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Multicast outing protocols and architectures in mobile ad-hoc wireless networks

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ABSTRACT

MULTICAST ROUTING PROTOCOLS AND ARCHITECTURES IN MOBILE AD-HOC WIRELESS NETWORKS

by
Beongku An

The basic philosophy of personal communication services is to provide user-to-user, location independent communication services. The emerging group communication wireless applications, such as multipoint data dissemination and multiparty conferencing tools have made the design and development of efficient multicast techniques in mobile ad-hoc networking environments a necessity and not just a desire. Multicast protocols in mobile ad-hoc networks have been an area of active research for the past few years.

In this dissertation, protocols and architectures for supporting multicast services are proposed, analyzed and evaluated in mobile ad-hoc wireless networks. In the first chapter, the activities and recent advances are summarized in this work-in-progress area by identifying the main issues and challenges that multicast protocols are facing in mobile ad-hoc networking environments and by surveying several existing multicasting protocols. a classification of the current multicast protocols is presented, the functionality of the individual existing protocols is discussed, and a qualitative comparison of their characteristics is provided according to several distinct features and performance parameters.

In the second chapter, a novel mobility-based clustering strategy that facilitates the support of multicast routing and mobility management is presented in mobile ad-hoc networks. In the proposed structure, mobile nodes are organized into nonoverlapping clusters which have adaptive variable-sizes according to their respective

mobility. The mobility-based clustering (MBC) approach which is proposed uses combination of both physical and logical partitions of the network (i.e. geographic proximity and functional relation between nodes, such as mobility pattern etc.).

In the third chapter, an entropy-based modeling framework for supporting and evaluating the stability is proposed in mobile ad-hoc wireless networks. The basic motivations of the proposed modeling approach stem from the commonality observed in the location uncertainty in mobile ad-hoc wireless networks and the concept of entropy.

In the fourth chapter, a Mobility-based Hybrid Multicast Routing (MHMR) protocol suitable for mobile ad-hoc networks is proposed. The MHMR uses the MBC algorithm as the underlying structure. The main features that the proposed protocol introduces are the following: a) mobility based clustering and group based hierarchical structure, in order to effectively support the stability and scalability, b) group based (limited) mesh structure and forwarding tree concepts, in order to support the robustness of the mesh topologies which provides "limited" redundancy and the efficiency of tree forwarding simultaneously, and c) combination of proactive and reactive concepts which provide the low route acquisition delay of proactive techniques and the low overhead of reactive methods.

In the fifth chapter, an architecture for supporting geomulticast services with high message delivery accuracy is presented in mobile ad-hoc wireless networks. Geomulticast is a specialized location-dependent multicasting technique, where messages are multicast to some specific user groups within a specific zone. An analytical framework which is used to evaluate the various geomulticast architectures and protocols is also developed and presented. The last chapter concludes the dissertation.

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To my beloved family

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CHAPTER 1

SUPPORTING MULTICAST IN MOBILE AD-HOC WIRELESS NETWORKS: ISSUES, CHALLENGES AND CURRENT PROTOCOLS

1.1 Introduction

The basic philosophy of personal communication services is to provide user-to-user, location independent communication services. The emerging group communication wireless applications, such as multipoint data dissemination and multiparty conferencing tools have made the design and development of efficient multicast techniques in mobile ad-hoc networking environments a necessity and not just a desire. Multicast protocols in mobile ad-hoc networks have been an area of active research for the past couple of years. This chapter summarizes the activities and recent advances in this work-in-progress area by identifying the main issues and challenges that multicast protocols are facing in mobile ad-hoc networking environments, and by surveying several existing multicasting protocols [1]. Specifically, it presents a classification of the current multicast protocols, discusses the functionality of the individual existing protocols, and provides a qualitative comparison of their characteristics according to several distinct features and performance parameters. Furthermore, since many of the additional issues and constraints associated with the mobile ad-hoc networks are due, to a large extend, to the attribute of user mobility, we also present an overview of research and development efforts in the area of group mobility modeling in mobile ad-hoc networks.

As the technology and the popularity of Internet have grown dramatically over the last few years, applications that require multicasting are becoming more widespread. Multicasting provides an efficient way of transmitting data from a sender to a group of receivers. A single source node or a group of source nodes sends identical messages simultaneously to multiple destination nodes. Since in multicasting the sender sends a single copy to all the receivers instead of broadcasting the data to all the receivers or sending a separate copy to each individual receiver, there are a lot of advantages associated with, which vary from bandwidth efficiency to lower network and node overhead. For those reasons multicasting has emerged as one of the most focused areas in the field of networking and many multicast protocols have been proposed and developed in wired networks [2].

At the same time, mobile wireless networking has enjoyed dramatic increase in popularity over the last few years. The advances in hardware design, the rapid growth in the communication infrastructure, and the increased user requirement for mobility and geographic dispersion, continue to generate a tremendous need for dynamic mobile networking. The emerging wireless applications such as audio/video conferencing, distance learning, e-commerce, and distributed and multiparty games will benefit by multicast support in the underlying wireless and mobile networks. Many of the emerging and existing wireless and mobile networks deploy widely different technologies, protocols, and wireless links, and therefore, the support for multicasting is an interesting challenge. Regardless of the network environment, multicast communication is a very useful and efficient means of supporting group-oriented applications. Supporting multipoint communications for emerging applications in wireless and mobile networks is an interesting challenge especially due to the user mobility and limited resources. Multicasting techniques and approaches used in conventional wired networks [3][4] are not well suited for the mobile environment due to the considerable overhead produced by periodic route messages and their slow convergence to topological changes.

There are currently two kind of wireless networks. The first is known as the infrastructure-based network. The infrastructure needed to support such communication networks often includes the use of many fixed radio transceiver sites that serve as the gateways for communication with wireless units. The fixed transceivers are networked through fixed links. The second one is known as mobile ad-hoc network. In such environments there are no dedicated base stations as in conventional cellular networks, and all nodes interact as peers for data forwarding. This distributed nature eliminates single points of failure and makes those mobile ad-hoc networks more robust and survivable than other wireless networks.

In this dissertation, it is emphasized on the multicasting problem for mobile ad-hoc networks. The multicast issues in the infrastructure-based networks are somewhat less complex due to the availability of fixed infrastructure support for multicast tree/mesh building and maintenance. The main engineering obstacles in those networks have to do with the last hop delivery and membership tracking, and are not discussed in this dissertation. In the ad-hoc networks, where all nodes may be mobile/portable, the interconnection pattern changes between any two nodes over a period of time, therefore multicast routing involves frequent route discovery and the management of the tree/mesh structures for multicast using limited or scoped broadcast. This chapter presents a first effort in the literature to identify, report, and summarize the work in progress and the most recent advances in the area of multicasting in ad-hoc networks. The main objective of this work is to reveal the main philosophy of each protocol in the literature, identify commonalities and differences among the various protocols, and categorize them accordingly. Among our objectives, is to understand and compare the main design characteristics of the different protocols, to identify their corresponding strengths and drawbacks, and finally present a comparative qualitative study.

The remaining of this chapter is organized as follows. In section 1.2 we identify and describe the main issues and challenges that multicasting techniques have to face and address in mobile ad-hoc networking environments. Section 1.3 examines several multicast techniques designed for mobile ad-hoc networks, by first giving a classification of those multicast techniques, then describing the functionality of the individual existing protocols, and finally comparing their various characteristics. Section 1.4 presents the impact of mobility modeling on multicast protocols' performance.

1.2 Issues and Challenges

In general, the multicast routing protocols designed for infrastructure based wireless networks (i.e. cellular networks) can not be used in ad-hoc networks, mainly for the following three reasons: a) the routes in ad-hoc networks change frequently, b) the fixed infrastructure does not exist for route (re) computation, and c) there are power, coverage and bandwidth restriction. If such protocols were to be used in ad-hoc wireless networks, the amount of processing and storage overhead may exceed the limited capabilities of mobile nodes. It has been argued [5]that just routing table updates can consume about half of the bandwidth even under medium mobility level under certain conditions.

The development of efficient and applicable protocols to support the various networking operations in mobile ad-hoc networks presents many issues and challenges due to the fact that such networks have rapidly changing, random, multi-hop topologies. In this section, the main issues and requirements that existing and future protocols should take into consideration are summarized.

- *Dynamic multi-hop topology*: The continuous and random movement of nodes in mobile ad-hoc networks results in rapidly changing multi-hop topologies. Since not every pair of nodes is within transmission range of each other, a packet must often be relayed over several hops before reaching its final destination. In addition, the ad-hoc wireless nodes may experience change of topology during a multicast session. In general, strategies designed to support internetworking and multicasting in mobile ad-hoc networks should handle such topological changes with minimal overhead by limiting the scope of control packets that may have to be generated and propagated after a change in topology.

- *Routing information (in)accuracy*: In mobile ad-hoc networks, the available state information for routing inherently includes inaccuracies due mainly to user mobility, variable delays or even loss of control packets. Multicast protocols should attempt to reduce the impact of those inaccuracies on the efficiency and reliability of their operation.

- *Scalability*: Scalability in ad-hoc mobile wireless networks presents more complex problems than in wired or last-hop networks, due to the random movement of nodes and the bandwidth and power limitations. The protocol scalability is expressed in the efficient support of large numbers of users, links, nodes, simultaneous sessions, etc.

- *Interoperability and Adaptability*: Current multicast solutions in ad-hoc networks differ substantially from those offered in fixed networks or last-hop networks. However hosts should be able to migrate freely among ad-hoc, fixed infrastructure wireless, and traditional wired networks. In order to offer seamless and integrated multicast services, additional novel mechanisms should be developed and supported for interoperation of fixed and wireless multicast solutions. Additionally, hosts should be able to switch on the fly among multiple mechanisms with the minimum of both effort and inconvenience (i.e. packet loss).

- *Network resource usage efficiency*: With limitations of bandwidth and other resources in wireless networks, the efficient construction and support of multicast trees and other mesh topologies is very critical to successful communication in wireless ad-hoc networks. Keeping accurate state multicast information at each router becomes impractical if the set of neighbors changes at very high rate. On the other hand, excessive propagation of control information (i.e. flooding) in highly mobile networks creates substantial overhead and consumes a considerable amount of resources. There is an inherent trade-off between efficient usage of network resources and robustness or reliability.

- *Power Consumption*: Another important factor is the limited power supply in hand-held devices, which can seriously inhibit packet forwarding in an ad-hoc mobile environment. Hence, techniques that take into account each node's power metrics and try to minimize power consumption are more desirable and provide a way to create more long-lived routes. There are two non-orthogonal approaches to optimizing the power consumption in wireless ad-hoc networks. The first is to minimize the overall power dissipated throughout the network on the average under the techniques adopted. The second is to minimize the average power dissipated by the individual nodes.

- *Reliability and Security*: Reliable services are very important in some applications such as military battlefields and emergency operations that are supported by mobile ad-hoc wireless networks. Offering reliable delivery of data to a group of fast moving nodes that change their position continuously adds substantial complexity to the already complicated problem of efficient multicasting in ad-hoc networks. Moreover since multicast traffic may pass through unprotected routers and/or links and since the nature of such applications is many times of high security and importance (as is the case with military applications), additional efforts should be devoted to provide secure communication.

- *Group membership (join/leave operation)*: Due to the user mobility, the process of group management becomes of major concern in mobile ad-hoc networks. Since nodes are constantly moving operations for leaving or joining a multicast group, or leaving at some point and joining at another, could place a significant amount of overhead in the multicast protocol. Thus group membership protocols should efficiently process such membership changes in order to minimize their impact on the overall protocols performance.

- *Quality of Service (QoS)*: Many, if not all, of the above considerations contribute to the user and/or network quality of service models. Many applications require the support of a certain QoS for optimum performance. Offering such kinds of applications particularly in a wireless environment places additional limitations which need to be accounted for in developing protocols in ad-hoc networks. Given the problems associated with the dynamics of the nodes (i.e. fluctuating link characteristics, node movement), supporting end-to-end QoS is a nontrivial issue that requires in-depth investigation. Currently, there is a trend towards an adaptive QoS approach instead of the plain resource reservation method with hard QoS guarantees.

- *Mobility*: In ad-hoc networks, all network components (nodes) may function as routers and may move at high speeds and in random directions. This node mobility could lead to inefficient multicast trees or mesh configurations, loss of packets or incorrect routing, therefore placing additional constraints on the design of multicast routing protocols that must overcome those mobility problems in an efficient way. Mobility patterns add another dimension to the problem of routing in mobile ad-hoc networks. Mobility contributes to a large extent to almost all the previous issues and constraints. In evaluating the performance of different techniques for ad-hoc networking, realistic mobility modeling is crucial. Mobility models for ad-hoc networks range from random individual models to more structured group-oriented models. Mobility of users will not only impact the networking techniques such as routing, multicasting and reconfiguration, but also the underlying physical layer constraints.

1.3 Existing Multicast Protocols

The goal of this section is to provide an overview of the recent progress in the field of multicast protocol design and development in mobile ad-hoc networking environments. We first classify the existing protocols according to a taxonomy consisting of several distinct characteristics. Then, the main characteristics of each protocol are discussed and highlighted with their respective strengths and drawbacks. Finally, a qualitative comparison of the various protocols based on a set of performance metrics is provided in mobile ad-hoc networks. It should be noted here that this section does not intend to provide a full survey and quantitative performance comparison of all the various existing protocols. It rather presents a first effort in the literature to identify, report, and summarize the work in progress in the area of multicasting in ad hoc networks. However, a qualitative comparison of the various protocols is provided.

In [6] a quantitative performance comparison study of a small subset of the current multicast protocols for ad hoc networks is presented. In that study, the authors simulated five protocols and presented results regarding some specific performance parameters of the protocols, such as: packet delivery ratio and control information as function of traffic load, mobility speed and multicast group size. Our work evaluates all the current protocols from a different angle, trying to identify the various design characteristics and strategies of the different protocols proposed in the literature. As it will be seen in detail in the following sections, the scope of our effort is more general and broader, in the sense that we try to reveal the main philosophy of each protocol, identify commonalities and differences among the various protocols, and categorize them accordingly. Among the primary objectives, is the understanding and comparison of the main design characteristics of the different protocols, as well as the evaluation of those protocols based on a set of qualitative criteria and requirements, such as: routing philosophy, dependency on other protocols, reliability, quality of service support provision etc.

1.3.1 Taxonomy

Several protocols have been developed for group-oriented communication in mobile ad-hoc wireless networks. In general, these multicast routing protocols can be classified as follows:

- Proactive Multicast Routing Protocols

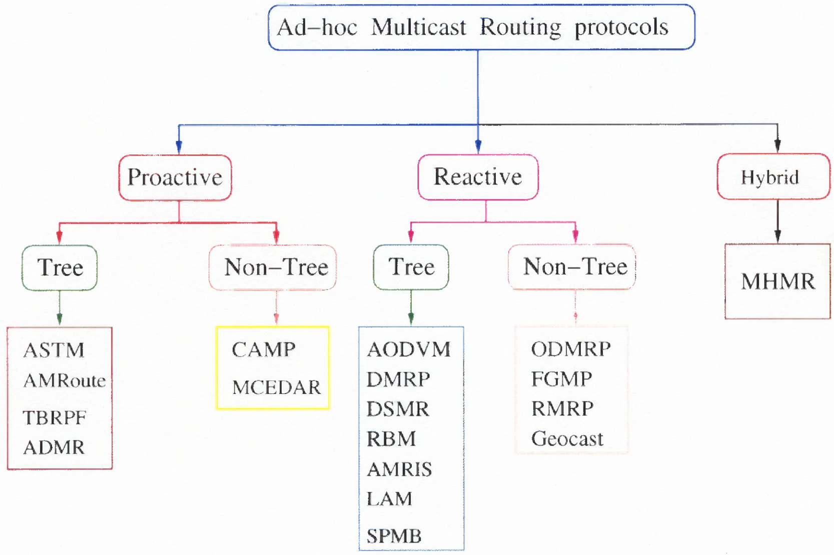


Figure 1.1 Classification of ad-hoc multicast routing protocols.

- Tree Based [7][8][9][10]
- Non-Tree Based [11][12]

- Reactive Multicast Routing Protocols
  - Tree Based [13][14][15][16][17][18][19]
  - Non-Tree Based [20][21][22][23]
- Hybrid Multicast Routing Protocols [24]

Figure 1.1 shows a schematic representation of these categories along with the individual protocols that belong to each subgroup. In the following subsections, we provide a discussion regarding the main characteristics, advantages and disadvantages of each category identified, which actually presents the basis used to classify the various multicasting protocols.

1.3.1.1 Proactive Multicast vs. Reactive Multicast. Proactive Multicasting Protocols maintain up-to-date multicasting information from each node to the other nodes that are members of the multicasting groups in the network. In these protocols, each node maintains one or more routing information tables. They maintain and update the necessary multicasting information constantly and with no regard to when and how frequently such multicasting routes are desired. Such proactive mechanisms involve the constant and often generation and propagation of the appropriate multicasting related data to keep the associated tables and multicast topologies updated, in order to keep track of the wireless link status changes in the networks. Those protocols may consume substantial power and high bandwidth, especially in a highly mobile environment where the topological changes are quite fast and often, and have high storage capacity requirements. On the other hand, their implementation is simple, and the source has always a route available to a multicast group to be used immediately when a node has data to send to the multicast group.

Reactive Multicasting Protocols create multicast routes only on demand, that is only when such routes are desired by the source node. Group membership and multicast routes are established, maintained and updated on demand. Therefore, the associated control overhead in those protocols heavily depends on the actual traffic characteristics of the network. In general and under normal network operation, those protocols reduce the channel overhead while at the same time they may introduce route acquisition delay since the source has to wait until the appropriate multicast route is discovered.

1.3.1.2 Tree Based Multicast vs. Non-Tree Based Multicast.

Tree-based Multicasting Protocols use the tree mechanism as the vehicle to forward multicast data to the appropriate destinations. Multicast trees provide an efficient and simple way of creating a single path between source and destination pairs. However, maintaining a routing tree for the purposes of multicasting packets when the underlying topology changes frequently can incur substantial control traffic. Additionally during periods of routing-table instability, mobile nodes may be forced to stop forwarding packets while they wait for the multicast routing tree to be reconstructed.

There are two kinds of approaches that implement the tree based multicasting and have been adopted by the various multicast routing protocols. The first one "per-source trees" distributes the traffic evenly in the network (assuming that sources and receivers are evenly distributed) and do not require any aggregation of the traffic to central points. However, in highly mobile networks such an approach may present many problems that mainly stem from the fact that the packets may never reach the destination since the network may find itself with obsolete routing tables which may point towards the wrong direction. The remedy to such a problem is to increase the routing update rate with mobility which in turn may result to increased control traffic that may present difficulties in the scaling of the protocol.

The second tree-based approach is the "shared-tree" multicast technique which partially overcomes the problem mentioned above. However, the shared tree approach has the drawback that most of the traffic is generated on the backbone tree, rather than evenly distributed across the network and the paths are often not optimal. This may actually lead to low throughput efficiency. Additionally as the entire network moves fast and the membership changes dynamically, the "center points" of the shared tree may be "off center" further aggravating the non optimality of the paths.

Non-tree based multicasting protocols use other kind of approaches (i.e. mesh-based topologies) to deliver data to the members of the multicast groups. A multicast mesh is a subset of the network topology that provides at least one path (usually more than one) from each source to each receiver in the multicast group. The mesh provides richer connectivity among multicast members compared to tree-based protocols. Having redundant paths among different nodes of the mesh group help overcome the problems of node displacement and channel fading. Therefore, unlike trees frequent reconfigurations may not be required and communication disruption may rarely occur. On the other hand to achieve that target additional redundant traffic may be generated in the network (i.e. some kind of flooding redundancy). The advantages achieved by those approaches versus the drawback of the increase in the traffic that may be introduced depend on the degree of connectivity and redundancy among the nodes of the forwarding or mesh groups.

1.3.2 Comparison

In the following section, a set of parameters that we are going to use for the protocols' qualitative comparison is presented. For each parameter, the set of possible values is also provided. It is found that most of the papers surveyed do not explicitly address each of these considerations. The following is an attempted comprehensive list of parameters that provides for a fair and meaningful basis for comparison between the individual multicast routing protocols. This comparison provides a first effort to characterize and identify the qualitative behavior of the various multicasting protocols, and is by no means exhaustive or quantitative. Therefore, no parameters such as time and communications complexity of the various protocols, that may require a detailed modeling, simulation and/or analysis of each technique, are evaluated here.

1. Routing Philosophy: (Flat, Hierarchical)
2. Multicast Control Overhead: (High, Low)
3. Route Acquisition Delay: (High, Low)
4. Quality of Service Support: (Yes, No)
5. Reliability: (High, Medium, Low)
6. Reaction to High Mobility: (Good, Medium, Poor)
7. Scalability Property: (Good, Medium, Poor)
8. Need for Underlying Unicast Routing Protocol: (Yes*, Yes, No)
9. Flooding: (Yes, Limited, No)
10. Support of Multiple Routes: (Yes, No)
11. Supportability and Maturity: (University, IETF, Others)

Regarding the "Flooding" parameter and its associated values, within the content of this paper, the value "Limited" refers to the flooding of control only information within a forwarding group, while the value "Yes" refers to cases where data flooding is required. Similarly, the values of the parameter "Need for Underlying Unicast Routing Protocol" have the following meaning. "Yes*" refers to those multicast protocols where their operation depend on specific underlying unicast routing protocol(s). "Yes" refers to cases where the corresponding multicast routing protocols require the use of any underlying unicast routing protocol and do not depend on specific implementations or routing algorithms, while "No" means that no separate underlying unicast routing protocol is required to support the multicasting operation.

Regarding the "Routing Philosophy" parameter two categories (values), "flat" or "hierarchical" are identified. Within the context of this proposal and comparison, the attribute "flat" is assigned to protocols where all nodes act (physically and logically) as peers in the network and there is not any kind of traffic aggregation to "central points", while the value "hierarchical" is assigned to those protocols that either explicitly or implicitly build some kind of hierarchy. The hierarchy could be based on the use of multiple levels (i.e. multiple mobility levels, creation of backbone etc.), or on the use of special nodes that may act as information concentrators such as, core nodes, RPs, clusterheads etc. However, in the special case where the concept of core nodes is used for limiting only control information, and those nodes are not necessarily used as data forwarding core nodes then the corresponding protocol is identified as "flat".

Finally, it should be noted that most of the values used in this qualitative evaluation have relative meaning (i.e. this is a comparative evaluation), and no absolute values are used. Table 1.1 presents the comparisons of multicast routing protocols.

1.4 Impact of Mobility Modeling on Multicast Protocols' Performance

In order to evaluate in depth the performance of the various multicasting protocols, a large number of parameters should be evaluated under different scenarios and conditions. Metrics that can been used include [6], but are not limited to: packet

Multicast Routing Protocols / Comparison Parameters	Proactive							Reactive											Hybrid
	Tree							Tree											
	ASTM	AMROUTE	TBRPF	ADMR	CAMP	MCEDAR	AODVM	DMRP	DSMR	RBM	AMRIS	LAM	SPMB	ODMRP	FGMP	RMRP	Geocast	MHMR[1]
Routing Philosophy (Flat, Hierarchical)	Hierarch.	Flat	Flat	Flat	Flat	Hierarch.	Flat	Flat	Flat	Hierarch.	Flat	Hierarch.	Flat	Flat	Flat	Flat	Flat	Hierarch.
Multicast Control Overhead (High, Medium, Low)	High	High	Medium	High	High	High	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low	Medium
Route Acquition Delay (High, Low)	Low	Low	Low	Low	Low	Low	High	High	High	High	High	High	High	High	High	High	High	Low
Quality of Service Support (Yes, No)	No	No	No	No	No	No	No	Yes	No	Yes	No	No	No	No	No	No	No	Yes
Reliability (High, Medium, Low)	Low	Low	Medium	Medium	Medium	Medium	Low	Low	Low	Medium	Low	Low	Medium	High	Medium	High	High	High
Reaction to High Mobility (Good, Medium, Poor)	Medium	Poor	Medium	Good	Medium	Medium	Poor	Poor	Poor	Medium	Poor	Medium	Medium	Good	Medium	Good	Good	Good
Scalability Property (Good, Medium, Poor)	Good	Poor	Medium	Poor	Good	Medium	Poor	Medium	Poor	Good	Poor	Good	Poor	Medium	Poor	Poor	Poor	Good
Need for Underlying Unicast Protocol(Yes*,Yes, No)	Yes*	Yes	No	Yes	Yes	Yes*	Yes*	Yes*	Yes*	Yes*	No	Yes*	No	No	No	No	No	No
Flooding (Yes, Limited, No)	No	Limited	No	Limited	No	No	No	No	No	No	Limited	No	Limited	Limited	Limited	Yes	Yes	No
Support of Multiple Routes (Yes, No)	No	Yes	Yes	No	Yes	Yes	No	No	No	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Supportability & Maturity (Univ., IETF, Other)	Univ	Other IETF	Other IETF	Univ IETF	Univ	Univ	Univ	Univ	Univ	Univ	Univ IETF	Univ	Univ IETF	Univ IETF	Univ	Univ	Univ	Univ

Yes*: Special Protocol Required
Limited Flooding : Only Control Information Flooding
1: Requires Mobility Based Clustering
Other: Company Research Laboratory

Table 1.1 Comparisons of Multicast Routing Protocols in Mobile Ad-hoc Wireless Networks

delivery ratio, number of data packets transmitted per data packet delivered, number of control bytes transmitted per data bytes delivered, number of control and data packets transmitted per data packet delivered.

All those parameters should be evaluated under different scenarios such as: mobility patterns, number of senders, multicast group size, network traffic load, network size and density, etc. Many of those scenarios or procedures have been used in the past for the evaluation of many different protocols in wired and wireless networks. However, the attribute of mobility, as described before adds an additional dimension to the evaluation of multicasting in networks with mobile nodes. As we can see from the discussion in the previous sections, many of the issues and challenges associated with the mobile ad-hoc networks stem from that fact: user mobility. Among the main objectives of the protocol's performance evaluation process is to define an effective operating region and estimate the overhead of the protocol's components within this region. To achieve that, one of the most important factors is to determine the sensitivity of each of the system's/protocol's components to the transmission range and mobility of nodes.

In wireless networks, mobile nodes can move in many different ways. Mobility modeling attempts to describe the mobility behavior of an individual node or a set of nodes. Mobility models are commonly used to analyze newly designed systems or protocols in both cellular and ad-hoc wireless networks. There is no doubt that the the node mobility behavior influences most of the performance related parameters. Ad-hoc networks are more sensitive to mobility than cellular wireless networks since in the latter the base stations are stationary providing a core fixed backbone network, and the state related to routing and multicasting information changes only when a mobile user leaves the cell, irrespective of relative connectivity with other mobile users. While in cellular networks mobility models are mainly focused on individual movements since communications are primarily point to point rather than among groups, in ad-hoc networks communications are often among teams which tend to coordinate their movements. Hence, the need arises for developing efficient and realistic group mobility models in addition to the individual mobility models for ad-hoc networks, especially when evaluating multicast protocols that involve communication among teams. Those models may be used to optimize the design of the multicast strategies and are used as realistic models for the motion patterns in order to evaluate the various protocols' performance. Most of the earlier research on mobility patterns was based on cellular networks [25]. Recently, mobility models have been explored also in ad-hoc networks.

In general, the existing mobility models may be classified according to the strategy of the dependent behavior among mobile nodes (i.e. individual mobility and group mobility), as well as according to the mechanisms used to get the main elements that govern the next moving time interval (i.e. random mobility and pre-information aided mobility). In ad-hoc wireless networks, the mobility models focus on the motion behavior between mobility epochs, which are the smallest time periods in which we can assume that a mobile node moves in a constant direction at a constant speed.

In the random mobility model, the speed and direction of motion in a new time interval have no relation to their past values in the previous epoch. In pre-information aided mobility, the speed and direction of individual motion in a new time interval is related to their past values (i.e. previous values, predefined trajectory). A group mobility model for dependent behavior in ad-hoc networks must capture both motion dependencies over time epochs and the relationship among members of the same group. This team relationship makes it possible to partition the network into several groups, each one with its own mobility behavior. Most of the mobility models that have been developed and used in the literature deal with the motion behavior of the individual nodes ([23][26][27][28][29][30][31]).

It is strongly believed that in order to evaluate the various multicast protocols under realistic environments and obtain meaningful results we need to use group mobility models in addition to the modeling of each individual node in order to capture the motion dependencies over time and the relationship among the nodes. Therefore, the development of realistic group mobility models to be used for the evaluation of the various multicasting and routing protocols in ad-hoc networks is more a need rather than a desire. However, the group mobility modeling development has been an under appreciated area and very few efforts are reported in the literature regarding the modeling of the group behavior. In the following, a brief overview of representative existing group mobility models is presented, by noting that the purpose of this discussion is to emphasize on the need of group mobility modeling and to register the first few efforts towards this direction.

RPGM: In the Reference Point Group Mobility(RPGM) model [32], each group (set of nodes) has a logical center. The center's motion defines the entire group's motion behavior(group trajectory), including location, speed, direction, acceleration, etc. Each node is assigned a reference point which follows the group movement.

Figure 1.2 describes the RPGM with a two-group model [32]. $\overrightarrow{V_{g_i}}$ presents the motion vectors of each group. The reference point of a node moves from $RP(\tau)$ to $RP(\tau + 1)$ with the group motion vector $\overrightarrow{GM}(\overrightarrow{V_{g_i}})$. The new node position is generated by adding a random motion vector $\overrightarrow{RM}$ to the new reference point $RP(\tau+1)$. The length of the random motion vector $\overrightarrow{RM}$ is uniformly distributed within a certain radius centered at the reference point and its direction is uniformly distributed between 0 to 360 degree. The random vector $\overrightarrow{GM}$ is independent from the node's previous location. The RPGM defines a sequence of check points(path) to model the motion behaviors of group. When the group center reaches a new check point, it computes the new motion vector $\overrightarrow{V_{g_i}}$ from current check point and next check point locations.

This model can be used to model a battlefield situation where different battalions are carrying out same operations in different areas; or to model the rescue operation in a disaster recovery area where multiple rescue teams are randomly spread out over a given area (yet each group may have a unique motion pattern); or to model the interaction between exhibitors and attendees in a convention scenario

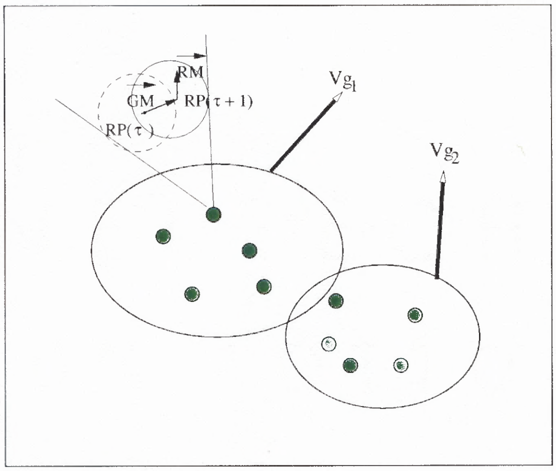


Figure 1.2 The RPGM model.

where attendees may roam from room to room to attend demos and/or project presentations.

ECRM: The Exponential Correlated Random Mobility(ECRM) [33] model reproduces all possible movements, including individual and group, by adjusting the parameters of a motion function. The new position of a network element (group of nodes or individual nodes) $\overrightarrow{b(t+1)}$ is a function of the previous position $\overrightarrow{b(t)}$, to which a random deviation $\vec{r}$ is added. The model is described by the following equation:

$$b(t+1) = b(t)e^{1/\tau} + s\sigma\sqrt{1 - e^{-2/\tau}}r \tag{1.1}$$

where, $b(t)$ is the position (r, θ) of a group or a node at time t, τ is a time constant that regulates the rate of change, σ is the variance that regulates the variance of change, s is the speed of the node, and r is a Gaussian random variable.

Using this model, the movement of each group as a whole is controlled independently of the movements of other groups and nodes within the group. At each time step, a group moves a random distance in a randomly selected direction. The τ and σ variables, specified separately for the distance and direction, control the nature of the movement. In general, smaller values of τ result in more random movement, and larger values of σ result in more variation from a given direction. Within a group, all nodes have the same set of τ and σ variables; nodes in different groups may have different sets of variables.

This mobility model permits representation of typical node movements in a tactical network, such as the maneuvers of a battalion consisting of several squads of soldiers. The squads may be represented as groups that move as a whole; the soldiers within a squad, while exhibiting some randomness of movement, are aligned with the overall movement of their squad. ECRM requires a complete set of (τ, σ) per group to define the motion of entire network. The drawback is that it is not easy to force a given motion pattern by selecting the parameters.

1.5 Concluding Remarks

In this chapter, the activities in the work-in-progress area of the development of multicasting protocols are presented in mobile ad-hoc networks, by identifying the main issues and challenges that multicast protocols are facing in these environments, and by surveying several existing multicasting protocols. This chapter presents a first effort in the literature to classify all the current multicast protocols, discusses the functionality of the individual existing protocols, and provides a qualitative comparison of their characteristics according to several distinct features and performance parameters, such as: routing philosophy, dependency on other protocols, reliability, scalability property, mobility support, quality of service support provision etc. The main objectives of this chapter are to identify the various design characteristics and strategies of the different protocols proposed in the literature, reveal the main philosophy of each protocol, identify commonalities and differences among the various protocols, and categorize them accordingly.

Furthermore, since many of the additional issues and constraints associated with the mobile ad-hoc networks are due to a large extend, to the attribute of user mobility, an overview of research and development efforts is presented in the area of mobility modeling in mobile ad-hoc networks, to be used as means to provide a realistic environment to carry out the performance evaluation process of multicasting protocols. Since in ad-hoc networks communications are often among teams which tend to coordinate their movements, and multicasting protocols deal by default with the dissemination of information to groups of nodes, our discussion mainly emphasizes on the need to design, develop and use advanced realistic mobility models that provide for the modeling and emulation of the motion of individual nodes as well as of motion patterns of the corresponding groups and their interrelations.

CHAPTER 2

MOBILITY-BASED CLUSTERING IN MOBILE AD-HOC WIRELESS NETWORKS

2.1 Introduction

In this chapter, a novel mobility-based clustering strategy that is suitable for application is presented in mobile ad-hoc networks [34][35][36][37]. In the proposed structure, mobile nodes are organized into nonoverlapping clusters which have adaptive variable-sizes according to their respective mobility. The mobility-based clustering (MBC) approach [38][39] we are proposing uses combination of both physical and logical partitions of the network (i.e. geographic proximity and functional relation between nodes, such as mobility pattern etc.). In order to characterize the degree of mobility, a node exhibits with respect to its peers for a given period of time, we introduce the concept of relative mobility in the clustering process. The performance evaluation of our method is accomplished via modeling and simulation. The performance results demonstrate that our clustering algorithm generates stable clusters and reduces significantly the need for clusterhead changes, therefore making the proposed technique suitable for implementation in mobile ad-hoc networks.

As mentioned before, management functions, routing and multicasting, and scalability in ad-hoc mobile wireless networks present more complex problems than in wired or last-hop networks, due to the random movement of nodes, the bandwidth and power limitations, and the lack of fixed infrastructure. A major challenge in mobile ad-hoc, multimedia networks is the ability to account for location management and resource allocation so that routing/multicasting functions and bandwidth reservations can be efficiently placed on them. It should be noted that in cellular (single-hop) networks accountability is made easy by the fact that all stations learn of each others requirements usually through a control station (i.e. base station). Similarly, the use of base station simplifies the problem of routing and multicasting in cellular networks. However, this solution can be extended to mobile ad-hoc (multihop) networks by creating clusters of nodes in such a way that resource allocation and management functions can be controlled and implemented efficiently [40].

Mobile node clustering and group based hierarchical structures can be used to effectively support scalable multicasting techniques and mobility management functions in mobile ad-hoc networks. In general, the goals of clustering are the efficient utilization of radio channel resources and the reduction of overhead [41]. For example, at the MAC layer, by using different spreading codes across clusters the interference is reduced and the spatial reuse is enhanced. Moreover, while in cellular networks communications are primarily point to point rather than among groups, in ad-hoc networks communications are often among teams which tend to coordinate their movements. This collaboration among members of the same team makes it possible to partition the network into several groups, each with its own mobility behavior. For instance, each multicast group corresponds to a particular user group with common characteristics (e.g., tank battalion in the battlefield, search team in a search and rescue operation, professionals on the move belonging to the same company, students within the same class, etc.). A different mobility pattern can be defined for different groups or formations. Those observations have motivated our research in using mobility based clustering approaches and group based hierarchical structures in order to facilitate the implementation of efficient and scalable multicasting techniques and mobility management functions in ad-hoc networks.

Specifically, in this chapter a mobility-based clustering (MBC) approach that uses combination of both physical and logical partitions of the network , as well as the concept of relative mobility to characterize the degree of mobility of a node with respect to its peers are proposing. The performance results for the algorithm it is proposed with the corresponding results of other existing clustering algorithms are compared. The performance evaluation of the various clustering algorithms is done in terms of the achievable stability of the created clustered topology. The obtained numerical results verify the considerable improvement on the cluster stability that can be achieved by our algorithm, therefore making MBC algorithm an ideal vehicle for the implementation of efficient multicasting and management functions.

The remaining of this chapter is organized as follows. Section 2.2 provides some discussion about the objectives of clustering and the existing clustering techniques for mobile ad-hoc networks. In section 2.3, the proposed clustering approach is presented by first providing some definitions and then describing the operation of the method. Section 2.4 contains the performance evaluation of the proposed method, and section 2.5 concludes this chapter.

2.2 Clustering and Background

Clustering is the method which attempts to organize unlabeled feature vectors into groups(clusters) such that points within a cluster are more similar to each other than to vectors belonging to different groups(clusters). In conventional cellular networks(single-hop), where there are fixed base stations connected by a wired backbone, communications between two mobile nodes that are only one hop away from a base station, is achieved through fixed base stations and the wired backbone. In this case, clustering is used to select and allocate channel groups to all the base stations within a system, to achieve efficient frequency reuse. In multihop mobile wireless networks, clustering is the method which aggregates nodes into groups (clusters) to provide a convenient framework for the development of important features(i.e routing, bandwidth allocation, mobility and topology management). For every subset of nodes (cluster) one node is selected as the clusterhead of the cluster. The clusterhead acts as a local coordinator of transmissions within the cluster. It differs from the base station concept in current cellular systems, in that it does not have special hardware and in fact is dynamically selected among the set of stations. However, it performs additional work with respect to ordinary stations, and therefore it may become the bottleneck of the cluster. An efficient clustering scheme tends to preserve its structure when a few nodes are moving and the topology is slowly changing. Otherwise, high processing and communications overheads will be paid to reconstruct the clusters.

In general, clustering provides a convenient framework for the development and deployment of important features and management procedures, such as channel access, code separation, power control, bandwidth allocation and mobility management. The objective of the clustering procedure is to find a feasible interconnected set of clusters covering the entire node population. A good clustering algorithm should be stable to radio motion, that is should not change cluster configuration drastically and often, when a few nodes are moving and the motion is coordinated, as is the case with mobile ad hoc networks supporting military communications. Otherwise, the clusterheads will lose control of their clusters and thus their role as local coordinators and managers [41].

In general, there are two families of distributed clustering algorithms. One is the lowest-ID algorithm [42], where the lowest-ID node in a neighborhood is elected as the clusterhead. The other one is the highest-connectivity (degree) algorithm [43]. In this case the highest connectivity (degree) node in a neighborhood becomes the clusterhead. One of the most important criterion in clustering is stability. The frequent changes of cluster head may adversely affect the performance of other protocols such as scheduling and resource allocation which rely on it. In the lowest-ID algorithm if there is the lowest-ID node with highest mobility, the cluster has to re-elect its clusterhead every time the lowest-ID node moves into other clusters. Similarly in the highest-connectivity algorithm if the highest-connectivity node has high mobility, the cluster has to re-elect its clusterhead when the highest-connectivity node moves into other clusters.

Moreover, in [44] an adaptive hybrid scheme in which node mobility based parameters are introduced to bound the probability of intra-cluster path failure was proposed. In this work, the authors assumed the existence of some underlying proactive intra-cluster routing algorithm and they utilize path availability information maintained by this routing protocol to determine cluster feasibility. Mobility based criteria were also utilized in the scheme proposed in [45]. However, that scheme builds clusters that consist only of a set of nodes that are adjacent to a clusterhead.

In this chapter, the adaptive and dynamic creation of multi-hop clusters depending on both individual node and group mobility characteristics is adopted. The clustering approach proposed in this chapter, namely the Mobility Based Clustering (MBC) is based on mobility concepts (individual mobility, group mobility) [32] and the availability of position information via a reliable position locating system (i.e. GPS). It uses combination of both physical and logical partitions of the network (i.e. geographic proximity and functional relation between nodes, such as mobility pattern etc.), as well as the concept of relative mobility to characterize the degree of mobility of a node with respect to its peers, without the need of an underlying unicast routing protocol. The mobility-based hierarchical clustering algorithm MBC may result in variable-size clusters depending on the mobility characteristics of the nodes. A group may consist of clusters that present similar mobility characteristics. Several groups can be hierarchically merged into one group depending on the mobility of each group.

The introduction of the concept of relative mobility in order to characterize the degree of mobility a node exhibits with respect to its peers for a given period of time, is mainly motivated by the observation that mobile ad hoc networks support multipoint communications among nodes that demonstrate group-oriented mobility patterns [32][33] and tend to coordinate their movements. Since the objective is the creation of adaptive clusters for the purpose of geomulticasting and multicasting support, our approach uses directly individual and group mobility information, and does not depend on the use of any underlying routing protocol. This is different from the algorithm proposed in [44][46] that adaptive clustering schemes are proposed using a probabilistic model that characterizes the future availability of network links maintained by some underlying unicast proactive routing algorithm, and therefore implicitly they adapt to mobility.

In general, a node with high relative mobility is more prone to unstable behavior than a node with less relative mobility and therefore should not be elected as clusterhead. A node may compute its relative mobility by exchanging its mobility profile with current and potential peer nodes. As a node moves, its relative mobility may also change, and therefore the relative mobility of a node must be periodically reevaluated to allow for adaptation to future states of the network.

2.3 MBC: Mobility-Based Clustering

The clustered topology in a mobile ad-hoc network can be modeled as follows. Consider a network topology which is modeled by a graph $G = (V,\ E)$, where V is the set of nodes, and E is the set of bi-directional links which operate independently in each direction. The distance $d(x, y)$ of two nodes x and y of G is defined to be the minimal number of hops between nodes x and y. A cluster $C_i \subset V$ is a set of nodes, where for any two nodes $x,\ y \in C_i$, $d(x, y) \leq L$. Namely, any two nodes in a cluster are at most L- hops away, where L is a parameter that depends on the network stability. Let us define by W the set of all feasible clusters C_i. A cluster coverage K_l in our clustered topology is defined as follows:

$$K_l = \{C_i,\ \ C_i \in W\ \ and\ \ C_i \cap C_j = 0\ \ and\ \ \cup_{c_i \in k_l} C_i = V\} \tag{2.1}$$

Figure 2.1 presents a sample network topology while Figure 2.2 and Figure 2.3 describe the basic concept and structure of the mobility-based clustering, respectively. In the following, let us denote by $v(m,\ t)$, the velocity vector of node m and $v(n,\ t)$, the velocity vector of node n at time t. Please note that velocity vectors $v(m,\ t)$ and $v(n,\ t)$ have two parameters, namely speed and direction. The relative velocity vector $v(m, n,\ t)$ between nodes m and n at time t is defined as:

$$v(m, n, t) = v(m, t) - v(n, t) \tag{2.2}$$

Then, the relative mobility, $M_{m,n,T}$, between any pair $(m,\ n)$ of nodes during time period T is defined as their absolute relative speed averaged over time T. That is:

$$M_{m,n,T} = \frac{1}{N}\sum_{i=1}^{N} |v(m, n, t_i)| \tag{2.3}$$

where N is the number of discrete times t_i that velocity information is calculated and disseminated to other nodes within time interval T. We define two kinds of cluster mobilities as follows. $CM1_i$ presents the motion behavior(speed, direction) of a cluster C_i as a whole. To obtain $CM1_i$ as defined here, we add the velocities(vectors) of all nodes in the *cluster* C_i, and then average over the total number of nodes in the cluster. Thus:

$$CM1_i = \frac{1}{M_i} \sum_{n_k \in c_i} v(n_k, T) \tag{2.4}$$

where M_i denotes the number of all nodes in the cluster, C_i. $CM2_i$ represents the motion behavior(uncertainity) of nodes within a cluster, C_i. To obtain $CM2_i$ as defined here, we add the relative mobilities for all node pairs(m, n) in the *cluster* C_i, and then take average over the total number of all node pairs in the cluster. Thus:

$$CM2_i = \frac{1}{N_i} \sum_{(m,n) \in c_i} M_{m,n,T} \tag{2.5}$$

where N_i denotes the number of all node pairs (m, n) in the *cluster* C_i. These two cluster mobilities are used to group clusters hierarchically.

In the following section, a description of the proposed mobility-based algorithm is provided in order to construct and maintain the various clusters.

Step 1 : Mobility Information Dissemination

Each node n periodically disseminates its velocity information($v(n, t_i)$, i = 1, 2, ...) which have speed and direction to its neighboring nodes.

Step 2 : Calculation of Mobility Metrics

Upon reception of node's n velocity information, each node m calculates its relative

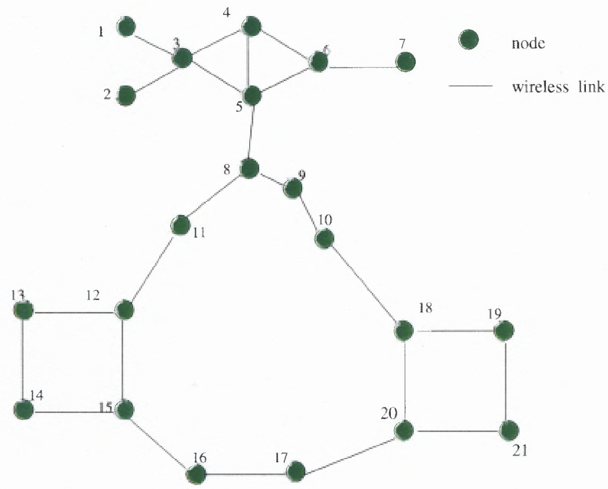


Figure 2.1 The system topology.

velocity between itself and node n respectively. Specifically for every neighbor n, the node m under consideration calculates parameter $v(m, n, t)$ according to relation (2.2). Then periodically(with period T), each node m calculates the relative mobility $M_{m,n,T}$ between itself and node n.

Step 3 : Initial(Tentative) Cluster Construction

Lets denote by S_m the set that includes node m and all the nodes from which node m receives mobility information. Among the nodes of S_m, the node-i with the lowest ID that satisfies the following condition: $M_{m,i,T} < Th_{mob}$, $i \in S_m$ is selected as tentative clusterhead (TCH). That is:

$$TCH = Least_{i \in S_m}\{ID | M_{m,i,T} < Th_{mob}\} \tag{2.6}$$

Then, node m requests clustering(i.e to become part of this clusterhead's cluster) to node TCH. It should be noted here that the mobility threshold Th_{mob} is a design

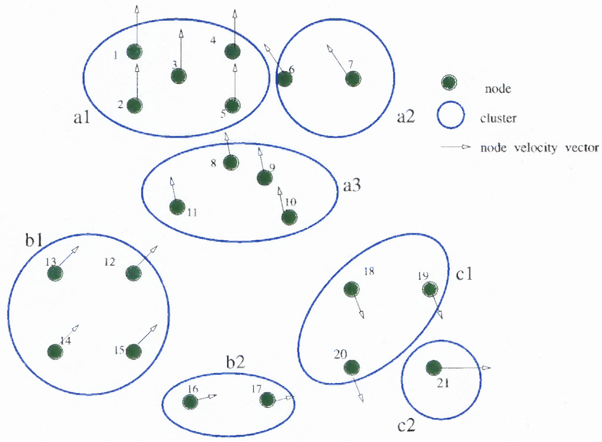
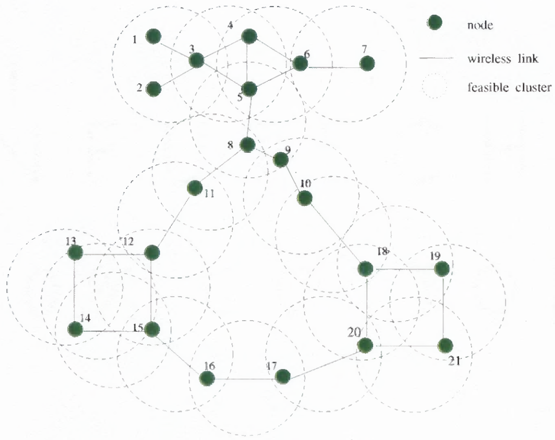


Figure 2.2 The basic concept of mobility-based clustering.

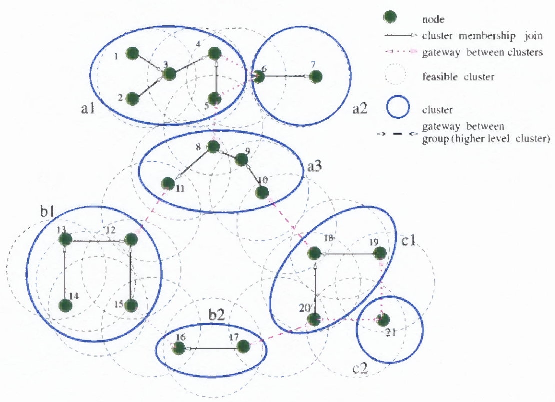
parameter of the algorithm and can be used to control the stability of the generated clusters in different networks. Moreover, different mobility threshold parameters that may change dynamically and adaptively during the operation of the network can be used, in order to provide a realistic representation of a mobile ad-hoc network where random mobility and group mobility patterns can occur simultaneously.

Step 4 : Cluster Merging

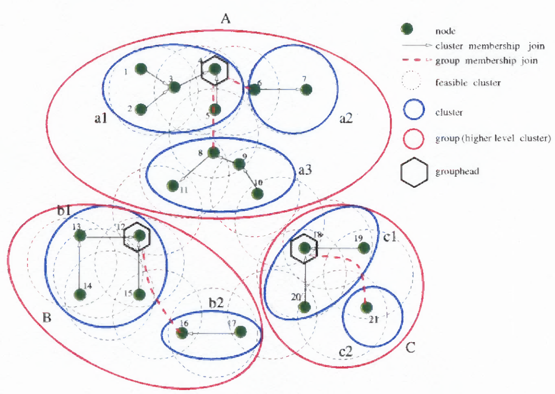
If a tentative clusterhead(TCH_1) is to be included into another cluster(TCH_2) according to step 3, then the child cluster (the tentative cluster(TCH_1)) joins into the parent cluster(uppercluster, TCH_2) with its current cluster members. There is an upperbound(i.e., L hops) rule for culster merging. After merging the clusterheads(CHs), the higest-parent cluster's head is selected as the clusterhead(CH) of the new generated cluster. Each node in the child cluster(TCH_1) holds TCH_1 information(mobile id). TCH_1 holds its parent clusterhead information(mobile id), and so on. The new generated CH holds routing information of all nodes within the



(a) Feasible clusters with L = 1



(b) Mobility-based clusters with L < 3



(c) Hierarchical structure

Figure 2.3 Hierarchical supporting structure with MBC.

new cluster.

Step 5 : Cluster Maintenance/Reconstruction

When a node m in cluster C_i moves into a cluster C_j, if a node n in the cluster C_j satisfies the condition: $M_{m,n,T} < Th_{mob}$, and node n is the clusterhead of the cluster C_j then node m requests clustering to node n(no clusterhead change). If these conditions are not satisfied, node m repeats step 5 during its motion.

2.4 Performance Evaluation

In this section, the framework that is used to evaluate the algorithms' performance, as well as some numerical results are presented. The performance of the proposed algorithm with the corresponding performance of the lowest-ID algorithm [42] and the highest-connectivity (degree) algorithm [43] is compared. Since the frequent changes of cluster head may adversely affect the performance of the network as well as the operation of all the other related protocols and management functions, the emphasis of the algorithm performance evaluation is placed on the stability of the created clustered topology.

2.4.1 Framework

The performance evaluation of the protocol is accomplished via modeling and simulation using the Optimized Network Engineering Tool (OPNET). A mobile ad-hoc network consisting of 200 nodes that are placed randomly within a rectangular region of 10 km x 10 km is modeled in the simulation. Each node is modeled as an infinite-buffer, store-and-forward queuing station, and is assumed to be aware of its position with the aid of a reliable position location system(i.e., GPS). Moreover the mobile nodes are assumed to have constant radio range of Z=1000m. Therefore, we may interpret this behavior as follows: any packet can be received error free within the transmission range of a node (i.e. radius of Z from the transmitter), but is lost beyond Z. Since packet delivery is guaranteed to any destination in the range of the source, we are able to further reduce the complexity of our model by eliminating retransmission at the data link layer.

Throughout the study, it is assumed that a link fails, or reappears, as a node goes out or in transmission range of another node, due to the mobility of the nodes. Note that in our model, it is possible for a node to receive multiple packets from different neighbors simultaneously. All those packets are placed in the nodes' receiving queue to be served by the node (in an order determined by OPNET).

Mobile nodes are assumed to be moving around throughout the network. Two different mobility scenarios are considered in this study. In the first one (in the following we refer to as mobility 1) the speed and the direction of each move are uniformly distributed, with speed range [0, 72 km/h] and direction range [0, 2π], respectively.

In the second mobility scenario (in the following we refer to it as mobility 2), a group-based mobility pattern is modeled. Specifically, nodes are grouped into several groups, where we assume that nodes in the same group have similar mobility characteristics (e.g. similar but not the same speed and moving direction). At the initial movement, the speed and the direction of each mobile in the same group are selected with the same initial speed(v_{int}) and direction(θ_{int}) respectively within the speed range [0, 72 km/h] and direction range [0, 2π]. After the initial movement, at every movement the speed and direction of each mobile are selected independently within the range [v_{ref} - 10 km/hr, v_{ref} + 10 km/hr] and [θ_{ref} - $\pi/6$, θ_{ref} + $\pi/6$], where

v_{ref} is the previous mobile speed and θ_{ref} is the previous mobile direction respectively. As a result mobile nodes belonging to the same group present some similarity in the direction towards which they are moving. Initially, each group consists of 10 nodes, however, as the system evolves the number of nodes per group changes dynamically. If a mobile arrives at the boundary of the given network coverage area, the node reenters into network.

Finally, throughout this simulation, the mobility threshold Th_{mob} is selected as follows. Let m_{mob} be the average value of all mobility information that the node m received and δ_{mob} its corresponding standard deviation. Then Th_{mob} is selected as: $Th_{mob} = m_{mob} + \mathrm{k}\delta_{mob}$, where k is constant and can be changed according to the network under consideration and the desired cluster stability. In this study parameter k was chosen as k = 1.5 based on experimentation.

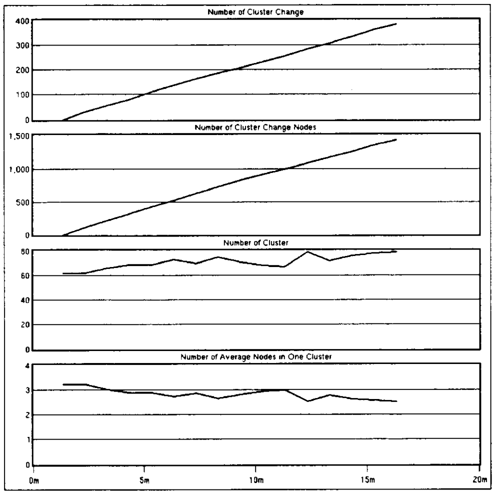
2.4.2 Numerical Results and Discussion

The metrics used in this study to measure and evaluate the stability of the created clustered topology are the following: 1) Number of cluster changes, that represents a measure of the rate of clusterhead changes (or construction of new clusters), and 2) Number of cluster change nodes, that represents a count of how many nodes switch from one cluster to another (or construct new clusters). In addition in the following graphs, we present the evolution of the number of clusters and the corresponding average number of nodes in a cluster, as the system evolves.

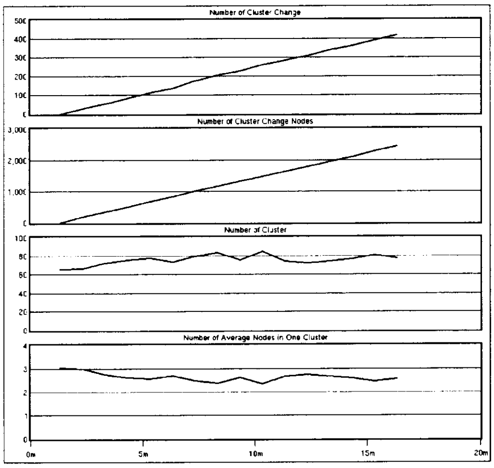
Specifically, Figure 2.4 presents the numerical results for mobility model 1 (mobility 1) under three different clustering algorithms: lowest-ID algorithm, highest-connectivity (degree) algorithm, and MBC algorithm. Similarly, Figure 2.5 shows the corresponding results under the group mobility scenario (i.e. mobility 2). As can be seen by the first set of figures (Figure 2.4), lowest-ID and highest-connectivity algorithms demonstrate similar behavior, with lowest-ID performing slightly better than the highest-connectivity algorithm in this experiment. However, MBC algorithm outperforms both of them by improving the cluster stability metrics by more than 50%. The improvement is considerably higher in the second set of experiment (Figure 2.5) where MBC algorithm reduces the clusterhead change ratio by approximately 10 times compared to the lowest-ID algorithm and 20 times compared to the highest-connectivity algorithm. This is achieved because MBC algorithm takes advantage of the similarity that several nodes demonstrate in this experiment due to the group mobility pattern assumed. However, as mentioned before such mobility patterns represent the node mobility more accurately than the random one in realistic mobile ad-hoc environments where communications are often among teams which tend to coordinate their movements.

2.5 Concluding Remarks

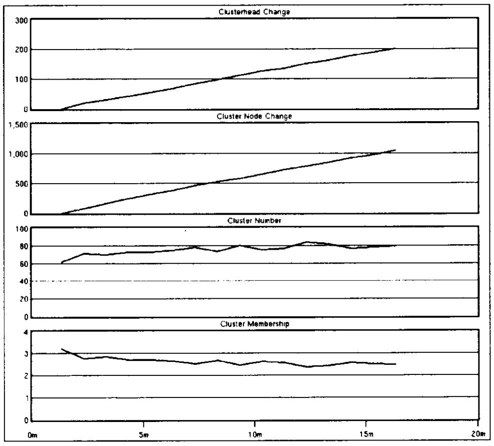
In this chapter, a mobility-based clustering approach that can be applied in wireless mobile ad-hoc networks is proposed in order to facilitate the implementation of efficient mobility management solutions and multicasting strategies. Our proposed cluster architecture consists of variable-size clusters that may change adaptively according to nodes' mobility. The proposed MBC algorithm uses combination of both physical and logical partitions of the network (i.e. geographic proximity and functional relation between nodes, such as mobility pattern etc.), as well as the concept of relative mobility that characterizes the degree of mobility of a node with respect to its peers. The performance evaluation of our algorithm demonstrated that MBC outperforms considerably the lowest-ID and highest connectivity clustering algorithms and improves the stability of the clustered topology, by reducing signif-



(a) Least-ID

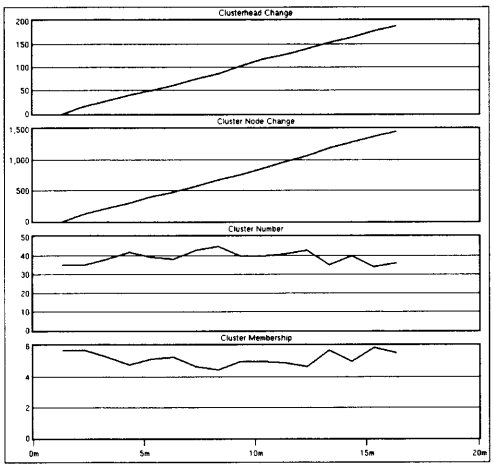


(b) Highest-Connectivity

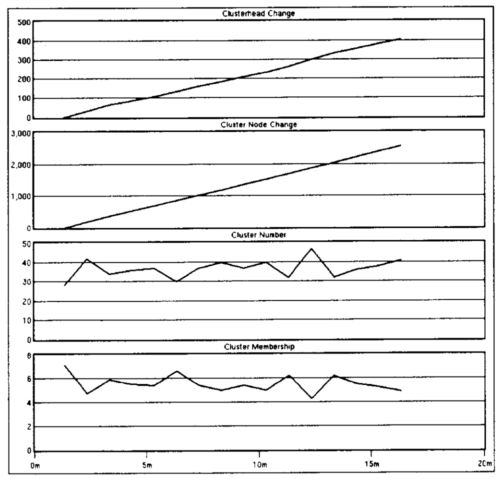


(c) MBC

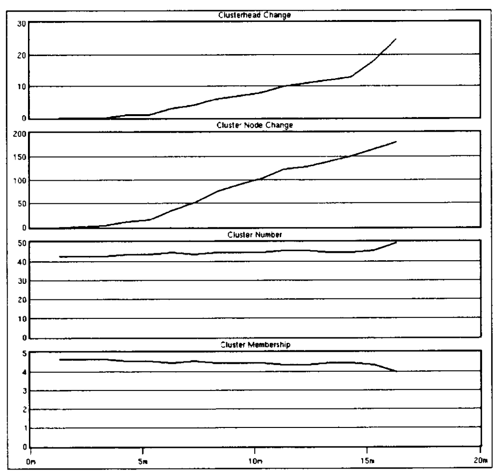
Figure 2.4 Stability for mobility scenario 1.



(a) Least-ID



(b) Highest-Connectivity



(c) MBC

Figure 2.5 Stability for mobility scenario 2.

icantly the number of clusterhead changes under different mobility scenarios. The proposed cluster architecture provides for a very robust infrastructure, which is not easily disrupted by mobility and can support stable paths (reduction of routing overhead) and cost effective mobility management solutions.

CHAPTER 3

AN ENTROPY-BASED MODEL FOR SUPPORTING AND EVALUATING STABILITY IN MOBILE AD-HOC WIRELESS NETWORKS

3.1 Introduction

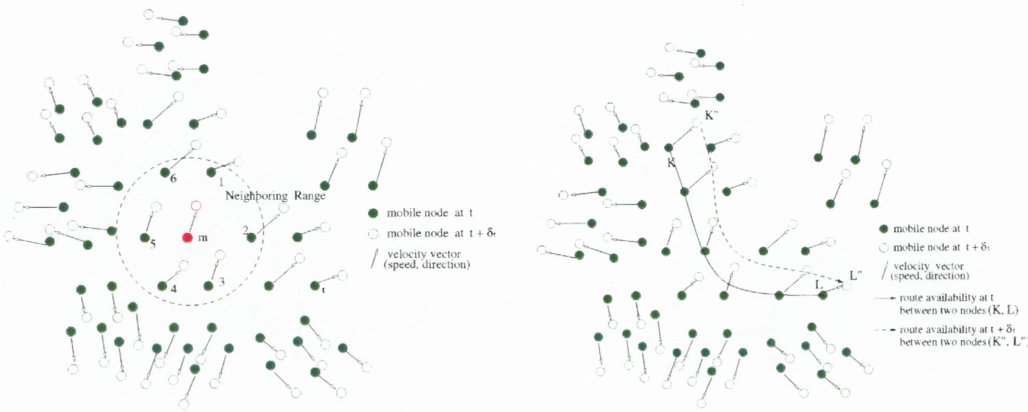
In this chapter, an entropy-based modeling framework for supporting route stability is proposed in mobile ad-hoc wireless networks. The basic motivations of the proposed modeling approach stem from the commonality observed in the location uncertainty in mobile ad-hoc wireless networks and the concept of entropy.

Entropy [47][48] presents the uncertainty and a measure of the disorder in a system. There are some common characteristics among self-organization, entropy, and the location uncertainty in mobile ad-hoc wireless networks. These common characteristics have motivated our work in developing an analytical modeling framework using entropy concepts and utilizing mobility information as the corresponding variable features, in order to support route stability in self-organizing mobile ad-hoc wireless networks.

The corresponding methodology, results and observations can be used by the routing and multicasting protocols to select the most stable route between a source and a destination, in an environment where multiple paths are available, as well as to create a convenient performance measure to be used for the evaluation of the stability and connectivity in mobile ad-hoc networks.

3.2 The Modeling

Every self-organizing system capable of change has certain variable features that can take on different values. For example, a particle can have different positions, move with different speeds, and have different directions. All these variable features can



(a) Local network stability by entropy

(b) Route stability by entropy

Figure 3.1 The modeling: basic concepts.

determine the characteristics of the system. Figure 3.1 presents the basic concepts of the modeling.

In the following section, consider a mobile ad-hoc wireless network and let's denote by M_m the number of neighboring nodes of a mobile node m, and by S_m the corresponding set. is is also associated with each node m a set of variable features denoted by $a_{m,n}$ where node n is a neighbor of node m. In this chapter, two nodes are considered neighbors if they can reach each other in one hop (e.g. direct communication). These variable features $a_{m,n}$ represent a measure of the relative speed among two nodes and are defined rigorously later in this section. Any change of the system can be described as a change of variable values $a_{m,n}$ in the course of time t such as $a_{m,n}(t) \rightarrow a_{m,n}(t + \Delta_t)$. In the following, it is assumed that nodes exchange periodically mobility information [38] as well as other local information (e.g. node ID) with their neighbors [40].

Also denote by $v(m, t)$, the velocity vector of node m and by $v(n, t)$, the velocity vector of node n at time t. Please note that velocity vectors $v(m, t)$ and $v(n, t)$ have two parameters, namely speed and direction. The relative velocity $v(m,n,t)$ between nodes m and n at time t is defined as:

$$v(m,n,t) = v(m,t) - v(n,t) \tag{3.1}$$

Then, the relative mobility between any pair $(m,\ n)$ of nodes during some time interval Δ_t is defined as their absolute relative speed averaged over time Δ_t. As mentioned before the variable features considered here is the relative mobility between two nodes.Therefore we have:

$$a_{m,n} = \frac{1}{N}\sum_{i=1}^{N}|v(m,n,t_i)| \tag{3.2}$$

where N is the number of discrete times t_i that velocity information can be calculated and disseminated to other neighboring nodes within time interval Δ_t. Based on this, the entropy $H_m(t,\Delta_t)$ can be defined at mobile m during time interval Δ_t. The entropy can be defined either within the whole neighboring range of node m (e.g. within setS_m), or for any subset of neighboring nodes of interest. In general, the entropy $H_m(t,\Delta_t)$ at mobile m is calculated as follows:

$$H_m(t,\Delta_t) = \frac{-\sum_{k\in F_m} P_k(t,\Delta_t) log P_k(t,\Delta_t)}{log C(F_m)} \tag{3.3}$$

where $P_k(t,\Delta_t) = \frac{a_{m,k}}{\sum_{i\in F_m} a_{m,i}}$.

In this relation by F_m, the set (or any subset) of the neighboring nodes of node m is denoted, and by $C(F_m)$ the cardinality (degree) of set F_m. If it is wanted to calculate the local network stability (with reference to node m), then F_m refers to the set that includes all the neighboring nodes of mobile node m (e.g. $F_m = S_m$), while if it is interested in the stability of a part of a specific route then F_m represents the two neighboring nodes of mobile node m over that route. As can be observed from the previous relation, the entropy $H_m(t, \Delta_t)$ is normalized so that $0 \leq H_m(t, \Delta_t) \leq 1$. It should be noted that the entropy, as defined here, is small when the change of the variable values in the given region is severe and large when the change of the values is small [48].

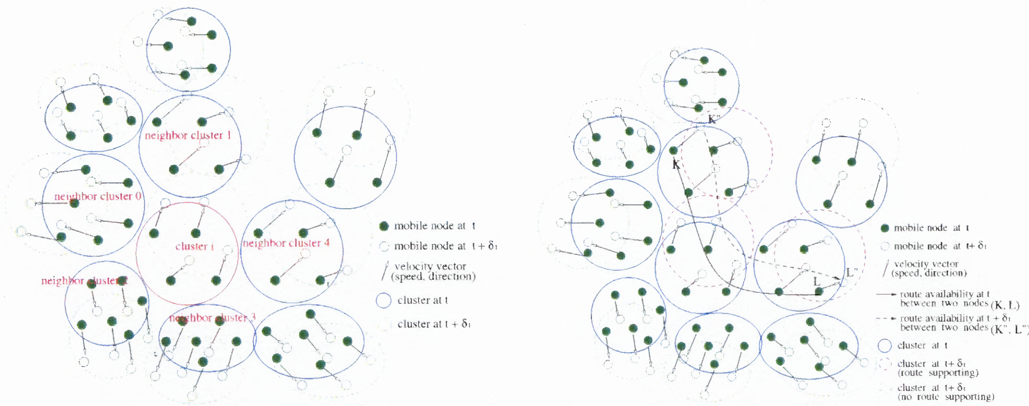
In the following section, it is described how to apply this modeling framework in order to measure the route stability. The local route (or the part of the route that represents the links of the path associated with an intermediate node), is stable if $H_m(t, \Delta_t)$ is large while the local route is unstable if $H_m(t, \Delta_t)$ is small. However, in general in a mobile ad-hoc network the route between a source and destination may traverse multiple intermediate nodes (hops). Figure 3.1 presents the basic concepts of the modeling. Let's present the route stability (RS) between two nodes k and l during some interval Δ_t as $\gamma = RS_{k,l}(t, \Delta_t)$. Two different measures to estimate and quantify end to end route stability are defined and evaluated, denoted by $\gamma^1 = RS^1_{k,l}(t, \Delta_t)$ and $\gamma^2 = RS^2_{k,l}(t, \Delta_t)$ and defined as follows respectively:

$$\gamma^1 = RS^1_{k,l}(t, \Delta_t) = \Pi_{i=1}^{N_r}[H_i(t, \Delta_t)] \tag{3.4}$$

and

$$\gamma^2 = RS^2_{k,l}(t, \Delta_t) = \min_{i=[1,2,3,\ldots,N_r]}[H_i(t, \Delta_t)] \tag{3.5}$$

where N_r denotes the number of intermediate mobile nodes over a route between the two end nodes (k, l). Parameter γ^1 (γ^2) can be used to measure the route availability and stability. That is, if γ^1 (γ^2) is large, there is available route and the route is stable during some time interval Δ_t, while if γ^1 (γ^2) is small, even though there may be an available route, the route may be unstable.



(a) Local network stability by entropy

(b) Route stability by entropy

Figure 3.2 The modeling for clustered networks.

3.3 Extension of the Modeling for Supporting Multicast Services

As explained before in this dissertation, in mobile ad-hoc networks communications are often among teams which tend to coordinate their movements. This collaboration among members of the same team makes it possible to partition the network into several groups, each with its own mobility behavior. Therefore, in this section the model and concepts presented in the previous section are extended and apply them into a clustered self-organizing mobile ad-hoc wireless network [38] in order to support multicast services. Specifically, in order to analyze the network stability and behavior in these cases, an approach is proposed and developed where cluster mobility characteristics are utilized as the corresponding feature variables in the proposed entropy based model. Figures 3.2 (a) and (b) illustrate the local network stability and the route availability respectively, with relation to the cluster mobility characteristics.

Denote by CM_i the mobility cluster parameter that presents the motion behavior (speed, direction) of a cluster C_i as a whole. To obtain CM_i, the velocities (vectors) of all nodes in the *cluster* C_i are added, and then are averaged over the total number of nodes in the cluster. Thus:

$$CM_i = \frac{1}{M_i} \sum_{k \in c_i} v(n_k, \Delta_t) \tag{3.6}$$

where M_i denotes the number of all nodes in the cluster, C_i. In this case, the entropy can be defined either within the whole neighboring range of cluster C_i(e.g., within the set S_i), or for any subset of neighboring clusters of interest.

In the following, the entropy H_{c_i} at cluster C_i is defined as:

$$H_{c_i}(t, \Delta_t) = \frac{-\sum_{k \in G_i} P_{c_k}(t, \Delta_t) log P_{c_k}(t, \Delta_t)}{log C(G_i)} \tag{3.7}$$

where $P_{c_k}(t, \Delta_t) = \frac{CM'_{(i,k)}(t, \Delta_t)}{\sum_{j \in G_i} CM'_{(i,j)}(t, \Delta_t))}$ and
$CM'_{(i,j)} = |CMi - CMj| = \sqrt{(CM_{(i_x)} - CM_{(j_x)})^2 + (CM_{(i_y)} - CM_{(j_y)})^2}$.
In this relation by G_i, the set (or any subset) of the neighboring clusters to cluster i is denoted, and by $C(G_i)$ its cardinality (degree). If it is wanted to calculate the local network stability (with reference to cluster C_i), then by G_i let's denote the set that includes all the neighboring clusters of cluster C_i (e.g. $G_i = S_i$), while if it is interested in the stability of a part of a specific multicast route then G_i represents the two neighboring clusters of cluster C_i over that route. As can be observed from the previous relation, the entropy $H_{c_i}(t, \Delta_t)$ is normalized so that $0 \leq H_{c_i}(t, \Delta_t) \leq 1$. It should be noted that the entropy, as defined here, is small when the change of the variable values in the given region is severe and large when the change of the values is small [48].

In the following, it is described how to apply this modeling framework in order to measure the route stability in the clustered self-organizing mobile ad-hoc wireless networks to support multicast services. In Chapter 4, MHMR uses mobility-based clustering (MBC) as underlying structure and clusterhead(CH)-based mesh structure to support multicast services. First, these two structures(i.e., MBC and mesh) and the cluster entropy $H_{c_i}(t, \Delta_t)$ are used and route stability γ_c^1 (γ_c^2) are calculated over these two structures(i.e, MBC and mesh) by the following relations (3.7), (3.8) and (3.9). The local route (or the part of the route that represents the links of the path associated with an intermediate CH node), is stable if $H_{c_i}(t, \Delta_t)$ is large while the local route is unstable if $H_{c_i}(t, \Delta_t)$ is small. However, in general in the clustered(i.e., MBC) mobile ad-hoc network the route between a source and destination may traverse multiple intermediate CH nodes. The route stability (RS) between two nodes k and l is presented during some interval Δ_t as $\gamma_c = RS_{k,l}^c(t, \Delta_t)$. Two different measures are defined and evaluated to estimate the route stability, denoted by $\gamma_c^1 = RS_{k,l}^{1c}(t, \Delta_t)$ and $\gamma_c^2 = RS_{k,l}^{2c}(t, \Delta_t)$ and defined as follows respectively:

$$\gamma_c^1 = RS_{k,l}^{1c}(t, \Delta_t) = \Pi_{i=1}^{N_{rc}}[H_{c_i}(t, \Delta_t)] \tag{3.8}$$

and

$$\gamma_c^2 = RS_{k,l}^{2c}(t, \Delta_t) = \min_{i=[1,2,3,\ldots,N_{rc}]}[H_{c_i}(t, \Delta_t)] \tag{3.9}$$

where N_{r_c} is the number of clusters over the route between two nodes k and l. Parameter γ_c^1 (γ_c^2) can be used to measure the path availability and stability. That is, if γ_c^1 (γ_c^2) is large, there is available route and the route is stable during some time interval Δ_t, while if γ_c^1 (γ_c^2) is small, even though there may be an available route, the route may be unstable.

3.4 Evaluation and Discussion

In order to evaluate the proposed modeling framework and corresponding parameters, a mobile ad-hoc network consists of 50 nodes that are placed randomly within a rectangular region of 1km x 1km is modeled. Each node is assumed to have constant radio range of Z=200 meters. That is, any pair of nodes within a distance of Z meters are considered to be neighbors. Throughout the evaluation, it is assumed that a link fails, or reappears, as a node goes out or in transmission range of another node, due to the mobility of the nodes. Mobile nodes are assumed to be moving around throughout the network. The speed and the direction of each move are uniformly distributed, with speed range [0, v_{max} km/hr] and direction range [0, 2π], respectively. If a mobile arrives at the boundary of the given network coverage area, the node reenters into network.

Two sets of experiments are performed. In the first one (refer to as Experiment 1), our objective is to evaluate the potential use of the developed framework and parameters as the decision factor in selecting the most stable routes, between a source and a destination whenever multiple routes are available, as well as to gain some insight about estimating the potential stability of a selected route. Therefore, one communication pair of nodes and at various points are selected during the system operation we select three different routes between the source and destination (in the following Tables they are denoted by Route1, Route2 and Route3, respectively). At the same time of route selection, the expected corresponding route stability γ^1 and γ^2 is calculated based on relations (3.4) and (3.5) in the general mobile ad-hoc networks and route stability γ_c^1 and γ_c^2 based on relations (3.8) and (3.9) in the clustered mobile ad-hoc networks respectively, for each one of these routes. Moreover, for each one of the routes the lifetime of the route is measured, that is the time from route establishment until the specific route breaks. In order to assess the capability of the proposed method, the route stability is evaluated, and its effectiveness under different environments is studied, in Tables 3.1, 3.2 and in Tables 3.5 and 3.6, respectively. The corresponding results for two different mobility scenarios (refer to as mobility1 with v_{max}=20 km/hr and mobility2 with v_{max}=40 km/hr) are presented. The results reported here correspond to three different points (identified in the Tables as point 1, point 2 and point 3 respectively) during the operation of the system where we selected new routes between the source and destination. As it is observed from these Tables, the lifetime of the route between a pair of end nodes is large when the route stability estimated by our proposed model is high. As expected, in Table 3.1 and Table 3.5(mobility1) the route stability and route lifetime present better values than the corresponding ones in Table 3.2 and Table 3.6(mobility2) respectively, since mobile nodes are moving with lower speed and therefore, overall the system presents a more stable topology.

In the second experiment (referred to as Experiment 2), the overall average route availability and stability between different pair of nodes (source and destination) are evaluated, without considering any specific path or route for each pair. Specifically, in this experiment three different pair of nodes are considered and a review of the available connectivity between these pairs of nodes is presented. Therefore, a time interval of $\Delta_t = 5$ seconds is considered as the time interval where mobiles exchange information, and calculate the route stability within that time interval, while at the same time we calculate new routes between the different pair of nodes, if required. Table 3.3, Table 3.4 and Table 3.7, Table 3.8 present the corresponding numerical results (average values for the whole duration of the experiment) in the general mobile ad-hoc wireless networks and the clustered mobile ad-hoc wireless networks for supporting multicast services respectively. In these Tables, it is represented by Route1, Route2 and Route3 the three corresponding communicating pairs of nodes. The route availability denotes the percentage of time that a route was available between the source mobile node and the corresponding destination mobile node during the experiment. As can be seen from Table 3.3, Table 3.4 and Table 3.7, Table 3.8, the routes with higher estimated route stability values (as calculated by relations equation (3.4), (3.5) and (3.8), (3.9) respectively) have also higher measured route availability. As expected, in Table 3.3 and Table 3.7(mobility1), the route stability and availability present better values than the corresponding ones in Table 3.4 and Table 3.8 (mobility2), since mobile nodes are moving with lower speed and therefore overall the system presents a more stable topology. As can be concluded from all the results presented in this section, the proposed model and corresponding parameters provide a very good measure to estimate, quantify, and evaluate the end to end stability in dynamic mobile ad-hoc networks.

3.5 Concluding Remarks

In this chapter, an entropy-based modeling framework is proposed for supporting and evaluating route stability in mobile ad-hoc wireless networks. The basic motivations of the proposed modeling approach stem from the common concepts of location uncertainty in mobile ad-hoc wireless networks and entropy. The corresponding results have demonstrated that the proposed modeling can be used as the ideal vehicle by various routing protocols for evaluation, selection and assignment of priorities to various routes according to route stability, in order to enhance the offered connectivity and QoS [49]. Furthermore, the proposed concepts and approaches have been extended and applied into a clustered self-organizing mobile ad-hoc wireless network for supporting multicast services.

Parameters / Routes	Point 1 $\gamma 1$	Point 1 $\gamma 2$	Point 1 Life Time (sec)	Point 2 $\gamma 1$	Point 2 $\gamma 2$	Point 2 Life Time (sec)	Point 3 $\gamma 1$	Point 3 $\gamma 2$	Point 3 Life Time (sec)
Route1	0.73	0.81	5.2	0.53	0.72	3.6	0.70	0.83	5.0
Route2	0.35	0.71	2.6	0.39	0.67	2.6	0.53	0.78	3.6
Route3	0.33	0.70	2.4	0.16	0.50	1.4	0.70	0.83	5.0

Table 3.1 Experiment 1 in general mobile ad-hoc networks: Route Stability(v_{max}=20km/hr)

Parameters / Routes	Point 1 $\gamma 1$	Point 1 $\gamma 2$	Point 1 Life Time (sec)	Point 2 $\gamma 1$	Point 2 $\gamma 2$	Point 2 Life Time (sec)	Point 3 $\gamma 1$	Point 3 $\gamma 2$	Point 3 Life Time (sec)
Route1	0.71	0.78	4.6	0.48	0.61	3.2	0.51	0.52	3.4
Route2	0.61	0.76	3.4	0.46	0.61	3.0	0.47	0.51	3.2
Route3	0.42	0.71	3.0	0.48	0.61	3.2	0.46	0.51	3.2

Table 3.2 Experiment 1 in general mobile ad-hoc networks: Route Stability(v_{max}=40km/hr)

Parameters / Routes	Route Stability $\gamma 1$	Route Stability $\gamma 2$	Route Availability (%)
Route1	0.74	0.81	91.3
Route2	0.72	0.79	90.6
Route3	0.68	0.78	79.4

Table 3.3 Experiment 2 in general mobile ad-hoc networks: Route Stability(v_{max}=20km/hr)

Parameters / Routes	Route Stability		Route Availability (%)
	$\gamma 1$	$\gamma 2$	
Route1	0.69	0.78	78.4
Route2	0.66	0.77	72.0
Route3	0.65	0.76	71.2

Table 3.4 Experiment 2 in general mobile ad-hoc networks: Route Stability(v_{max}=40km/hr)

Parameters / Routes	Point 1			Point 2			Point 3		
	$\gamma 1$	$\gamma 2$	Life Time (sec)	$\gamma 1$	$\gamma 2$	Life Time (sec)	$\gamma 1$	$\gamma 2$	Life Time (sec)
Route1	0.79	0.84	9.4	0.67	0.72	5.6	0.78	0.83	9.0
Route2	0.79	0.84	9.4	0.75	0.78	7.4	0.65	0.72	5.6
Route3	0.69	0.74	6..4	0.56	0.69	3.4	0.62	0.66	4.0

Table 3.5 Experiment 1 in clustered mobile ad-hoc networks: Route Stability(v_{max}=20km/hr)

Parameters / Routes	Point 1			Point 2			Point 3		
	$\gamma 1$	$\gamma 2$	Life Time (sec)	$\gamma 1$	$\gamma 2$	Life Time (sec)	$\gamma 1$	$\gamma 2$	Life Time (sec)
Route1	0.71	0.76	6.6	0.73	0.78	7.0	0.70	0.76	6.4
Route2	0.70	0.75	6.4	0.60	0.65	3.4	0.74	0.79	7.2
Route3	0.52	0.60	3.0	0.71	0.77	6.6	0.56	0.61	3.2

Table 3.6 Experiment 1 in clustered mobile ad-hoc networks: Route Stability(v_{max}=40km/hr)

Parameters / Routes	Route Stability $\gamma 1$	Route Stability $\gamma 2$	Route Availability(%)
Route1	0.77	0.83	92.0
Route2	0.78	0.84	93.6
Route3	0.75	0.80	86..4

Table 3.7 Experiment 2 in clustered mobile ad-hoc networks: Route Stability(v_{max}=20km/hr)

Parameters / Routes	Route Stability $\gamma 1$	Route Stability $\gamma 2$	Route Availability (%)
Route1	0.73	0.78	82.0
Route2	0.70	0.76	79.0
Route3	0.71	0.77	80.0

Table 3.8 Experiment 2 in clustered mobile ad-hoc networks: Route Stability(v_{max}=40km/hr)

CHAPTER 4

MOBILITY-BASED HYBRID MULTICAST ROUTING PROTOCOL IN MOBILE AD-HOC WIRELESS NETWORKS

4.1 Introduction

Multicasting protocols for infrastructure-based wireless networks have mainly focused on just the last-hop extension environments of wire-line networks. The multicast routing protocols [50][51][52][53][54] designed for infrastructure based networks can not be used in mobile ad-hoc wireless networks mainly for the following reasons: a) the routes in ad-hoc networks change frequently, b) the fixed infrastructure does not exist for route (re) computation, and c) there are power, coverage and bandwidth restrictions.

In this chapter, a Mobility-based Hybrid Multicast Routing (MHMR) protocol suitable for mobile ad-hoc networks is presented. In our proposed structure, we use mobility-based clustering and group mobility-based hierarchical structures which use mobility information(individual mobility, group mobility) and position information. This is motivated by the observation that in mobile ad-hoc wireless network nodes participating in multicasting are very inclined to group-oriented communication and operation.

As part of the overall proposed multicast protocol, the MBC clustering method proposed in Chapter 2 which is based on the combination of the concepts of mobility and distributed clustering algorithms (i.e. such as the lowest-ID algorithm and the highest connectivity degree algorithm) is used. For every group of nodes (cluster), one node is selected as the clusterhead of the cluster. Among the groups of nodes (clusters) that are created based on the proposed clustering method, the protocol supports the creation of mesh structures, that is, it creates a subgraph of the group node graph (i.e. clusterheads), in order to provide limited redundancy (versus no redundancy or broadcasting techniques). The maximum number of possible paths between nodes is based on mobility patterns. Additionally the most stable paths (with minimum chance of disruption) as opposed to shortest or otherwise optimal paths are used for multicasting.

The remaining of the chapter is organized as follows. Section 4.2 describes the overall MHMR infrastructure. Specifically, subsection 4.2.1 introduces the concept of mesh structure, subsection 4.2.2 describes the multicast group construction and maintenance procedures in order to create the limited mesh structure, and subsection 4.2.3 presents the data forwarding strategy. Section 4.3 contains the performance evaluation of the proposed strategy, while section 4.4 concludes the chapter.

4.2 The MHMR Infrastructure

The Mobility-based Hybrid Multicast Routing (MHMR) protocol mainly consists of two basic architectures. The first architecture includes the mobility-based hierarchical clustering algorithm for supporting multicast [6]. This is used to form hierarchical clusters according to individual and group mobility, thus forming a hierarchical control structure. This structure was described in detail chapter 2. In the second structure a mesh is created as a subgraph of clusterheads' (CHs) graph to function as the routing infrastructure. The proposed algorithm first creates and maintains the underlying structure(i.e, mobility-based hierarchical clustering) and then selects the data forwarding structure over the created mesh topology. However, as mentioned above the mesh is based on the clusterheads, and not on all the members of the networks.

4.2.1 The Mesh Structure

Tree-based multicast routing schemes [6] have been used extensively in computer networks, internets, and wireless multi-hop networks because of their simplicity. However, when the underlying topology changes, the routers using tree-based methods may be forced to stop their operation and additional control traffic may occur during the tree-reconstruction phase. The inherent redundancy in mesh topologies can help overcome this problem. However, constructing mesh structure among all multicast members in dynamic mobile wireless networks is not feasible, especially in large-scale networks since it may generate high overhead and control traffic.

In MHMR, a limited mesh structure is proposed over the clusterheads only, that are created by the underlying mobility-based clustering described in the previous section. Figure 4.1 shows our clusterhead(CH)-based mesh structure. It should be noted that the mesh structure is a subgraph of the CHs only, and not a subgraph of the overall network. Thus, only CHs may become members of a mesh structure(i.e., limited mesh structure). Since the underlying structure for MHMR is very robust, the recomputation of multicast routes may not be necessary for every link breakage. Let $G_m = (V_m, E_m)$ represent an undirected mesh graph, where V_m is the set of CHs, and E_m is the set of links between them. Let $s \in V_m$ denote the clusterhead of a multicast source in the mesh and $r \in V_m$ represent the corresponding receiver in the mesh. For a given set of CHs (s(source), r(receiver)), $M_{s,r}$ =($V_{s,r}$, $L_{s,r}$) represents the mesh that is rooted at the source s to receiver r, where $V_{s,r}$ represents the set of CHs in $M_{s,r}$ and $L_{s,r}$ represents the set of links in $M_{s,r}$. One of the main objectives of our protocol is to construct a robust mesh structure in a cost effective way. To achieve this, Boundarycast and BoundaryCrosscast[29] are used and a simple loop-

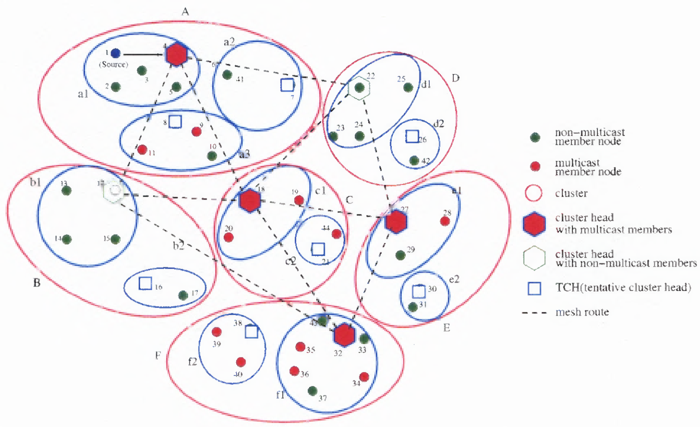


Figure 4.1 Mesh structure.

free method is introduced. These techniques are described in detail in the next section.

4.2.2 Multicast Group Construction and Maintenance

In the following section, the steps of the proposed multicast group construction and maintenance procedures are described. Figure 4.2 presents a schematical representation of the main steps involved in these procedures.

Step 1: When a source node that is already a member of a multicast group has multicast packets, it sends the packets to its CH. In the proposed mobility-based clustering, each node keeps next node-id to its CH, and the CH maintains routing information proactively within its cluster. When a non-multicast member node wants to become a member of a multicast group, it requests multicast membership to its CH. If its CH is not a member of the multicast group, the CH requests multicasting to its neighbor CHs as described in step 2 - step 5.

Step 2: The CH generates and advertises a JOIN REQUEST to its neighbor CHs using the Boundarycast and BoundaryCrosscast procedures[29]. The JOIN REQUEST consists of the address of the multicast group the node wishes to join, the source node ID, and source CH ID. Boundarycast is used to facilitate the forwarding of JOIN REQUEST within a cluster. In Boundarycast each CH sends JOIN REQUEST only to its boundary nodes to limit the propagation. Boundary node information can be obtained from the proposed underlying clustering structure and are proactively maintained in each CH. When a boundary node receives a JOIN REQUEST from the CH, the boundary node executes the BoundaryCrosscast operation. BoundaryCrosscast is used for routing between clusters. In BoundaryCrosscast each boundary node sends JOIN REQUEST to only its neighbor boundary nodes (limited search) within its neighbor cluster. Routing between clusters is implemented using on-demand based protocol that establishes paths by executing BoundaryCrosscast (i.e., limited path-search query and response method).

Step 3: When a CH that is not a member of the multicast group receives a non-duplicate JOIN REQUEST, it stores the upstream CH ID (to source CH) and forwards the messages to all neighbor CHs in accordance with the Boundarycast and BoundaryCrosscast techniques, except the one that received the request from.

Step 4: When an existing multicast clusterhead (CH) member receives the JOIN REQUEST, it responds to upstream CH(to source CH) with a JOIN REPLY and the CH creates or updates the source entry in its multicast member table. This table stores the multicast address, the source node ID, the source CH ID and the time when the last JOIN REQUEST is received. Then, the CH just forwards the first received JOIN REQUEST (non-duplication) to its nearby CHs and the same process is repeated. If no JOIN REQUEST is received from a source CH within a given period, that entry is removed from the multicast member table.

Step 5: When a inter-node (non-CH) between CHs receives a JOIN REPLY, it checks if the next node ID matches its own ID. If it does, the node realizes that it is on the path to the source. Then it forwards the JOIN REPLY to its upstream node (to source CH). When a CH receives a JOIN REPLY, it checks if the next CH ID of one of the entries matches its own ID. If it does, it updates the mesh table with its own upstream (to destination) CH ID information and forwards to the upstream (to source) CHs. The JOIN REPLY is finally propagated to the multicast source CH.

Step 6: When a multicast source want to leave the multicast group, it sends a stop message to the source CH and the source CH just stops sending JOIN REQUEST, since it does not have any multicast data to send to the group. When a receiver no longer wants to receive messages from a particular multicast group, it does not request multicast to its CH for the multicast group. The CH removes the corresponding entries from its multicast member table if the multicast member is not updated within a pre-specified time interval.

4.2.3 Data Forwarding Strategy

Although the MHMR creates a mesh infrastructure for multicast routing, the multicast packet forwarding is done only on a source based tree. The trees are constructed over the given mesh structure and can be created dynamically depending on the mesh stability. The main objective of data forwarding strategy is to reduce the unnecessary routes for bandwidth saving purposes. In our data forwarding strategy, the selected tree routes over mesh might be stable during some time duration(T), with the help of the mobility-based underlying structure. Let $G_t = (V_t, E_t)$ represent the directed multicast tree over the given mesh structure, where V_t is the set of CHs and E_t is the set of links between CHs. The tree is a subgraph of the given mesh structure (i.e., $V_t \subseteq V_m$ and $E_t \subseteq E_m$). Let also $s \in V_t$ denote a multicast source in the tree. The multicast data forwarding over the tree infrastructure saves redundant transmissions leading to efficient usage of the scarce bandwidth. In the following, the main steps of the proposed data forwarding strategy are outlined. Figure 4.3 provides a schematic representation of the main steps involved in this process.

Step 1: Source CH forwards multicast data to its neighbor CHs over the mesh.

Step 2: When a node CH_i receives the first data packet, CH_i checks whether it has other upstream(to source CH) clusterhead CH_k over the mesh. If it does, then it sends a FORWARD REJECT message to its other upstream CHs (i.e, all CH_k) over the mesh routes to inform them that it has already received the data packet. Any CH_i receiving data packet can repeat this operation after some time(T_r), where T_r depends on the network stability(mobility). Although in the current version of MHMR, based on this procedure, a tree-based forwarding topology is created, it is possible in unstable environments to apply the procedure described here adaptively, in the sense that it may be deviated from the strict tree topology to allow more additional paths to deliver the data to improve data delivery reliability, at the expense of additional bandwidth consumption. For instance, if the network is quite unstable, the FORWARD REJECT message can be sent adaptively to some (and not all) of its upstream CHs.

Step 3: When a node CH_k receives a FORWARD REJECT message, the CH_k does not forward data packets any more to its downstream CH_i that sent the FORWARD REJECT message during some time(T_f), where T_f depends on the network stability(mobility).

Step 4: Resources(bandwidth) can be reserved on the selected forwarding routes.

In the current version of the MHMR protocol, any specific bandwidth reservation scheme (i.e. step 4) has not been implemented. Instead it is assumed that there is sufficient bandwidth over the selected tree. The work for the design and development of efficient bandwidth reservation schemes that can be implemented in the MHMR protocol is currently in progress.

4.2.4 Data Structures

In the following section, the data structures that are required for the implementation of the MHMR algorithm are summarized.

- Mesh table: Mesh table contains next CH information(to receivers). Mesh table consists of current CH ID, next CH ID and route information(node-id, hops) between current CH ID and next CH ID. Mesh table is created on demand between CHs and is used for data forwarding to multicast members CHs.

- Cluster table: CH maintains its cluster memberships and routing information for all nodes within its cluster. This information is periodically updated and maintained proactively in the table.

- Node-to-CH table: Each node within cluster maintains next node information to its CH. This information is periodically updated and maintained proactively in the table.

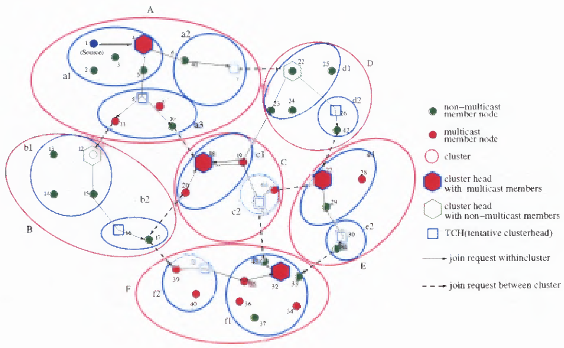
- Multicast member table: Each CH holds multicast group member information within its cluster. This table stores the multicast address, the source node ID, the source CH ID and the time when the last JOIN REQUEST is received.

4.3 Performance Evaluation

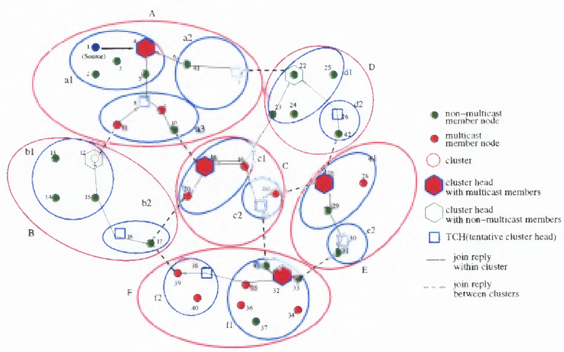
In this section, the protocol's performance is evaluated. In subsection 4.3.1 the modeling and simulation framework that are used to evaluate the protocol's performance are described, while in subsections 4.3.2 and 4.3.3 the performance metrics used throughout this study as well as the specific experiments that were conducted and the corresponding results are presented. The emphasis of the protocol's performance evaluation is placed mainly on its efficiency and effectiveness. Understanding the protocol's efficiency in addition to its effectiveness gives us the ability to study and discuss relative strengths, weaknesses, and applicability to various situations. The achieved performance of MHMR are also compared with the corresponding performance of ODMRP[20] which uses reactive (i.e., on-demand) and forwarding group concepts.

4.3.1 Simulation Scenario and Framework

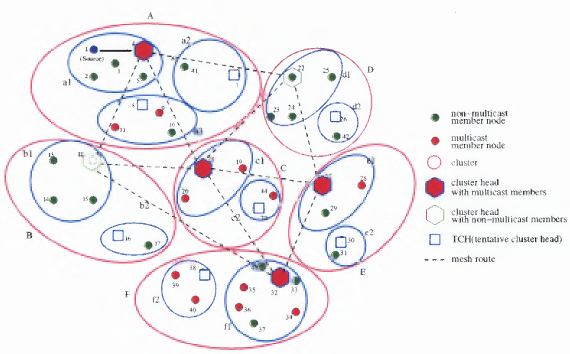
The protocol's performance evaluation is accomplished via modeling and simulation using the Optimized Network Engineering Tool (OPNET). A mobile ad-hoc network consisting of 50 mobile nodes that are placed randomly within a rectangular region of



(a) Multicast Join Request Operation

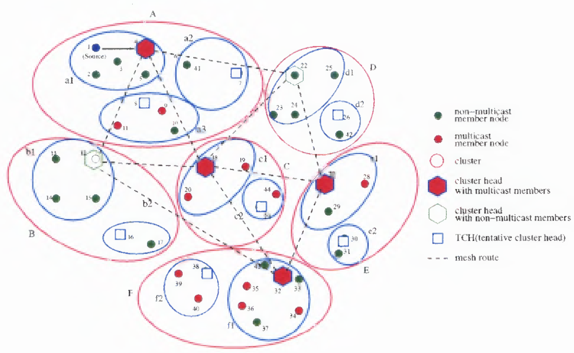


(b) Multicast Join Reply Operation

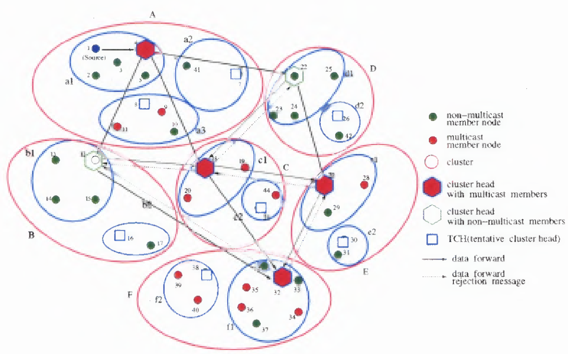


(c) Mesh Structure after Multicast Group Construction

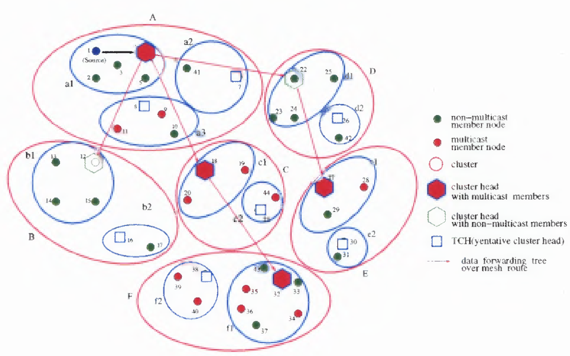
Figure 4.2 The procedures for multicast group construction.



(a) Mesh Structure after Multicast Group Construction



(b) Forwarding Tree Creation Operation



(c) Forwarding Tree over Mesh Structure

Figure 4.3 Strategy of data forwarding tree creation over mesh structure.

1000 m x 1000 m is modeled in the simulation. Each node is modeled as an infinite-buffer, store-and-forward queuing station, and is assumed to be aware of its position with the aid of a reliable position location system. Moreover, the mobile nodes are assumed to have constant radio range of Z=300 m. Therefore, this behavior may be interpreted as follows: any packet can be received error free within the transmission range of a node (i.e. radius of Z from the transmitter), but is lost beyond Z. The main objective of this study is to evaluate the efficiency and effectiveness of the multicast routing strategy, and therefore our study is mainly focused on network layer details, while simplified models are assumed for the data link layer. Throughout the study, we assume that a link fails, or reappears, as a node goes out or in transmission range of another node, due to the mobility of the nodes.

Mobile nodes are assumed to be moving around throughout the network. Two different mobility scenarios are considered in this study. In the first one (in the following we refer to it as mobility 1), the speed and the direction of each node's move are uniformly distributed, with speed range [0, v_{max} km/h] and direction range [0, 2π], respectively. The speed and direction are updated independently for each node every Δ_t seconds (in our simulation $\Delta_t = 5 seconds$). In the second mobility scenario (in the following it is referred to as mobility 2), a group-based mobility pattern is modeled. Specifically, nodes are grouped into several groups, where it is assumed that nodes in the same group have similar mobility characteristics (e.g. similar but not the same moving direction). At every movement, the speed of each mobile is selected independently within the range [0, v_{max} km/h]. Regarding the moving direction of the mobiles, at the beginning of the simulation a starting moving direction is selected randomly for each group (different groups have different initial directions). Every mobile belonging to a group selects independently its actual moving direction within a range of $(-\pi/6, +\pi/6)$ with reference to its own group's original selected direction. As a result, mobiles belonging to the same group present some similarity in the direction towards which they are moving. Initially, each group consists of five nodes, however as the system evolves the number of nodes per group changes dynamically.

For both mobility scenarios (i.e. mobility 1 and mobility 2), the results presented in the following subsection correspond to three different values of v_{max}: 20km/hr, 50 km/hr and 80 km/hr, to represent slow, medium and high moving speeds, respectively. If a mobile arrives at the boundary of the given network coverage area, the node reenters into the network. Multicast members are selected randomly. Finally, throughout this study, the mobility threshold Th_{mob} described in section 2.1 is selected as follows. Let m_{mob} be the average value of all mobility information that the node m received and δ_{mob} its corresponding standard deviation. Then, Th_{mob} is selected as: $Th_{mob} = m_{mob} + \mathrm{k}\delta_{mob}$, where k is constant and can be changed according to the network under consideration and the desired cluster stability. In this simulation, parameter k was chosen as k = 1.5 based on experimentation.

4.3.2 Performance Metrics

The performance metrics that it is used in this paper for the evaluation purposes are the following:

- Packet delivery ratio (PDR): It is defined as the number of data packets delivered to multicast receivers over the number of data packets supposed to be delivered to multicast receivers. This ratio represents the routing effectiveness of our strategy.

- Control overhead: It is defined as the average number of control packets related to the route creation process that are received by a node per multicast data delivered.

- Delay: It is defined as the average latency time for multicast route creation between multicast source and receivers.

In this chapter, the performance metrics were studied mainly in two dimensions: mobility and scalability. Since in mobile ad-hoc networks one of the most distinct characteristics is mobility, the protocols' performance is evaluated as a function of mobility speed, in order to study and determine their applicability in different networking environments. Moreover, in order to investigate the scalability of the respective protocols we investigated the protocols' behavior as we varied the multicast group size. As it is mentioned before, the performance of MHMR is also compared with the corresponding performance of ODMRP[20] under the same networking scenarios. ODMRP applies on-demand routing techniques to avoid channel overhead and improve scalability. In ODMRP, group membership and multicast routes are established and updated by the source on demand. While a multicast source has packets to send, it periodically broadcasts to the entire network a member advertising packet. This periodic transmission refreshes the membership information and updates the route. This process of constructing and updating the routes from sources to receivers builds a mesh of nodes, the forwarding group. The forwarding group consists of a subset of nodes that is responsible of forwarding the multicast packets via mesh-based topology rather than multicast tree scheme. It supports shortest paths between any member pairs. All nodes inside the forwarding group forward multicast data packets. The created mesh subnetwork provides richer connectivity among multicast members compared to trees. Hence unlike trees frequent reconfigurations are not required. As an on-demand routing mechanism, ODMRP reduces unnecessary channel overhead. As long as the number of members is high (dense networks), the forwarding group creates richer connectivity among members and therefore this mesh makes the protocol quite robust to speed. On the other hand, since routes are setup on demand, delay is increased. Also the richer the connectivity, the higher the effect of the forwarding group concept on network congestion.

4.3.3 Numerical Results

Figure 4.4 (Figure 4.10) illustrates the packet delivery ratio of the protocol as a function of mobility for a given Packet Transmission Rate (PTR) of 5 packets/sec in mobility 1 (mobility 2) scenario. As seen by the results of this figure, MHMR shows very good performance in highly dynamic situations where both random or group-oriented mobility patterns are supported, which means that the fact that our protocol uses a tree structure for data dissemination does not affect significantly its effectiveness. The reason is that in our protocol the tree is selected and created based on the underlying structure of the created mesh topology of the clusterheads. Therefore the impact of a link break is minimal on the protocol's capability of delivering the data to the appropriate destinations. Similar behavior is observed in Figure 4.5 (Figure 4.11) where the packet delivery ratio achieved by the protocol is presented as a function of the packet transmission rate for mobility 20 km/hr, for the mobility 1 (mobility 2) case.

In Figure 4.6 (Figure 4.12), the scalability property of the protocol is presented by presenting the packet delivery ratio as a function of the multicast group size in mobility 1 (mobility 2) case with mobility speed of 20 km/hr. As it is demonstrated in these figures, MHMR was not affected by the number of multicast members. This

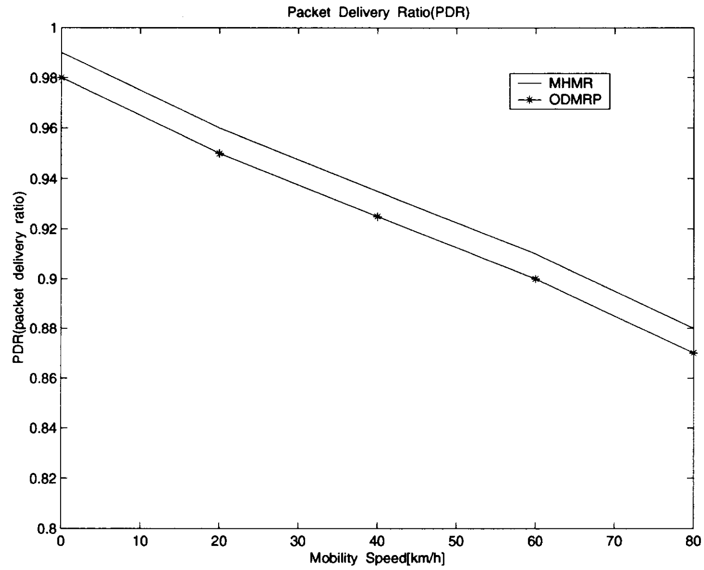


Figure 4.4 Packet delivery ratio as function of mobility speed (random mobility).

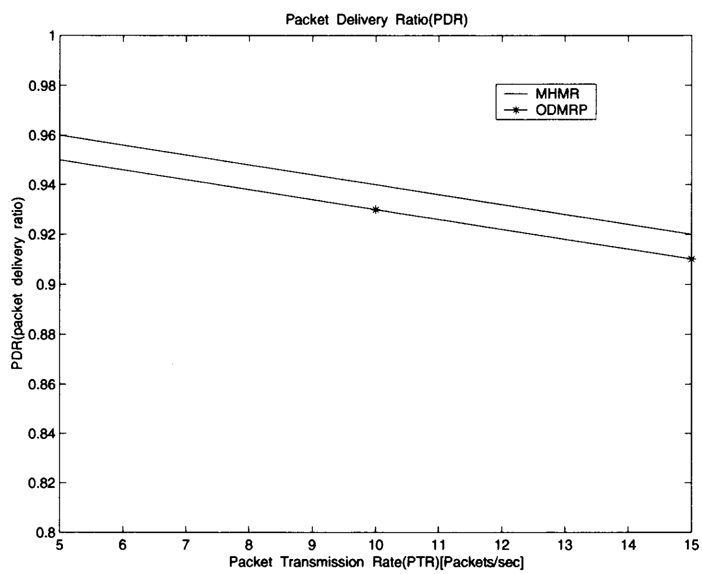


Figure 4.5 Packet delivery ratio as function of PTR (random mobility).

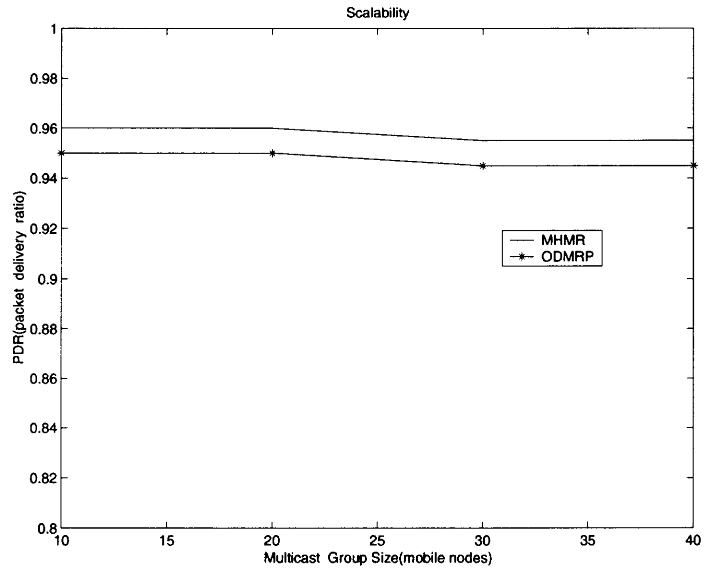


Figure 4.6 Packet delivery ratio as function of multicast group size (random mobility).

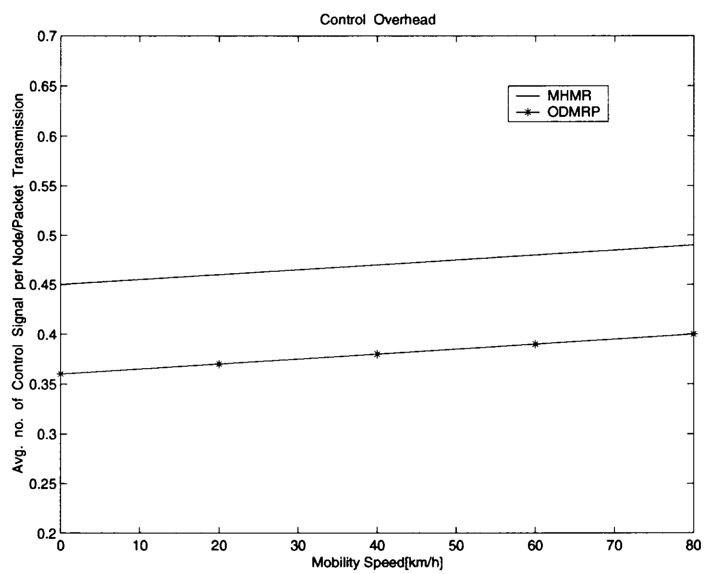


Figure 4.7 Control overhead for route creation as function of mobility speed (random mobility).

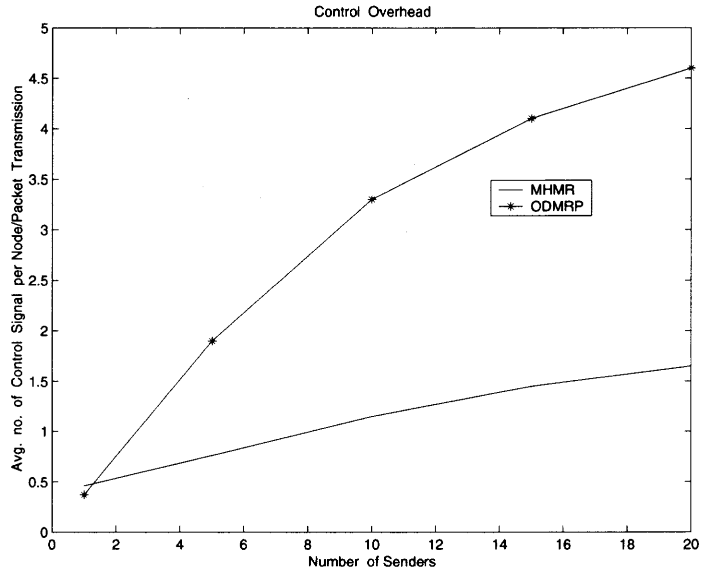


Figure 4.8 Control overhead for route creation as function of number of senders (random mobility).

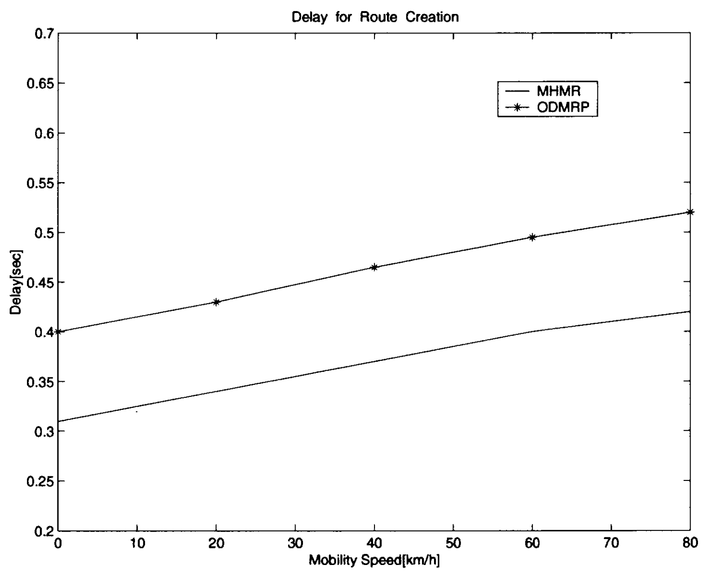


Figure 4.9 Delay for route creation as function of mobility speed (random mobility).

behavior trend is similar to the one presented by flooding technique and ODMRP protocol [20]. The reason that the protocol is not affected by the membership group size, while for other mesh-based protocols their behavior may vary with the multicast group size, is that in MHMR the mesh structure mainly depends on the underlying mobility-based clustering algorithm, and not on the number of receivers, as in other protocols [i.e. CAMP[11]]. Furthermore, the fact that our protocol uses group-mobility characteristics to create the underlying structure contributes to the improved stability and scalability of MHMR under mobility 2 scenario.

Figure 4.7 (Figure 4.13) show the control overhead associated with the multicast route creation and maintenance as a function of the number of senders for mobility 1 (mobility 2) scenario for speed $v_{max} = 20km/hr$, while Figure 4.8 (Figure 4.14) presents the control overhead as function of mobility speed for mobility 1 (mobility 2) scenario. The control overhead includes all the signals (packets) that need to be exchanged among the various nodes in order to create and maintain the routes and clusters. As can be seen from Figure 4.7 (Figure 4.13), the control overhead associated with MHMR increases only slightly with increasing number of senders, while the corresponding control overhead in ODMRP increases drastically. The reason is that MHMR uses clustering as the underlying structure, and at a large extend the overhead associated with MHMR is due to the cluster creation and maintenance, that is performed proactively and in some sense is independent of the number of senders and/or receivers. In this case, only a small amount of additional control signals has to be exchanged for the actual support of the multicast communications. As a result, the overall overhead has lower dependence on the number of senders, compared to other reactive approaches. For instance, as observed in Figure 4.7 (Figure 4.13) since ODMRP uses on-demand method for route creation, the corresponding number of control signals drastically increases with increasing number of senders.

As it is observed from Figure 4.8 (Figure 4.14), the control overhead remains relatively constant as the speed increases (i.e. only slightly increases with increasing speed). The reason is that the updates (for clustering and route creation and maintenance) are operated periodically. However, the number of control signals for the updates may slightly increase with speed during this period because although the mobility-based clustering approach groups nodes that present similar mobility characteristics, as mobility increases the structure (e.g., neighbors of a node) is changing more drastically, and therefore more control signals nay need to be exchanged within each update period.

Figure 4.9 (Figure 4.15) presents the average delay (latency time) for route creation to multicast members. The delay includes all the latency times that need to be spent between source and all multicast members for route creation. As can be seen from Figure 4.9 (Figure 4.15), the delay of MHMR is less than the corresponding delay of ODMRP. The main reason is that, as explained before, MHMR uses hybrid (reactive and proactive) approach while ODMRP just uses reactive approach. Furthermore, the delay increases only slightly with the increasing mobility speed. One of the main reasons is that the MBC method that is an integrated part of the MHMR strategy creates a very stable underlying structure that reduces significantly the need for clusterhead changes [38][39]. However, even though the underlying structure is stable, as the speed increases the probability that the mesh structure and the created routes may be broken also increases, and therefore the delay may increase as well.

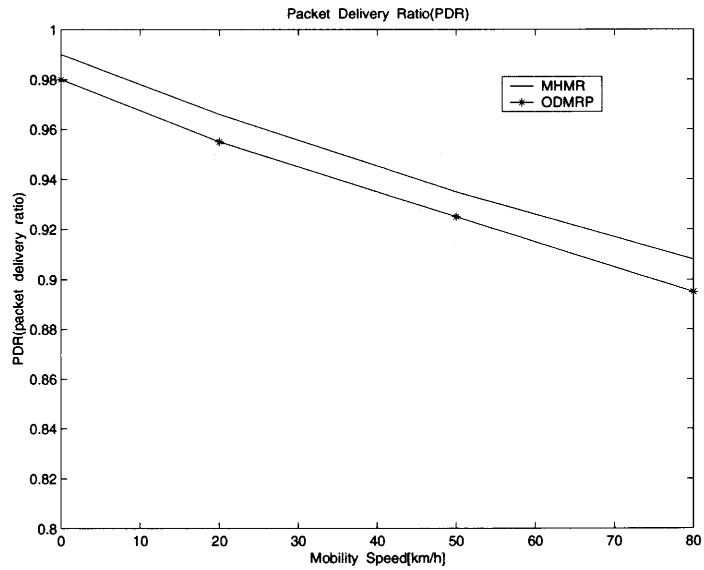


Figure 4.10 Packet delivery ratio as function of mobility speed (group mobility).

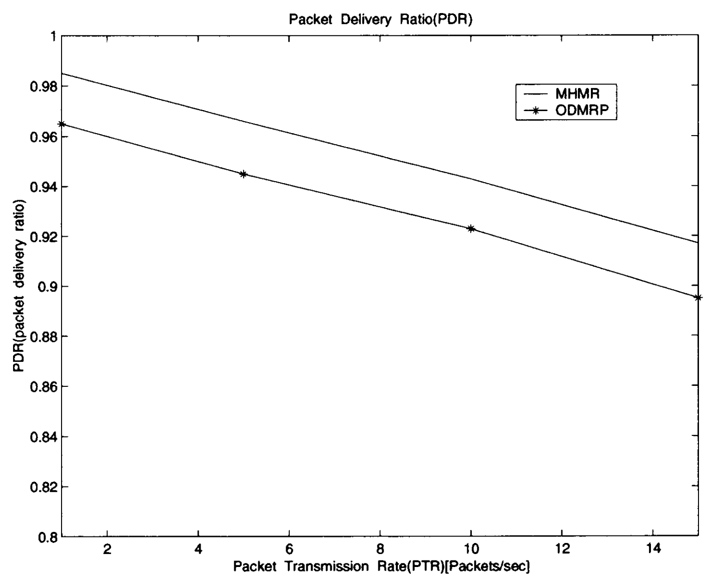


Figure 4.11 Packet delivery ratio as function of PTR (group mobility).

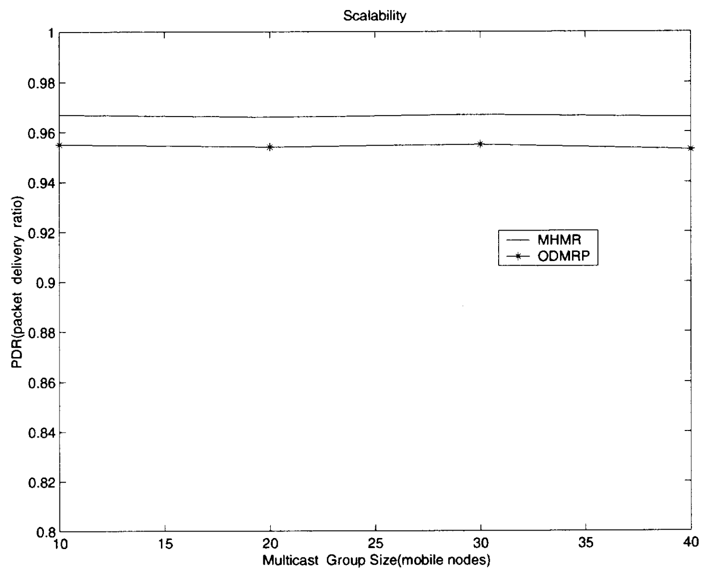


Figure 4.12 Packet delivery ratio as function of multicast group size (group mobility).

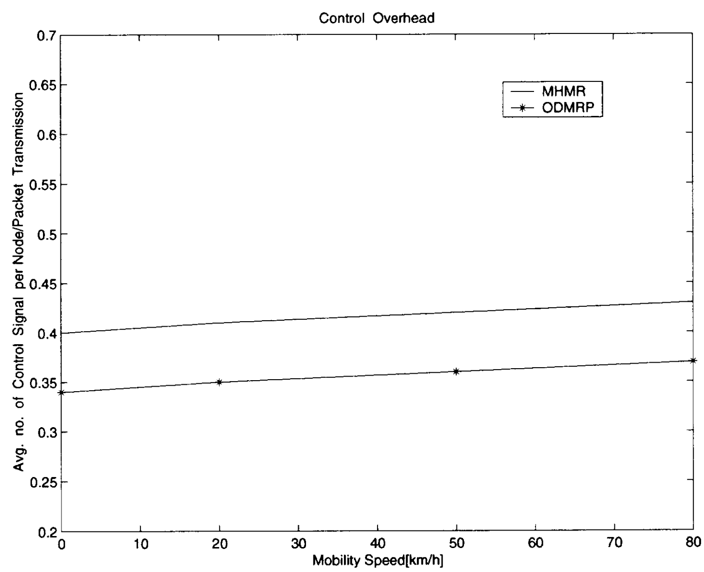


Figure 4.13 Control overhead for route creation as function of mobility speed (group mobility).

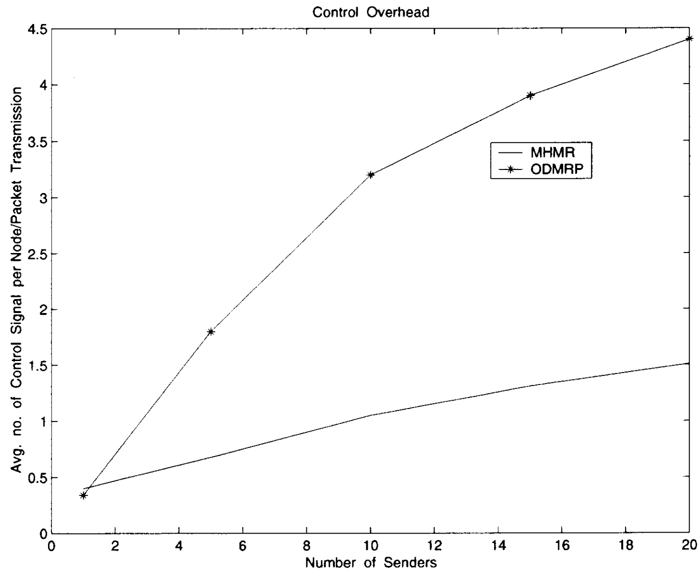


Figure 4.14 Control overhead for route creation as function of number of senders (group mobility).

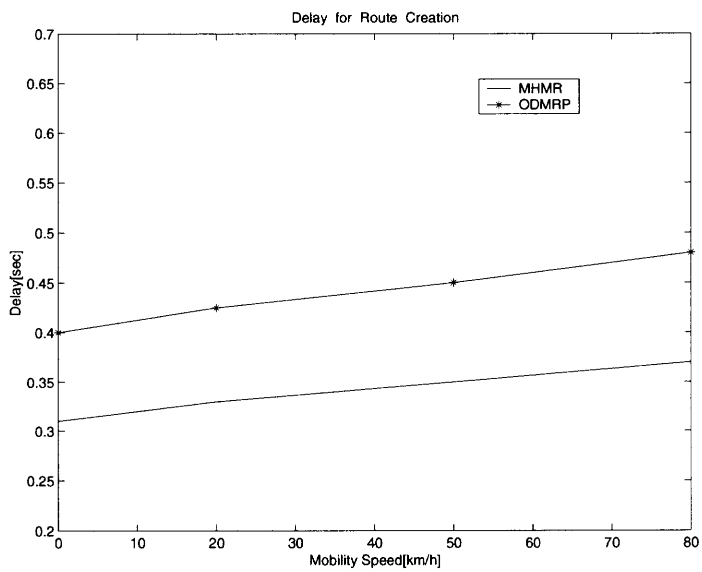


Figure 4.15 Delay for route creation as function of mobility speed (group mobility).

As can be seen from Figure 4.13, Figure4.14 and Figure 4.15, the performance (i.e., control overhead and delay) of MHMR in mobility 2 scenario (i.e., group mobility) is much better than the corresponding performance under mobility 1 scenario (i.e. Figure 4.7, Figure 4.8 and Figure 4.9). The main reason for that is that one of the MHMR's design features and principles is the use of an underlying structure that depends upon nodes' mobility patterns, and thus, as a natural result, it provides improved performance when the participating nodes present similar mobility characteristics as in the case of group-oriented movements and communications, where the changes of the underlying structure are less drastic.

4.4 Concluding Remarks

In this chapter, a Mobility-based Hybrid Multicast Routing protocol (MHMR) suitable for mobile ad-hoc networks is proposed. As part of the MHMR protocol, a mobility-based clustering (MBC) approach that uses combination of both physical and logical partitions of the network is used. This architecture is mainly used to form hierarchical clusters and provides the underlying structure for the implementation of the multicast protocol. The main features that MHMR introduces can be summarized as: a) mobility-based clustering and group based hierarchical structure, in order to effectively support the stability and scalability, b) group-based (limited) mesh structure and forwarding tree concepts, in order to support the robustness of the mesh topologies which provides "limited" redundancy and the efficiency of tree forwarding simultaneously, and c) combination of proactive and reactive concepts which provide the low route acquisition delay of proactive techniques and the low overhead of reactive methods.

The performance evaluation of MHMR demonstrate the proposed multicast protocol's efficiency in terms of packet delivery ratio, scalability, control overhead and end-to-end delay, as a function of mobility, packet transmission, multicast group size, and number of senders, and therefore indicate that MHMR provides a very efficient dynamic multicast strategy that is suitable for application in large scale mobile ad-hoc networks. Furthermore, the numerical results demonstrated, as expected, that our protocol's improved performance is even more significant in the case of group-oriented movements. Since in mobile ad-hoc networks the multicasting applications are usually among teams that tend to coordinate their movements, our protocol provides the ideal vehicle for the support of multipoint communications in mobile ad-hoc networks.

CHAPTER 5

GEOMULTICAST: ARCHITECTURES AND PROTOCOLS FOR MOBILE AD-HOC WIRELESS NETWORKS

5.1 Introduction and Background

Geomulticast is a specialized location-dependent multicasting technique, where messages are multicast to some specific user groups within a specific zone. While conventional multicast protocols define a multicast group as a set of nodes with a multicast address and geocast defines a geocast group as all the nodes within a specified zone at a given time, a geomulticast group is defined as a set of nodes of some specific groups within a specified zone. In general, multicast is more efficient than multiple unicasts and broadcasts in terms of communication costs. Cost considerations are more critical in mobile ad-hoc wireless networks because these networks present dynamic, sometimes rapidly changing, random, multihop topologies and the mobile nodes communicate with each other over wireless links. In this chapter, architectures and protocols for supporting geomulticast services [55][56] are proposed in a cost effective way and with high message delivery accuracy in the challenging environment of mobile ad-hoc wireless networks.

The problem of geocasting has become an active research topic over the last few years. In [57] the problem of GPS based geographic addressing and routing in networks with a fixed infrastructure is considered. This work focuses mainly on the integration of the concept of physical position into the current design of the Internet, thus assuming fixed geographic routers. To support geocast services, the authors used location aware routers, multicast routing modifying IP multicast, and an application layer solution using extended Domain Name Service (DNS). When no fixed infrastructure is available, as in ad-hoc networks, a mechanism distributed among all the mobile nodes of the network has to be provided for maintaining position awareness. This requires that the position coordinates of each node are disseminated throughout the network. In [23][58] geocasting protocols in networks with no fixed infrastructure were considered. In that paper, the flooding algorithm was used to deliver packets to mobile nodes within a specific area (geocast area). With the use of the forwarding zone concept, geocast packets are forwarded by a smaller set of nodes as compared to just geocast flooding.

Recently, the use of geographic position as a means of routing has become increasingly popular in mobile, ad-hoc networks. In [59] the authors, based upon ZRP (Zone Routing Protocol) [29] scheme and the GPS query optimization mechanism, have proposed a routing mechanism with the objective to reduce the number of the route queries within the ZRP protocol. This scheme (GZRP) examines an adaptation of the reactive part of ZRP and uses the position of neighboring mobile nodes, thereby taking advantage of the Global Positioning System (GPS) within the ZRP protocol. In [60] a routing protocol that combines the advantages of reactive protocols, such as the Dynamic Source Routing (DSR) protocol [31][61], with the improved performance that can be achieved by the location based solutions to reduce delay, bandwidth and energy, is provided and evaluated.

In [62] a mechanism for the efficient dissemination of geographic position information in ad-hoc networks, is presented. The basic principles of this scheme is that each node should adapt its own dissemination frequency locally, according to its own mobility rate, and that the greater the distance separating two nodes, the slower they appear to be moving with respect to each other. Thus, nodes that are far apart, need to update each other's position less frequently than nodes closer together. Based on this dissemination concept several multipoint communication protocols for mobile ad-hoc wireless networks have been proposed in the literature [e.g. [63] and [64]].

In [64] a simulation based detailed performance evaluation that compares various characteristics, such as throughput, end-to-end delay and overhead of several on-demand routing protocols for mobile ad-hoc networks is presented. Furthermore, [65][66] considered and studied the problem of congestion control in mobile ad-hoc networks, with the objective of reducing dynamically the amount of traffic routed through a node which is temporarily congested.

In general, geomulticast combines geocast and multicast for dynamic message delivery to a specific group within a geomulticast zone. If a specific geographic zone is very large and there are many different kind of groups within this zone, it does not need to broadcast to all nodes within the specific zone. In this chapter, several geomulticast zone formulation methods are introduced that range from simple specific techniques (i.e. circle with given radius) to the most general case where the zone is formulated arbitrarily. In general, a geomulticast zone is represented by some closed n-sided polygon, where each vertex of each polygon is represented using GPS coordinates. The general zone formulation method may involve high overhead if the target area (geomulticast zone) is very complicated. Therefore, several approximation methods for geomulticast zone representation are used to reduce routing overhead. For the implementation of an efficient geomulticast strategy to support location-dependent services, the mapping of the boundaries of the specific area to the mobile nodes within this area is required. In mobile cellular networks, the mapping is obtained in a cost effective and timely manner using the given cellular structure. In mobile ad-hoc wireless networks, there are no fixed base stations. However, we may extend this concept to ad-hoc networks if we use clustering techniques to cluster the various mobile nodes.

In this chapter, the mobility based clustering (MBC) approach that was proposed and evaluated in Chapter 2 is used, as the underlying structure to facilitate the support of geomulticast services in a similar manner with the cellular networks. Using this structure as the basis, a direction guided routing (DGR) protocol which creates cluster-head based limited mesh structure within a guided region is proposed. The objective of the DGR is to deliver packets with reliability and reduced overhead. Two geomulticast membership management strategies which depend on geolocation storage position are presented and investigated. The first strategy is used to reduce the delivery error while the second one aims to minimize the delay. Moreover, a framework is defined and formulated in order to evaluate the performance of the design alternatives used for the support of geomulticast services in mobile ad-hoc networks. Based on this framework, the performance of the proposed architectures and protocols are evaluated, and via a numerical study some insight is gained about the impact of the various design parameters and operational characteristics, on the system performance.

The remaining of the chapter is organized as follows. Section 5.2 describes in detail the proposed architectures and protocols for supporting geomulticast services. In section 5.3, the performance analysis framework used to evaluate geomulticast architectures and protocols is provided. Section 5.4 presents the corresponding numerical results and some discussion, while section 5.5 concludes this chapter.

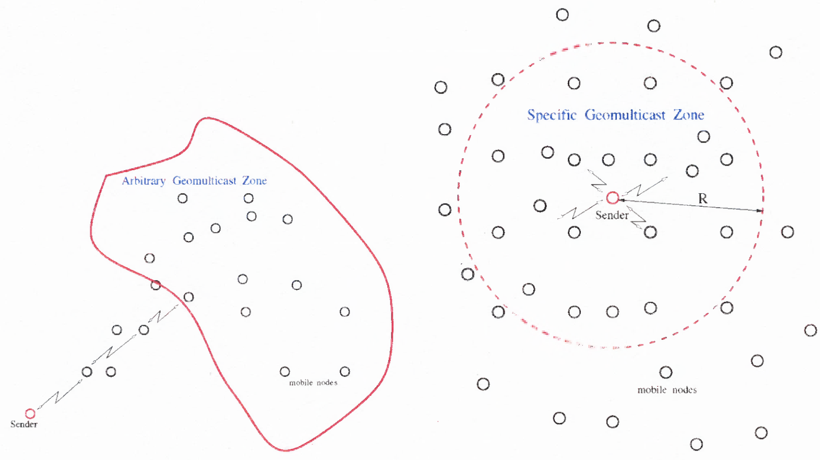
5.2 Architectures and Protocols for Geomulticast

In the following section, the proposed architecture for supporting cost-effective geographic message services to special user groups is presented in mobile ad-hoc wireless networks. Since bandwidth and energy limitations are very critical issues in mobile ad-hoc wireless networks, the proposed architectures (mechanisms) place special emphasis on their efficiency. The main questions and issues that are addressed in such an architecture include the following: i) How do we formulate the target area? ii) How do we efficiently represent the target area? and iii) What is the mechanism to efficiently send a message to the target area in order to minimize the overhead and wasted bandwidth?

5.2.1 Geomulticast Zone Formulation and Representation

To support geomulticast, it is first needed to define the geomulticast zone formulation method. In this chapter, several methods that range from simple specific zone formulation techniques (i.e. circle with given radius) to the most general case are considered where the zone is formulated arbitrarily (Figure 5.1). Here it is assumed that the service is of local interest. For example, it is likely that the group of interest would include people within close proximity of a particular area. In a military scenario, a brigade commander may wish to know which ground troops have penetrated a certain area. The boundaries of the geomulticast zone are simply presented by the zone representation methods described in the following and sent along with the geomulticast join request. In specific cases, the sender could be a mobile node that wishes to reach other mobile nodes around it, within a given radius. In this case, the geomulticast zone, is a circle of given radius around the sender. Examples may include finding soldiers or police groups within given distance around the sender.

Generally, geomulticast zones can be represented by a n-sided polygon (Figure 5.2) specified by the GPS coordinates of the corresponding n points (vertices) (x_1, y_1) ,..., (x_n, y_n), where line segments connect points (x_{i-1}, y_{i-1}) and (x_i, y_i), $i = 1$,..., n. A sender would send a message to mobile nodes within the specified geographical



(a) Arbitrary zone formulation

(b) A specific zone formulation

Figure 5.1 Geomulticast zone formulation.

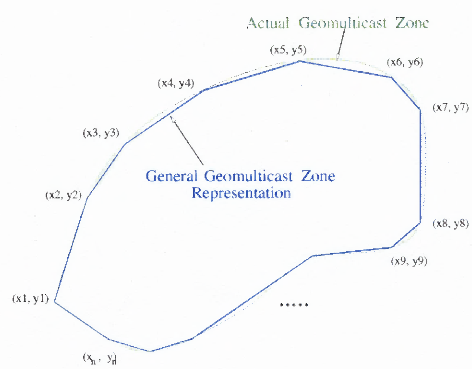


Figure 5.2 General geomulticast zone representation.

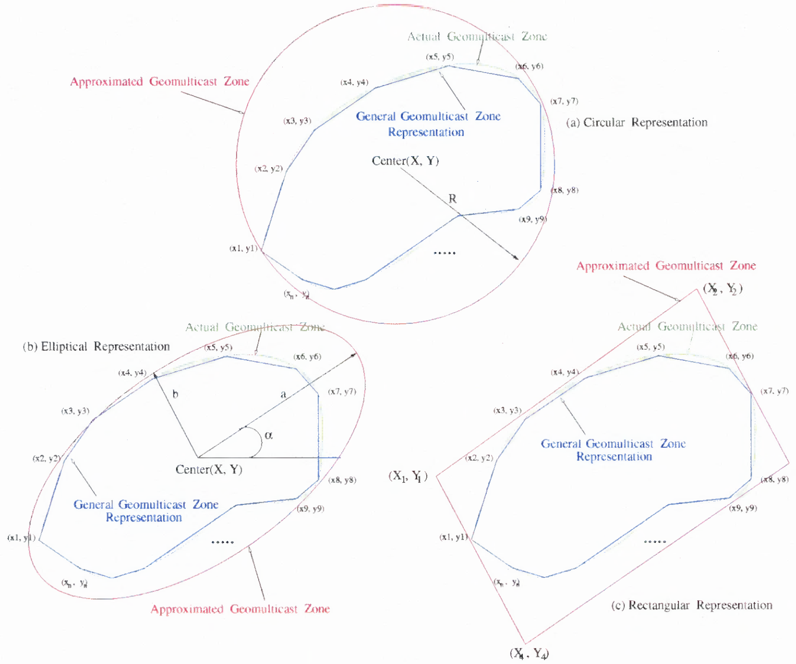


Figure 5.3 Geomulticast zone representations.

area (geomulticast zone) defined by the closed polygon. However, this general zone formulation method may involve high overhead if the target area (geomulticast zone) is very complicated. Therefore, several approximation methods are used for geomulticast zone representation to reduce routing overload, as follows: circular representation, elliptical representation, and rectangular representation. Figure 5.3 provides a graphical illustration of these representation methods. The choice of the appropriate representation method may depend on the actual application and desired accuracy. Circular Representation is the simplest method. Only the center (x, y) position and radius are needed for geomulticast zone representation. However, large unnecessary additional regions may be included into the geomulticast zone. The Elliptical Representation method requires the center(x, y) position, length(a), height(b), and the slope angle α. If a is equal to b, this method is the same as circular representation method. Arbitrary parks and battle fields can be represented by this method. Finally the Rectangular Representation needs four position information: (x_1, y_1), (x_2, y_2), (x_3, y_3) and (x_4, y_4). This method for example can be applied when the target area (geomulticast zone) is a highway.

5.2.2 Network Structure and Components

Figure 5.4 presents a high level description of the proposed network architecture for supporting geomulticast in mobile ad-hoc wireless networks. As mentioned above, the key idea of the proposed network structure is the extension of cellular network concepts into mobile ad-hoc wireless networks to support geomulticast services in a stable and cost-effective way [67]. Our network structure for supporting geomulticast services consists of the following elements and components: Geomulticast Control Office (GeoCO), clusterheads (CHs), mobile nodes (MNs). The functions performed by CH and GeoCO are similar to those performed by BS (base station) and MSC (mobile switching center) respectively in cellular networks. In our structure the source clusterhead (CH) plays the role of GeoCO. The main function of GeoCO is the membership management (i.e. geomulticast group construction and maintenance).

In the following section, some parameters that is will be used throughout the remaining of the chapter are defined. A geomulticast zone as defined before represents a geographical area that includes a set of mobile nodes S_1 whose members may or may not be members of the specific geomulticast group under consideration. The geomulticast group defines a subset K of nodes that belong to set S_1, that have the same geomulticast ID. Moreover, let us denote by M_1 the set of clusterheads that serve any part of a specific geomulticast zone, by M_2 the set of clusterheads that serve any part of a specific geomulticast zone with geomulticast member mobile nodes, and by N the set of all active mobile nodes that are served by the the M_1 CHs

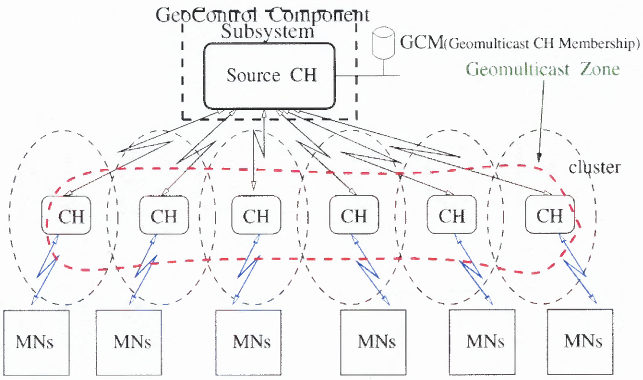


Figure 5.4 Network architecture for supporting geomulticast.

(i.e. all mobile nodes, either inside or outside the geomulticast zone). Furthermore, let us define by $d(S_1)$, $d(M_1)$, $d(M_2)$, $d(N)$, and $d(K)$ the degree (cardinality) of sets S_1, M_1, M_2, N and K respectively. It should be noted here that the actual relations among the cardinalities of the above sets depend on the topology and distribution of nodes in the network. For instance there may be cases where nodes that belong to set N do not belong to set S_1 (they are outside the geomulticast zone while they are served by CHs that serve some part of a specific geomulticast zone), while there may be cases where all the nodes that belong to set N belong to set S_1 as well. The corresponding relations are depicted in Figure 5.5 for a specific geomulticast scenario. The same reasoning can apply to the other parameters as well. However, the following relations are always true: $d(M_1) \geq d(M_2) \geq 0$, and $d(N) \geq d(K) \geq 0$.

5.2.3 Underlying Structure

For the implementation of an efficient geomulticast strategy to support location-dependent services, the mapping of the boundaries of the specific area to the mobile nodes within this area is required. To achieve this in mobile ad-hoc wireless networks

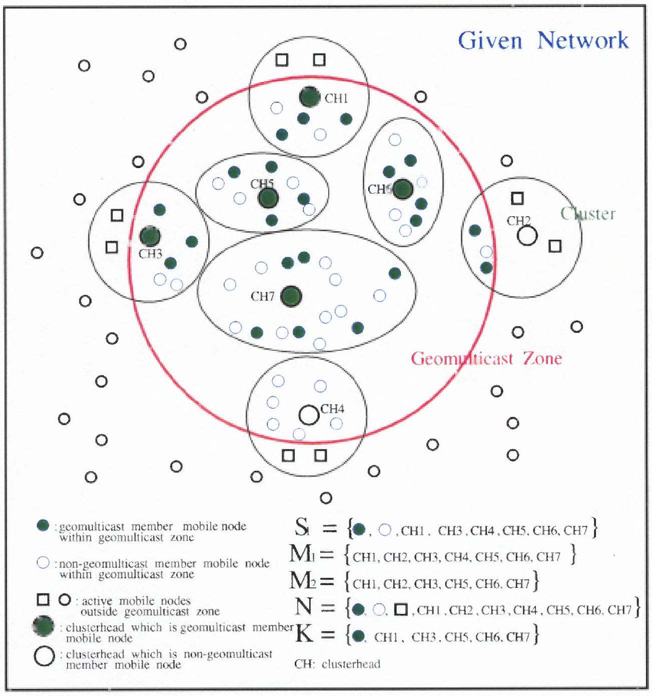


Figure 5.5 Geomulticast scenario example.

where no infrastructure exists, clustering techniques is used to initially cluster the various mobile nodes. As mentioned before, the clustering approach used in this chapter, namely the Mobility Based Clustering (MBC) is based on mobility concepts (individual mobility, group mobility) [32] and the availability of position information via a reliable position locating system (i.e. GPS). It uses combination of both physical and logical partitions of the network (i.e. geographic proximity and functional relation between nodes, such as mobility pattern etc.), as well as the concept of relative mobility to characterize the degree of mobility of a node with respect to its peers, without the need of an underlying unicast routing protocol.

5.2.4 Direction Guided Routing

In this section, a direction guided routing (DGR) protocol which creates cluster-head based limited mesh structure within a guided region is proposed. This guided region can be adjusted based on the network stability and specifications. The objective of the DGR is to deliver packets with reliability and reduced overhead (i.e., limited mesh structure using position information). Figure 5.6 depicts the mesh route structure and the route search operation. In the following section, the detailed steps of the proposed algorithm are described.

Step 1: Sender(source) specifies(formulates and represents) the geomulticast zone and calculates the distance(L_0) between the source (x_s, y_s) and the center point(x_c, y_c) of the geomulticast zone. Next the sender transmits the geomulticast messages to the clusterhead(CH) via next node, where the message packet header holds the geomulticast zone boundary information, and next node-id information can be obtained from the underlying structure (i.e., MBC).

Step 2: When the source CH receives the geomulticast message, the Source CH generates a GeoJOIN REQUEST message and advertises it to its neighbor CHs by Boundarycast and BoundaryCrosscast operations [29]. The GeoJOIN REQUEST consists of geomulticast zone boundary information, geomulticast group ID the node wishes to join, the source node ID, and source CH ID. Boundarycast is used to facilitate the forwarding of GeoJOIN REQUEST within a cluster. Each CH sends GeoJOIN REQUEST only to its boundary nodes to limit the propagation. Boundary node information can be obtained from the proposed underlying clustering structure (i.e., MBC) and is proactively maintained within each CH. When a boundary node receives a GeoJOIN REQUEST from the CH, the boundary node executes the Boundarycast operation. BoundaryCrosscast is used for routing between clusters and each boundary node sends the GeoJOIN REQUEST message to only its neighbor boundary nodes (limited search) within its neighbor clusters.

Step 3: When a node (non-CH node) receives a GeoJOIN REQUEST message, first it checks whether it is inside or outside the geomulticast zone by comparing (mapping) the geomulticast zone's boundary information in the message header with its position information. If it is inside the geomulticast zone, the node accepts the GeoJOIN REQUEST message and sends the message to the CH. If it is outside of geomulticast zone, it calculates the distance(d_i) from its current position(x_i, y_i) to the geomulticast zone center (x_c, y_c) and the distance(d_s) from its current position(x_i, y_i) to the sender(source)(x_s, y_s). The node accepts the GeoJOIN REQUEST and sends the message to the CH if all the following three conditions are satisfied: i)$d_i < d_{i-1}$, ii)$d_i < L_0$, iii)$(d_s + d_i) < D_{th}$, where d_i and d_{i-1} are the distances from node's current position(x_i, y_i) and previous position(x_{i-1}, y_{i-1}) to the geomulticast zone center(x_c, y_c) respectively. If any of the above conditions are not satisfied, the node rejects the GeoJOIN REQUEST message. The objective of the use of threshold D_{th} is to reduce the overhead associated with the route discovery process by limiting the region that is involved with the propagation of the related messages. It should be noted that the choice of D_{th} depends on the network stability and mobility, as well as on the trade off between the breadth and the overhead of the route discovery/search process.

Step 4: When a CH receives the GeoJOIN REQUEST, the CH stores the upstream (to source CH) CH ID in the CH table and checks the geomulticast membership information. In the next section, we present two membership management strategies for supporting geomulticast services. There are two operations in step 4. First, if there are geomulticast memberships, it replies with GeoJOIN REPLY to its upstream (to source CH) CHs using CH table information. When each CH receives GeoJOIN REPLY message, the CH stores the downstream (to geomulticast zone) CH ID. When the source CH (i.e., GeoCO) receives the GeoJOIN REPLY message, the first operation is completed. In the second operation, the CH forwards the GeoJOIN REQUEST to its neighbor CHs by using step 2 and step 3 while there are neighbor CHs.

Step 5: While the source CH holds the GeoJOIN REPLY message during a specified time interval, the CH transmits the geomulticast packets over the mesh routes to the geomulticast members within the geomulticast zone.

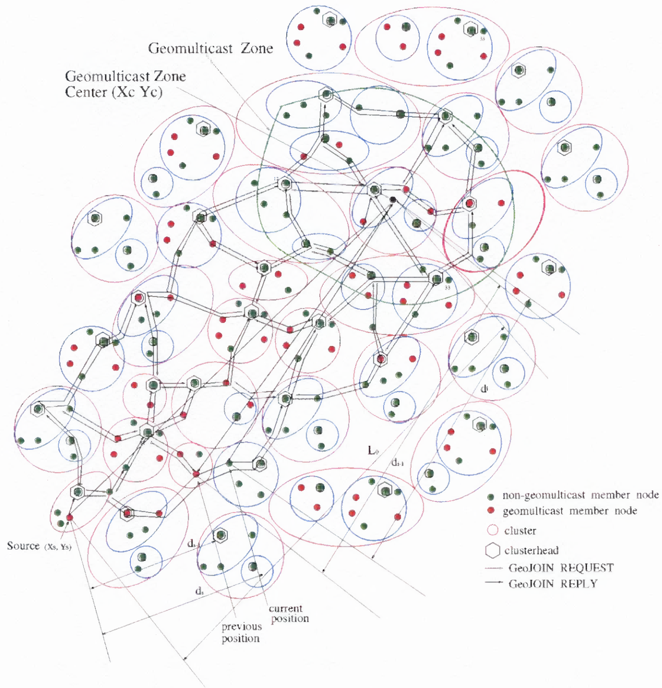
5.2.5 Geomulticast Group Construction and Maintenance

In this section, two geomulticast membership management strategies which depend on the geolocation storage position are presented and discussed. In the first strategy, each mobile node holds its geolocation information via GPS while in the second strategy each CH holds geolocation information of all its members. In the following we present the main operational steps for each strategy.

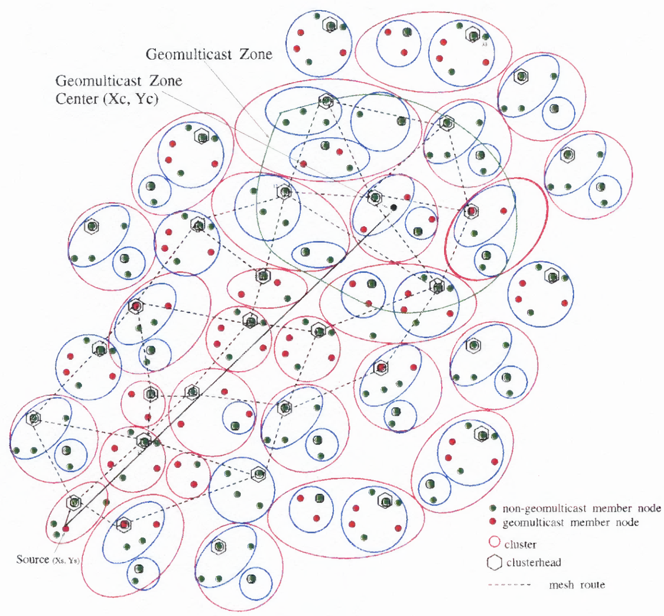
Strategy 1

Step 1: When a CH receives a GeoJOIN REQUEST, the CH simply relays this information to all the MNs in its respective service area.

Step 2: The MNs compare their geolocation with the geomulticast zone boundaries included in the GeoJOIN REQUEST message and decide whether they are inside or



(a) Route search operation



(b) Mesh route structure

Figure 5.6 Direction guided routing (DGR).

outside the geomulticast zone.

Step 3: If a MN decides that it is inside the geomulticast zone and has the geomulticast group ID, then it returns a positive response to the CH, where geomulticast ID is generated and transmitted from source CH and is used to identify a specific multicast group. Please see step 2 in Direction Guided Routing.

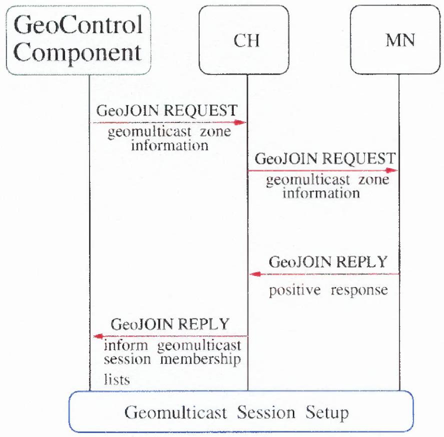
Step 4: The CH checks the geomulticast memberships periodically. If there are geomulticast memberships, it replies with GeoJOIN REPLY message to the GeoCO (its source CH) using CH table information.

Figure 5.7 (a) describes the signal flow of geomulticast membership management strategy 1. Following the notation introduced in subsection 3.2.2 the number of messages, in worst case, transmitted across the network under this strategy is: $((d(N) + d(K)) + d(M_1) + d(M_2))$. If we denote by λ the arrival rate of geomulticast sessions then the signaling load per time unit due to geomulicast in the network is: $\lambda((d(N) + d(K)) + d(M_1) + d(M_2))$.

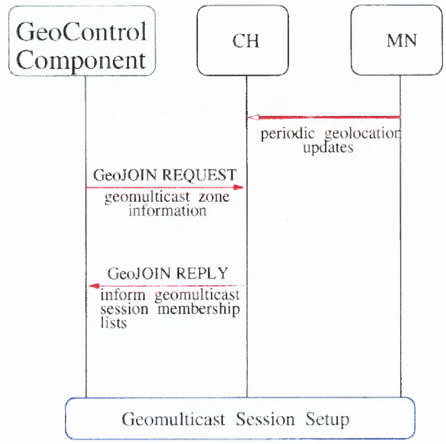
Strategy 2

Step 1: Each MN periodically updates with its geolocation the CH that belongs to.

Step 2: CHs maintain a table of the geolocations for the mobile nodes currently within their respective clusters.



(a) Strategy 1



(b) Strategy 2

Figure 5.7 Signal flows for geomulticast group construction and management.

Step 3: When a CH receives a GeoJOIN REQUEST, the CH compares the geomulticast zone boundary information with the geolocation information of its members and checks the geomulticast ID.

Step 4: If there are geomulticast memberships in the CH, it replies with GeoJOIN REPLY message to the GeoCO (its source CH) using CH table information.

The main objective of strategy 2 is to reduce the delay during the geomulticast session setup process. When a geomulticast session arrives, the most recent geolocation updates from all mobiles are used to decide about the geomulticast group membership. The number of messages transmitted across the network, when a geomulticast session arrives is: $(d(M_1) + d(M_2))$, and therefore the signaling load per time unit due to geomulticast is: $\lambda(d(M_1) + d(M_2))$. However, in this signaling load we need to add the signaling load that results from the periodic updates of the geolocation information that each mobile node generates. This additional load depends on the update time interval, and can be immense with increasing number of mobiles and decreasing update intervals. It should be noted here that there is a trade off between the signaling load and the probability of error in the geomulticast group membership. This trade off, which is closely related to the periodic update interval, is discussed and studied in more detail in the following sections. If it is denoted by L the set that represents all the active mobile nodes in the network, by $d(L)$ the cardinality of set L, and by α the rate at which geolocation updates are generated by a mobile node (e.g. updates per time unit) the signaling load due to geomulticast session setup is: $\lambda(d(M_1) + d(M_2)) + \alpha d(L)$. Figure 5.7 (b) describes the signal flow of geomulticast membership management strategy 2.

5.3 A Framework for Performance Analysis and Evaluation

In this section, a framework is defined and formulated in order to evaluate the performance of the design alternatives, algorithms and implementations used for geomulticast services in mobile ad-hoc wireless networks. Since one of the main objectives of the efforts is to design architectures that support geomulticast services with high delivery accuracy in the following subsection, the probability of geomulticasting error (GeoError), P_{ge}, and the Accuracy of Geomulticast Packet Delivery (AGPD) are introduced and defined as performance measures.

The probability of GeoError P_{ge}, (Figure 5.8), P_{ge}, refers to the probability of occurrence of either of the following events: a) a mobile that is inside the geomulticast zone does not receive the geomulticast message for some time, and b)a mobile that is not in the geomulticast zone does receive the geomulticast message for some time. Let us denote by τ the geolocation update time interval and by T_e the GeoError time interval for a specific mobile due to either one of the two events described above (see figure 5.8). The first event may occur when a mobile that was initially (e.g. at time $t = 0$) outside the geomulticast zone and therefore the CH has identified it as a non-member of the geomulticast group during the membership identification process, has moved in the meantime inside the geomulticast zone (e.g. after some time T_g), however has not yet updated its CH with its new geolocation position (i.e. before the new geolocation update point $t = \tau$, which means before the expiration of the update time interval τ). In this case for some time interval T_e the mobile node will not be receiving the geomulticast messages, although during this time interval it is within the geomulticast zone and intends to be member of the geomulticast group.

The mobile node will become a member of the intended geomulticast group and will start receiving the corresponding messages at the next geolocation update point. Similarly, the second event may occur when a mobile node that was initially (e.g. at time $t = 0$) inside the geomulticast zone and its CH has identified it as a member of the geomulticast group during the membership identification process, has moved in the meantime outside the geomulticast zone (e.g. after some time T_g), however has not yet updated its CH with its new geolocation position (i.e. before the new geolocation update point $t = \tau$, which means before the expiration of the update time interval τ). In this case for some time interval T_e, the mobile node will continue to receive the geomulticast messages, although it is outside the geomulticast zone and is not supposed to be member of the geomulticast group.

From the above discussion, it is obvious that the rate of geomulticast zone boundary crossing, λ_c, before the geomulticast membership list is updated is one of the most significant contributors to the total probability of GeoError, especially when the geomulticast membership decision is made at the network level, where the mobiles need to send periodic updates of their geolocation to the clusterhead (i.e.

strategy 2). Overall the geomulticast error probability depends on the packet to mobility ratio, i.e. how often a user receives a packet and how mobile the node is, as well as on the geolocation update time interval. Optimization of location update mechanism and interval has been a subject of intense research in the framework of cellular networks mainly for location management [68][69][70][71][72]. In general, there is a strong and complicated relation between the update interval and other system and traffic parameters. Here, a framework is developed in order to evaluate the effects and associated trade offs, and some insight is gained about the optimum location update interval through a numerical study.

Specifically, the effect of the mobile node geolocation periodic update interval on the packet delivery accuracy and the associated overhead (signaling load) is studied. As this update interval decreases, the probability of geomulticast error decreases as well at the cost of increased signaling traffic and processing in order to maintain accurate mobile node position information at the CH, propagate the updated information from each individual node to the clusterhead(CH), and compare (map) this position to the geomulticat zone boundary information.

5.3.1 The Model

For the purposes of the performance evaluation, in this work the movement of the mobile nodes is modeled by a random and uniform model ([72][73][74]). This model assumes that the mobile nodes move with constant velocity during time interval τ in a random direction θ that is uniformly distributed in $[0, 2\pi]$. Considering a geomulticast area with perimeter S where ρ mobile terminals per unit area are located the rate of geomulticast zone boundary crossing per unit time (average number of mobile nodes crossing the area border per unit of time), denoted by λ_c is [72][73]:

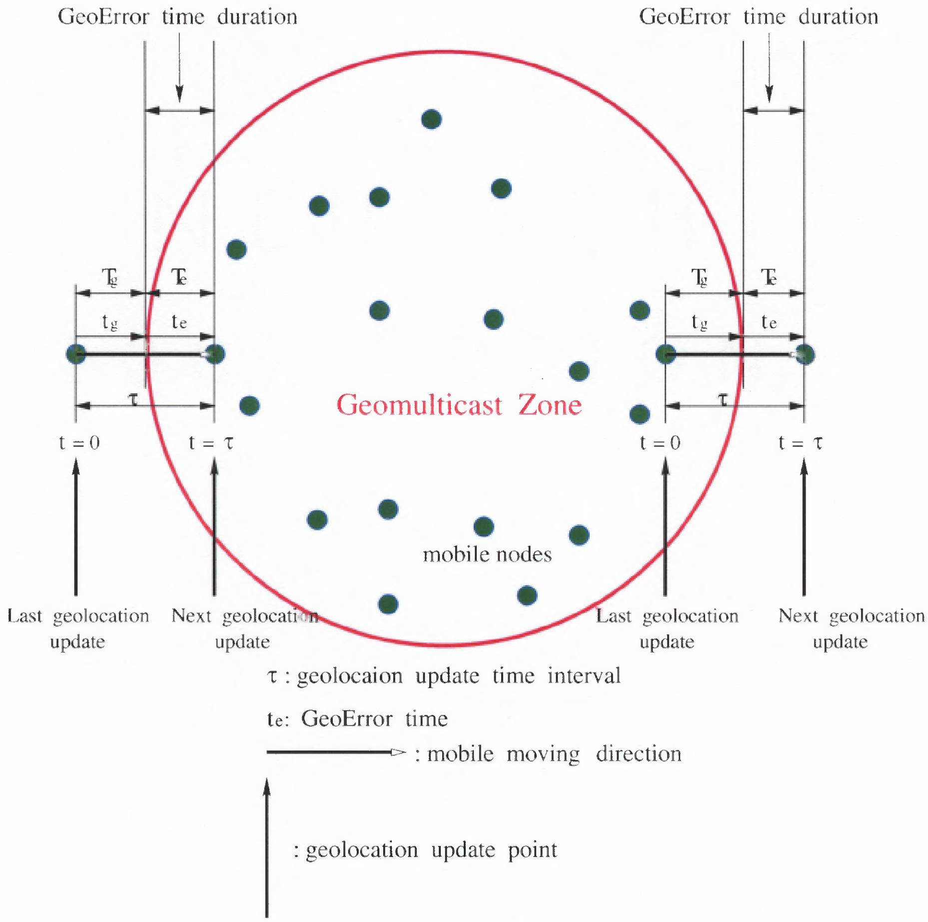


Figure 5.8 The model.

$$\lambda_c = \frac{\rho V S \beta}{\pi} \tag{5.1}$$

where β denotes the activity ratio of mobiles (in the following without loss of generality we may assume $\beta = 1$), and V is the average mobile node velocity. For example, if the geomulticast zone is represented by a circle with radius R then $\lambda_c = 2\rho VR$. In general λ_c depends on the actual size of the geomulticast zone, the network density, and the mobility pattern of the mobile nodes (e.g. velocity).

It is assumed that the number of messages that arrive at a mobile node during a time t is a Poisson random variable with rate λ_a. Moreover, let us denote by t_e the random variable that represents the GeoError time interval (i.e. the time between the point that a mobile is erroneously considered (or not considered) member of the geomulticast session due to the two events described before, and the point until the next position update). Assuming that the interval between two boundary crossing of a mobile is much longer than τ, which should be case in any practical system, then it is proved that t_e has a uniform distribution in interval $[0, \tau]$. That is the density function $f_e(t_e)$ of t_e is:

$$f_e(t_e) = \begin{cases} \frac{1}{\tau} & 0 \leq t_e \leq \tau \\ 0 & t_e \geq \tau \end{cases} \tag{5.2}$$

In the following, the derivation of the density function $f_e(t_e)$ of t_e is in detail presented. Suppose that a mobile node resides in a geomulticast zone for a period t_s and $E[t_s] = \frac{1}{\mu}$, where let μ be the mobility of a mobile node(i.e., the rate that the mobile node leaves a geomulticast zone). In other words, $\frac{1}{\mu}$ is the expected residual time of the mobile node in a geomulticast zone. Figure 5.9 presents the time diagram for geomulticast services. In the following, some preliminary results that will be used throughout the proof of the claim that t_e has an uniform distribution (e.g., relation (5.2)) are first obtained.

Let's consider Figure 5.9 and f_s be the density function of the traveling time of a mobile node in geomulticast zone. The relationship between t_s and t_e is

$$t_s = (i+1)\tau - t_e \quad for \quad some \quad i \geq 0 \tag{5.3}$$

Thus, the density function f_e for t_e is

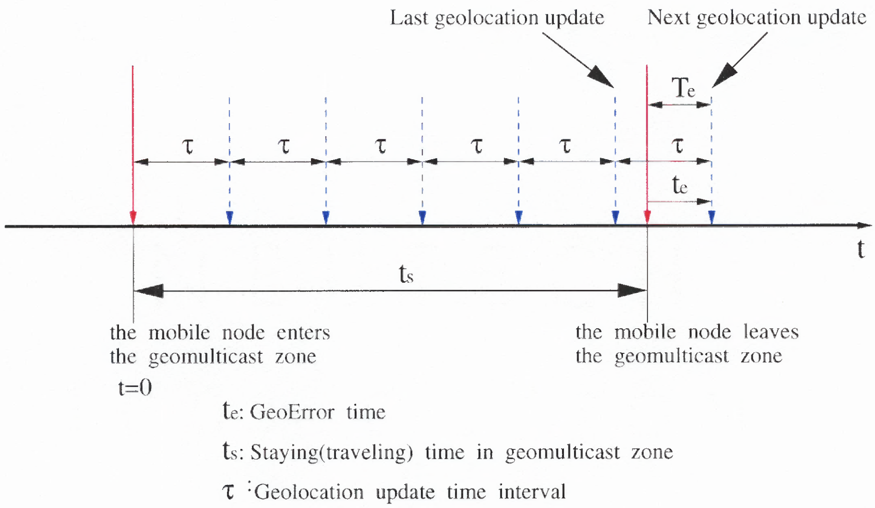


Figure 5.9 The time diagram for geomulticast services.

$$f_e(t_e) = \sum_{i=0}^{\infty} f_s((i+1)\tau - t_e) \tag{5.4}$$

Since the message arrivals forms a Poisson Process with rate λ_a and because of the excess life property[75] of the exponential distribution, the probability of n message arrival[76][77] during the time period t_e is

$$P[n = k | T_e = t_e] = \frac{e^{-\lambda_a t_e}(\lambda_a t_e)^k}{k!} \tag{5.5}$$

Let u be the probability that there are message arrivals during the time duration T_e. The probability $u^* = 1 - u$ that no message arrives during T_e is

$$\begin{aligned} u^* &= \int_{t_e=0}^{\tau} P[n = 0|T_e = t_e] f_e(t_e) dt_e && (5.6) \\ &= \int_{t_e=0}^{\tau} [\sum_{i=0}^{\infty} f_s((i+1)\tau - t_e)] e^{-\lambda_a t_e} dt_e && (5.7) \end{aligned}$$

Let $q = (i+1)\tau - t_e$, then equation (5.7) is rewritten as

$$u^* = \sum_{i=0}^{\infty} \int_{q=(i+1)\tau}^{i\tau} f_s(q) e^{-\lambda_a((i+1)\tau - q)} d((i+1)\tau - q) \tag{5.8}$$

$$= \sum_{i=0}^{\infty} e^{-(i+1)\lambda_a \tau} \int_{q=i\tau}^{(i+1)\tau} f_s(q) e^{\lambda_a q} dq \tag{5.9}$$

In the following, it is considered that the residual time in a geomulticast zone can be represented by Gamma distribution. Depending upon the values of the associated parameters, it can be shaped to represent many distributions as well as measured data. For example, one may measure the mobile residual time in geomulticast zone in a real network, and the measured data can be approximated by a Gamma distribution as the input to the model. If $f_s(t)$ is a Gamma density function $f_{\gamma,\eta}(\mathrm{t})$ with the shape parameter γ and the scale parameter η [78], then $f_s(t) = f_{\gamma,\eta}(t)$ and the distribution function $F_s(t) = F_{\gamma,\eta}(t) = \int_{q=0}^{t} f_{\gamma,\eta}(q)dq$. Equation (5.9) is rewritten as

$$u^* = \sum_{i=0}^{\infty} e^{-(i+1)\lambda_a \tau} \int_{q=i\tau}^{(i+1)\tau} \frac{\eta^{\gamma} q^{(\gamma-1)} e^{-\eta q}}{\Gamma(\gamma)} e^{\lambda_a q} dq \tag{5.10}$$

$$= \sum_{i=0}^{\infty} e^{-(i+1)\lambda_a \tau} (\frac{\eta}{\eta - \lambda_a})^{\gamma} \int_{q=i\tau}^{(i+1)\tau} \frac{(\eta - \lambda_a)^{\gamma} q^{(\gamma-1)} e^{-(\eta-\lambda_a)q}}{\Gamma(\gamma)} dq \tag{5.11}$$

$$= \sum_{i=0}^{\infty} e^{-(i+1)\lambda_a \tau} (\frac{\eta}{\eta - \lambda_a})^{\gamma} [F_{\gamma,\eta-\lambda_a}((i+1)\tau) - F_{\gamma,\eta-\lambda_a}(i\tau)] \tag{5.12}$$

The values of $F_{\gamma,\eta-\lambda_a}(i\tau)$ and $F_{\gamma,\eta-\lambda_a}((i+1)\tau))$ can be obtained from the Gamma distribution function table [78]. If γ is a nonnegative integer, then from [79]

$$F_{\gamma,\eta-\lambda_a}(t) = 1 - \sum_{j=0}^{\gamma-1} \frac{[(\eta - \lambda_a)t]^j}{j!} e^{-(\eta-\lambda_a)t} \tag{5.13}$$

Equation (5.12) is rewritten as

$$
\begin{aligned}
u^* &= (\frac{\eta}{\eta-\lambda_a})^\gamma \sum_{i=0}^{\infty} e^{-(i+1)\lambda_a\tau}[\sum_{j=0}^{\gamma-1}\frac{[(\eta-\lambda_a)i\tau]^j}{j!}e^{-(\eta-\lambda_a)i\tau} \\
&\quad -\sum_{j=0}^{\gamma-1}\frac{[(\eta-\lambda_a)(i+1)\tau]^j}{j!}e^{-(\eta-\lambda_a)(i+1)\tau}] \qquad (5.14)\\
&= (\frac{\eta}{\eta-\lambda_a})^\gamma(\sum_{j=0}^{\gamma-1}\frac{[(\eta-\lambda_a)\tau]^j}{j!} \\
&\quad \times(\sum_{i=0}^{\infty} e^{-(i+1)\lambda_a\tau}[i^j e^{-(\eta-\lambda_a)i\tau}-(i+1)^j e^{-(\eta-\lambda_a)(i+1)\tau}])) \qquad (5.15)\\
&= (\frac{\eta}{\eta-\lambda_a})^\gamma(\sum_{j=0}^{\gamma-1}\frac{[(\eta-\lambda_a)\tau]^j}{j!} \\
&\quad \times[\sum_{i=0}^{\infty} i^j e^{-i\eta\tau}e^{-\lambda_a\tau}-\sum_{i=0}^{\infty}(i+1)^j e^{-(i+1)\eta\tau}]) \qquad (5.16)\\
&= (\frac{\eta}{\eta-\lambda_a})^\gamma(\frac{e^{-\lambda_a\tau}-e^{-\eta\tau}}{1-e^{-\eta\tau}}+\sum_{j=1}^{\gamma-1}\frac{[(\eta-\lambda_a)\tau]^j}{j!} \\
&\quad \times[\sum_{i=0}^{\infty} i^j e^{-i\eta\tau}e^{-\lambda_a\tau}-\sum_{i=0}^{\infty}(i+1)^j e^{-(i+1)\eta\tau}]) \qquad (5.17)\\
&= (\frac{\eta}{\eta-\lambda_a})^\gamma(\frac{e^{-\lambda_a\tau}-e^{-\eta\tau}}{1-e^{-\eta\tau}}+(e^{-\lambda_a\tau}-1) \\
&\quad \times[\sum_{j=1}^{\gamma-1}\frac{[(\eta-\lambda_a)\tau]^j}{j!}(\sum_{i=1}^{\infty} i^j e^{-i\eta\tau})]) \qquad (5.18)
\end{aligned}
$$

Note that $\sum_{i=1}^{\infty} i^j e^{-i\eta\tau} = (\frac{e^{-\eta\tau}}{1-e^{-\eta\tau}})\sum_{i=1}^{\infty} i^j(1-e^{-\eta\tau})(e^{-\eta\tau})^{i-1}$, where the summation term in the right-hand side is the j^{th} moment of the Geometric distribution with probability function $P_k = (1-e^{-\eta\tau})(e^{-\eta\tau})^{i-1}$ for $i \geq 1$ and the moment generating function

$$
\Phi(s) = \frac{1-e^{-\eta\tau}}{e^{-s}-e^{-\eta\tau}} \qquad (5.19)
$$

The j^{th} moment of the geometric distribution can be obtained by differentiating equation (5.19) j times with $s = 0$. Thus equation (5.18) is rewritten as

$$
\begin{aligned}
u &= 1-(\frac{\eta}{\eta-\lambda_a})^{\gamma}(\frac{e^{-\lambda_a\tau}-e^{-\eta\tau}}{1-e^{-\eta\tau}}+(e^{-\lambda_a\tau}-1) \\
&\quad \times(\sum_{j=0}^{\gamma-1}(\frac{e^{-\eta\tau}[(\eta-\lambda_a)\tau]^j}{j!(1-e^{-\eta\tau})}[\frac{d^j\Phi(s)}{ds^j}|_{s=0}]))) \qquad (5.20)\\
&= 1-(\frac{\eta}{\eta-\lambda_a})^{\gamma}(\frac{e^{-\lambda_a\tau}-e^{-\eta\tau}}{1-e^{-\eta\tau}}+(e^{-\lambda_a\tau}-1) \\
&\quad \times(\sum_{j=0}^{\gamma-1}(\frac{[(\eta-\lambda_a)\tau]^j}{j!}[\frac{d^j}{ds^j}(\frac{e^{-\eta\tau}}{e^{-s}-e^{-\eta\tau}})|_{s=0}]))) \qquad (5.21)
\end{aligned}
$$

Let's consider the case when the mobile node residual(traveling) time in a geomulticast zone is very long; i.e., $\frac{1}{\mu} \longrightarrow \infty$. From equation (5.21), it is obtained

$$
\lim_{\mu\to 0} u = \lim_{\eta\to 0} u = 1-[u_1+(e^{-\lambda_a\tau}-1)u_2] \qquad (5.22)
$$

where

$$
\begin{aligned}
u_1 &= \lim_{\eta\to 0}(\frac{\eta}{\eta-\lambda_a})^{\gamma}(\frac{e^{-\lambda_a\tau}-e^{-\eta\tau}}{1-e^{-\eta\tau}}) \qquad (5.23)\\
&= \lim_{\eta\to 0}(\frac{\eta}{\eta-\lambda_a})^{\gamma}[\frac{e^{-\lambda_a\tau}-e^{-\eta\tau}}{-\sum_{k=0}^{\infty}(-\eta\tau)^k}] \qquad (5.24)\\
&= \lim_{\eta\to 0}(\frac{1}{\eta-\lambda_a})^{\gamma}[\frac{e^{-\lambda_a\tau}-e^{-\eta\tau}}{-(\frac{1}{\eta^{\gamma}})\sum_{k=0}^{\infty}(-\eta\tau)^k}] \qquad (5.25)\\
&= (-\frac{1}{\lambda_a})^{\gamma}[\frac{1-e^{-\lambda_a\tau}}{\lim_{\eta\to 0}(\frac{\tau}{\eta^{\gamma-1}})}] \qquad (5.26)\\
&= 0 \qquad (5.27)
\end{aligned}
$$

and

$$
\begin{aligned}
u_2 &= \lim_{\eta\to 0}(\frac{\eta}{\eta-\lambda_a})^{\gamma}(\sum_{j=0}^{\gamma-1}\frac{[(\eta-\lambda_a)\tau]^j}{j!}[\frac{d^j}{ds^j}(\frac{e^{-\eta\tau}}{e^{-s}-e^{-\eta\tau}})|_{s=0}]rgroup \qquad (5.28)\\
&= \lim_{\eta\to 0}(\frac{\eta}{\eta-\lambda_a})^{\gamma}(\sum_{j=0}^{\gamma-1}[(\eta-\lambda_a)\tau]^j[\sum_{l=0}^{j}\frac{X_{j,l}e^{-\eta\tau}}{(1-e^{-\eta\tau})^{l+1}}]) \qquad (5.29)
\end{aligned}
$$

where $X_{j,l}$ is a constant with respect to η ($0 \leq l \leq j < \gamma$) and $X_{\gamma-1,\gamma-1}=1$. Equation (5.29) is rewritten as

$$u_2 = \lim_{\eta\to 0}\left(\frac{1}{\eta-\lambda_a}\right)^{\gamma}\left(\sum_{j=0}^{\gamma-1}\left[\frac{\tau^j e^{-\eta\tau}}{(\eta-\lambda_a)^{\gamma-j}}\right]\right.$$
$$\left.\times\left(\sum_{l=0}^{j}\frac{X_{j,l}}{(\frac{1}{\eta^\gamma})[-\sum_{k=1}^{\infty}(-\eta\tau)^k]^{l+1}}\right)\right) \quad (5.30)$$

Note that for $l,j < \gamma$-1, $\lim_{\eta\to 0}\frac{X_{j,l}}{(\frac{1}{\eta^\gamma})[-\sum_{k=1}^{\infty}(-\eta\tau)^k]^{l+1}} = 0$ and equation (5.30) is rewritten as

$$u2 = \lim_{\eta\to 0}\left(\left[\frac{\tau^j e^{-\eta\tau}}{(\eta-\lambda_a)^{\gamma-j}}\right]\right.$$
$$\left.\times\left(\frac{X_{j,j}}{(\frac{1}{\eta^\gamma})[-\sum_{k=1}^{\infty}(-\eta\tau)^k]^{j+1}}\right)\right)\Big|_{j=\gamma-1} \quad (5.31)$$
$$= \left(\frac{\tau^{\gamma-1}}{-\lambda_a}\right)\left[\frac{1}{(\frac{1}{\eta^\gamma})(\eta\tau)^\gamma}\right] \quad (5.32)$$
$$= \frac{1}{-\lambda_a\tau} \quad (5.33)$$

From Equation (5.22), (5.27), and (5.33), it is obtained

$$\lim_{\mu\to 0} u = 1 - \frac{(1-e^{-\lambda_a\tau})}{\lambda_a\tau} \quad (5.34)$$

Suppose that a mobile node resides in a geomulticast zone for a period t_s and $E[t_s] = \frac{1}{\mu}$. In other words, $\frac{1}{\mu}$ is the expected residual time of the mobile node in a geomulticast zone. The number of geolocation update messages sent from mobile node to its clusterhead(CH) is $\lfloor\frac{t_s}{\tau}\rfloor$. Let w be the expected number of geolocation update messages sent during a time unit. Then

$$w = \frac{E[\lfloor\frac{t_s}{\tau}\rfloor]}{E[t_s]} \quad (5.35)$$

$$= \mu \int_{t_s=0}^{\infty} \lfloor \frac{t_s}{\tau} \rfloor f_s(t_s) dt_s \tag{5.36}$$

$$= \mu \sum_{i=0}^{\infty} \int_{q=i\tau}^{(i+1)\tau} f_s(q) dq \tag{5.37}$$

$$= \mu \sum_{i=0}^{\infty} i[F_s((i+1)\tau) - F_s(i\tau)] \tag{5.38}$$

$$= \mu \lim_{i \to \infty} [iF_s((i+1)\tau) - \sum_{j=1}^{i} F_s(i\tau)] \tag{5.39}$$

$$= \mu \sum_{i=0}^{\infty} [1 - F_s(i\tau)] \tag{5.40}$$

If F_s is a Gamma distribution $F_{\tau,\eta}$ with a nonnegative shape parameter γ(where η $= \gamma\mu$), then Equation (5.40) is rewritten as

$$w = \mu \sum_{j=0}^{\gamma-1} \frac{(\gamma\mu\tau)^j}{j!} [\sum_{i=1}^{\infty} i^j e^{-i\gamma\eta\tau}] \tag{5.41}$$

$$= \mu \sum_{j=0}^{\gamma-1} \frac{(\gamma\mu\tau)^j}{j!} [\frac{d^j}{ds^j} (\frac{e^{-\gamma\mu\tau}}{e^{-s} - e^{-\gamma\mu\tau}})|_{s=0}] \tag{5.42}$$

Since

$$\frac{E[\frac{t_s}{\tau}] - \tau}{E[t_s]} \leq w \leq \frac{E[\frac{t_s}{\tau}]}{E[t_s]} \tag{5.43}$$

and

$$\lim_{t_s \to \infty} \frac{E[\frac{t_s}{\tau}] - \tau}{E[t_s]} = \frac{1}{\tau} - \lim_{t_s \to \infty} \frac{\tau}{E[t_s]} = \frac{1}{\tau} \tag{5.44}$$

and

$$\frac{E[\frac{t_s}{\tau}]}{E[t_s]} = \frac{1}{\tau} \tag{5.45}$$

we have

$$\lim_{t_s \to \infty} w = \lim_{\mu \to 0} w = \frac{1}{\tau} \tag{5.46}$$

Based on the above results and observations, it can be easily shown that if the interval between two boundary crossings of a mobile node is much longer that τ, then t_e has an uniform distribution in interval [0, τ]. This statement is proved as follows. If t_e has a uniform distribution, then its density function $f_e(t_e)$ of t_e is:

$$f_e(t_e) = \begin{cases} \frac{1}{\tau} & 0 \le t_e \le \tau \\ 0 & t_e \ge \tau \end{cases} \tag{5.47}$$

For message arrival rate λ_a, the probability that no message arrives during t_e is $e^{-\lambda_a t_e}$ according to equation (5.5), and the probability that a message arrives during the time period t_e is

$$u = 1 - \int_{t_e=0}^{\tau} \frac{1}{\tau} e^{-\lambda_a t_e} dt_e = 1 - \frac{(1 - e^{-\lambda_a \tau})}{\lambda_a \tau} \tag{5.48}$$

Equation (5.48) is the same as (5.34).

The probability of k message arrival[76] during time T_e is

$$\begin{aligned} P_e[n = k] &= \int_0^{\tau} P[n = k | T_e = t] f_e(t) dt && (5.49) \\ &= \int_0^{\tau} \frac{e^{-\lambda_a t} (\lambda_a t)^k}{k!} \frac{1}{\tau} dt && (5.50) \end{aligned}$$

Since as mentioned before t_e follows a uniform distribution between [0, τ], it can be easily shown based on the properties of conditional expectation, $E[error\ \ packet\ \ rate$ $|T_e = t_e] = \lambda_a t_e$, that the average rate of error ($E[error\ \ packet\ \ rate]$) message arrival is

$$\begin{aligned} E[error\ \ packet\ \ rate] &= 2 * \lambda_c * h * \int_0^{\tau} E[error\ \ packet\ \ rate | T_e = t_e] f_e(t_e) dt_e \\ &= 2 * \lambda_c * h * \int_0^{\tau} \lambda_a * t_e * \frac{1}{\tau} dt_e \end{aligned}$$

$$= \quad 2 * \lambda_c * \lambda_a * \frac{\tau}{2} * h \tag{5.51}$$

where it is multiplied by two to account for the two cases of possible errors that may occur and correspond to the occurrence of the two events described in the beginning of section 3, and by h we denote the percentage of the total number of nodes within the zone, that are members of the geomulticast group under consideration (for the special case that all nodes within the zone are geomulticast members it has $h = 1$, otherwise $h < 1$). Then, the probability of GeoError(P_{ge}) can be calculated as follows:

$$P_{ge} = \frac{E[error\ packet\ rate]}{E[desired\ packet\ rate]} \tag{5.52}$$

$$= \frac{2 * \lambda_a * \lambda_c * \frac{\tau}{2} * h}{\lambda_a * B} \tag{5.53}$$

$$= \frac{\lambda_c * \tau * h}{B} \tag{5.54}$$

where B denotes the average number of nodes within the geomulticast zone that are geomulticast members. Based on the model under consideration, the total number of nodes within a zone of area F is given by $\rho * F$, and therefore $h = \frac{B}{\rho * F}$. Substituting this in the previous relation we obtain:

$$P_{ge} = \frac{\lambda_c * \tau}{\rho * F} \tag{5.55}$$

The Accuracy of Geomulticast Packet Delivery(AGPD) can be defined as:

$$AGPD = 1 - P_{ge} \tag{5.56}$$

Of course, one would like to reduce the probability of GeoError and therefore increase the Accuracy of Geomulticast Packet Delivery. When geomulticast management strategy 2 is employed, this could be done by having the mobiles to update their location often (i.e., small τ). However, location updates consume wireless resources and processing power and should not be too frequent. On the other hand as mentioned before, infrequent updates may result in errors in packet delivery. In the following section, a cost function is developed to quantify the trade off between the penalty associated with the occurrence of errors in packet delivery and the associated cost for supporting certain degree of accuracy in the proposed geomulticast architecture. Only the cost is considered directly related to the geomulticast session setup, the update of the geolocation and the loss of packets due to the inaccuracy of position information as a result of the node mobility and the geolocation update time interval, while other cost associated with functions such as cluster construction and maintenance, system maintenance etc., is the same for different cases (depends only on the underlying structure) and is not considered here. Therefore, the following estimated cost contain: the average cost per time unit of geolocation updates, the average cost per time unit of geomulticast session setup and the average error cost (penalty) per time unit, due to the inaccuracy of position information as a result of the node mobility and the geolocation update time interval. Let's denote by c_s the per signal cost for geomulticast session setup, by c_g the cost of a single geolocation update per node, and by C_{error} the GeoError cost per time unit. Then the corresponding average cost per time unit, $Cost_{total}$, is:

$$\begin{aligned} Cost_{total} &= Cost_{setup} + Cost_{geo-update} + Cost_{error} && (5.57) \\ &= c_s * \lambda(d(M_1) + d(M_2)) + c_g * d(L) * a + C_{error} && (5.58) \end{aligned}$$

Let's denote by $c_n, n = 1, 2, ...,$ the cost of loosing n calls. Then the corresponding average GeoError cost per time unit, C_{error} is:

$$C_{error} = 2 * \lambda_c * h * \sum_{n=1}^{\infty} c_n P_e[n] \tag{5.59}$$

For the sake of simplicity in the following, it can be reasonably assumed that the cost of loosing the nth message arrival after geomulticast zone boundary crossing by a mobile node is independent of n. Thus, $\forall n$, $c_n = nc_1$. Consequently:

$$\begin{aligned} C_{error} &= 2 * \lambda_c * h * (c_1 \sum_{n=1}^{\infty} n P_e[n]) && (5.60) \\ &= c_1 * E[error\ packet\ rate] && (5.61) \\ &= c_1 * 2 * \lambda_c * h * \lambda_a * \frac{\tau}{2} && (5.62) \end{aligned}$$

Finally, substituting relation (5.62) in (5.58) we get:

$$Cost_{total} = c_s * \lambda(d(M_1) + d(M_2)) + c_g * d(L) * a + c_1 * \lambda_c * h * \lambda_a * \tau \tag{5.63}$$

5.4 Numerical Study and Discussion

In this section, some numerical results are presented that it is obtained based on the analytical framework it is developed in the previous section, as well as via modeling and simulation using the Optimized Network Engineering Tool (OPNET). The aim of this numerical study is to evaluate the performance of the proposed architectures and obtain some insight about the impact on the overall system performance, of the design parameters, as well as of various operational parameters and characteristics such as mobility, geolocation update rate, geomulticast group size, etc.

5.4.1 Evaluation Framework

A mobile ad-hoc network consisting of 50 mobile nodes that are placed randomly within a rectangular region of 1000 m x 1000 m is modeled for the purposes of this study. The results presented in the following section correspond to the use of circular geomulticast zone with radius R (150 m - 300 m). The mobile nodes are assumed to have constant radio range of Z=300 m. Throughout our study, it is assumed that a link fails, or reappears, as a node goes out or in transmission range of another node, due to the mobility of the nodes. Mobile nodes are assumed to be moving around throughout the network. The speed and the direction of each move are uniformly distributed, with speed range [0, 80 km/h] and direction range $[0, 2\pi]$, respectively. One geomulticast source node (sender) is used while the geomulticast members are selected randomly within the geomulticast zone.

5.4.2 Numerical Results and Discussion

One of the main objectives of this numerical evaluation is to study the accuracy of geomulticast packet delivery. As mentioned before, accuracy of geomulticast packet delivery is defined as the number of geomulticast data packet delivered to multicast receivers over the number of geomulticast data packets supposed to be delivered to multicast receivers. In this numerical study, the performance metrics are studied mainly in two dimensions: mobility and scalability. Since in mobile ad-hoc networks one of the most distinct characteristics is mobility the system's performance is initially evaluated as a function of mobility speed, in order to study and determine its applicability in different networking environments. Moreover, the scalability of the proposed architecture and algorithms by studying the corresponding behavior are investigated as the multicast group size is varied, the multicast zone size and the packet generation rate. Finally, some insight is obtained about the trade-off between the accuracy of the geolocation packet delivery service and the geolocation update interval.

Specifically, Figure 5.10 illustrates the accuracy of geomulticast packet delivery (AGPD) as a function of mobility for packet arrival rate (PAR) 5 packets/sec, geomulticast zone with Radius 250 m and geolocation update time interval $\tau = 1$ sec. As demonstrated in this figure the AGPD shows very good performance even in highly dynamic situations. One of the reasons that contribute to this is that the underlying structure that results from the use of MBC strategy is very stable and the route selection is based on the corresponding created mesh structure. This means that the impact of a link break on protocol's capability of delivering the data to the appropriate destinations is minimal. Similar behavior is observed in Figure 5.11 where the accuracy of geomulticast packet delivery achieved by our architecture is presented as a function of the packet arrival rate for mobility 40 km/hr, geomulticast zone with Radius 250 m and geolocation update time interval $\tau = 1$ sec.

Figures 5.12 and 5.13 demonstrate the scalability property of our protocol. Specifically, Figure 5.12 presents the accuracy of geomulticast packet delivery as a function of the geomulticast zone size (i.e., radius R) for mobility 40 km/hr, PAR 5 packets/sec and geolocation update time interval $\tau = 1$ sec, while Figure 5.13 illustrates the accuracy of geomulticast packet delivery (AGPD) as a function of geomulticast memberships for mobility 40 km/hr, PAR 5 packets/sec and geomulticast zone with Radius 250 m for three different values of τ. As it can be seen from both these figures, the proposed architecture posses the scalability property, since the the accuracy of geomulticast packet delivery ratio remains relatively constant with the change of the geomulticast zone size and the geomulticast group size.

Figure 5.14 presents the accuracy of geomulticast packet delivery (AGPD) as a function of geolocation update time interval (i.e., τ) for mobility 40 km/hr, PAR 5 packets/sec and geomulticast zone with Radius 250 m. From this figure it can be seen that AGPD is decreasing with the increase of τ. However, as it is discussed before, this is accompanied with a decrease in signaling load due to the position update generation process.

Figure 5.15 presents the control overhead for route creation and maintenance associated with the proposed structure and strategies for PAR 5 packets/sec and geomulticast zone with Radius 250 m. Note that the overhead contains all the control signals (packets) that need to be exchanged among the various nodes in order to create and maintain the routes and clusters. The control overhead can be changed (i.e., increased or decreased) by the direction range control parameter, D_{th}, that controls the mesh route search range (region). In this study, D_{th} = 1.5* L_0 is used, where (L_0) is the distance between the source (sender)(x_s, y_s) and the center point(x_c, y_c) of the geomulticast zone. As it can be seen from Figure 5.15 the control overhead remains relatively constant (i.e., only slightly increases with increasing speed). The reason is that the updates (for clustering and route creation and maintenance) are operated periodically. However, the number of control signals for the updates may slightly increase with speed during this period because although the mobility-based clustering approach groups nodes that present similar mobility characteristics, as mobility increases the structure (e.g. neighbors of a node) is changing more drastically, and therefore more control signals may need to be exchanged within each update period.

5.5 Concluding Remarks

Geomulticast is a specialized location-dependent multicasting technique, where messages are multicast to some specific user groups within a specific zone. In this chapter, architectures and protocols are proposed to support geomulticast services with high packet delivery reliability in mobile ad-hoc wireless networks. The main elements of these architectures and protocols include: a mobility based clustering method to be used as the underlying structure, techniques for geomulticast zone formulation and representation, and a direction guided geomulticast routing strategy. The direction guided routing (DGR) protocol creates cluster-head based limited mesh structure within a guided region, in order to deliver packets with reliability and reduced overhead to the final destinations. Moreover, two geomulticast membership management strategies which depend on geolocation storage position are also presented and investigated. The first strategy is used to reduce the message delivery error while the second one aims to minimize the session setup delay.

An analytical framework is also presented in order to evaluate the performance of the design alternatives for algorithms and implementations used for geomulticast services. The probability of GeoError and the accuracy of geomulticast packet delivery are derived and the tradeoff between the geolocation update interval and signaling load is discussed. The performance evaluation of the proposed architectures has demonstrated their efficiency in terms of accuracy of geomulticast packet delivery, scalability, and control overhead, as a function of mobility, geomulticast zone size, geolocation update time interval, number of geomulticast memberships, and therefore indicate that the proposed architectures can be used to support geomulticast services with high message delivery accuracy in mobile ad-hoc networks.

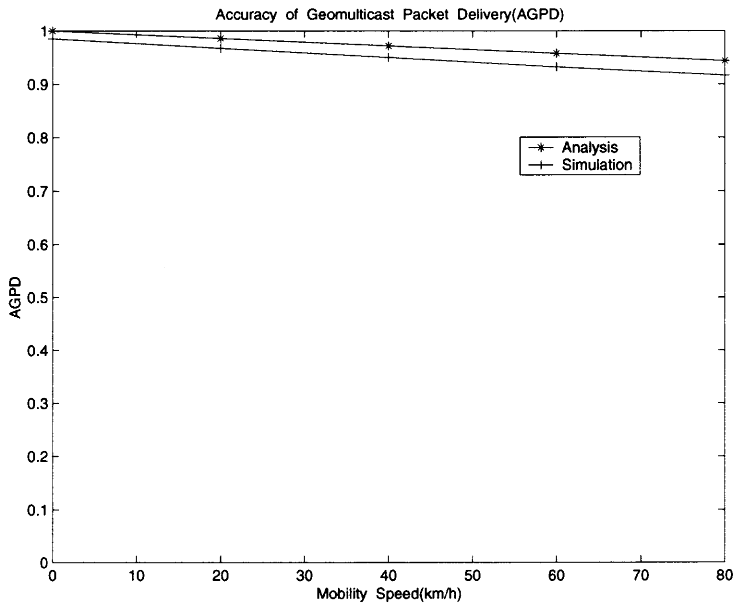


Figure 5.10 Accuracy of geomulticast packet delivery as a function of mobile speed.

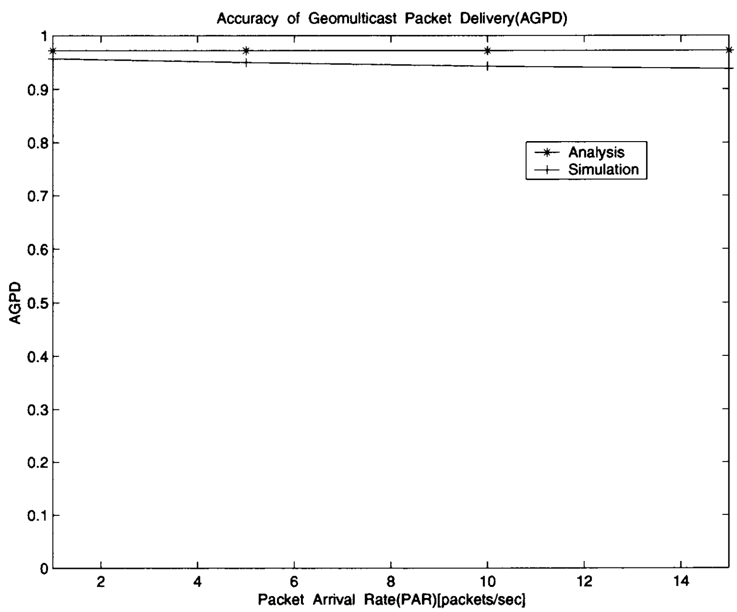


Figure 5.11 Accuracy of geomulticast packet delivery as a function of packet arrival rate.

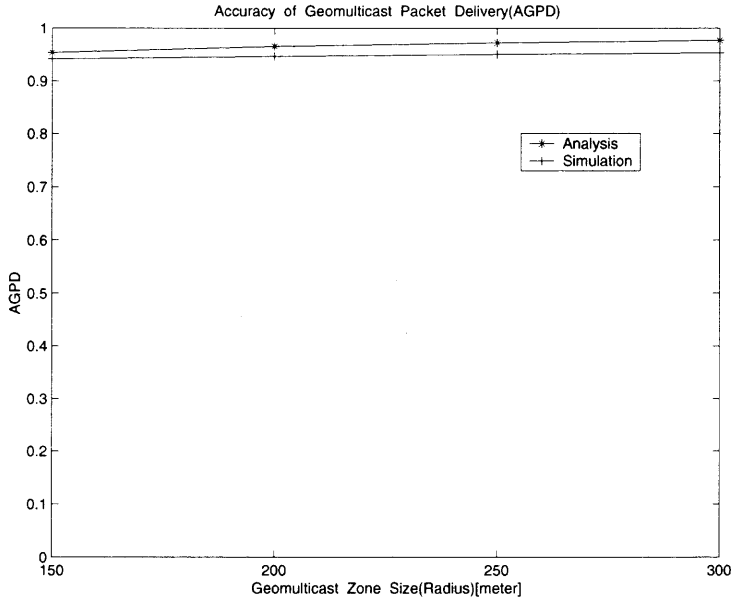


Figure 5.12 Accuracy of geomulticast packet delivery as a function of geomulticast zone size.

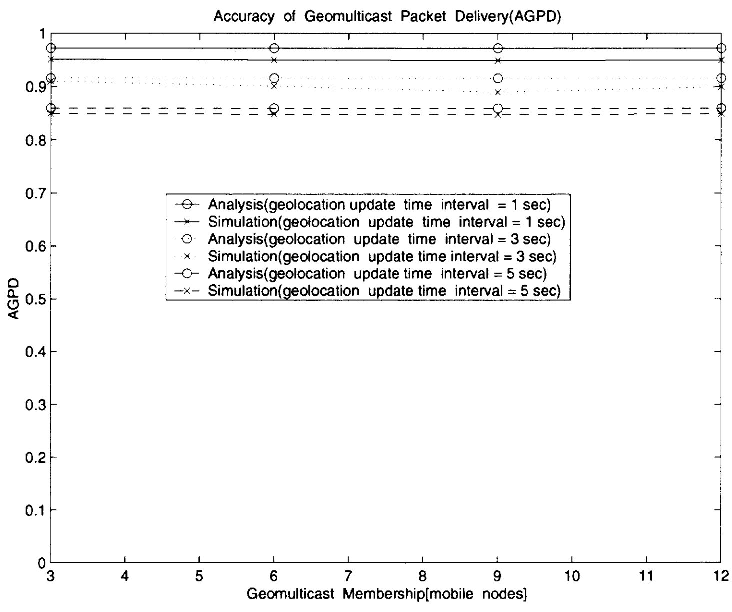


Figure 5.13 Accuracy of geomulticast packet delivery as a function of geomulticast membership.

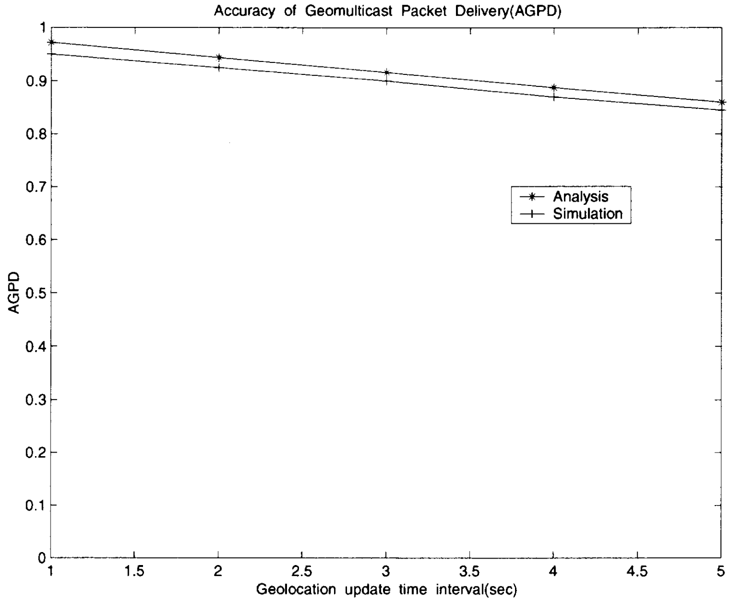


Figure 5.14 Accuracy of geomulticast packet delivery as a function of geomulticast update rate.

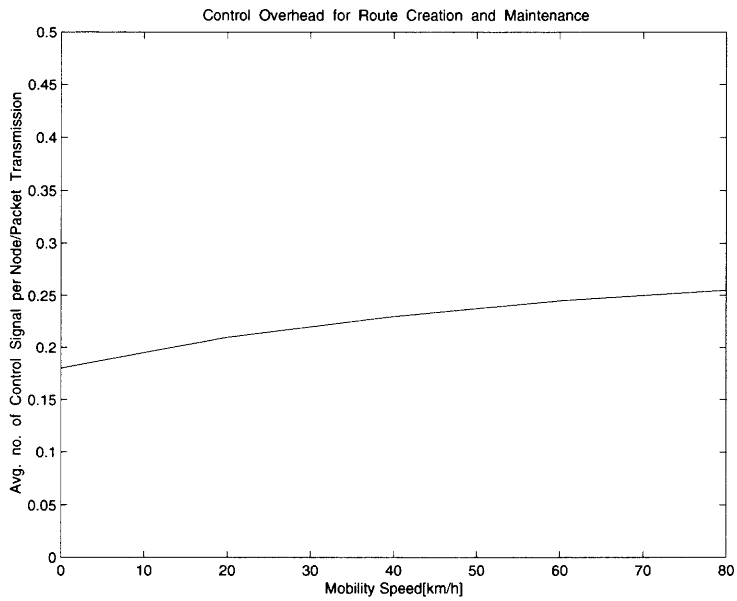


Figure 5.15 Average number of total control signal/node/packet transmission as a function of mobility speed.

CHAPTER 6

CONCLUSIONS

The emerging group communication wireless applications, such as multipoint data dissemination and multiparty conferencing tools have made the design and development of efficient multicast techniques in mobile ad-hoc networking environments a necessity and not just a desire. In this dissertation, first the activities and recent advances are summarized in this work-in-progress area by identifying the main issues and challenges that multicast protocols are facing, and by providing a brief overview of the main current strategies in mobile ad-hoc wireless networks. A first effort in the literature to classify the existing multicast protocols is also presented, and to provide a qualitative comparison of their characteristics according to several distinct features and performance parameters.

Next, a mobility-based clustering(MBC) approach that can be applied in wireless mobile ad-hoc networks is proposed in order to facilitate the implementation of efficient mobility management solutions and multicasting strategies. The proposed cluster architecture consists of variable-size clusters that may change adaptively according to nodes' mobility. The proposed MBC algorithm uses combination of both physical and logical partitions of the network (i.e. geographic proximity and functional relation between nodes, such as mobility pattern etc.), as well as the concept of relative mobility that characterizes the degree of mobility of a node with respect to its peers. The performance evaluation of the algorithm demonstrated that the proposed strategy improves the stability of the clustered topology, by reducing significantly the number of clusterhead changes under different mobility scenarios. The proposed cluster architecture provides for a very robust infrastructure, which is not easily disrupted by mobility and can support stable paths (reduction of routing overhead) and cost effective mobility management solutions.

An entropy-based modeling framework for supporting route stability is presented in mobile ad-hoc wireless networks. The basic motivations of the proposed modeling approach stem from the commonality observed in the location uncertainty in mobile ad-hoc wireless networks and the concept of entropy. The corresponding results have demonstrated that the proposed modeling can be used as the ideal vehicle by various routing protocols for evaluation, selection and assignment of priorities to various routes according to route stability, in order to enhance the offered connectivity and QoS. Furthermore, the proposed approach has been extended into a clustered self-organizing mobile ad-hoc wireless network for supporting QoS and stability for multicast services.

Based on the underlying structure, MBC, a Mobility-based Hybrid Multicast Routing protocol(MHMR) suitable for mobile ad-hoc networks is proposed. The main features that MHMR introduces can be summarized as: a) mobility based clustering and group based hierarchical structure, in order to effectively support the stability and scalability, b) group based (limited) mesh structure and forwarding tree concepts, in order to support the robustness of the mesh topologies which provides "limited" redundancy and the efficiency of tree forwarding simultaneously, and c) combination of proactive and reactive concepts which provide the low route acquisition delay of proactive techniques and the low overhead of reactive methods. The performance evaluation of the proposed protocol demonstrates the proposed multicast protocol's efficiency in terms of packet delivery ratio, scalability, control overhead, end-to-end delay, as a function of mobility and multicast group size, and therefore, indicate that MHMR provides a very efficient multicast protocol that is suitable for application in large scale mobile ad hoc networks.

Finally, since geomulticast is a specialized location-dependent multicasting technique where messages are multicast to some specific user groups within a specific zone, the geomulticast problem is studied by presenting a range of possible geomulticast architectures for mobile ad-hoc wireless networks. Specifically, geomulticast zone representation, geomulticast zone formulation, network architecture, and geomulticast routing strategy are described for supporting geomulticast. An analytical framework and model are also provided that can be used to evaluate the performance of the design alternatives, algorithms and implementations used for geomulticast services in mobile ad-hoc wireless networks.

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