simulation time	300 s
Transmission range	300 m, 450 m, 600 m
Geocast distance	1 km - 6.5 km
Geocast methods evaluated	Flooding, Directed flooding, HOG
Total vehicles simulated	1545
Road length	20 km
Lanes per direction	2
Average vehicle density	72 vehicles/km
Vehicle Speed	20 m/s - 30 m/s
Distance travelled	6 km - 9 km

IV.6.1 Simulation Setup and Performance Metrics

A VANET was simulated according to the previously stated network model and assumptions. For each simulation the first 300 s of simulation time were examined. The communication radius of nodes was varied in increments of 150 m starting from 300 m up to 600 m. Vehicles were simulated to travel on a 20 km long four-lane road, with an initial speed between 20 m/s to 30 m/s. The vehicle density was represented as a function of the vehicle generation rate, which was set up to create an average density of 72 vehicles per kilometer. The network runs a beaconing service, where each node transmits a beacon every half a second by means of broadcast to its neighbors. A beacon contains the node's ID, position, heading, and speed. Additionally, each node will send a geocast message every half a

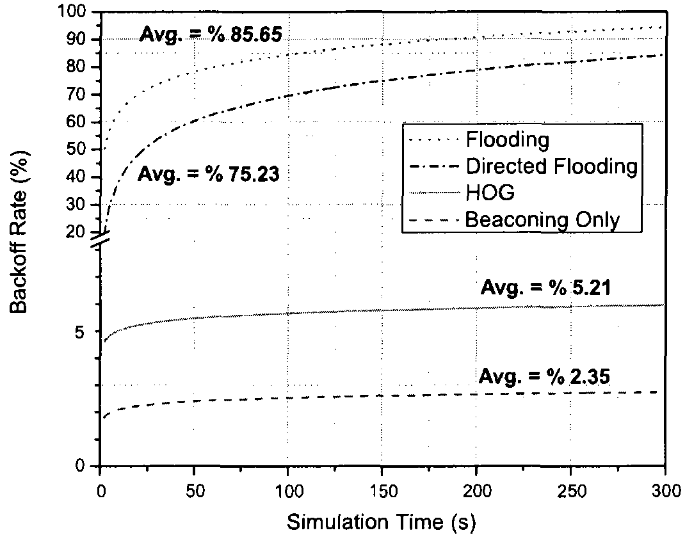


Fig. 25: Backoff rates.

second. In all of the simulation runs the HOG protocol was compared to flooding, blind re-broadcasting of messages to all neighboring nodes, and directed flooding, re-broadcasting of messages to nodes along the direction of the geocast. The simulation parameters are summarized in Table 1.

IV.6.2 Backoff and Reception Rates

The backoff and reception rates of the protocol were first examined and then compared to flooding, which could be considered to be a worst-case scenario, and directed flooding, a better, yet, still inefficient approach to geocast. Figure 25 shows the baseline backoff rate created by simply running the beaconing service. All nodes employ CSMA, and thus will first listen to the channel before transmitting. If the channel is busy, then the node will backoff untill a futher time when the channel is available. From the simulations it was observed that over time the beaconing service will cause on average 2.35 percent

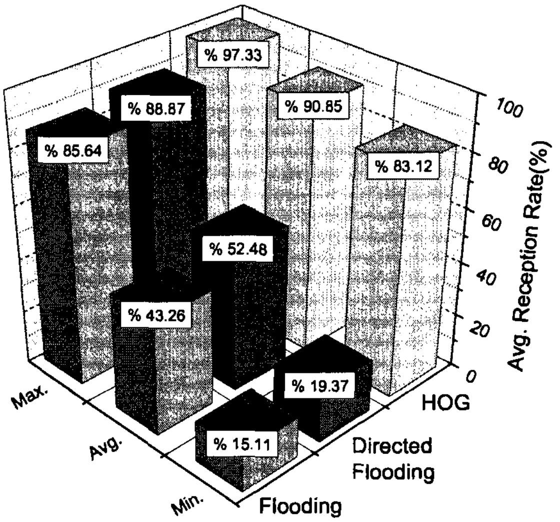


Fig. 26: Average reception rates.

of all nodes which are ready to transmit to back off. Since the HOG protocol utilizes the information obtained from the beaconing updates to create an overlay backbone, its backoff rate on average is less than 3 percent higher than that off backoff rate created by the baseline beaconing service. In contrast, flooding creates such a broadcast storm that over time on average 85.65 percent of nodes who have something to transmit have to back off. Directed flooding improves on flooding, but the channel remains unavailable on average to about three quarters of the nodes who wish to transmit.

Figure 26 shows the effect collisions have on the reception rate of messages. Even though CSMA allows for the nodes to listen to the channel before transmitting, collisions

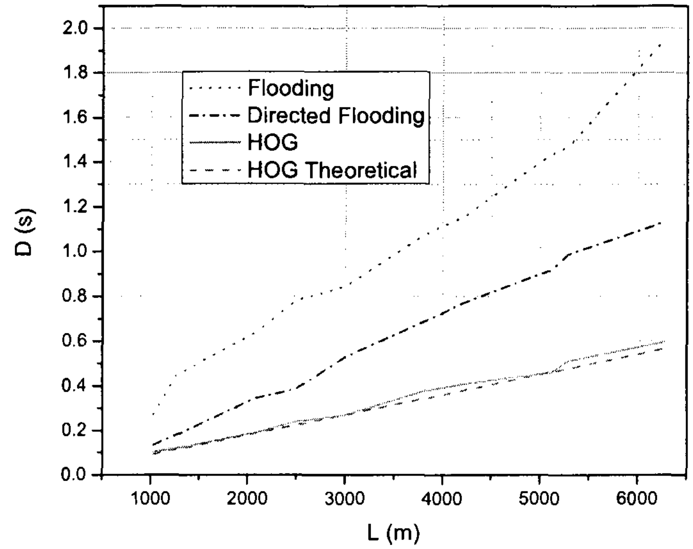


Fig. 27: Delay for $R = 300$ m.

may still occur due to the hidden terminal problem. Figure 25 illustrates the channel contention, while Figure 26 illustrates the effect of the broadcast storm problem on delays. Collisions increase the time of message propagation due to re-transmissions. On average the flooding methods, blind or directed, achieve a reception rate between forty and fifty percent. The HOG protocol's reception rate is, on the average, in the ninetieth percent. These figures clearly show that flooding is very inefficient and that it may cause large delays in message delivery due to rebroadcasts of packages, and that the HOG protocol exhibits very low channel contention (on top of the beaconing service) and very high delivery ratios.

IV.6.3 Delays

The data shown in Figures 27-29 was extracted from simulation runs in which the geocast distance specified by each node was varied from 1 km to 6.5 km in 500 m increments. On top of the beaconing updates, each node created a geocast message every half a second which was forwarded in an arbitrary direction. The information gathered from the beaconing updates was used by the HOG protocol to create an overlay backbone for geocast support. The figures show the delays associated with geocasting using flooding, directed flooding, and HOG unidirectional geocasting, as well as the expected values for the protocol's delay extracted from the equations presented in the analysis section. Figure 27 shows the delays when $R = 300$ m. Initially the delays for geocasting in the range of one kilometer are very close, regardless of the method used. The difference in the delay between the methods increases drastically as the geocast distance increases up to 6.5 km, where the HOG protocol outperforms flooding by a factor of three and directed flooding almost by a factor of two. The simulation results closely follow this study's theoretical model, as it is shown in the figures. Increasing the communicating range to 450 m increases the effectiveness of the protocol, as the per-hop reach is increased, yet the reduction in delay is not as dramatic in the smaller geocast ranges. The same can be said for setting $R = 600$ m. In the maximum geocast range, however, the delays are reduced by about one third when $R = 450$ m and by half when $R = 600$ m. Figures 28-29 show that the performance improvement for flooding also comes at larger geocast distances, yet at the lower range the delays are much larger when R is larger, which is due to the fact that more collisions are created with the increased communicating range. Even though directed flooding is an

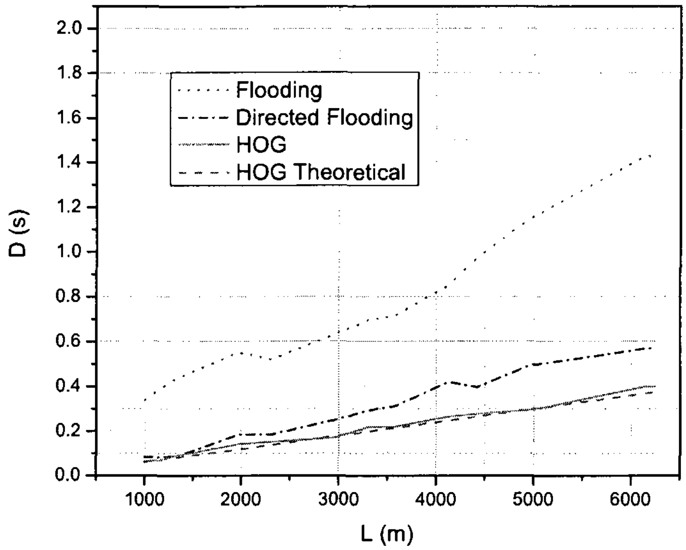


Fig. 28: Delay for $R = 450$ m.

improvement to flooding, the delays associated with the HOG protocol's operation are a far better improvement on both.

Table 2 further illustrates the effectiveness of the protocol by comparing its average reach per hop to those of flooding and directed flooding. The data was extracted from simulation runs in which nodes specified the number of hops that a geocast message should take, and when the number of hops expired the distance travelled by that message was examined. Since the communicating range was fixed to 300 m, Table 2 shows that flooding, averaging little more than 200 m per hop is very inefficent as a method for geocast since its effectiveness in per hop reach is very poor. Directed flooding is a better approach to geocasting, as it improves greatly upon flooding, yet the results confirm that the HOG protocol performs best by utilizing more than 90 percent of the hop capacity.

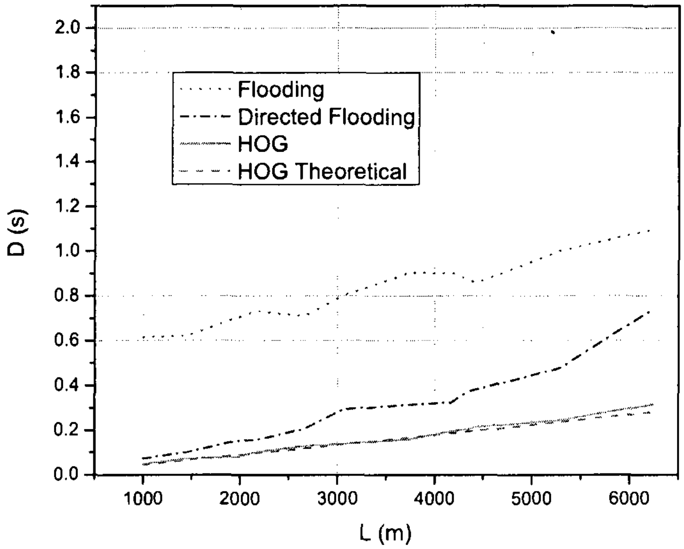


Fig. 29: Delay for $R = 600$ m.

Table 2: HOG Average reach for R = 300 m.

N_{Fu}	Flooding	Directed flooding	HOG
5	1027.41 m	1270.64 m	1397.51
10	2072.19 m	2495.54 m	2831.44
15	3004.32 m	3835.97 m	4147.95
20	4228.73 m	5116.71 m	5569.60
25	5291.27 m	6268.84 m	6736.25
L/N_{Fu}	207.22 m/hop	253.20 m/hop	277.42 m/hop

IV.7 CONCLUSIONS ON THE HOG PROTOCOL

In this chapter a hybrid overlay geocast protocol was presented that creates a dedicated virual backbone in an unstructured VANET. The backbone provides stable geocast support and features beacon-driven cached forwarding, reverse-direction message propagation, and stable geocast router selection. The protocol operates in a distributed manner and provides persistent geocast service incorporating greedy stateless methods. Through simulations it is shown that the protocol's communication is very efficient as it creates very low channel contention while exhibiting large delivery ratios and maximizing the per-hop reach of messages. The end-to-end delays of the HOG protocol are also very low, and provide a drastic improvement on flooding and directed flooding as methods for geocast.

CHAPTER V

GEOCAST-DRIVEN STRUCTURELESS DISSEMINATION

In this chapter, a geocast-driven structureless information dissemination scheme for VANETs is presented which utilizes the HOG protocol and aims to extend the vehicles' view of local traffic conditions, as well as provide large distance aggregated information of traffic conditions, while preserving the full detail of specific emergency messages.

V.1 SYSTEM MODEL AND ASSUMPTIONS

Each vehicle in the system is assumed to be equipped with a wireless transceiver and a positioning device, or a GPS. The wireless radio is assumed to operate at the same power level on each node, such that the communication radius R is common for all nodes. Each vehicle can extract its position from the GPS device, as well as speed, heading, and global time. Further, the VANET runs a beaconing service application, where each node periodically transmits its location and velocity information to its neighbors that are within its communication radius R. From this information, vehicles are able to contruct an immediate view of their surroundings as shown in Figure 30. The vehicles also send the list of their neighbors during the beaconing updates. From this message exchange a vehicle is able to obtain an extended view of its surroundings, i.e. the neighbors of its neighbors. For the information dissemination phase, it is assumed that an underlying geocast protocol can be utilized to forward the data in such a way that, for each transmission, all nodes within a geocast region can receive and process the original data. The geocast protocol at each

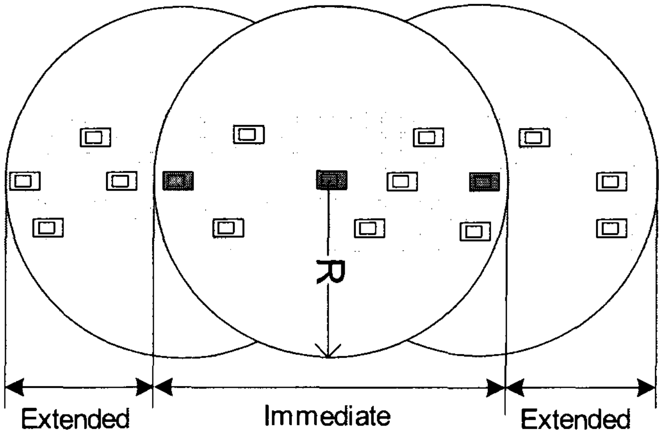


Fig. 30: Local view of neighbors using beaconing only.

node also maintains and provides a list of intermediate forwarding nodes which maximize the reach of the communication. Here the HOG protocol detailed in the previous chapter is specifically employed.

V.2 SCHEME OPERATION

The beaconing service allows for each vehicle to be aware of its neihbors, their position, speed, and heading. This information is exchanged between nodes every 0.5 s, so that each node has very fresh immediate view of its surroundings, see Figure 30. Since vehicles will append their neighbor information within these beacons, it is possible for any vehicle to have information about its neighbors' neighbors which is referred to as an extended view. Even though the extended view is not as fresh as the immediate view, since the records have been collected one beaconing cycle before, it still presents relatively fresh information about a vehicle surroundings, while roughly doubling its view. The combination of the immediate and extended view is referred to as the local view of a vehicle. The local view is

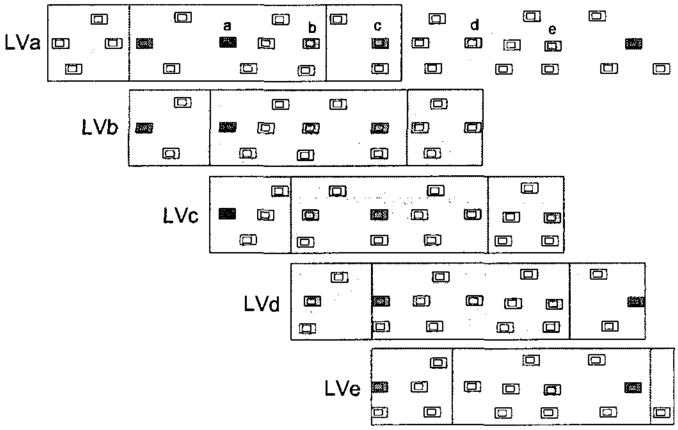


Fig. 31: Local view of forwarding nodes.

unique for each vehicle and provides visibility of at most twice the communication radius in each direction. If we take for example $R = 300$ m, then a vehicle can have a fresh local view of its surroundings at most 600 m in each direction, which given the frequency of the updates, provides sufficient fresh information to a driver to react in emergency scenarios, such as accidents or traffic standstills.

Here the aim is to increase the local view of a vehicle by employing intelligent information dissemination, and even provide information about the road for large distances ahead in diminishing resolution so that drivers can be even more aware of the road conditions miles ahead. This is accomplished by disseminating local views of vehicles using geocast methods, and aggregating this information at points where new information is available to be added. This study's scheme allows for vehicles to generate periodic reports which contain a local view and a distance describing how far down a given road this report is to be disseminated. The reports creation can be done at an interval of every n seconds and propagated a distance of L meters. Once a report has been sent, all vehicles along the geocast path will refrain from creating another one until the time expires. Once a vehicle sends a local view frame to be disseminated, all nodes within its communication range receive this message and extract any relevant information, and the forwarding node (specified by the geocast protocol) determines whether to forward the message as is to another intermediate forwarding node or to apply an aggregation function. The scheme employs a simple aggregation function that extracts the total number of vehicles and their average speed from a local view frame, even though any other aggregating algorithm can be used. The originating node, and any forwarding node, can specify a set of information that is never to be aggregated, that is to be kept at full resolution. A sample type of this data could be an accident site, a stopped vehicle, or an emergency vehicle information.

When an intermediate forwarding node receives a Local View Frame (LVF), a message containing the local view of all nodes and their specifics, it will first check if the originator of the LVF is in its own Local View (LV). If so, then the message will be forwarded to the next intermediate forwarding node. It is important to note that all nodes which receive the geocasted LVF will update their local view by adding all the nodes and their specifics to their extended view. This way even if a node does not participate in the forwarding of the LVF, it can still extract detailed information about its surroundings. The forwarding of the LVF message will continue until an intermediate forwarding node that does not have the originating node in its LV or any of the LVF's nodes in its Immediate View (IV). For example, if node *a* in Figure 31 wishes to disseminate information in the traveling direction, it will create a message that will contain all the details of its local view (LVF) and will send it using a geocast method, specifying the distance *L* that it wishes for the data to be disseminated. Node *b* is the forwarding node of node *a* in the direction selected, and since node *b* has node *a* in it's local view (LVb) it will forward the message to node *c*, which in return, for the same reasons (see LVc) will forward the message to node *d*. Node *d* does not have node *a* in its LV, but it has one of the LVF's nodes in its immediate view (namely, node *c* according to LVd). Thus node *d* will once again forward the message to *e* which does not have the source *a* or any other nodes from the LVF in its immediate view, yet its local view has some similarities with the LVF (node *c* and the one below it). Node *e* will therefore apply an aggregation function to the original LVF, while still preserving the original timestamp, the positions of the edge nodes within the LVF, and any anomalies encountered. An example anomaly could be where a vehicle in the original LVF may be stopped, or an accident, i.e. some important information that must be excluded from the aggregation function. All the preserved and aggregated information will then be added to a new message created by node *e* which will also contain node *e*'s LVF (excluding the common nodes with the original LVF) and the remainder of the distance that the original information needed to be disseminated. The pseudocode shown in Figure 32 explains the processing of a received LVF.

In effect, this scheme aims to maximize the distance that a local view frame travels before it is aggregated. This way all nodes along the path of the geocast to the aggregating node receive detailed information about the originating node's local view, in effect broadening their own extended view of the roadway. Once the LVF reaches the aggregating node, the scheme makes sure that the dimensions, timestamp, and other unique information of the LVF are preserved before the aggregation is executed. The scheme also ensures that only unique vehicle information is disseminated by the aggregating node's exclusion

```
NODE RECEIVE($\mathbf{LVF}, L$):
for $\forall Nodes \in \mathbf{LVF} \mid Nodes \notin ThisNode.\mathbf{LV}$
    do ADDNODES($Nodes$) to $ThisNode.\mathbf{EV}$
if $ThisNode$ is a forwarding node
  then
      if $\mathbf{LVF}.Source \in ThisNode.\mathbf{LV}$
        then FORWARD($\mathbf{LVF}, L$)
             return
      if $\exists Node \in (\mathbf{LVF} \wedge ThisNode.\mathbf{IV})$
        then FORWARD($\mathbf{LVF}, L$)
             return
      if $\exists Node \in \mathbf{LVF} \mid Node \in ThisNode.\mathbf{LV}$
        then AGGREGATE($\mathbf{LVF}, ThisNode.\mathbf{LVF}$):
             $\mathbf{NewLVF} \leftarrow \mathbf{LVF}.TimeSent$
             $\mathbf{NewLVF} \leftarrow \mathbf{LVF}.EdgeNodeLocations$
             $\mathbf{NewLVF} \leftarrow \mathbf{LVF}.Anomalies$
             $\mathbf{NewLVF} \leftarrow Aggregated(\mathbf{LVF})$
             $\mathbf{NewLVF} \leftarrow ThisNode.\mathbf{LVF}$
             FORWARD($\mathbf{NewLVF}, Ladjusted$)
             return
  else return
```

Fig. 32: Pseudocode for processing a LVF.

of common nodes with the original LVF when creating a new LVF. This way nodes farther down the dissemination path will know of the characteristics of sections of vehicles at given times and the fresh LVF from the last aggregating node, in effect creating a layered view of the network. The layered view provides the precise information at the immediate view, less so at the extended, and with diminishing resolution from the aggregated local view frames of other nodes.

Figure 33 shows a sample of this layered view where R is set to 300 m, the position of the road bounds where the local view frames exist are simplified, and the densitiy of vehicles is sufficiently high to maximize the frame reach. In this Figure, the grey vehicle

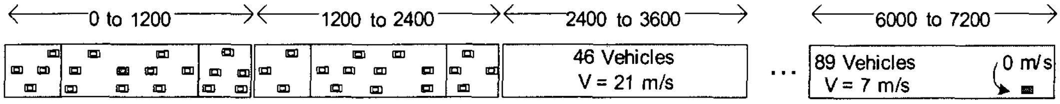


Fig. 33: A sample layered view for $R = 300$ m.

in the left has a clear local view, an extended local view from the last geocast and several aggregated frames each showing the position of the frame, number of vehicles and average speed, including a report of a broken-down vehicle more than 7 km away. This Figure clearly shows that in such a scenario by using this scheme a vehicle is able to effectively double its local view, and have a layered view with diminishing resolution of the traffic ahead, all to the service of the driver to make better choices about a commute.

V.3 EVALUATION

Next the scheme is evaluated first analyticaly, then is compared to the obtained simulation results to the performance analysis.

V.3.1 Analysis

An estimate of the average number of vehicle records is first estimated so that any node can obtain through beaconing, thus creating its immediate view, using the following formula:

$$NR_{IV} = 2R\frac{\lambda}{\upsilon} - 1, \tag{31}$$

where λ is the vehicle arrival rate and υ is average speed of vehicles on a given road. The number of immediate view records should lead, under ideal circumstances to where the density of vehicles is high enough so that the underlying geocast protocol can maximize its reach under the specified communication radius R, to the following number of vehicle records in the local view:

$$NR_{LV} = 4R\frac{\lambda}{\upsilon} - 1. \tag{32}$$

To calculate the average visibility of road conditions that the immediate view provides it is assumed that the distance between the vehicles in the system conforms to a Poisson-distribution:

$$f(x) = C\lambda e^{-\lambda x}, \tag{33}$$

where λ represents the arrival rate of vehicles per meter. The normalization constant C is calculated by forcing the condition that the probability needs to be equal to unity on the interval from the minimum distance (0 m) to the maximum distance ($\frac{1}{\lambda}$ m) between two consecutive vehicles, leading to the final expression for the probability function:

$$f(x) = \frac{1}{(e-1)}\lambda e^{1-\lambda x}. \tag{34}$$

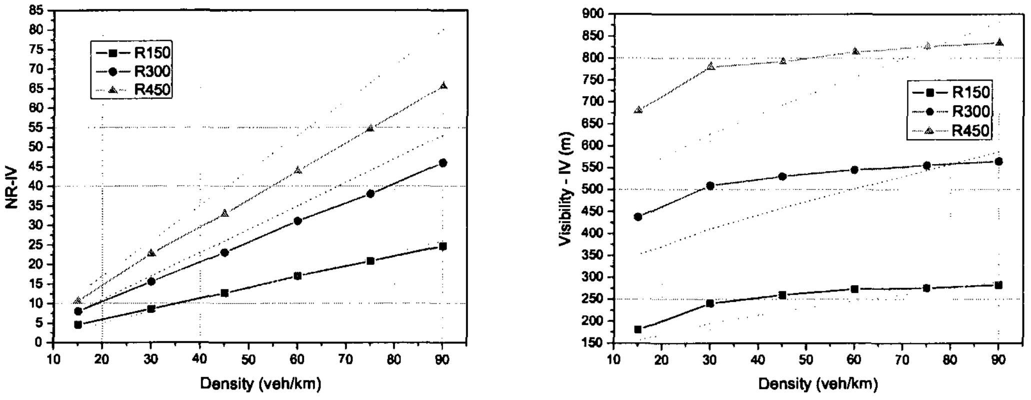
The average distance between any two vehicles can then be calculated, which is given by:

$$< x >= \frac{1}{(e-1)}\int_0^{1/\lambda} x\lambda e^{1-\lambda x}dx = \frac{1}{\lambda} - \frac{(e-2)}{\lambda(e-1)}. \tag{35}$$

The total visibility range that the immediate view would provide is then the total length of all the vehicles in the communicating range plus the total length of the inter-vehicle space:

$$V_{IV} = 2R\frac{\lambda}{\upsilon}L_{car} + \left(2R\frac{\lambda}{\upsilon} - 1\right)\left[\frac{1}{\lambda} - \frac{(e-2)}{\lambda(e-1)}\right]. \tag{36}$$

Again, under the ideal circumstances mentioned before, the visibility range that the



(a) Average number of records.

(b) Average visibility.

Fig. 34: Immediate view characteristics.

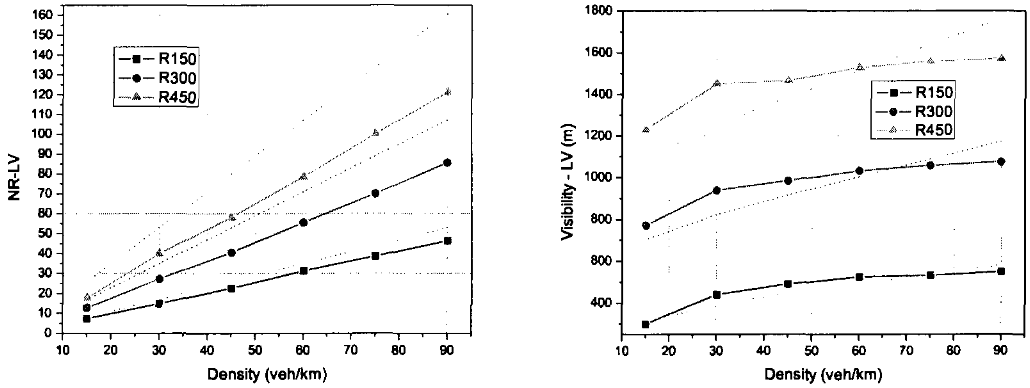
local view would provide would be $V_{LV} = 2 * V_{IV}$, or twice as much visibility of the road conditions by simply using beaconing to discover neighbors and their specifics.

V.3.2 Simulation and Results

Table 3: Dissemination scheme simulation parameters.

Parameter	Value
Simulation time	300 s
Transmission range	150m, 300 m and 450 m
Vehicles densities	15 to 90 vehicles/km
Road length	10 km
Number of lanes	2
Vehicle Speed	20 m/s - 30 m/s
Distance travelled	6 km - 9 km

A VANET was simulated according to the simulation parameters shown in Table 3. The simulations were run on a two-lane road 10km long, where vehicles moved in one direction with an initial speed between 20 m/s to 30 m/s, traveling a maximum distance of 9 km during the 300 s runtime. The vehicle density was controlled through the vehicle



(a) Average number of records.

(b) Average visibility.

Fig. 35: Local view characteristics.

arrival rate, and was varied between 15 to 90 vehicles per kilometer in increments of 15 vehicles per kilometer. The transmission radius *R* was also varied between 150 m, 300 m, and 450 m. Each vehicle ran a beaconing service, which broadcast a message containing the vehicle position, speed, and heading to all nodes within *R*. One vehicle was set up to be static and positioned on one end of the highway. In order to test the scheme, every 5 s this static vehicle emmited a LVF to be geocasted up to the full lenght of the road. In effect this simulated a broken down vehicle warning message that triggered the scheme to disseminate the data down the highway and warn other drivers of the danger, as well as to provide them with a layered view of the full road conditions.

The average number of record exchanges required for each node to construct an immediate view of its surroundings was first examined. The simulation results closely follow the previously presented analysis, as can be observed from Figure 34(a). For each of the communication radii, as the density of the vehicles increases, so does the number of neighbors discovered by each node through beaconing. This was an expected result, as the more neighbors a node has the higher its visibility is in the immediate view. This correlation is shown in Figure 34(b), illustrating the visibility of nodes using beaconing only. From this Figure it can be seen that for the lowest density range, nodes barely can reach half their visibility potential ($2R$). As the density increases, the visibility of the nodes approaches that of twice their communicating radius. The dotted lines show the theoretical analysis for each of the R used in the simulation.

The local view, constructed by the exchange of the list of neighbors between nodes during beaconing, is theoretically expected to create almost double the number of vehicle records as that of its immediate view counterpart, which is represented by the dotted lines in Figure 35(a) for each R examined. The simulation results show that when the communication radius is small, the number of records to construct a local view closely follows the analysis. As R is increased, it can be seen that the number of reports deviates more from the theoretical analysis. This means that less number of vehicle records are placed in a LVF, making the dissemination phase of the scheme a bit more lightweight than expected. The effect of the number vehicle records on the visibility obtained in the local view range is shown in Figure 35(b). The Figure shows that using neighbor information exchanges between nodes during beaconing can almost double the visibility of road conditions, which was an expected result.

Figure 36 shows the extent to which the scheme extends the visibility of traffic conditions for vehicles. The visibility is extended, on average, from a bit more than one and a half times to two times that of the local view, depending on the density of vehicles and R used. This Figure only shows the high detail average visibility of vehicles, while aggregated LVFs provide even more of a view of the road conditions. The simulation results

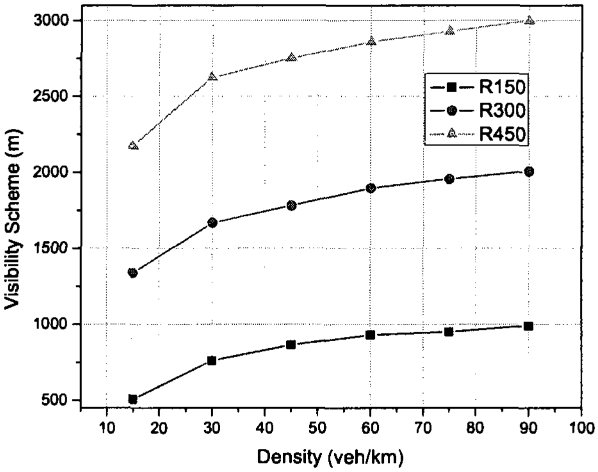


Fig. 36: Average visibility for the dissemination scheme.

show that the aggregated LVFs preserve the information about the broken down vehicle at the edge of the road, and regardless on the location of the vehicle they provide full view of the highway conditions. For example, vehicles closer to the begining of the road can have high detail visibility from 1 km to 3 km, depending on the *R* used, and visibility of the rest of the highway through aggregrated LVFs. The figure shows that, unlike the ideal scenario shown in Figure 33, for $R = 300$ m the high fidelity visibility provided by the scheme can vary from less than 1,500 m in low density scenarios to approximately 2,000 m in high density scenarios, which is unlike the 2,400 m expected ideal visibility. Nonetheless, the scheme provides the driver with, on average, three times larger visibility than the one obtained only through beaconing, and it does so using less than double the vehicle records needed to create an immediate view.

V.4 CONCLUSIONS ON THE INFORMATION DISSEMINATION SCHEME

In this chapter a structureless information dissemination scheme was presented that creates a layered view of road conditions with a diminishing resolution as the geocast distance increases. The extended local view at each vehicle created by the scheme almost doubles that of the view created by exchanging neigbor information between nodes. The simulation results conform to the analysis and show that the scheme provides the driver with a high detail view of road conditions sufficiently far ahead, as well as with aggregated information for the length of the whole road, all while preserving safety critical reports in high detail.

CHAPTER VI

CONCLUSIONS

This dissertation presented supporting protocols for structuring and intelligent information dissemination in vehicular *ad hoc* networks. A novel mobility-aware, general-purpose clustering scheme designed for VANETs was first presented, which takes the directionality of moving vehicles into consideration during the cluster creation and maintenance phases. The GVC scheme promotes the spatial reuse of network resources by introducing a structure in VANETs, and allows for more efficient use of the available bandwidth, which can effectively increase the capacity of the network. The simulation results of the GVC scheme show that robust cluster structures are created, which exhibit a relatively long lifetime, even in scenarios with low vehicle densities and reduced communication radius. The results also show that the GVC cluster structure is very stable, especially when directionality is taken into consideration. Due to the directional property of the scheme, the overhead associated with cluster creation and maintenance is greatly reduced. Additionally, if all GVC-related data was to be piggybacked onto DSRC periodic safety messages, then the only cost associated with the operation of the GVC scheme would be computational.

The clustering scheme was then utilized to provide support for more efficient large distance routing and data dissemination by formulating a hybrid overlay-network geocast protocol which creates a dedicated multicast cluster head backbone overlay virtual infrastructure on top of the physical network. The backbone created by the HOG protocol provides support for group-oriented communication in VANETs. The protocol is a hybrid approach which uniquely utilizes an intrinsic structure to simplify the routing computation and provides persistent support for location-based communication in VANETs. The backbone created by the HOG protocol provides stable geocast support and features beacon-driven cached forwarding, reverse-direction message propagation, and stable geocast router selection. HOG operates in a distributed manner and provides persistent geocast service by incorporating greedy stateless methods. The simulation results show that the protocol's communication is very efficient as it creates very low channel contention while exhibiting large delivery ratios and maximizing the per-hop reach of messages. The end-to-end delays of the HOG protocol are also very low, and provide a drastic improvement on flooding and directed flooding as methods for geocast.

Finally, the HOG protocol was utilized to create an information dissemination scheme which creates a detailed local view and layered extended view of traffic conditions for each vehicle. The structureless information dissemination scheme creates a layered view of road conditions with a diminishing resolution as the viewing distance increases. The scheme first provides a high-detail immediate neighbor view, and a high-detailed local neighbor view. This view is further extended when information dissemination is employed. The scheme provides each vehicle with aggregated information for road conditions beyond the extended local view, and allows for the preservation of unique reports within aggregated frames, such that safety-critical notifications are kept in high detail, all for the benefit of the driver's improved decision making during emergency scenarios.

BIBLIOGRAPHY

[1] Y. Zhang, and J. M. Ng, "A Distributed Group Mobility Adaptive Clustering Algorithm for Mobile Ad Hoc Networks," in *IEEE ICC'08*, pp. 3161-3165, May 2008.

[2] D. Gavalas, G. Pantziou, C. Konstantopoulos, and B. Mamalis, "Clustering of Mobile Ad Hoc Networks: An Adaptive Broadcast Period Approach," in *IEEE ICC'06*, vol. 9, pp. 4034-4039, Jun. 2006.

[3] L. Wang, and S. Olariu, "A unifying look at clustering in Mobile Ad Hoc Networks," *Journal of Wireless Communications and Mobile Computing*, vol. 4, pp. 623-637, 2004.

[4] A. B. McDonald, and T. F. Znati, "A mobility-based framework for adaptive clustering in wireless ad hoc networks," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 8, pp. 1466-1487, Aug. 1999.

[5] P. Basu, N. Khan, and T. D. C. Little, "A mobility based metric for clustering in mobile ad hoc networks," in *International Conference on Distributed Computing Systems*, pp. 413-418, Apr. 2001.

[6] C. R. Lin, and M. Gerla, "Adaptive clustering for mobile wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 15, no. 7, pp. 1265-1275, Sep. 1997.

[7] C.C. Chiang, "Routing in Clustered Multihop, Mobile Wireless Networks with Fading Channel," in *IEEE SICON'97*, pp. 197-21, Apr. 1997.

[8] T. J. Kwon, M. Gerla, V. K. Varma, M. Barton, and T. R. Hsing, "Efficient flooding with passive clustering-an overhead-free selective forward mechanism for ad hoc/sensor networks," in *Proceedings of the IEEE*, vol. 91, no. 8, pp. 1210-1220, Aug. 2003.

[9] J. Luo and J. -P. Hubaux, "A Survey of Inter-Vehicle Communications," *Technical report IC/2004/04, EPFL*, Mar. 2004.

[10] X. Zhang, H. Su, and H. H. Chen, "Cluster-based multichannel communications protocols in vehicle ad-hoc networks," *IEEE Wireless Communications*, vol. 13, no. 5, pp. 4451, Oct. 2006.

[11] A. B. McDonald, and T. F. Znati, "Design and performance of a distributed dynamic clustering algorithm for ad-hoc networks," in *Proceedings of the 34th Annual Simulation Symposium*, pp. 27-35, 2001.

[12] E. Sakhaee, A. Jamalipour, "Stable Clustering and Communications in Pseudolinear Highly Mobile Ad Hoc Networks," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 6, pp. 3769-3777, Nov. 2008.

[13] H. Su, X. Zhang, "Clustering-Based Multichannel MAC Protocols for QoS Provisionings Over Vehicular Ad Hoc Networks," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 6, pp. 3309-3323, Nov. 2007.

[14] M. Raya, A. Aziz and J. -P. Hubaux, "Efficient secure aggregation in VANETs," *ACM VANET'06*, pp. 67-75, Sep. 2006.

[15] H. -J. Reumerman, M. Roggero, and M. Ruffini, "The application-based clustering concept and requirements for intervehicle networks," *IEEE Communications Magazine*, pp. 108113, Apr. 2005.

[16] J. Blum, A. Eskandarian, and L. Hoffman, "Mobility management in IVC networks," in *Proceedings of the IEEE Intelligent Vehicles Symposium*, pp. 150-155, Jun. 2003.

[17] Q. Xu, T. Mak, J. Ko, and R. Sengupta, "Vehicle-to-vehicle safety messaging in DSRC," in *ACM VANET'04*, pp. 19-28, Oct. 2004.

[18] M. Ge, S. V. Krishnamurthy, and M. Faloutsos, "Overlay Multicasting in Ad Hoc Networks," in *Third Meditteranean Ad Hoc Networking Workshop (Med-Hoc-Net*, Jun. 2004.

[19] C. Gui, P. Mohapatra, "Efficient overlay multicast for mobile ad hoc networks," in *IEEE WCNC'03*, vol. 2, pp. 1118-1123, Mar. 2003.

[20] L. Sung-Ju, M. Gerla, and C. Ching-Chuan, "On-demand multicast routing protocol," in *IEEE WCNC'99*, vol. 3, pp. 1298-1302, Sep. 1999.

[21] M. Bechler and L. Wolf, "Mobility management for vehicular ad hoc networks," in *IEEE VTC 2005*, vol. 4, pp. 2294-2298, May 2005.

[22] P. Sinha, R. Sivakumar, and V. Bharghavan, "MCEDAR: multicast core-extraction distributed ad hoc routing," in *IEEE WCNC'99*, vol. 3., pp. 1313-1317, Sep. 1999.

[23] P. Bucciol, F. Ridolfo, and J. C. De Martin, "Multicast Voice Transmission over Vehicular Ad Hoc Networks: Issues and Challenges," in *IEEE ICN'08*, pp. 746-751, Apr. 2008.

[24] E. M. Royer and C. E. Perkins, "Multicast operation of the ad-hoc on-demand distance vector routing protocol," in *IEEE MobiCom'99*, pp. 207-218, Aug. 1999.

[25] K. Chen and K. Nahrstedt, "Effective location-guided tree construction algorithms for small group multicast in MANET," in *IEEE INFOCOM 2002*, vol. 3, pp. 1180-1189, 2002.

[26] T. Kosch, C. Schwingenschlogl, and A. Li, "Information dissemination in multi-hop inter-vehicle networks," in *IEEE ITS'02*, pp. 685-690, 2002.

[27] J. Xie., R. R. Talpde, A. Mcculey, and M. Liu, "AMRoute: Ad Hoc Multicast Routing Protocol," in *ACM Mobile Network and Applications*, vol. 7., iss. 6., Dec. 2002.

[28] J. Lusheng and M. S. Corson, "Differential destination multicast-a MANET multicast routing protocol for small groups," in *IEEE INFOCOM 2001*, vol. 2, pp. 1192-1201, 2001.

[29] J. Luo, P. T. Eugster, and J. -P. Hubaux, "Route driven gossip: probabilistic reliable multicast in ad hoc networks," in *IEEE INFOCOM 2003*, vol. 3, pp. 2229-2239, Mar. 2003.

[30] R. Baldessari, A. Festag, and J. Abeille, "NEMO meets VANET: A Deployability Analysis of Network Mobility in Vehicular Communication," in *IEEE ITST 2007*, pp. 1-6, Jun. 2007.

[31] C. Gui and P. Mohapatra, "Scalable multicasting in mobile ad hoc networks," in *IEEE INFOCOM 2004*, vol. 3, pp. 2119-2129, Mar. 2004.

[32] T. D. C. Little and A. Agarwal, "An information propagation scheme for VANETs," in *IEEE ITS'05*, pp. 155-160, Sep. 2005.

[33] P. Muhlethaler, A. Laouiti, and Y. Toor, "Comparison of Flooding Techniques for Safety Applications in VANETs," in *IEEE ITST 2007*, pp. 1-6, Jun. 2007.

[34] H. Wu, R. Fujimoto, R. Guensler, and M. Hunter, "MDDV: a mobility-centric data dissemination algorithm for vehicular networks," in *ACM VANET 2004*, pp. 47-56, Oct. 2004.

[35] T. Kaya, G. Lin, G. Noubir, and A. Yilmaz, "Secure multicast groups on ad hoc network," in *ACM SASN 2003*, pp. 94-102, Oct. 2003.

[36] R. Vaishampayan and J. J. Garcia-Luna-Aceves, "Efficient and robust multicast routing in mobile ad hoc networks," in *IEEE International Conference on Mobile Ad-hoc and Sensor Systems*, pp. 304-313, Oct. 2004.

[37] J. G. Jetcheva and D. B Johnson, "Adaptive demand-driven multicast routing in multi-hop wireless ad hoc networks," in *ACM MobiHoc 2001*, pp. 33-44, Oct. 2001.

[38] A. Bachir and A. Benslimane, "A multicast protocol in ad hoc networks inter-vehicle geocast," in *IEEE VTC 2003*, vol. 4, pp. 2456-2460, Apr. 2003.

[39] M. Kihl, M. Sichitiu and H. Joshi, "Design and evaluation of two geocast protocols for vehicular ad-hoc networks," *Journal of Internet Engineering*, 2008.

[40] A. Agarwal, D. Starobinski, and T. D. C. Little, "Exploiting Downstream Mobility to Achieve Fast Upstream Message Propagation in Vehicular Ad Hoc Networks," in *IEEE INFOCOM MOVE 2007*, pp. 13-18, May 2007.

[41] A. Bachir and A. Benslimane, "A multicast protocol in ad hoc networks inter-vehicle geocast," in *IEEE VTC 2003-Spring*, vol. 4, pp. 2456-2460, Apr. 2003.

[42] B. Bako, E. Schoch, F. Kargl, M. Weber, "Optimized Position Based Gossiping in VANETs," in *IEEE VTC 2008-Fall*, pp. 1-5, Sept. 2008.

[43] C.-K. Chau and P. Basu, "Exact Analysis of Latency of Stateless Opportunistic Forwarding," *INFOCOM 2009*, pp. 828-836, Apr. 2009

[44] F. Dürr and K. Rothermel, "An Overlay Network for Forwarding Symbolically Addressed Geocast Messages," in *IEEE ICCCN 2006*, pp. 427-434, Oct. 2006.

[45] F. Farnoud and S. Valaee, "Reliable Broadcast of Safety Messages in Vehicular Ad Hoc Networks," in *IEEE INFOCOM 2009*, pp. 226-234, Apr. 2009.

[46] C. Gui and P. Mohapatra, "Efficient overlay multicast for mobile ad hoc networks," in *IEEE WCNC 2003*, vol.2, pp. 1118-1123, Mar. 2003.

[47] C. Gui and P. Mohapatra, "Scalable multicasting in mobile ad hoc networks," in *IEEE INFOCOM 2004*, vol.3, pp. 2119-2129, Mar. 2004.

[48] M. Heissenbuttel, T. Braun, M. Wälchli, and T. Bernoulli, "Optimized Stateless Broadcasting in Wireless Multi-Hop Networks," in *INFOCOM 2006*, pp. 1-12, Apr. 2006.

[49] K. Ibrahim, M. C. Weigle, and A. Mahmoud, "p-IVG: Probabilistic Inter-Vehicle Geocast for Dense Vehicular Networks," in *IEEE VTC 2009-Spring*, pp. 1-5, Apr. 2009.

[50] K.-I. Kim and S.-H. Kim, "DREAM : Density Aware Overlay Multicast Forwarding in Mobile Ad Hoc Networks," *Wireless Personal Communications*, vol. 39, no. 3, pp. 381-400 , Nov. 2006.

[51] Y. Ko and N. H. Vaidya, "Location-Aided Routing (LAR) in mobile ad hoc networks," *Wireless Networks*, vol. 6, no. 4, pp. 307-321, Sept. 2000.

[52] U. Lee, S. Y. Oh, K.-W. Lee, amd M. Gerla, "RelayCast: Scalable multicast routing in Delay Tolerant Networks," in *IEEE ICNP 2008*, pp. 218-227, Oct. 2008.

[53] X. Ma and X. Chen, "Delay and Broadcast Reception Rates of Highway Safety Applications in Vehicular Ad Hoc Networks," *INFOCOM MOVE 2007*, pp. 85-90, May 2007.

[54] C. Maihöfer and R. Eberhardt, "Geocast in vehicular environments: caching and transmission range control for improved efficiency," *IEEE Intelligent Vehicles Symposium*, pp. 951-956, Jun. 2004.

[55] V. Naumov and T. R. Gross, "Connectivity-Aware Routing (CAR) in Vehicular Ad-hoc Networks," in *IEEE INFOCOM 2007*, pp. 1919-1927, May 2007.

[56] M. Piórkowski, "Mobility-centric geocasting for mobile partitioned networks," in *IEEE ICNP 2008*, pp. 228-237, Oct. 2008.

[57] N. Wisitpongphan, F. Bai, P. Mudalige, V. Sadekar, and O. Tonguz, "Routing in Sparse Vehicular Ad Hoc Wireless Networks," *IEEE Journal on Selected Areas in Communications*, vol. 25, no.8, pp. 1538-1556, Oct. 2007.

[58] Q. Yu and G. Heijenk, "Abiding Geocast for Warning Message Dissemination in Vehicular Ad Hoc Networks," in *IEEE ICC Workshops 2008*, pp. 400-404, May 2008.

[59] J. Zhao and G. Cao, "VADD: Vehicle-Assisted Data Delivery in Vehicular Ad Hoc Networks," *IEEE Transactions on Vehicular Technology*, vol.57, no.3, pp. 1910-1922, May 2008.

[60] Torok, A., Laborczi, P.and Gerhath, G., "Spatially Constrained Dissemination of Traffic Information in Vehicular Ad Hoc Networks," in *IEEE VTC '08*, pp. 1-5, 2008.

[61] Wu, H., Fujimoto, R., Guensler, R., and Hunter, M., "MDDV: A Mobility-Centric Data Dissemination Algorithm for Vehicular Networks," in *ACM VANET '04*, pp. 47-56, Oct. 2004.

[62] Leontiadis, I. and Mascolo, C., "Opportunistic Spatio-Temporal Dissemination System for Vehicular Networks," in *ACM MobiOpp '07*, pp. 39-46, Jun. 2007.

[63] C.L. Hu and M.S. Chen, "Adaptive Multichannel Data Dissemination: Support of Dynamic Traffic Awareness and Push-Pull Time Balance," *IEEE Transactions on Vehicular Technology*, vol. 54, no. 2, pp. 673686, Mar. 2005.

[64] J. Zhao, Y. Zhang, and G. Cao, "Data Pouring and Buffering on the Road: A New Data Dissemination Paradigm for Vehicular Ad Hoc Networks," *IEEE Transactions on Vehicular Technology*, vol. 56, no.6, pp. 32663277, Nov. 2007.

[65] Yu, B., Gong, J., and Xu, C., "Catch-Up: A Data Aggregation Scheme for VANETs," in *ACM VANET'08*, pp. 49-57, Sep. 2008.

[66] Ibrahim, K., Weigle, M.C., "CASCADE: Cluster-Based Accurate Syntactic Compression of Aggregated Data in VANETs," in *IEEE GLOBECOM Workshops*, pp. 1-10, 2008.

[67] Dietzel, S., Bako, B., Schoch, E., and Kargl, F., "A Fuzzy Logic Based Aapproach for Structure-Free Aggregation in Vehicular Ad-Hoc Networks," in *ACM VANET '09*, pp. 79-88, Sept. 2009.

[68] Huaying Xu and Barth, M., "An Adaptive Dissemination Mechanism for Inter-Vehicle Communication-Based Decentralized Traffic Information Systems," in *IEEE ITSC '06*, pp. 1207-1213, 2006.

[69] Brickley, O., Chong Shen, Klepal, M., Tabatabaei, A., and Pesch, D., "A Data Dissemination Strategy for Cooperative Vehicular Systems," in *IEEE VTC '07*, pp. 2501-2505, Apr. 2007.

[70] Dietzel, S., Bako, B., Schoch, E., and Kargl, F., "A fuzzy logic based approach for structure-free aggregation in vehicular ad-hoc networks," in *ACM VANET'09*, pp. 79-88, Sept. 2009.

[71] Brickley, O., Chong Shen, Klepal, M., Tabatabaei, A. and Pesch, D., "A Data Dissemination Strategy for Cooperative Vehicular Systems," in *IEEE VTC'07*, pp. 2501-2505, Apr. 2007.

[72] Yu, B., Gong, J., and Xu, C., "Catch-up: a data aggregation scheme for vanets," in *ACM VANET'08*, pp. 49-57, Sep. 2008.

[73] Ibrahim, K., Weigle, M. C., "CASCADE: Cluster-Based Accurate Syntactic Compression of Aggregated Data in VANETs," in *IEEE GLOBECOM Workshops*, pp. 1-10, 2008.

[74] C. L. Hu and M. S. Chen, "Adaptive multichannel data dissemination: Support of dynamic traffic awareness and push-pull time balance," *IEEE Transactions on Vehicular Technology*, vol. 54, no. 2, pp. 673686, Mar. 2005.

[75] Torok, A., Laborczi, P.and Gerhath, G., "Spatially Constrained Dissemination of Traffic Information in Vehicular Ad Hoc Networks," in *IEEE VTC'08*, pp. 1-5, 2008.

[76] Huaying Xu and Barth, M., "An adaptive dissemination mechanism for inter-vehicle communication-based decentralized traffic information systems," in *IEEE ITSC '06*, pp. 1207-1213, 2006.

[77] Wu, H., Fujimoto, R., Guensler, R., and Hunter, M., "MDDV: a mobility-centric data dissemination algorithm for vehicular networks," in *ACM VANET'04*, pp. 47-56, Oct. 2004.

[78] Leontiadis, I. and Mascolo, C., "Opportunistic spatio-temporal dissemination system for vehicular networks," in *ACM MobiOpp '07*, pp. 39-46, Jun. 2007.

[79] J. Zhao, Y. Zhang, and G. Cao, "Data pouring and buffering on the road: A new data dissemination paradigm for vehicular ad hoc networks," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 6, pp. 32663277, Nov. 2007.

VITA

Filip Cuckov
Department of Electrical and Computer Engineering
Old Dominion University
Norfolk, VA 23529

Filip Cuckov received his B. S. and M. S. degrees in Computer and Electrical engineering from Old Dominion University (ODU), Norfolk, Virginia in 2003 and 2005, respectively. During his Ph. D. studies he was a research and teaching assistant working in the ODU Wireless Communications and Networking Laboratory under the supervision of Dr. Min Song. His research interests include distributed simulations, and design of communication protocols. Filip is a recepient of a Ph. D. fellowship from the Ministry of Education and Science of the Republic of Macedonia and holds a departmental outstanding teaching award. He acts as a frequent reviewer for many domestic and international journals and conferences.

Typeset using LaTeX.