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LOCATION-AWARE ROUTING AND GEOCASTING IN WIRELESS AD HOC NETWORKS

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Location-Aware Routing and Geocasting in Wireless Ad hoc Networks

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To

My Parents

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ABSTRACT

This thesis is primarily concerned with two main topics in wireless ad hoc networks: location-aware routing and geocasting. First, a new location-aware routing protocol called Location-aware Grid-based Hierarchical Routing (LGHR) protocol is proposed for mobile ad hoc networks that attempts to reduce the overhead generated by other protocols falling in the same category. In LGHR, the network area is divided into non-overlapping zones. A hierarchy is established in such a manner that the whole network is partitioned into zones and each zone is then further divided into smaller regions called grids. A centralized approach is used within each zone and grid. A leader is elected from each zone whereas a central node called gateway is elected from each smaller grid. The leader is responsible for making routing tables which then sends these tables to the respective gateways. Both intra-zone and inter-zone routing mechanisms are explained. The proposed protocol is compared with other location-aware routing protocols known as Zone-based Hierarchical Link State (ZHLS) and GRID. ZHLS which is also a hierarchical protocol uses link state routing in each zone. Each node in a zone sends its link state packets to all other nodes in its zone. Hence, each node stores and makes its intra-zone and inter-zone routing tables causing huge communication overhead in case there are large numbers of nodes in a zone. The proposed protocol LGHR reduces the communication and storage overhead by further partitioning each zone into smaller grids. Unlike ZHLS, only gateway nodes keep the routing tables and routing is performed in a gateway-by-gateway manner. In order to compare both protocols, the mathematical analysis is done for both ZHLS and LGHR and then evaluation is performed. The analysis clearly indicates that the proposed protocol performs better than ZHLS in terms of the storage overhead as well as communication overhead generated by all nodes. The protocol is also compared with another location-aware protocol called GRID. The stability factor is analyzed by doing simulations for both protocols. The stability factor is chosen on the basis of gateway election mechanisms. GRID uses only the distance from the center of the grid for electing a gateway whereas LGHR takes into account the velocity of a node along with the distance form the center of the grid. The simulation

results clearly show that the proposed protocol LGHR is more stable than GRID especially in scenarios where the wireless nodes are moving with very high velocity.

The second topic discussed in the dissertation is the problem of guaranteeing the delivery of geocast packets to all nodes inside a geocast region for wireless ad hoc networks. The nodes in the geocast region may not be directly connected to one another, causing isolated groups of nodes that do not have direct access to some other nodes within a geocast region. These isolated groups of nodes are named as islands. In order to ensure the delivery of packets to all nodes, a geocasting protocol called Grid-based Guaranteed Geocast (GGG or G3) is proposed that uses the nodes outside the geocast region to deliver packets to these islands. Several nodes outside the geocast region can have direct connections with islands, but only one node is elected called Main Entry Point (MEP) which is responsible for delivering the packets to the nodes inside the geocast region. This helps in avoiding duplicate packets entering the geocast region. Also, the concept of location server is redefined and is given the routing responsibilities as well. Simulations are performed to compare the proposed mechanism with two other geocasting protocols, LBM and GAMER. The simulations prove that the proposed mechanism not only guarantees the delivery of geocast packets but also performs better than the other two protocols, LBM and GAMER in terms of throughput, end-to-end delay, packet delivery ratio and data packet overhead.

요 약 문

본 논문은 무선 Ad hoc 네트워크에 관련된 두 가지 주된 라우팅 알고리즘 중 위치 인지 라우팅과 geocasting 에 관해 연구하였다.

첫째로, 무선 Ad hoc 네트워크를 위해 LGHR (Location-aware Grid-based Hierarchical Routing)이라고 불리는 새로운 위치 인지 라우팅 프로토콜을 제안하여 같은 범주 내의 다른 알고리즘들 에서 발생되는 오버헤드를 감소시키고자 하였다. LGHR 에서 네트워크 영역은 겹치지 않는 존 들로 분리되어져 있다. 하나의 그룹은 전체 네트워크에서 존 들로 분할되어지고, 각각의 존 들은 그리드 라고 불리는 더 좁은 영역들로 나누어지는 방식으로 이루어져 있다. 각각의 존과 그리드 내에서는 중앙집중형 접근방식이 사용되어지고 있다. 각각의 존으로부터 하나의 리더가 선택되며 각각의 그리드로부터는 게이트웨이라 불리는 중심 노드들이 선택된다. 각 리더는 라우팅 테이블을 구성할 책임이 있으며 이는 이후 게이트웨이들에게 보내져 존 내 혹은 존 간 라우팅 기법을 위하여 사용된다.

제시된 LGHR 프로토콜은 ZHLS와 GRID로 알려진 다른 위치 인지 라우팅 프로토콜들과 비교하였다. ZHLS 역시 각각의 존 에서 링크 상태 라우팅을 사용하는 계층형 프로토콜이다. 존 안에 있는 각각의 노드들은 그 존 내의 모든 다른 노드들에게 LSP (Link State Packet) 들을 보내며 각각의 노드들은 존 내 또는 존 간의 경로배정표를 저장하여 라우팅 동작을 수행하게된다. 따라서 존 내에 많은 노드들이 있을 경우 매우 많은 통신 오버헤드가 발생하게 된다. 본 논문에서 제시된 프로토콜인 LGHR은 더 작은 그리드들로 각각의 존을 분할 함으로써 통신 오버헤드와 저장 오버헤드를 감소시키고자 하였다. ZHLS와는 달리, 게이트웨이 노드들만이 라우팅 테이블들을 유지하게 되고 실제적인 전송은 gateway-by-gateway 방식으로 수행된다. 각 프로토콜들의 비교를 위해 ZHLS와 LGHR에 대한 수학적 분석을 수행한 후 성능 분석을 하였다. 제안된 프로토콜은 모든 노드들에 의해 발생하는 통신 오버헤드 뿐만 아니라 저장

오버헤드 관점에서도 ZHLS 보다 더 우수한 특성을 보이고 있다. 또한 제안한 프로토콜은 GRID로 불리는 위치 인지 프로토콜과도 비교되어졌으며 게이트웨이 선출 기법들을 기반으로 안정성 요소들에 대하여도 분석이 이루어졌다. GRID는 하나의 게이트웨이 선정을 위해 단지 그리드의 중심으로부터의 거리만을 사용하는 반면 LGHR은 그리드의 중심으로부터의 거리는 물론 노드에 따른 이동속도를 이용하고 있다. 시뮬레이션 결과 무선 노드들이 매우 빠른 속도로 움직이는 경우 LGHR이 GRID 기법보다 더 안정적으로 동작함을 명확하게 보여주고있다.

본문에서 다루어진 두 번째 주제는 무선 Ad hoc 네트워크에서 모든 노드들이 하나의 geocast 영역 안으로 geocast 패킷 전달을 보장하는 문제에 대한 것이다. Geocast 영역 안에 있는 일부 노드들은 같은 영역 내의 다른 노드들에 직접적으로 접근하지 못하는 경우가 발생하는데 이들 노드들의 분리된 그룹을 Islands 이라 한다. Geocast 영역 내의 모든 노드들에게 패킷들의 전달을 보장하기 위하여 G3 (Grid-based Guaranteed Geocast) 라고 불리는 geocasting 프로토콜이 제시 하였으며, 여기에서는 Island들에게 패킷들을 전달하기 위해 geocast 영역 바깥 쪽 노드들을 사용하였다. Geocast 영역 밖의 몇몇 노드들은 Island들에게 직접적으로 연결될 수 있지만 이들 중 Main Entry Point (MEP) 라고 불리는 하나의 노드만이 선택 되어 패킷전달역할을 수행하게된다. 이와같은 MEP들은 geocast 영역 안쪽 노드들에게 패킷들을 전달할 책임을 가지고 있으며 geocast 영역 안으로 중복적인 패킷 전송을 피할 수 있도록 하고있다. LS(위치기반 서버) 의 개념 또한 새롭게 정의 되어졌으며 경로배정의 역할을 수행하여야 할 책임이 있다. 제안된 기법의 성능 평가를 위하여 두 가지 다른 LBM과 GAMER를 가지고 시뮬레이션을 수행하여 비교하였다. 제안된 기법이 geocast 패킷들의 전달을 보장함은 물론 처리율, 종단간의 지연, 패킷 전달율과 데이터 패킷 오버헤드에 대해서도 다른 두 프로토콜 (LBM, GAMER)들 보다는 더 나은 성능을 지니고 있음을 시뮬레이션을 통해 검증하였다.

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Chapter 1

INTRODUCTION

Mobile ad hoc networks started gaining popularity since 1990s and there has been a rapid growth of interest by researchers in this field. More specifically, people are interested in routing in ad hoc networks and several routing protocols have been added into the literature. Generally, ad hoc routing protocols can be classified into three major categories: pro-active, reactive and hybrid routing protocols. All these three kinds of routing protocols can be either *flat* or *hierarchical.* Moreover, these routing protocols can be *location-aware* or *location-unaware.* A detailed review of ad hoc routing protocols can be found in Abolhasan *et al.* (2004). Location-aware routing (also called position-based routing or geographic routing) is a phenomenon in which the physical location of nodes is utilized for delivering a message from one node to another. The location information can be taken either with the help of a GPS (Grewal *et al.,* 2001) receiver or some other positioning method. Several techniques have been proposed by researchers for GPS-free positioning (Capkun *et al.,* 2001) or positioning based on virtual co-ordinates (Caruso *et al.,* 2005; Rao *et al.,* 2003). Moreover, several location-based routing protocols for mobile ad hoc and sensor networks have been proposed by authors during the past few years (Basagni *et al.,* 1998; Fang *et al.,* 2005; Joa-Ng and Lu, 1999; Ko and Vaidya, 2000a; Liao *et al.,* 2001). Majority of these protocols base their routing decisions entirely on the physical locations of nodes whereas some of them partially utilize the location information for routing.

In this thesis, two main topics are discussed. First, a location-aware routing protocol called Location-aware Grid-based Hierarchical Routing (LGHR) is proposed that attempts to reduce the overhead generated by some of the other ad hoc routing protocols. Secondly, the problem of guaranteeing the delivery of packets to all nodes in a geocast region is addressed. For this purpose, a geocasting protocol called Grid-based Guaranteed Geocast (GGG or G3) is proposed and is compared with some other existing geocasting protocols.

1.1 Location-aware Routing Protocol

The main purpose of the proposed location-aware routing protocol is to reduce the drawbacks of some of the existing routing protocols. A hierarchical routing protocol called Location-aware Grid-based Hierarchical Routing (LGHR) is proposed for mobile ad hoc networks which uses non-overlapping zones for efficient routing. The hierarchy is made in such a way that the network is partitioned into zones and each zone is then further divided into smaller grids. Moreover, each zone has a node called leader which is responsible for maintaining routing tables and making routing decisions. Each smaller grid in a zone has a gateway node which is responsible for its own grid. The leader sends the routing tables to respective gateway nodes present in its zone. On the basis of these routing tables, the gateway nodes forward packets to other nodes. LGHR is compared with another hybrid zone-based routing protocol called Zone-based Hierarchical Link State (ZHLS) (Joa-Ng and Lu, 1999). ZHLS tries to reduce the overhead of the traditional Link State Routing by dividing the whole network into zones. Moreover, ZHLS is a hybrid pro-active/reactive protocol for which the pro-active link state routing is performed within a zone and a reactive zone search strategy is initiated if a node wants to send a packet to a node in another zone. A node can know its position with the help of a GPS receiver and hence, can easily figure out which zone it lies in.

A major problem with ZHLS is that if there are large numbers of nodes present in a zone, every node in a zone has to store all the routing information for all nodes. This includes the link state packets periodically exchanged by all nodes as well as the intra-zone and inter-zone routing tables. Since, in ad hoc networks, the nodes can be mobile and can move frequently in the network, the nodes have to send their neighbor connectivity information very often. Therefore, the network’s bandwidth is mostly utilized by bombarding the link state packets in the network resulting in huge communication overhead. As mentioned, the protocol initiates a reactive zone search mechanism if the destination node lies outside the current source's zone. Since almost all location-based routing protocols use a location service to determine the position of the destination, this problem could be easily solved by fully utilizing the location-aware capability of the protocol i.e., it could use the zone map for mapping the destination's position and find out which zone the destination lies in. This way, a lot of extra communication overhead induced by initiating the zone search mechanism could be reduced.

The proposed protocol solves the above-mentioned problems by assigning the routing table creation responsibilities to a centralized node within a zone called leader. The neighbor information is sent by nodes to only the leader, not to all the other nodes in a zone. On the basis of this neighbor information, the leader constructs the routing tables. Moreover, all nodes are not supposed to carry the routing tables and perform the routing operations. Since, each zone is further divided into smaller grids and each grid has a responsible node called gateway, all the routing is performed in a gateway-by-gateway manner. The leader sends the routing tables to respective gateway nodes and hence, only the gateway nodes are responsible for packet forwarding. Non-gateway nodes do not participate in the packet forwarding process. This approach avoids a lot of extra communication and storage overhead which could be caused by using a peer-to-peer approach as in ZHLS.

LGHR uses pro-active mechanism inside a zone but unlike ZHLS, it does not initiate a reactive zone search mechanism if the destination lies outside the zone of the source node. Instead, it uses the location-based strategy to identify the destination's zone by mapping the position of the destination on the zone map. Both protocols are analyzed and it is shown that the proposed protocol LGHR is efficient and performs better than ZHLS in terms of amount of routing information stored as well as the communication overhead generated by various nodes.

LGHR is also compared with another location-aware ad hoc routing protocol called GRID (Liao *et al.,* 2001). GRID is a fully location-aware reactive routing protocol which also uses non-overlapping grids and nodes in a grid elect a gateway node in which the routing is performed in a grid-by-grid manner. Stability of both protocols is analyzed and the frequency of gateway election mechanisms is used as a parameter for stability. GRID uses only the distance from the center of the grid as a criterion for electing a gateway, whereas, LGHR takes into account the distance from the center as well as the velocity of mobile nodes in order to elect a gateway. The performance comparison shows that LGHR tends to work in a more stable manner than the GRID protocol especially in situations of high mobility.

1.2 Geocasting with Delivery Guarantee

Geocasting is a phenomenon in which a packet is supposed to be sent to all the nodes inside a physical region. Guaranteed delivery means the ability of successfully forwarding a message from a source node to the destination. The definition requires that source and destination are connected by at least one path in the network and that there is an idealized MAC layer where messages are not lost during any forwarding step (Stojmenovic, 2006). In case of geocasting, the destination comprises of all the nodes inside a geocast region. So far, a few algorithms are known to have been proposed by authors that guarantee the delivery of geocast packets in the geocast region. One is proposed in Seada and Helmy (2004), three proposed in Stojmenovic (2004) and one in Lian *et al.* (2006).

In this thesis, the problem of delivering the geocast packets to all nodes inside a geocast region is addressed for ad hoc networks, where the nodes are not directly connected to one another. A geocast routing protocol is proposed which guarantees the delivery of geocast packets to all nodes inside a geocast region. In order to guarantee the delivery of packets to all nodes, the nodes outside the geocast region are utilized. The isolated groups of nodes inside the geocast region are named as islands. A grid-based approach is used for determining the islands as well as sending geocast packets to the geocast region. There can be several nodes outside the geocast region that have direct connections with the islands, but only one node is elected which is responsible for delivering the packets to the nodes inside the geocast region. The concept of location server is also redefined and it is given the routing responsibilities as well. Simulations are performed to compare the proposed mechanism with other geocasting protocols such a Location-Based Multicast (LBM) (Ko and Vaidya, 1998) and Geocast Adaptive Mesh Environment for Routing (GAMER) (Camp and Liu, 2003). LBM is a geocasting protocol based on restricted flooding whereas GAMER is a mesh-based geocasting protocol. The simulations show that the proposed protocol not only guarantees the delivery of geocast packets to all nodes in a geocast region but also performs better than these two protocols in terms of throughput, end-to-end delay, packet delivery ratio and data packet overhead.

1.3 Organization of the Dissertation

The rest of the dissertation is organized as follows:

Chapter 2 provides an overview of the related and previous literature on location-based routing, geocasting and mechanisms for guaranteeing the delivery of geocast packets to nodes in a geocast region.

Chapter 3 proposes a location-aware routing protocol for mobile ad hoc networks called Location-aware Gird-based Hierarchical Routing (LGHR). The basic network architecture is discussed for the routing mechanism.

Chapter 4 shows the analysis and comparison of the proposed protocol with other routing mechanisms.

Chapter 5 describes the geocasting phenomenon for guaranteeing the delivery of packets in a geocast region. A geocasting protocol is proposed and the mechanism is described in detail.

Chapter 6 evaluates the geocasting mechanism and compares with other geocasting protocols using simulations. The comparison is done for delivery guarantee as well as other parameters.

Chapter 7 summarizes the work in this research and concludes with open questions and possible future directions for further research that builds upon the work in this dissertation.

Chapter 2

RELATED WORK

This chapter summarizes the related work already done in the area of ad hoc routing protocols. The main emphasis is on location-aware routing and geocasting in wireless ad hoc networks. The working of various protocols is described and their main features, strengths and weaknesses are discussed. The chapter shows a direction on how to reduce or avoid the limitations of the existing mechanisms.

2.1 Ad hoc Routing Protocols

Unlike other wireless mobile networks, such as cellular and wireless IP networks having wired backbones and centralized base stations, a mobile ad hoc network neither has a wired backbone nor a centralized access point. A wireless node acts both as a host as well as a router. The network topology changes very frequently as the route from a source to a destination dynamically changes due to node mobility. Consequently, searching a route for a destination with minimum overhead has been a challenging task for researchers for the past several years. Moreover, the limited resources in mobile ad hoc networks such as bandwidth, power etc., have made the designing process of a reliable and stable routing protocol a very challenging task. A routing strategy should be able to efficiently utilize the limited resources as well as it should adapt to the rapidly changing network conditions.

Generally, ad hoc routing protocols can be classified into 3 main categories:

- Proactive Routing Protocols
- Reactive Routing Protocols
- Hybrid Routing Protocols

All these three kinds of routing protocols can be:

- Flat
- Hierarchical

Moreover, these routing protocols can also be:

- Location-aware
- Location-unaware

Proactive routing algorithms make their routing decisions on the basis of prior topology information available which is provided by nodes in the network. In reactive routing, a path is searched on-demand whenever there is a need to send a message to a destination. Hybrid mechanisms employ both the above strategies depending upon different criteria and situations. The architecture of all these three kinds of protocols can be either flat or hierarchical and they can be location-aware or location-unaware. The classification of ad hoc routing protocols is shown in Figure 2.1. Several ad hoc routing protocols have been proposed by researchers during the past few years in the categories mentioned in the figure. A few existing routing protocols for ad hoc networks are shown in Table 2-1 as an example. In the location-unaware category, DSDV (Perkins and Bhagwat, 1994), OLSR (Jacquet *et al.,* 2003) and TBRPF (Bellur *et al.,* 2003) are pro-active, flat routing protocols whereas STAR (Garcia-Luna-Aceves and Spohn, 1999) is pro-active hierarchical routing protocol. AODV (Perkins *et al.,* 2003) and DSR (Johnson and Maltz, 1996) are reactive, flat routing protocols whereas CBRP (Jiang *et al.,* 1999) is a reactive hierarchical routing protocol. ZRP (Haas and Pearlman, 1998) is a hybrid, flat routing protocol whereas DDR (Nikaein *et al.,* 2000) is a hybrid, hierarchical routing protocol.

In the location-aware category, DREAM (Basagni *et al.,* 1998) is classified as a proactive flat routing protocol whereas LAR (Ko and Vaidya, 2000a) and GPSR (Karp and Kung, 2000) are reactive flat routing protocols. GRID (Liao *et al.,* 2001) is a reactive hierarchical routing protocol. ZHLS (Joa-Ng and Lu, 1999) is a hybrid hierarchical routing protocol. A detailed review and classification of ad hoc routing protocols can be found in Abolhasan *et al.* (2004).

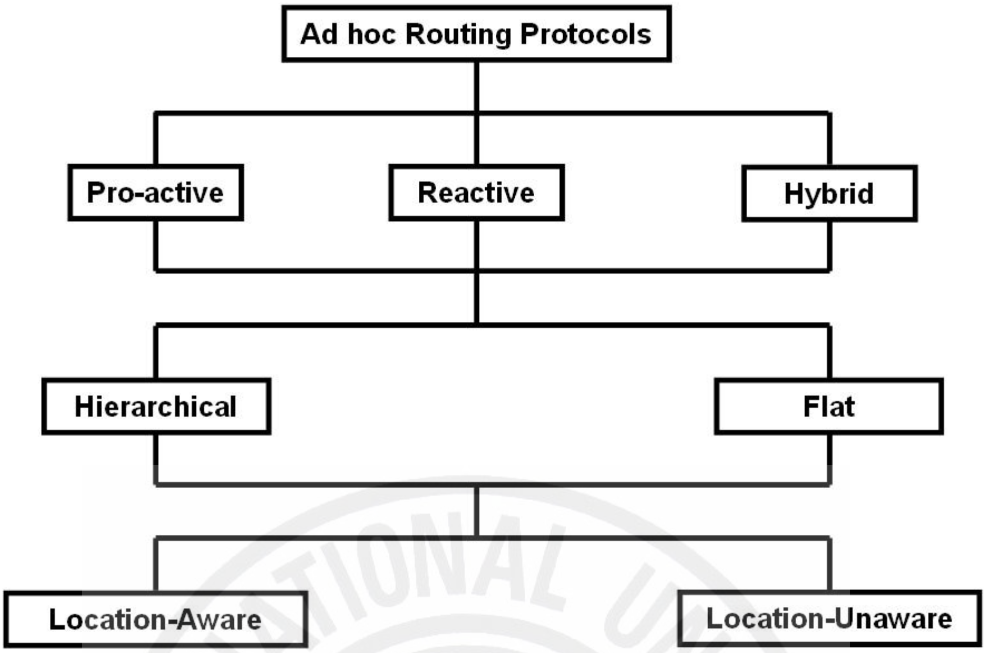


Figure 2.1: Classification of ad hoc routing protocols.

Table 2-1: A few example ad hoc routing protocols

Protocol	Proactive/ Reactive/Hybrid	Flat/ Hierarchical	Location-aware/ Location-unaware
OLSR	Proactive	Flat	Location-unaware
DSDV	Proactive	Flat	Location-unaware
TBRPF	Proactive	Flat	Location-unaware
STAR	Proactive	Hierarchical	Location-unaware
AODV	Reactive	Flat	Location-unaware
DSR	Reactive	Flat	Location-unaware
CBRP	Reactive	Hierarchical	Location-unaware
ZRP	Hybrid	Flat	Location-unaware
DDR	Hybrid	Hierarchical	Location-unaware
DREAM	Proactive	Flat	Location-aware
LAR	Reactive	Flat	Location-aware
GPSR	Reactive	Flat	Location-aware
GRID	Reactive	Hierarchical	Location-aware
ZHLS	Hybrid	Hierarchical	Location-aware

2.2 Location-aware Routing Protocols

Location-aware routing is a routing phenomenon in which the physical location of a node is considered while making the routing decisions in a network. Some routing protocols fully utilize the location information for making routing decisions depending entirely on the physical location while other protocols utilize the location information partially in decision making process. For example, GRID, LAR and GPSR etc., make their routing decisions completely on the basis of the location information of nodes whereas ZHLS is location-aware routing protocol in which location information in partially utilized during the routing process. In fully location-aware routing, the routing is based on the following three assumptions:

1. All nodes can determine their own position with the help of GPS etc.
2. Nodes know the positions of their direct neighbors.
3. The source node knows the position of the destination.

Several location-aware routing protocols exist in the literature. A detailed survey of location-based routing can be found in Mauve *et al.* (2001). In the subsequent subsections, some of the most famous location-aware routing protocols are described such as LAR, GRID, GPSR and ZHLS.

2.2.1 Location-Aided Routing Protocol (LAR)

The location-aided routing (LAR) (Ko and Vaidya, 2000a) protocol uses restricted flooding to exploit location information in order to reduce the route search overhead in an ad hoc network. LAR protocol uses the GPS (Global Positioning System) to get this location information. With the availability of GPS, a mobile node can easily know its physical location. Traditional reactive routing protocols such as DSR and AODV, broadcast a route request packet which floods throughout the entire network. This activity wastes a lot of bandwidth and can initiate a broadcast storm problem (Ni *et al.,* 1999) because of contention and collisions on the mediumaccess layer. To overcome this problem, LAR uses a flooding region called request zone and the packet is flooded only in the request zone.

Two LAR protocols have been proposed by authors. One is called LAR scheme 1 and another is known as LAR scheme 2. In LAR scheme 1, in order to search a route from source S to destination D, the protocol defines a smaller forwarding region called request zone that covers both S and D, instead of flooding the request to the entire network. The request zone is made up of the smallest rectangle that contains S's current location and D's possible location. In order to forward a packet, a node has to be in the Request Zone otherwise it cannot further forward the packet. In the example shown in Figure 2.2 (similar to a figure in Ko and Vaidya, 2000a), D's expected location is within the expected zone represented by the shaded circle within a rectangle. The rectangle represents the request zone. In the figure, since node N is located in the request zone, it can rebroadcast the route request packet to other nodes in the zone, but node O which is outside the request zone, cannot forward the packet.

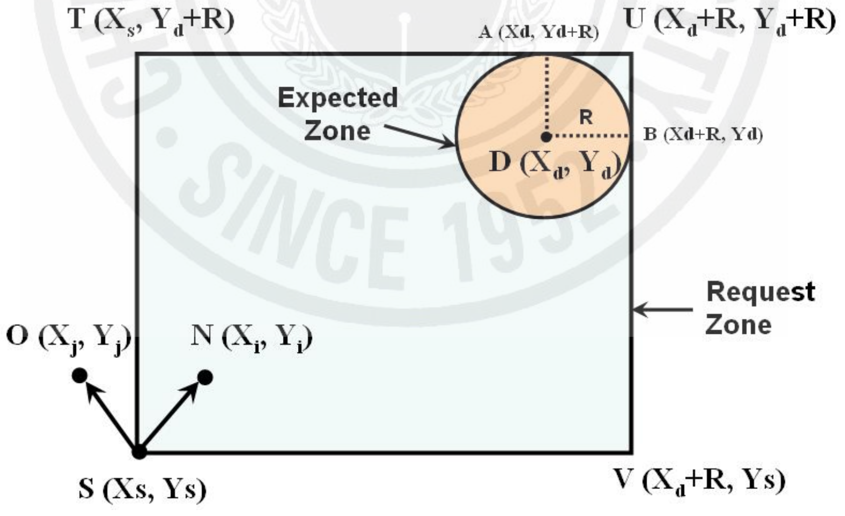


Figure 2.2: In LAR scheme 1, the packet is flooded only in the Request Zone.

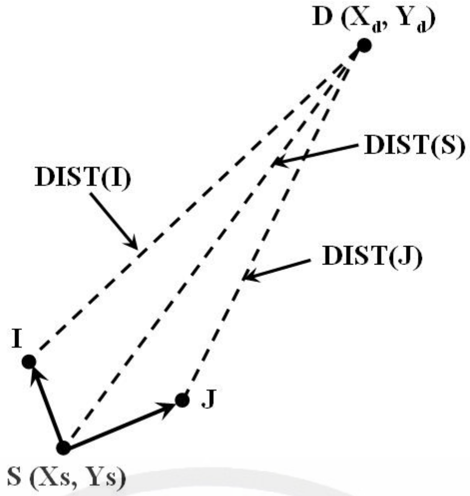


Figure 2.3: In LAR scheme 2, the packet is forwarded only if the distance of current node is shorter than the previous one.

The LAR scheme 2 does not take into account any request zone. Instead, it uses the physical distance from the destination node as a parameter to forward a packet to the next node. The coordinates of the destination are stored in the route request packets. These packets can only travel in the direction of the destination where the relative distance to the destination becomes smaller as they travel from one hop to another. As in Figure 2.3, on receiving a packet from node S, node I will check if its distance from destination DIST(I) is smaller than that of node S i.e., DIST(S). If so, it will forward the packet to its neighboring nodes otherwise it will discard the packet. Both LAR schemes limit the control overhead transmitted through the network and hence conserve bandwidth.

2.2.2 GRID protocol

GRID (Liao *et al.,* 2001) is a fully location-aware reactive routing protocol. In the GRID protocol, the network is partitioned into several square-shaped regions called grids. In each grid, one mobile host, if any, is elected as the grid's leader and is called gateway. Gateways perform routing grid by grid, while non-gateways are not involved in forwarding packets. This protocol is considered fully location-aware because it exploits the location information in route discovery, packet relay, and route maintenance phases. The GRID protocol uses location information in the following three ways:

Route Discovery. In the route discovery phase, the route search area is confined by a forwarding zone. The route search is performed by only the gateway nodes otherwise; the search can send many unnecessary route request packets by non-gateway nodes. Due to this reason, the GRID protocol can be useful in a dense environment.

Packet Relay. Since the routing is performed in a grid-by-grid manner, a grid ID rather than a host ID represents a route. Each entry in a routing table records the next grid that leads to the destination. The packet relay procedure in GRID is shown in Figure 2.4.

Route Maintenance. Route maintenance is used to offer route resilience to host mobility. When a gateway roams away, the protocol elects another gateway in the grid to take over packet-relaying responsibility. In other reactive routing protocols such as DSR, AODV and LAR, when an intermediate node in a route leaves its neighbors radio range, the route breaks. However, the authors of GRID claim that even if a node roams out of its original grid, the route can still persist since the routing is performed in a grid-by-grid manner.

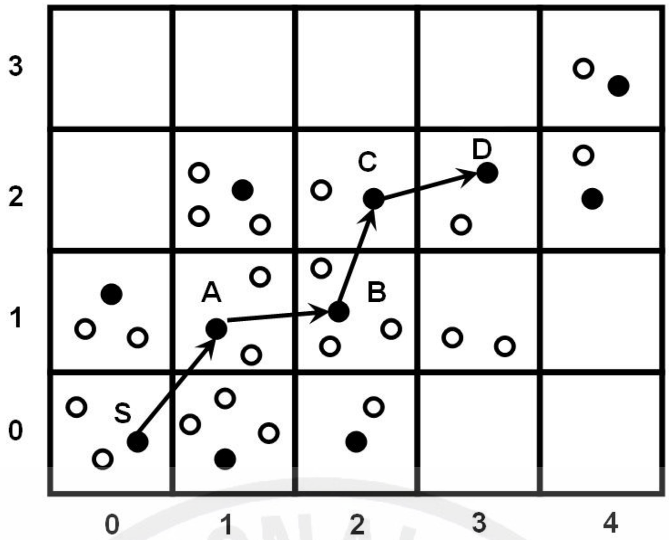


Figure 2.4: Routing operation in GRID is performed in a grid-by-grid manner.

The main advantage of GRID is that it reduces the routing overhead as packet delivery is performed by only the gateway nodes and not by non-gateway nodes. The disadvantage is that in GRID, the grid size is small therefore gateways can move out of grids very frequently as the criteria for gateway election is only the shortest distance from the center of the grid. Hence, nodes inside a grid have to initiate gateway election procedure very frequently causing the network to become unstable. Also, there is no consideration for speed and direction of movement of gateway nodes. In situations where the nodes are moving with very high speeds, this criterion does not seem to be suitable. Secondly, as mentioned in Liao *et al.* (2001), the side-length of grid should be kept in such a way that several grids can be present under one radio range. Since, the routing is performed in a grid-by-grid manner; the packet has to travel through many extra hops. This situation can be avoided if the packet is allowed to be forwarded to a gateway that lies in the sender's radio range but may not be present in its adjacent grid. These issues are addressed in chapter 4 in detail.

2.2.3 Greedy Perimeter Stateless Routing (GPSR)

GPSR (Karp and Kung, 2000) is a geographic routing protocol for wireless networks that works in two modes: greedy mode and perimeter mode. In the greedy mode, the packet is forwarded in a greedy manner i.e., each node forwards the packet to the neighbor closest to the destination. In regions where such a greedy path does not exist, GPSR recovers by forwarding the packet in perimeter mode in which a packet traverses successively closer faces of a planar sub graph (face routing) around dead-ends, until the packet reaches a node closer to the destination. At this point, the protocol switches back to the greedy forwarding. In perimeter mode a packet is forwarded using the right-hand rule in a planar sub graph of the network. Since wireless network connectivity in general is non-planar, each node runs the local planarization algorithm such as Gabriel Graph (GG) or Relative Neighborhood Graph (RNG) to create a planar graph. In this case, only a subset of the physical links is used during perimeter routing.

2.2.4 Zone-based Hierarchical Link State (ZHLS)

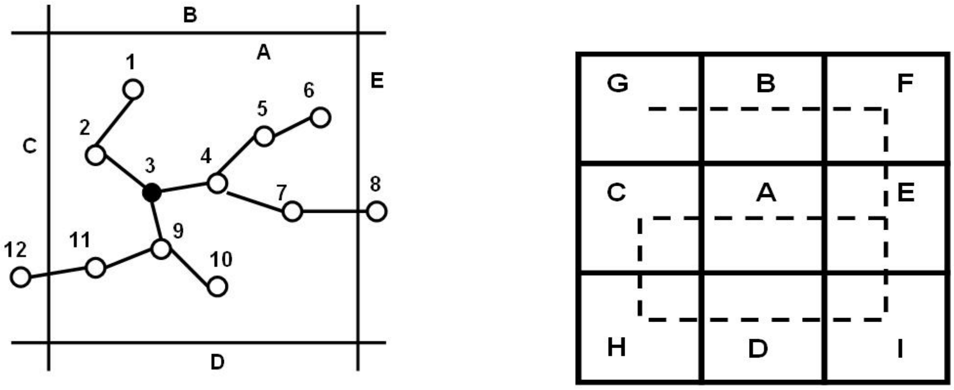
Zone-based Hierarchical Link State (ZHLS) (Joa-Ng and Lu, 1999) routing protocol is a location-aware routing protocol in which link state routing is performed by all nodes in the network in a peer-to-peer fashion. There is no central authority and every node is responsible for making routing decisions based on link state information sent by other nodes. The network is divided into non-overlapping zones and there are two kinds of topologies; a node level topology and a zone level topology as shown in Figure 2.5 (a) and (b) respectively. Each node constructs an intra-zone routing table for node level packet forwarding and an inter-zone routing table for zone level packet forwarding. The gateway nodes, such as 7 and 11 in Figure 2.5 (a) forward the packets between zones.

Initially, each node knows its own position and therefore, it can easily figure out its zone ID with the help of a GPS receiver. Each node also constructs an intra-zone and an inter-zone routing table. The intra-zone routing table is constructed according to the following steps.

1. Each node broadcasts a link request asynchronously.
2 Nodes within its communication range reply with a link response (node ID, zone ID).
3. After receiving all link responses, the node generates a node LSP (Link State Packet) containing node IDs of its neighbors in the same zone and zone IDs of its neighbors of different zones.
4. The node then floods the Node LSP locally throughout its zone.
5. Each node performs the same procedure; therefore, a list of all the Node LSPs can be stored in every node.
6. Using this list, the node constructs intra-zone routing table using the shortest path algorithm.

After each node receives all Node LSPs from other nodes in its zone, it generates a Zone LSP as well. There is only one Zone LSP for every zone and it tells which other zones are connected to it. The gateway nodes that connect two zones flood the Zone LSPs throughout the network. When all nodes receive Zone LSPs of all zones, they construct inter-zone routing tables again using the shortest path algorithm.

The main advantage of ZHLS is that it reduces the communication overhead of Link State Routing by partitioning the network into zones. The main disadvantage is that every node has to keep the information of whole zone topology. Every node has to keep and update routing tables which is not suitable if there are large numbers of nodes inside a zone. Moreover, although it is a location-aware routing protocol, it does not effectively exploit the location-aware capability.



(a) (b)

Figure 2.5: (a) Node level topology (b) Zone level topology.

2.3 Geocasting Protocols for Ad hoc Networks

In geocasting, a packet is supposed to be sent to all the nodes inside a physical region. Existing geocasting protocols can be classified into two categories.

1. Topology-based Geocasting protocols
2. Face Traversal-based Geocasting protocols

Several protocols are present in the first category but the most famous ones are LBM (Ko and Vaidya, 1998), GeoGRID (Liao *et al.,* 2000) and GAMER (Camp and Liu, 2003). These protocols are mainly based on restricted flooding. Pure flooding is the easiest way to guarantee the delivery of geocast packet to all nodes in a geocast region. Since these geocasting protocols use restricted flooding and packets are forwarded only in a restricted region, these protocols do not guarantee the delivery of geocast packets to all nodes in the geocast region.

In the second category, the protocols use planar graphs and mainly use greedy forwarding in combination with face traversals. Protocols present in this category are more likely to guarantee the delivery of geocast packets to all nodes in a geocast region. The details about some of the geocasting protocols are discussed in the following subsections.

2.3.1 Topology-based Geocasting protocols.

The protocols falling in this category are discussed as follows:

2.3.1.1 Location-Based Multicast (LBM)

Location Based Multicast (LBM) (Ko and Vaidya, 1998) is a geocasting protocol based on flooding but avoids flooding the whole network by defining a forwarding zone. Outside the forwarding zone the packet is discarded. Two schemes are proposed for LBM that improve multicast flooding with position information. Both the schemes are derived from Location Aided Routing (LAR) (Ko and Vaidya, 2000a), which is a location based protocol for unicast routing in ad hoc networks.

In LBM scheme 1, a forwarding zone is defined to avoid simple flooding that includes at least the destination geocast region and a path between the sender and the geocast region. An intermediate node forwards the packet only if it lies inside the forwarding zone. Authors have defined a parameter δ for increasing the size of the forwarding zone. By increasing the value of δ, the forwarding zone increases and hence the probability of delivering a geocast packet to all destination nodes can be increased. However, the overhead is also increased. In the simulations, the value of δ is increased from 0 to 150. Results show that if the value of δ is increased to 150, the protocol behaves similar to flooding which increases the overhead to a large extent. Similar to the unicast routing protocol LAR, the forwarding zone can be the smallest rectangular region that includes the sender and the destination region. The co-ordinates of the forwarding zone are included in each geocast packet so that each node can determine whether it belongs to the forwarding zone.

The second scheme of LBM defines the forwarding zone by the location coordinates of the sender, the geocast region, and the distance of a node from the center of the geocast region. A node that receives a geocast packet determines whether it belongs to the forwarding zone by calculating its own distance from the center of the geocast region. If its distance is smaller than the distance of its one-hop predecessor, the geocast packet is forwarded to all neighbors and the packet sender's distance is replaced by its own distance. Finally, the packet is flooded to all neighbors if the predecessor node is located inside the geocast region.

2.3.1.2 GeoGRID

GeoGRID (Liao *et al.,* 2000) is based on its predecessor unicast routing protocol called GRID. GeoGRID partitions the network into logical grids, with a single elected gateway in each partition. One host close to the grid center is elected as gateway which is responsible for propagating geocast packets to neighboring grids. Only gateways forward packets, which relieves other nodes from inefficient flooding. Similar to GRID protocol, geocast packets are sent in a grid-by-grid manner through their gateways. This decreases message overhead by excluding non-gateways from packet flooding. Prior to sending a geocast packet, no routes are established. A rectangular forwarding region is used for forwarding a geocast packet in order to have restricted flooding. Packets are forwarded by only those nodes that are present in the forwarding region. Outside the forwarding region a received packet is discarded.

Another geocasting protocol called ticket-based GeoGRID is also proposed. In the second scheme a gateway within the forwarding region forwards geocast packets, but only a limited number of gateways do this job. To limit the number of gateways, a gateway forwarding a packet sends it to at most three neighbors rather than to every neighbor. The idea is that each ticket is responsible for carrying one copy of the geocast packet to the destination region. Thus, by selecting a certain number of tickets the initial sender not only determines the overhead of geocast delivery but also the success probability of delivery.

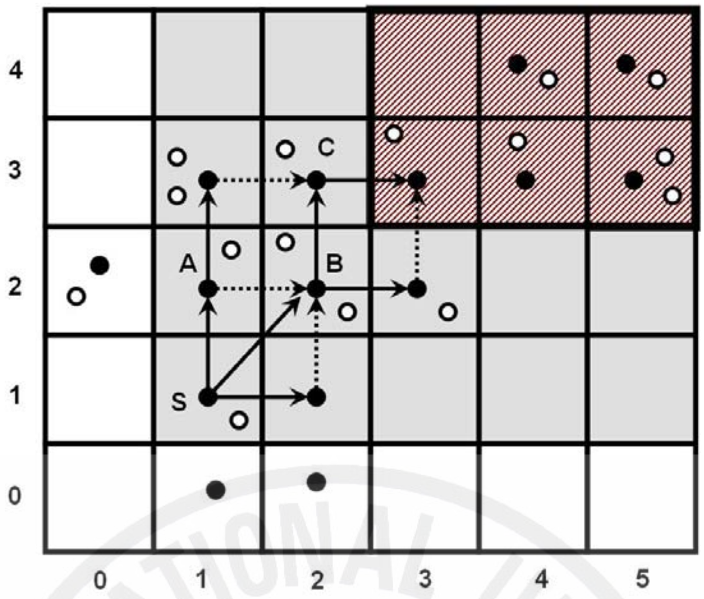


Figure 2.6: Flooding-based GeoGrid operation.

2.3.1.3 Geocast Adaptive Mesh Environment for Routing (GAMER)

The authors of Geocast Adaptive Mesh Environment for Routing (GAMER) (Camp and Liu, 2003) protocol propose a mesh-based geocasting protocol that provides redundant paths between the source and the geocast region. A node that wants to send packets to a geocast region first floods a JOIN-DEMAND (JD) packet in a forwarding zone until it reaches a node in the geocast region. After receiving the packet, this node unicasts a JOIN-TABLE (JT) packet back to the source node following the reverse route taken by the JOIN-DEMAND packet. When the source node receives its first JOIN-TABLE packet, it can start sending geocast packets via the path created to the geocast region. Since more than one node can send back the JOIN-TABLE packet, a mesh will be created which is used for sending packets on multiple redundant links.

GAMER defines three candidate Forwarding Approaches (FAs) for sending the JOIN-DEMAND packet. In each FA, the JD packet is flooded in their respective forwarding zones. These Forwarding Approaches are, CONE, CORRIDOR and FLOOD FAs that a source can choose based on the network condition. Therefore, when nodes are highly mobile, a dense mesh is created and when nodes are moving slowly, a sparse mesh is created. These three Forwarding Approaches are illustrated in Figures 2.7, 2.8 and 2.9 (The figures are similar to those in Camp and Liu, 2003).

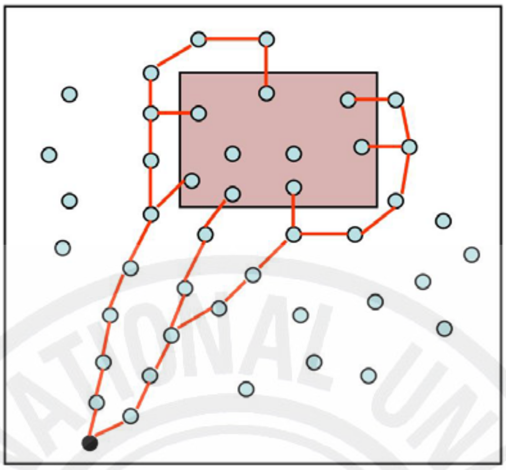


Figure 2.7: GAMER with FLOOD Forwarding Approach where the forwarding zone is the whole network. The filled rectangular area is the geocast region.

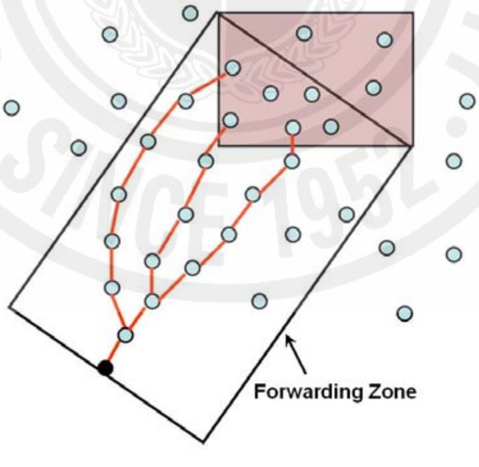


Figure 2.8: GAMER with CORRIDOR Forwarding Approach.

Two versions of GAMER are proposed by the authors: passive GAMER and active GAMER. In passive GAMER, the JOIN-DEMAND packets are transmitted at a fixed frequency at every JOIN-DEMAND packet interval regardless of whether a

JOIN-TABLE packet is received. Whereas, in active GAMER, the JOIN-DEMAND packets can be sent at a higher rate if a JOIN-TABLE packet is not returned within a given timeout period.

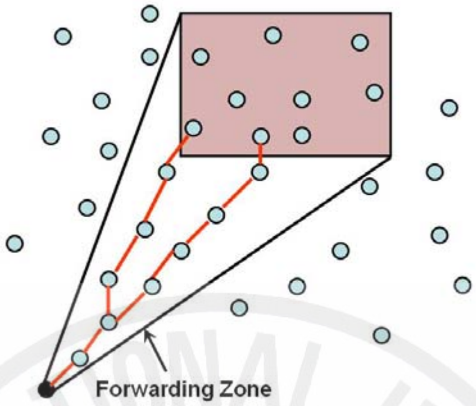


Figure 2.9: GAMER with CONE Forwarding Approach.

2.3.2 Face Traversal based Geocasting protocols

The face traversal based geocasting protocols use the planar graphs for routing the packets to the geocast region. Some of these protocols are discussed as follows:

2.3.2.1 Geographic Forwarding Perimeter Geocast (GFPG)

In Seada and Helmy (2004), authors proposed a Geographic Forwarding Perimeter Geocast (GPFG) algorithm that attempts to guarantee the delivery of geocast packets to all nodes in a geocast region. Authors observed that it is sufficient to traverse only those faces that intersect the boundary of a given geocasting region to ensure delivery of packets to nodes in a geocast region. The source node first sends the packet towards the geocast region using the GFG algorithm (Bose *et al.* 2001). After reaching the geocast region, each node inside the region retransmits the packet when receiving it for the first time. This is termed as regional flooding.

A node is considered as a border node if it has neighbors connected outside of the geocast region. The faces intersecting the region are traversed by sending perimeter packets to the neighbors outside the region in the planar graph. After receiving the perimeter mode packet, the node outside the region forwards it to its neighbor using the right-hand rule. The packet traverses the face until it enters the region again. The first node inside the region floods it inside the region if it receives for the first time, otherwise ignores it (Seada and Helmy, 2004).

Although, the authors of Seada and Helmy (2004) claim that their protocol guarantees the delivery of geocast packets, Stojmenovic (2004) shows that GFPG does not guarantee delivery. The author improved the algorithm presented in Seada and Helmy (2004) and proposes an enhanced geocasting algorithm that shows the delivery guarantee. The authors of Lian et al. (2006) name this improved protocol as Restricted Flooding with Intersected Face Traversal (RFIFT).

2.3.2.2 Restricted Flooding with Intersected Face Traversal (RFIFT)

The main difference between GFPG and RFIFT is that, in RFIFT external border nodes perform right hand rule based face traversals with respect to all corresponding neighboring internal border nodes no matter how the message arrives to them. Whereas, in GPFG, it is activated only from internal border neighbor, for one face at a time as described in Seada and Helmy (2004).

In RFIFT, by sending perimeter packets to neighbor nodes outside the geocast region, the faces intersecting the region are traversed. The node outside the region receiving the perimeter mode packet forwards the packet using the right-hand rule to its neighbor and so on (Stojmenovic, 2004). Here, every face intersecting the geocasting region and connected to the source is fully traversed by the combination of regional flooding and outer face traversals. The main point here is that the right-hand traversal of any face is composed of pieces containing regional flooding for consecutive face nodes inside a region, and pieces outside the region that are triggered when a packet is received there. The author says that, regional flooding, piecewise face traversal, and connectivity ensure that all possible nodes are reached hence guaranteeing the delivery of packets to all nodes (Stojmenovic, 2004). The author also shows that the scheme is close to a message optical scheme, since each node in the region transmits the packet only once. The details of the algorithm can be found in Stojmenovic (2004).

Although the author of RFIFT shows with proofs that their proposed protocol guarantees the delivery of packets to all nodes, there are no simulations shown for this purpose. Moreover, the face traversal based algorithms using planar graphs are usually very slow in terms of computation time as they spend a lot of time in traversing faces of a planar graph. The high maintenance costs and complexities associated with the deployment of face routing algorithms make them quite expensive.

Chapter 3

LOCATION-AWARE GRID-BASED HIERARCHICAL ROUTING IN MOBILE AD HOC NETWORKS

In this chapter, a hierarchical routing protocol called Location-aware Grid-based Hierarchical Routing (LGHR) is proposed for mobile ad hoc networks, which uses non-overlapping zones for efficient routing. The whole network is divided into non-overlapping zones and each zone is then further divided into smaller grids. Each node knows its position with the help of a GPS receiver. The protocol is a location-aware routing protocol but the routing is performed in a similar way as in link state routing. That is, the neighbor node information is needed for creating routing tables and making routing decisions. Each zone has a leader node and all nodes in a zone send their neighbor node information to the leader. The leader is responsible for maintaining routing tables and making routing decisions. Each smaller grid in a zone has a gateway node which is responsible for its own grid. The leader sends the routing tables to respective gateway nodes present in its zone. On the basis of these routing tables, the gateway nodes forward the packets. The protocol is compared with another location-aware hybrid zone-based routing protocol called Zone-based Hierarchical Link State (ZHLS) (Joa-Ng and Lu, 1999). ZHLS, which is also a hierarchical routing protocol, uses link state routing in each zone. Each node in a zone sends its link state packets to all other nodes in its zone. Therefore, each node stores and makes intra-zone and inter-zone routing tables causing huge communication overhead in case there are large numbers of nodes in a zone. The proposed protocol LGHR reduces the communication and storage overhead by further partitioning each zone into smaller grids. Unlike ZHLS, only the gateway nodes keep the routing tables and routing is performed in a gateway-by-gateway manner. Non-gateway nodes are not responsible for keeping these tables and forwarding the incoming packets.

In ZHLS protocol, despite the fact that each node has a GPS receiver; it does not effectively utilize the location-based capability like other position-based routing protocols. The protocol initiates a reactive zone search mechanism if the destination node lies outside the current source's zone. The proposed protocol uses pro-active mechanism inside a zone but unlike ZHLS, it does not initiate a reactive zone search mechanism if the destination lies outside the zone of the source node. Instead, the location-based strategy is used to identify the destination's zone by mapping the position of destination on the zone map. The analysis of both protocols is shown in chapter 4.

The proposed protocol is also compared with another location-aware routing protocol called GRID (Liao *et al.,* 2001) in order to check the stability of the protocols. The stability factor is chosen on the basis of gateway election mechanisms. The evaluation of both protocols is done in chapter 4. The simulation results show that the proposed protocol LGHR is more stable than GRID especially in scenarios where the wireless nodes are moving with very high velocities.

3.1 Introduction

A mobile ad hoc network is composed of a number of wireless nodes connected through radio links forming a dynamic autonomous network in a mobile manner. Nodes communicate with one another without any centralized access points and each node acts both as a router as well as a host. Several routing protocols have been proposed by various researchers for mobile ad hoc networks (Basagni *et al.,* 1998; Joa-Ng and Lu, 1999; Haas and Pearlman, 1998; Jacquet *et al.,* 2003; Johnson and Maltz, 1996; Karp and Kung, 2000; Ko and Vaidya, 2000a; Park and Corson, 1999; Perkins *et al.,* 2003) which include proactive, reactive and hybrid routing. Zone Routing Protocol (ZRP) (Haas and Pearlman, 1998) is a hybrid routing protocol in which proactive mechanism is performed for the intra-zone routing whereas reactive strategy is initiated during the inter-zone routing. Zone-based Hierarchical Link State (ZHLS) (Joa-Ng and Lu, 1999) is another hybrid routing protocol in which there is no central zone-head or leader and all nodes communicate in a peer-to-peer fashion. Proactive link state routing is done inside the zone and a reactive zone search mechanism is initiated when the destination node lies in a different zone than that of the source node. The problem with this protocol is that every node has to keep the information of the whole zone topology which is not suitable if there are large numbers of nodes inside the zone. Since there is no central authority, every node has to keep and update routing tables even if they are not involved in forwarding packets to other nodes. Moreover, although ZHLS is a GPS-based protocol, it does not fully utilize the position information taken by the GPS receiver. For example, if a node wants to send a packet to a node and the destination node lies in the same zone, it uses its intra-zone routing table which is made on the basis of the local link state information. And if the destination node does not lie in the same zone, then it initiates a reactive zone search mechanism in order to get the zone ID of the destination. The protocol can save a lot of messages if it exploits the location information received by the GPS receiver. It only uses this information to let a node know which zone it lies in. Like other location based protocols, if it knows the location of the destination, it can easily identify the zone ID of the destination. The location of the destination can be found by using a location server, as used in other location-aware routing protocols like LAR, GPSR and GRID etc.

In GRID (Liao *et al.,* 2001), which is a location-aware reactive routing protocol, authors use the term “grid” instead of a zone and propose a grid-based routing mechanism in which every grid has a gateway node and routing is performed only through gateways in a grid-by-grid manner. The gateway node is elected by a gateway election procedure. Like all reactive routing protocols, this protocol also has to search a route if a node wants to send a packet to another node. Hence, there is a route request and route reply mechanism. One major problem with this protocol is that, since the grid size is small, the gateway nodes are likely to move out of the grid very frequently as the criteria for gateway election is only the shortest distance from the center of the grid. Hence, the nodes inside the grid have to initiate the gateway election procedure very frequently causing the network to become unstable. In GRID, there is no consideration for the speed and direction of movement of the gateway nodes. A second problem is that, since the routing is performed in a grid-by-grid manner and there can be several grids in a node's radio range, a packet has to travel through several extra hops which makes the protocol inefficient.

In this chapter, a Location-aware Grid-based Hierarchical Routing Protocol (LGHR) is proposed for mobile ad hoc networks. Each node in the network is assumed to know its position with the help of a GPS receiver etc. The network is partitioned into non-overlapping zones where each zone is represented in the form of a square.

3.2 Location-Aware Grid-based Hierarchical Routing Protocol

In this location-aware hierarchical routing protocol, the role of leader and gateway nodes is introduced. As stated earlier, the network is divided into non-overlapping zones. Each zone is controlled by a central node called leader. The leader is responsible for maintaining the routing information as well as making routing decisions inside a zone. A zone is further divided into smaller grids where one node is elected as a gateway node and is responsible for routing the packets to other nodes. The routing is performed in a gateway-by-gateway manner. The detail about these regions, leaders and gateway nodes is discussed in subsequent sections.

3.2.1 The Network Layout

The network is divided into zones. Each zone is further divided into smaller equal-sided grids. Each grid can have minimum zero or maximum one gateway node. A gateway node is elected out of all the nodes present in the grid. These gateway nodes are responsible for routing the packets in the network. Other nodes in the same grid are not mainly involved in performing the routing operations. The layout of the network including zones, grids and gateway nodes is shown in Figure. 3.1.

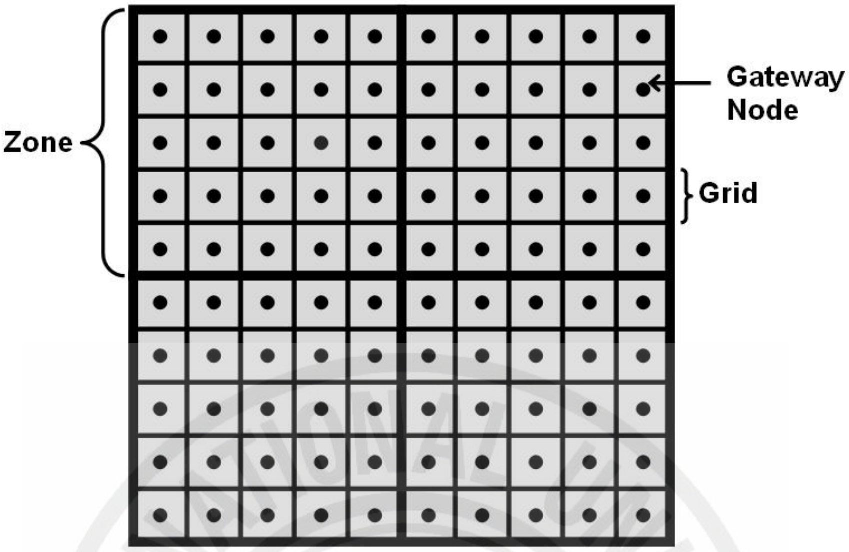
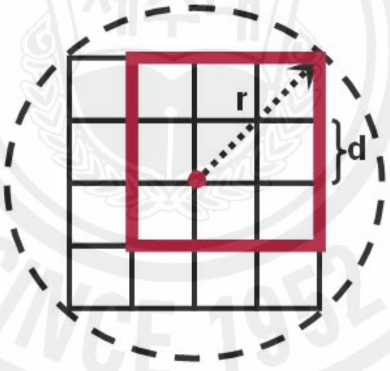


Figure 3.1: The network is divided into zones and each zone is further divided into smaller grids. Each grid can have a gateway node which is elected according to the gateway election procedure.

3.2.1.1 The Zone Size

An important thing while dividing the network into zones is fixing the size of a zone as well as the size of each small grid. The zone size should be kept in such a way that it should minimize the communication overhead as well as the routing overhead. If the zone size is large then there would be large numbers of nodes inside the zone and therefore, more overhead would be induced due to intra-zone routing table creation and updates. Moreover, there would be more gateways in the zone and more overhead would be incurred due to gateway election procedures for each gateway. The zone size should be such that if the leader is in the middle of the zone then it should be able to reach any node inside the zone in a fewer number of hops. It would be ideal if the leader can reach any node in one hop. But the problem in this case is that large numbers of zones would be present in the network which again would result in huge communication and control overhead. It would be more suitable if the leader can reach any node in a zone in two hops. This is because; within two hops a node can know the position of its two hop neighbors. Other wise, in order to know the position of a node, it will use flooding or some other mechanism which is more costly in terms of communication overhead.

Also, there is a need to fix the size of each small grid in a zone. In the proposed protocol, each side of a grid is kept to be equal to $r/2\sqrt{2}$. The reason behind this is that if each side of a grid is $r/2\sqrt{2}$, a node in a grid can access all nodes in its neighboring grids from anywhere in the grid. Even if it is at one corner of its own grid, it would still be able to access all the neighboring grids completely including the diagonal ones. Since the routing is performed on gateway-by-gateway basis, a node should be able to access its surrounding gateways so that it can send packet to one of these gateways. Figure 3.2 shows the reason why the side length of a grid is taken to be $r/2\sqrt{2}$. Moreover, the zone size is kept symmetric i.e., each zone can have 1x1, 2x2, 3x3, 4x4 etc. grids per zone.



$$d = r/2\sqrt{2}$$

Figure 3.2: The size length 'd' of each side of a grid.

3.2.2 The Leader Node

In LGHR, each zone in the network has one leader node. The main responsibility of a leader is to lessen the routing burden on other nodes in a zone. The leader maintains two kinds of tables; a neighbor table and a zone table. Neighbor table contains the neighbor node information of nodes inside a zone which is periodically sent to the leader by these nodes. Zone table contains information about all the connected zones in the whole network. The leader performs two major tasks. First, it stores the neighbor information periodically sent by nodes of a zone in a neighbor table. On the basis of this information, it constructs the intra-zone routing table for that zone. Secondly, it keeps the inter-zone connectivity information in a zone-table and performs the inter-zone routing based on this zone-table.

3.2.2.1 The Leader Region

The leader region is an area where the leader node can move around after becoming leader, without the need to elect another one. Also, only the nodes inside the leader region can compete for becoming a leader. Since all nodes are mobile, the leader node can also move out of its leader region. In order to make the routing process more stable, the size of the leader region is fixed in such a way that even if the leader is not at the center of the zone, it still functions as the leader node. In other words, as long as it is inside the leader region, it continues to perform its duties as leader. The leader region ‘LR’ is therefore taken to be $3d \times 3d$ i.e., each side of the leader region is taken to be $3d$ where $d = r / 2\sqrt{2}$ and ‘r' is the radius of the radio range of a mobile node. The reason for fixing the value of leader region to a value is that if the value of leader region changes frequently, the network may not work in a stable manner. Secondly, by fixing the value to $3r / 2\sqrt{2}$ is due to the reason that even if the leader is at the extreme corner of the leader region, it is still able to access the center of the zone easily. Once it moves out of the leader region, it can inform the nodes near that center of the zone that it is no more a leader now and therefore, the nodes near the center can initiate the leader election process again to elect a new leader. The leader election procedure is explained in the next subsection. This situation is depicted in Figure 3.3. In the proposed system, a zone can be composed of 3x3, 4x4, and 5x5 etc. grids. In case of a zone size equal to 3x3, the leader region would be equal to the whole zone size. If the zone size is smaller than 3x3 grids, the leader region would still be equal to the zone size and would not exceed the zone size. Figure 3.4 shows different zone sizes with each side of the leader region equal to $3r/2\sqrt{2}$. It is observed that if the zone is even smaller than a 3x3 grid zone, there would be too many zones in the whole network and therefore, large numbers of extra control packets would be transmitted within the network for selecting leaders and gateway nodes as well as maintaining routing tables for such large number of leaders. Therefore, the zone size should be large enough so that such kind of overhead is avoided.

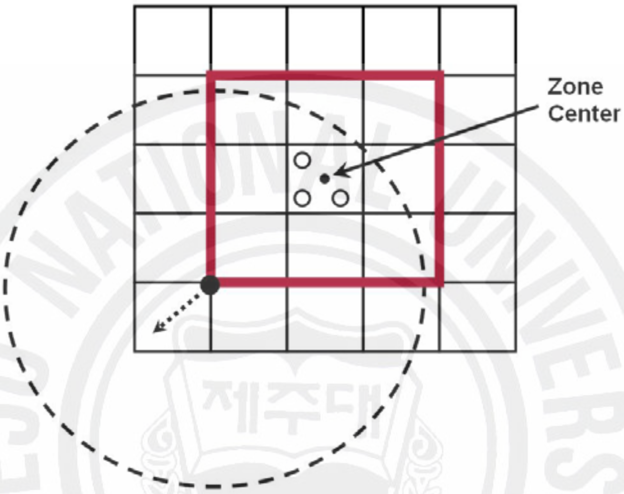
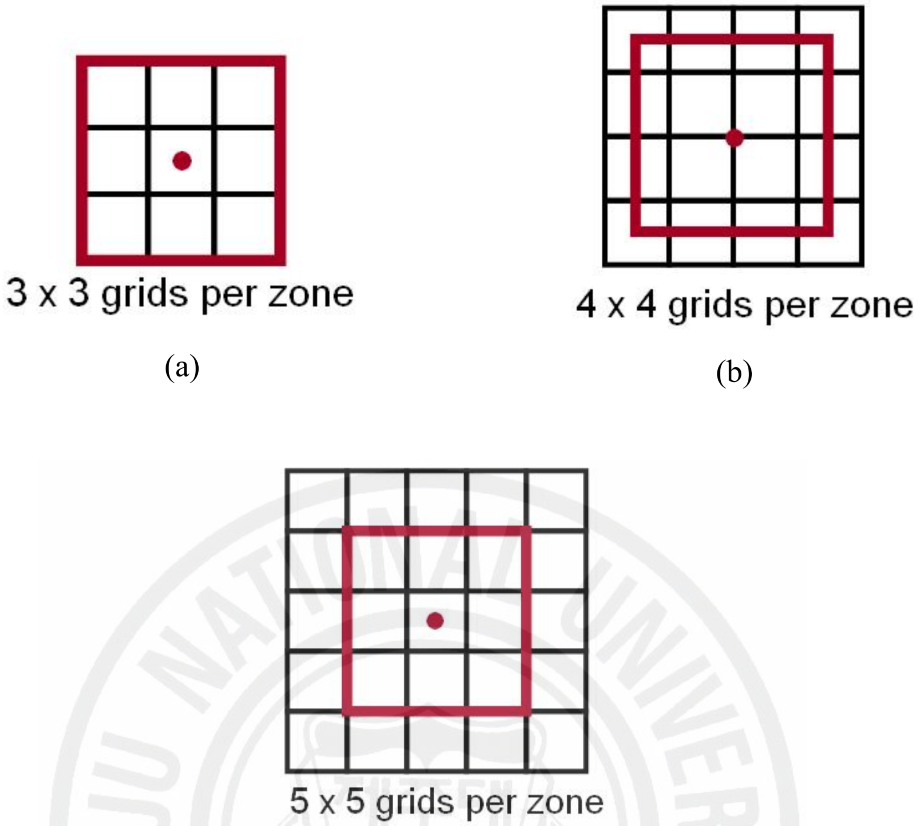


Figure 3.3: The leader moving outside the leader region is still able to access the nodes near the center of the zone asking them to initiate leader election procedure again.



(a) (b) (c)

Figure 3.4: Leader region 'LR' is shown for different sizes of zones. LR is fixed and its value on each side is 3*d* (a) 3x3 grids per zone (b) 4x4 grids per zone (c) 5x5 grids per zone

3.2.2.2 Leader Election

A node that is nearest to the physical center of a zone is chosen as leader. Any node is considered eligible for becoming a leader if it meets the following criteria: First, it should have enough resources e.g., storage, battery, and processing power etc. for which the values are predefined, and secondly, it should be inside the leader-region.

All eligible nodes inside the leader-region can compete for becoming the leader. Any contesting node can announce itself as leader and send its position to all nodes inside the leader-region. Any other node nearer to the physical center of the zone can reject the announcement and declare itself as new leader. If it does not hear any other claim within a predefined interval, it becomes the leader. The node will serve as a leader even if it moves to another position inside the leader-region. However, if it moves out of the leader-region, it automatically detects that. Therefore, it informs the nodes within the leader region that it is no more a leader and then other nodes do the same leader-election procedure and elect a new leader.

Every leader in a zone periodically broadcasts its identity to all the nodes in its zone. This packet from leader contains the leader-id and its position. The leader announcement packet is shown in Figure 3.5. Each node in the zone pro-actively sends its position and list of neighbors to the leader node. Therefore, the leader knows the local topology inside the zone and maintains the neighbor table. If a node is connected to a node in another zone, then the zone-id is written in the neighbor table instead of the node-id. The leader also maintains zone table and sends it to all the leaders in other zones. This is done by using its inter-zone routing table. This zone table shows which zones are connected to which other zones. Neighbor table and zone table are constructed on the similar principle as Node LSP (Link State Packet) and Zone LSP in ZHLS protocol respectively. But in case of LGHR, only leader keeps these tables instead of all the nodes in a zone. The leader also constructs and keeps the intra-zone and inter-zone routing tables. The routing tables are made by using the shortest path algorithm mainly based on the number of hops from the destination node.

In case the leader node fails or resets then the other nodes will stop receiving the periodic announcement packet from the leader. If the packet is not received until some predefine period of time, the nodes will assume that the leader is failed or it does not exist any more. In this case, the leader election process will start again and the nodes will elect a new leader. In case there is no node present in the leader region, then the leader region is expanded to the whole zone and the leader election process is performed using all nodes in the zone.

Leader ID	Position

Figure 3.5: Leader announcement packet.

3.2.3 The Gateway Node

A node in each grid in a zone is elected as a gateway which is mainly responsible for performing routing operations in the network. As mentioned earlier, nodes in a zone send their neighbor information to the leader node. Gateway nodes also send their neighbor information to the leader. While sending their neighbor information, they also identify themselves as the gateway in the same message so that the leader knows which nodes are gateway nodes. Based on this information, the leader constructs routing tables and periodically broadcasts it to the gateway nodes. One thing to note here is that all nodes in a zone send their neighbor information to the leader but the leader constructs the routing tables only for the gateway nodes. Moreover, the routing table entries contain only the gateway nodes as the next hop node for each destination. This is because in the proposed protocol, the routing is performed in a gateway-by-gateway manner. Therefore, although a source or a destination node can be a non-gateway node, the intermediate nodes which are involved in forwarding the packets must only be gateways. The gateway-by-gateway routing process is explained in detail in section 3.3.

In the proposed location-aware hierarchical routing protocol, there are two kinds of gateway nodes within a zone. One is called *Edge Gateway nodes* and another is called *Intermediate Gateway nodes*. Edge Gateways are those gateway nodes that are at the edge or boundary of a zone. All other gateways in a zone except the Edge Gateways are Intermediate Gateway nodes. The reason to classify gateways into two categories is due to their different functionality. Edge Gateways are responsible for storing both intra-zone as well as inter-zone routing tables whereas the Intermediate Gateways are responsible for storing only the intra-zone routing tables. Hence, Intermediate Gateways are supposed to forward a packet within their zone and Edge Gateways forward packets to or from other zones. The main reason for classifying gateways into two kinds is to lessen the burden from the Intermediate Gateway nodes. Since the Edge Gateways are at the boundary of a zone, they are in a better position to maintain inter-zone routing tables. The two kinds of gateway nodes are shown in Figure 3.6

All gateway nodes are meant to store routing tables, but they are not responsible for creating them. It is the leader's responsibility to create the routing tables for the gateway nodes. Any node that wants to send a packet to another node sends it to the gateway node. Gateway looks up the routing table and forwards it to next hop gateway node. The gateway nodes also send their identity to their neighboring nodes inside the periodic Hello message so that the nodes can know which nodes are gateway nodes and which are not.

As mentioned earlier, a zone is divided into smaller grids. Each side'd' of the grid is equal to $r/2\sqrt{2}$, where 'r' is the radio range of a mobile node. This distribution is kept so that any node anywhere in a grid should access all the gateways in their surrounding grids. Each grid also contains one gateway node that is responsible for routing operations.

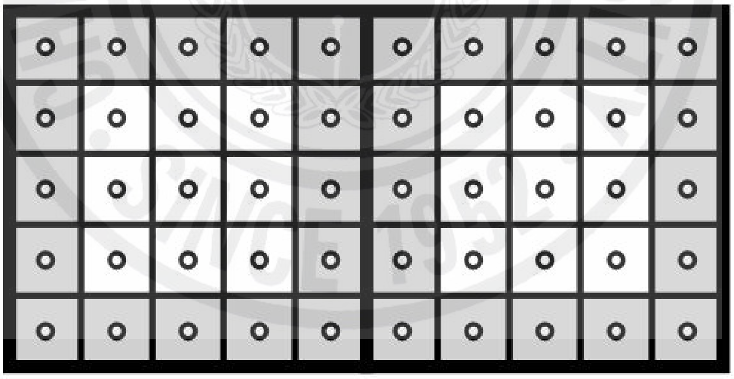


Figure 3.6: Two adjacent zones where the shaded grid contains the Edge Gateway nodes whereas the white grids have Intermediate Gateway nodes.

3.2.3.1 Gateway Election

Only one node can be elected as gateway out of several candidate nodes. Gateway election procedure is slightly different from the leader election but it is same for both Edge and Intermediate Gateways. Any eligible node that wants to become a gateway announces itself as gateway node and broadcasts its position as well as its velocity to other nodes in the grid. The decision of making it a gateway depends on the following distance formula:

$$dist_i = \sqrt{(X_i - X_c)^2 + (Y_i - Y_c)^2 + V_i^2} \tag{3.1}$$

where, X_i and Y_i are the position co-ordinates of the *ith* announcing node, X_c and Y_c are the center co-ordinates of the grid and V_i is the velocity of the *ith* node. The velocity V_i can be represented as:

$$\overrightarrow{V_i} = \overrightarrow{V_{ix}} + \overrightarrow{V_{iy}} \tag{3.2}$$

Based on the distance formula in equation (3.1), the distance from the center of the grid is calculated. This formula incorporates both position co-ordinates as well as the velocity of the moving nodes. It will elect that node as gateway which has the minimum value of '*dist'* i.e., a node that is closer to the center of the grid as well as it has a small value of velocity would be elected as gateway. Hence, if a node that is nearest to the center and has very high velocity will not be elected as gateway. Instead, a node that is not the nearest to the center of the grid but also not the farthest having low velocity would be elected as the gateway node. If any other node has less value of *'dist'* than the announcing node, it rejects its claim and announces itself as the new gateway. Until some predefined time, if there is no other claim heard, this node assumes the responsibilities of a gateway and sends a message to the leader telling it about its existence. It also periodically broadcasts its existence to other nodes inside the grid. Here, both position and velocity are considered for electing a gateway because the size of the grid is very small and the nodes are also mobile. Since the grid size is very small, if the only criterion for a gateway node is to be nearest to the center of the grid then there is a high probability that the gateway node would move out of the grid quite frequently and each time it moves out, a new gateway election procedure has to be started. Therefore, the network can become unstable causing the routing function to work in an undesirable manner.

One more thing to be noted is that even if the gateway elected is close to the center of the grid and its velocity is also slower than other nodes, it still can be a wrong choice to be elected as gateway. This can happen if the node is moving away from the center of the grid i.e., the direction of the moving node is opposite to the center. In this case, one has to consider the direction of velocity of the moving node.

In order to know the direction of a moving node, consider the following scenario as shown in Figure 3.7. In order to know the direction of velocity of a node, the angle θ is needed to be known with respect to the center of the grid. For this purpose, two angles are taken. The first angle θ_1 is taken with respect to the center of the grid when a node is at position (X_i, Y_i) and the second one θ_2 is taken along the X-axis with respect to the previous position $(X_i\text{-}1, Y_i\text{-}1)$ of the node currently at (X_i, Y_i). For each position, the slope m_1 and m_2 are needed. Finally the difference of both angles θ_1 and θ_2 is taken.

As shown in Figure 3.7, in order to know these two angles, the slopes at both positions should be known. Therefore, the slopes m_1 and m_2 can be calculated as:

$$m_1 = \frac{(Y_c - Y_i)}{(X_c - X_i)} \tag{3.3}$$

$$m_2 = \frac{(Y_i - Y_{i-1})}{(X_i - X_{i-1})} \tag{3.4}$$

θ_1 is calculated as:

$$\theta_1 = \tan^{-1}(m_1) \tag{3.5}$$

θ_2 is calculated as:

$$\theta_2 = \tan^{-1}(m_2) \tag{3.6}$$

The difference of both angles is:

$$\theta_{diff} = |\theta_1 - \theta_2| \tag{3.7}$$

In order to know the right direction, the following two conditions must be satisfied.

1. $$\theta_{diff} \le \frac{c}{1+e^{-\alpha dist_i}} \quad where \quad c = 45° \\ and \quad \alpha > 1 \tag{3.8}$$

2. $$sign(m_1).sign(m_2) > 0 \tag{3.9}$$

θ_{diff} in equation (3.8) determines the direction of the moving node. The value of *c* shows the maximum value of angle for the competing nodes and it can be other than 45° depending upon the situation. This angle can be higher if there are small numbers of nodes in the grid. The parameter α is used for having transition from the maximum angle to the minimum angle of moving nodes. Larger value of α corresponds to an abrupt transition from the maximum angle to the minimum angle whereas a smaller value of α shows a slow transition of angle from the maximum value to the minimum. The condition in equation (3.9) must also be satisfied i.e., the product of both the slopes m_1 and m_2 should be positive. This means that a node is moving in the same direction as it was at the previous step.

Hence, for the gateway election procedure two things are calculated: the distance and the direction of moving nodes. The distance formula is used from equation (3.1) and the direction of velocity is calculated from equations (3.8) and (3.9).

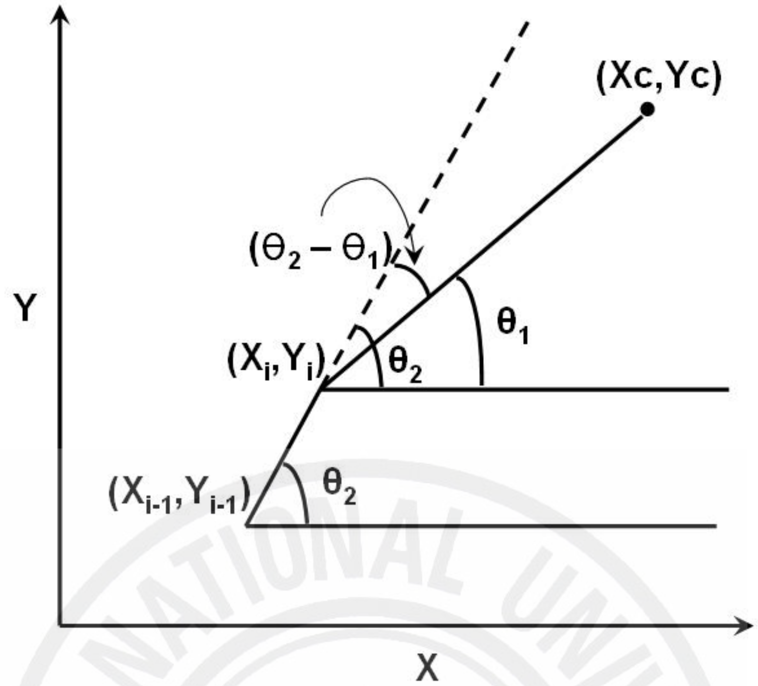


Figure 3.7: Two angles θ_1 and θ_2 are needed in order to calculate the direction of a moving node.

For the gateway election procedure, there can be three cases, which are listed as follows:

- If more than one nodes present in the grid and moving in different directions.
  - *Use distance formula with direction.*
- If more than one nodes present in the grid and no node is moving in the direction of the center.
  - *Use distance formula and ignore the direction.*
- If only one node present in the grid.
  - *Ignore the distance formula and ignore the direction.*

In the last case, the node will be elected as a gateway even if it is moving away from the center of the grid. A detailed simulation analysis is presented in chapter 4 for comparison of the proposed gateway election mechanism with another scheme.

3.3 Zone Discovery and Basic Routing Mechanism

When a new node is activated initially, it gets its position with the help of a GPS receiver. Once it knows the position, it can easily figure out which zone it lies in, using the zone map of the network.

3.3.1 Intra-zone Routing

Each node in a zone broadcasts a hello packet to its neighbors which contains its node-id. Also, every node in a zone sends its neighbor connectivity information to the leader node. This information includes its position and the list of its connected neighbors. From this neighbor information, the leader makes the neighbor table which contains the list of all the nodes and their neighbors. Based on the neighbor table, leader creates an intra-zone routing table for its own zone. Since only the gateway nodes forward the packet, the routing table entries include only the gateway nodes as the next hop node. Non-gateway nodes are included in the routing table only as destination nodes. The routing table is made on the basis of shortest path algorithm where the shortest path can be calculated depending on distance in terms of number of hops from the destination node. After making the routing table, leader sends the individual routing tables to the respective gateway nodes. Gateway nodes use this table for making routing decisions. An example in section 3.4 shows how the intra-zone routing tables and inter-zone routing tables are created as well as other details.

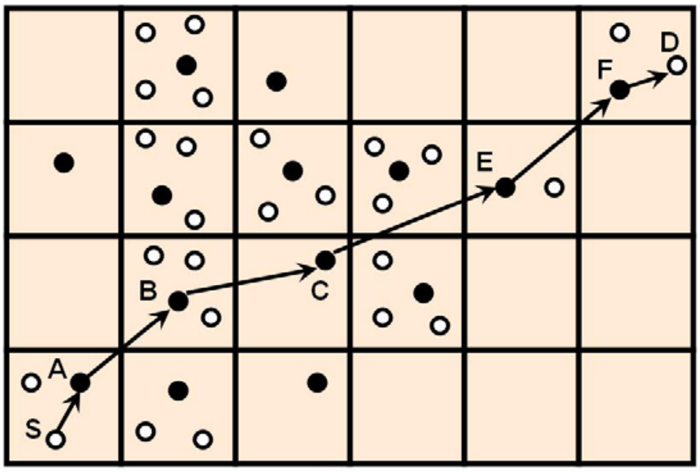


Figure 3.8: Intra-zone routing mechanism; filled black circles are gateway nodes whereas unfilled circles are non-gateway nodes. Routing is performed in a gateway-by-gateway manner.

The routing is mainly performed using the gateways nodes. A node that wants to send a message sends it to one of the gateways in its neighborhood. Whenever a non-gateway node wants to send the packet to the destination node, it sends it to the gateway of its own grid. If there is no other node present in the grid then the source node itself is a gateway node and it already has its respective routing tables. When packet reaches a gateway node, it looks up the next hop information in the routing table and forwards packet to the next gateway node. This whole process is repeated until packet reaches the destination. The intra-zone routing mechanism is shown in Figure 3.8.

Here, node S sends a packet to a gateway node in its grid. The gateway node then looks up its intra-zone routing table and sends the packet to a gateway in another grid. This process is repeated until the packet reaches the gateway in the destination grid. Since the destination node is not a gateway node so the next hop node will not be any other node than the gateway itself. This means that the destination node lies in the same grid. Since all nodes know their neighbor node information, the packet can be directly delivered to the destination node D by the gateway. One important thing to mention here is that in the proposed protocol, if a gateway node is in the radio range of another gateway that does not lie in the adjacent grid, it can still forward packet to this gateway in its non-adjacent grid. This situation can be seen in Figure 3.8 where node C sends a packet to node E despite the fact that there are other gateways present in C's adjacent grids. The reason is that in LGHR, the routing is performed in a gateway-by-gateway manner, not in a grid-by-grid manner. Since node E lies in the radio range of node C, therefore, the routing table is made in such a way even if node E does not lie in C's adjacent grid, it is still selected as the next hop gateway. This decision is made on the shortest path algorithm based on fewer numbers of hops. In section 3.4, such kinds of scenarios as well as the routing table creation mechanism is discussed in detail.

3.3.2 Inter-zone Routing

Every leader in the network sends the leader and zone information to all other leaders in the network. This information is forwarded based on its intra-zone routing table which contains the routing information of the connected zones as well. The leader information contains the leader ID and the connected neighbor zones along with the cost in reaching those zones, which is mainly the distance between leader and other zones. Based on this information, leader makes the zone table. Using this information, leader then creates inter-zone routing table and sends it to all the Edge Gateway nodes. These gateway nodes use this table for making inter-zone routing decisions.

The reason for sending the inter-zone routing table to only the Edge Gateways is that these gateways are at the boundary of a zone or in other words, these Edge Gateways are at the intersection of two zones whereas the Intermediate Gateways are inside the zone and are not connected to other zones. Therefore, by doing this, a lot of extra storage overhead as well as communication overhead can be reduced by giving this responsibility to only the Edge Gateways.

Initially, the source node that wants to send a packet sends it to the gateway node of its own grid. The gateway checks in its routing table whether the destination node is present in the same zone it lies in. If it cannot find the destination in its intra-zone routing table, inter-zone routing is initiated. It is assumed that, like other location-based routing protocols e.g., LAR, GRID etc., a node can know the position of the destination with the help of a location server. Here, if the gateway cannot find the destination node in its intra-zone routing table, it means that the destination lies in another zone. For this purpose, the gateway has to figure out which zone the destination lies in. Based on the position information, the gateway finds out the destination node's zone by mapping the position of the destination on a zone map. Here, there are two cases. If the current gateway is an Edge Gateway, it can forward the packet to the next gateway based on its inter-zone routing table. But, if the current gateway is an Intermediate Gateway, it has no way to know which gateway to forward the packet since it does not have the inter-zone routing table and keeps only the intra-zone routing table. Therefore, the Intermediate Gateway sends a Next-Zone request to the leader node. The leader replies back with the next zone ID. After receiving the next zone ID, the gateway node sends the packet to the next zone based on its intra-zone routing table. The next zone ID is appended in the packet and forwarded to the next gateway. Once the packet arrives at the Edge Gateway of the next zone, if the destination lies in the same zone, it sends the packet to the destination based on its intra-zone routing table. If the destination does not lie in that zone, the Edge Gateway appends the next zone ID in that packet and sends it to a gateway node in its zone. The next zone information is taken from the inter-zone routing table, not from the leader. Therefore, the source gateway has to take the next zone ID from the leader node only once in the beginning. Later on, the Edge Gateway of the next zone appends the next zone ID from its own inter-zone routing table. The process is repeated at every zone until the packet reaches the destination. Here, because of the next zone ID request to the leader, LGHR can be categorized as a hybrid routing protocol, where a proactive neighbor connectivity information is sent by all nodes to perform intra-zone routing and a reactive next zone ID request in initiated by an Intermediate Gateway node that wants to send a packet to a node in another zone. Inter-zone routing table is also made using the shortest path algorithm based on number of hops from the destination.

The important thing to mention here is that in LGHR protocol, since the location of the destination node is known from the location server, there is no need to initiate the zone search mechanism as done in ZHLS. By mapping the destination's location on the zone map, a node can easily figure out which zone the destination lies in. Therefore, the message can be forwarded to the Edge Gateway of the next zone based on intra-zone routing table. Once the message reaches the Edge Gateway of the next zone, it uses its inter-zone routing table to route the packet to the destination in another zone. Hence, LGHR saves lots of extra communication overhead as compared to ZHLS in which the protocol initiates a zone search mechanism if the destination does not lie in the same zone as that of the source. Secondly, since in the proposed mechanism, the Intermediate Gateways store only the intra-zone routing tables and only the Edge Gateways store both intra-zone and inter-zone routing tables, a lot of extra overhead is avoided as incurred by ZHLS where each node in a zone stores both intra-zone and inter-zone routing tables. This is shown mathematically in the evaluation section of the next chapter.

3.4 Example Scenarios

In this section, the proposed location-aware hierarchical protocol is compared with ZHLS with the help of an example. For this purpose, consider a scenario as shown in Figures 3.9 and 3.10. As mentioned earlier, the leader node in LGHR makes the neighbor table on the basis of information sent by nodes inside a zone. Similarly, every zone leader sends the zone connectivity information of the neighbor zones to all other leaders. Based on this information, the leader makes zone table. Neighbor table and zone table for the example scenario in Figures 3.9 and 3.10 are shown in Tables 3-1 and 3-2. Neighbor table contains the neighbor node information of all nodes. The position of each node is also written in the neighbor table which is utilized for constructing the routing tables.

In case of LGHR, the term "neighbor" needs to be defined as the criterion for being a neighbor is different for both gateway and non-gateway nodes. First, any node, either gateway or non-gateway, is said to be a neighbor of a non-gateway node if it lies in the same grid as that of the non-gateway node. Thus, the neighbor information sent by all non-gateway nodes contains only the neighbor nodes that lie in their respective grids. In Table 3-1, it can be seen that node 1 has only two neighbors, i.e., nodes 2 and 3. Node 2 is a gateway node whereas node 3 is a non-gateway node.

Secondly, the neighbors of a gateway node can be the non-gateway nodes within its own grid and the gateway nodes outside its grid that lie in its radio range. Hence, the neighbor information sent by the gateway nodes contains the non-gateway nodes in their respective grids as well as all the connected gateway nodes in their surrounding grids. The neighbor information sent by gateway nodes does not contain the non-gateway nodes in other grids. For example, in Table 3-1, node 5 has nodes 2, 4, 6 and 8 as its neighbors where node 4 and 6 are non-gateway nodes within its own grid whereas nodes 2 and 8 are gateway nodes outside its grid. Moreover, nodes 7 and 9 are not its neighbors though they lie within its radio range. The advantage of such a criterion is to avoid the extra information to be stored in the neighbor tables. Since the routing is performed only in gateway-by-gateway manner, therefore, the non-gateway nodes consider only those nodes as their neighbors that lie in their respective grids. The above-mentioned criterion for a neighbor node is for situations where large numbers of nodes are present in each zone. It may be different for other situations. In case of large numbers of nodes, another possibility can be to allow only the gateway nodes to send neighbor information to the leader.

As mentioned earlier, the gateway nodes do not necessarily send the IDs of the gateways that lie in their adjacent grids only. The neighbor nodes are those gateways that come within the radio range of a gateway node. There can be a case where the neighbor node of a gateway lies in a grid not adjacent to its own grid. For example, in Figure 3.9, node 19 does not lie in the adjacent grid of node 8 but it is connected with node 8 as it comes within its radio range, and therefore, is considered to be its neighbor. Same rule applies to nodes 2 and 10. The advantage of this gateway-by-gateway routing is that although there is no node in the adjacent grid, if there is a gateway node inside the radio range of a gateway node, it can still route the packet through that gateway. Moreover, if the numbers of nodes increase in the network, it will have no or very little effect on the routing performance. Since the routes are computed based on shortest path algorithm, therefore, the computed routes will always be the best routes with shortest distance in terms of number of hops. In GRID protocol, the routing is performed in a grid-by-grid manner even if there are gateways in non-adjacent grids that lie within the radio range of a gateway node. Hence, lots of useless hops have to be taken by each packet making the routing inefficient. In the next chapter, the proposed protocol LGHR is compared with GRID routing protocol as well.

3.4.1 Routing Table Construction

As mentioned previously, the routing table is created based on shortest path algorithm depending on the number of hops from the destination node. In other words, that node is decided as the next hop node which has the smallest number of hops from the destination node. If there is a situation where more than one path are available having same number of hops for the destination, then in that case, the physical distance of taken into consideration. Since each node that sends its neighbor information to the leader, also sends its position, therefore, the physical distance between two nodes can be easily calculated. Hence, if more than one path is available with same number of hops then the one with shortest physical distance from the destination would be selected. In Figure 3.9, it can be seen that if node 8 wants to send a packet to node 12, it has two paths with same number of hops i.e., one via node 19 and the other via node 10. In such a situation, node 8 selects node 10 as the next hop since the physical distance between node 8 and 10 is shorter using node 10 as the next hop than node 19. This thing can be confirmed from Table 3-3.

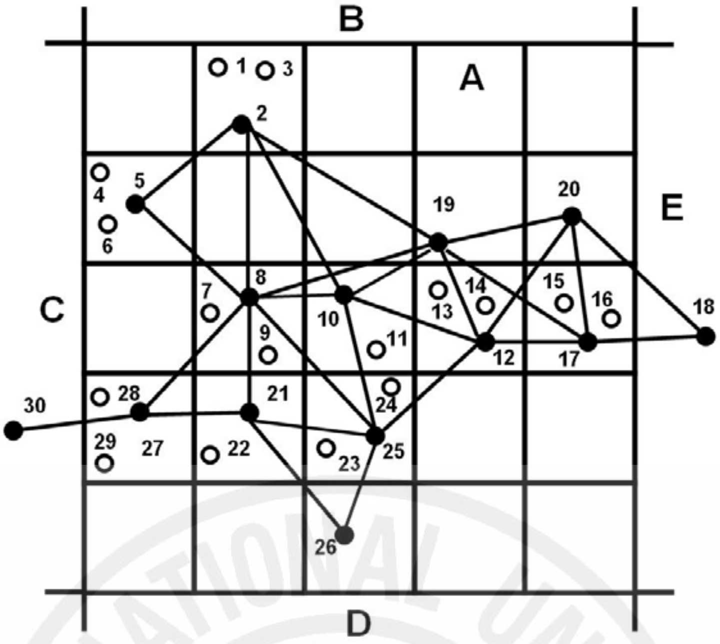


Figure 3.9: Local topology inside zone A for the example. The connectivity of gateway nodes with other gateways is shown with solid lines.

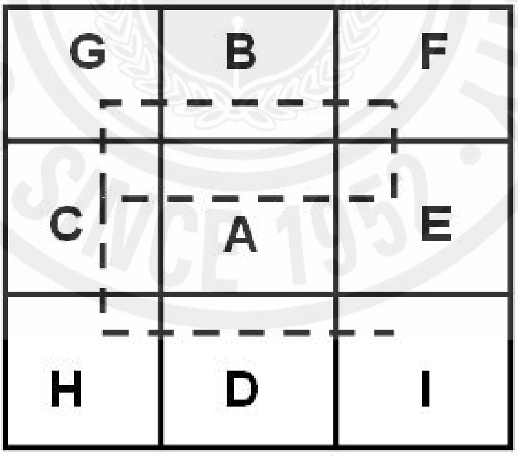


Figure 3.10: Complete inter-zone topology for the example scenario. The dotted line shows the connectivity among different zones.

3.4.2 Analyzing the Routing Entries

As mentioned earlier, in LGHR, a leader creates and maintains both intra-zone and inter-zone routing tables on the basis of neighbor and zone tables. Gateway nodes store their routing tables provided by the leader node but they do not keep the neighbor and zone tables. Moreover, neighbor and zone tables are created on the basis of node connectivity information and zone connectivity information which are almost similar as Node LSPs and Zone LSPs in ZHLS respectively. Therefore, both intra-zone and inter-zone routing tables can be computed easily for LGHR as well as for ZHLS.

The local topology for the example scenario inside a zone is shown in Figure 3.9. Solid line represents the direct radio connection between two gateway nodes. Figure 3.10 shows the complete zone-level topology with all the nine zones. The dotted line tells us which zone is connected to which other zone. Taking Figures 3.9 and 3.10 as an example, the routing entries are analyzed which are stored in Node LSPs, Zone LSPs, inter-zone and intra-zone routing tables in case of ZHLS and then are compared with entries stored by leader and gateway nodes in LGHR. A point to be noted here is that for the purpose of analysis, an entry is taken as one entity that has one row of information stored in some table in a node. The total number of bytes may differ in different entries.

In case of ZHLS, every node stores the Node LSP as well as Zone LSP and each node also maintains both intra-zone and inter-zone routing tables, which is a huge burden on each node. Table 3-3 shows the intra-zone routing entries stored by node 8 and Table 3-4 shows inter-zone routing table entries stored by node 17 on the basis of example scenario in Figures 3.9 and 3.10. The number of entries stored by these nodes as well as total entries stored by all nodes are shown in Table 3-5 for ZHLS. Based on the analysis, the total numbers of entries stored by all nodes are 2072. In case of LGHR, leader node stores neighbor and zone tables as well as intra-zone and inter-zone routing tables of only gateway nodes as routing is performed only through gateways. Edge Gateway nodes store both intra-zone and inter-zone routing tables whereas Intermediate Gateways store only intra-zone routing tables. Table 3.6 shows that LGHR stores only 829 entries for one zone in this example.

For the purpose of generalization, if it is assumed that the numbers of nodes are uniformly distributed in all the zones and the number of gateways is also same in all zones then the total number of entries for 9 zones would be 18648 in case of ZHLS and 7461 in case of LGHR. This clearly shows that LGHR stores much less entries than the total entries stored by ZHLS.

Table 3-1: Neighbor table for all nodes in the example

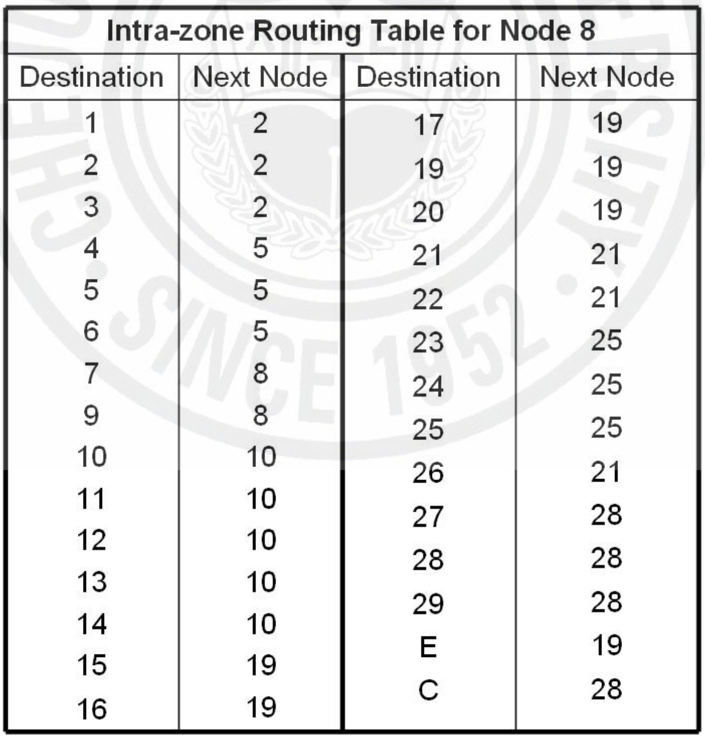
Neighbor Table					
Node	**Position**	**Neighbors**	**Node**	**Position**	**Neighbors**
1	(x1,y1)	2, 3	16	(x16,y16)	15, 17
2	(x2,y2)	1, 3, 5, 8, 10, 19	17	(x17,y17)	12, 15, 16, 19, 20, E
3	(x3,y3)	1, 2	19	(x19,y19)	2, 8, 10, 12, 17, 20
4	(x4,y4)	5, 6	20	(x20,y20)	12, 17, 19, E
5	(x5,y5)	2, 4, 6, 8	21	(x21,y21)	8, 22, 25, 27
6	(x6,y6)	4, 5	22	(x22,y22)	21, 26
7	(x7,y7)	8, 9	23	(x23,y23)	24, 25
8	(x8,y8)	2, 5, 7, 9, 10, 19, 25, 28	24	(x24,y24)	23, 25
9	(x9,y9)	7, 8	25	(x25,y25)	8, 10, 12, 21, 23, 24, 26
10	(x10,y10)	2, 8, 11, 12, 19, 25	26	(x26,y26)	25, 22
11	(x11,y11)	10	27	(x27,y27)	21, 28, 29, C
12	(x12,y12)	10, 17, 13, 14, 19, 20,25	28	(x28,y28)	8, 27, 29
13	(x13,y13)	12, 14	29	(x29,y29)	27, 28
14	(x14,y14)	13, 12			
15	(x15,y15)	16, 17			

Table 3-2: Zone table for all connected zones in the network

Zone Table

Zone	Neighbor Zones
A	C, E
B	G, F
C	A, G, H
D	H, I
E	A, F
F	B, E
G	B, C
H	C, D
I	D

Table 3-3: Intra-zone routing table for node 8



Intra-zone Routing Table for Node 8

Destination	Next Node	Destination	Next Node
1	2	17	19
2	2	19	19
3	2	20	19
4	5	21	21
5	5	22	21
6	5	23	25
7	8	24	25
9	8	25	25
10	10	26	21
11	10	27	28
12	10	28	28
13	10	29	28
14	10	E	19
15	19	C	28
16	19		

Table 3-4: Inter-zone routing table maintained by node 17

Inter-zone Routing Table for Node 17		
Dest. Zone	Next Zone	Next Node
B	E	18
C	C	19
D	C	19
E	E	18
F	E	18
G	C	19
H	C	19
I	C	19

Table 3-5: Entries stored by each node and all nodes in a zone in ZHLS

	Protocol	Node LSP Entries	Zone LSP Entries	Intra-zone Routing Table	Inter-zone Routing Table	Total Entries
Entries Stored by Each Node	ZHLS	28	9	29	8	74
Entries Stored by All Nodes	ZHLS	784	252	812	224	2072

Table 3-6: Entries stored by leader node and all one gateway nodes in one zone in LGHR

Protocol	Entries Stored By	Neighbor Table Entries	Zone Table Entries	Intra-zone Routing Table	Inter-zone Routing Table	Total Entries
LGHR	Leader	28	9	348	48	433
	All 6 Edge Gateways	0	0	174	48	222
	All 6 Intermediate Gateway	0	0	174	0	174
Total Entries stored by LGHR Protocol						829

Mathematical analysis is also done for both LGHR and ZHLS protocols in terms of storage overhead as well as communication overhead. The mathematical expressions derived from mathematical analysis are shown in the next chapter. Based on the mathematical analysis, and values used in above example scenario, it is proved that the Location-aware Grid-based Hierarchical Routing protocol (LGHR) works better than ZHLS in terms of numbers of entries stored in various tables as well as in terms of communication overhead.

3.5 Summary

An efficient routing protocol named as Location-aware Grid-based Hierarchical Routing (LGHR) protocol for mobile ad hoc networks has been presented in this chapter. In this protocol, the network is partitioned into non-overlapping zones. A hierarchy is made in such a way that the whole network is divided into zones and each zone is then further divided into grids. The role of leader node is introduced which is mainly responsible for making routing decisions. Both the intra-zone and inter-zone routing mechanisms are explained. The location-aware capability is utilized by LGHR is an effective manner and the zone search mechanism is avoided in case of the inter-zone routing. Moreover, a robust mechanism is introduced for the gateway election which uses both the position and velocity of a node for electing a gateway. This way the protocol works in a more stable way. The proposed protocol LGHR is analyzed and compared with other ad hoc routing protocols in the next chapter.

Chapter 4

ANALYSIS AND EVALUATION OF LGHR

In this chapter, the proposed protocol LGHR is compared with two other ad hoc routing protocols, ZHLS and GRID. In case of comparison with ZHLS, the mathematical analysis is done for both ZHLS and LGHR. Based on this analysis the evaluation and comparison is carried out for both protocols. The comparison of LGHR with GRID protocol cannot be fully done in all aspects as both protocols are different in basic routing functionality. GRID is a reactive routing protocol whereas LGHR is a proactive routing protocol. The common thing in both protocols is that a gateway election mechanism is carried out in each grid. It is shown that the mechanism proposed in LGHR is more robust and stable than the one shown in GRID protocol. The results are shown with simulations for each protocol.

4.1 Comparison with ZHLS

First, the evaluation of both LGHR and ZHLS is done and then both protocols are compared in terms of storage overhead as well as communication overhead.

4.1.1 Mathematical Analysis

This section shows the mathematical analysis done for both the storage overhead and the communication overhead generated by both ZHLS and LGHR protocols.

4.1.1.1 Storage Overhead

First of all, it is assumed that the total number of Nodes in the network are N and there are M zones in the whole network. It is also assumed that all the nodes are uniformly distributed in the whole network. Hence, the average number of nodes in one zone will be N/M. The average number of zones connected to each zone is Z.

(i) For ZHLS

For each node,

Entries in all Node LSPs = N / M

Entries in all Zone LSPs $= M$

Entries in Intra-zone Routing Table = N / M $-1+Z$

Entries in Inter-zone Routing Table = M -1

Hence the total number of entries stored in one node

$$= N / M + M + (N / M - 1 + Z) + (M - 1)$$
$$= 2N / M + 2M - 2 + Z$$

Total entries stored in N/M nodes in a zone = $N / M \ (2N / M + 2M - 2 + Z)$

Total entries stored by all nodes in M zones in the whole network

$$= M * N / M \ (2N / M + 2M - 2 + Z)$$
$$= 2N^2/M + 2NM - 2N + ZN$$

Hence, total entries stored by the ZHLS protocol i.e., $\text{Entries}_{\text{ZHLS}}$ are:

$$\text{Entries}_{\text{ZHLS}} = 2N^2/M + 2NM - 2N + ZN \qquad (4.1)$$

(ii) For LGHR

As mentioned earlier, there are two kinds of gateway nodes in LGHR. One is Edge Gateways and the other is Intermediate Gateways. Edge Gateways store both intra-zone and inter-zone routing tables, whereas the Intermediate Gateways store only the intra-zone routing tables. Since, the number zones and grids are known at the design time, the maximum number of gateway nodes present in a zone can be determined as each grid can have a maximum of one gateway. For the purpose of generalization, it is assumed that every grid has a gateway node in a zone.

Let G be the average number of Gateway Nodes in a zone.
Total number of Edge Gateways in a zone = G_E and
Total number of Intermediate Gateways in a zone = G_I
Therefore, $G = G_I + G_E$

In LGHR, the leader node makes and keeps routing tables for all the gateway nodes only, not for all the nodes in a zone.

In case of Leader Node:
Entries in Node Table = N/M
Entries in Zone Table = M
Entries in One Intra-zone Routing Table = $N/M - 1 + Z$
Entries in G Intra-zone Routing Tables = $G\ (N/M - 1 + Z)$
Entries in One Inter-zone Routing Table = $M - 1$
Entries in G_E Inter-zone Routing Tables = $G_E\ (M - 1)$

Entries stored in a Leader Node $= N/M + M + G(N/M - 1 + Z) + G_E(M - 1)$
Total entries stored by M leaders in the network
$= M\ \{N/M + M + G(N/M - 1 + Z) + G_E(M - 1)\}$
$= N + M^2 + MG(N/M - 1 + Z) + MG_E(M - 1)$
Hence, total entries stored by the leader nodes i.e., $\text{Entries}_{\text{Leader}}$ are:

$$Entries_{Leader} = N + M^2 + MG(N/M - 1 + Z) + MG_E(M - 1) \qquad (4.2)$$

In case of Gateway Node:

Since Edge Gateways store both intra-zone routing tables and inter-zone routing tables, and Intermediate Gateways store only intra-zone routing tables, therefore,

Entries stored in an Edge Gateway = $N/M + M + Z - 2$

Entries stored in all Edge Gateways in a zone = $G_E \ (N/M + M + Z - 2)$

Entries stored in all Edge Gateways in the whole network

$= MG_E \ (N/M + M + Z - 2)$

Therefore,

$$Entries_{Edge} = MG_E \ (N/M + M + Z - 2) \tag{4.3}$$

Entries stored in an Intermediate Gateway = $N/M - 1 + Z$

Entries stored in all Intermediate Gateways in a zone = $\mathrm{G_I}$ (N/M-1+Z)

Entries stored in all Intermediate Gateways in the whole network

$= MG_I \ (N/M - 1 + Z)$

Therefore,

$$Entries_{Intermediate} = MG_I \ (N/M - 1 + Z) \tag{4.4}$$

Hence, total entries stored by the Gateway nodes i.e., $\mathrm{Entries_{Gateway}}$ are:

$$Entries_{Gateway} = Entries_{Edge} + Entries_{Intermediate}$$

$$Entries_{Gateway} = MG_E \ (N/M + M + Z - 2) + MG_I \ (N/M - 1 + Z) \tag{4.5}$$

Hence, total entries stored by the LGHR protocol are:

$$Entries_{LGHR} = Entries_{Leader} + Entries_{Gateway}$$

$$\begin{aligned} &= \{N + M^2 + MG \ (N/M - 1 + Z) + MG_E \ (M - 1)\} + \\ &\{MG_E \ (N/M + M + Z - 2)\} + \{MG_I \ (N/M - 1 + Z)\} \end{aligned} \tag{4.6}$$

4.1.1.2 Communication Overhead

In this subsection, the communication overhead analysis is done for both ZHLS and LGHR protocols. For the communication overhead analysis, the following parameters are taken into consideration.

(i) Topology creation overhead
(ii) Overhead generated by Zone Request
(iii) Leader and Gateway Election Overhead
(iv) Periodic Hello messages by the leader node

For analysis, it is assumed that the nodes are uniformly distributed in the whole network. There are N nodes in the network and the average number of nodes in a zone is N/M.

Topology Creation Overhead

According to Joa-Ng and Lu (1999), the total communication overhead generated by the ZHLS protocol for creating the topology in one message exchange is:

$$S_{ZHLS} = N^2 / M + NM \tag{4.7}$$

where, N^2 / M is the message overhead due to node LSPs and NM is the overhead generated by zone LSPs.

In case of the proposed protocol LGHR,

(a) All nodes in a zone send their neighbor information to the leader node. Therefore, the amount of communication overhead generated by neighbor connectivity messages (Node LSPs in case of ZHLS) in one zone is (N/M – 1).

Since there are M zones in the network therefore the total overhead generated in the whole network because of the node connectivity messages is represented by $\text{Overhead}_{\text{node}}$ which is:

$$Overhead_{node} = M\ (N / M\ -\ 1)\ \ messages$$

$$Overhead_{node} = N - M \tag{4.8}$$

(b) Every leader in a zone sends the zone connectivity information (Zone LSP in case of ZHLS) to every leader in other zones. The amount of overhead generated by these messages is represented by $\text{Overhead}_{\text{zone}}$ which is:

$$Overhead_{zone} = M\ (M\ -\ 1) \tag{4.9}$$

(c) Every leader broadcasts the whole routing tables to the gateway nodes in its zone. Upon receiving the message, the gateway nodes store their own routing table and discard others. Non-gateway nodes just ignore the message upon receiving.

Number of routing table messages broadcasted by a leader intended for gateways in one routing table exchange in a zone = 1

Total number of routing table messages sent by the leaders in M zones in the whole network is $\text{Overhead}_{\text{gateway}}$ which is:

$$Overhead_{gateway} = M \tag{4.10}$$

Using equations (4.8), (4.9) and (4.10), the total communication overhead generated for topology creation by the proposed protocol is represented by:

$$Overhead_{LGHR} = Overhead_{node} + Overhead_{zone} + Overhead_{gateway}$$

$$Overhead_{LGHR} = N - M + M\ (M\ -\ 1) + M$$

$$Overhead_{LGHR} = M^2 - M + N \tag{4.11}$$

Overhead Generated by Zone Request

In LGHR, a source node can know the position of the destination from a location server, like any other location-based protocol. The location server sends the location of the destination to the requesting node. Once the position of the destination is known, it is very easy to know which zone the destination node lies in. This decision is done by mapping the position of the destination on the zone map. Based on this information, the intra-zone and inter-zone routing decisions are made.

The overhead generated by ZHLS for zone search request is L_{ZHLS} which is:

$$L_{ZHLS} = (M - 1) \tag{4.12}$$

Overhead generated by LGHR for one location request to the location server is L_{LGHR} which is:

$$L_{LGHR} = 1 \tag{4.13}$$

Hence, the overhead generated in case of LGHR is much smaller than the one by ZHLS.

Leader and Gateway Election Overhead

Leader nodes are elected very infrequently as the leader region in a zone is large enough for a leader to stay for longer periods of time. Therefore, the overhead generated due to leader election is not very high. The gateway nodes are elected on the basis of the lower speed and shorter distance from the center of the grid. The comparison of LGHR with the GRID protocol is done in detail in the evaluation section.

Periodic Hello Messages by the Leader Node

The leader node sends periodic Hello messages to all nodes inside the zone just to tell its identity. Again, the interval can be long as the leader region is large enough for the leader to stay there for quite long time.

The leader sends one Hello message to (N/M-1) nodes in a zone, so the overhead is (N/M-1) for one zone. Since there are M zones in the network, therefore:

Total overhead for leader announcement packet is $\text{Overhead}_{\text{LeaderAnnounce}}$ is:

$$\text{Overhead}_{\text{LeaderAnnounce}} = M * (N/M - 1)$$

or

$$\text{Overhead}_{\text{LeaderAnnounce}} = N - M \tag{4.14}$$

4.1.2 Evaluation

For evaluation, the equations of the mathematical analysis shown in section 4.1 are used. The proposed protocol LGHR is compared with ZHLS in terms of the storage overhead as well as communication overhead generated. Also, the effect of increasing the number of nodes and the number of zones is analyzed for the overhead generated by both protocols.

4.1.2.1 Storage Overhead

Based on the storage overhead analysis in the previous section, both protocols LGHR and ZHLS are compared separately for 9, 16 and 25 gateways per zone. The number of zones is also varied as 9, 16 and 25 zones in a network. The numbers of nodes in the entire network are increased up to 1000 for 9, 16 and 25 zones. Evaluation is also done by increasing nodes to 2000 for 25 zones in the network. It is assumed that each grid in a zone has one gateway and the gateways are separated as Edge and Intermediate Gateways. Naturally, as the numbers of nodes in the network are increased, the number of entries stored by both protocols also increases. Also, by increasing the number of gateways from 9 to 25, the number of entries increases as well. But, in all cases, LGHR performs better than ZHLS and stores much smaller amount of entries than ZHLS. The results of the analysis are shown in Figures 4.1 to 4.11.

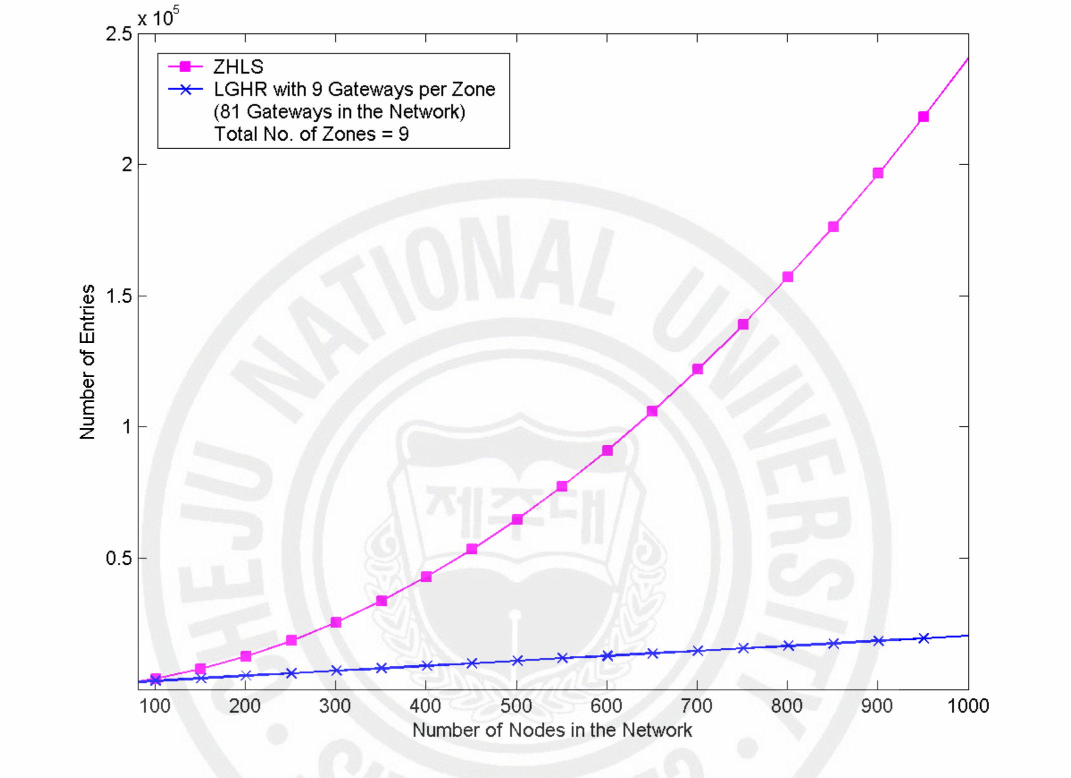


Figure 4.1: Comparison of LGHR with ZHLS in terms of number of entries stored for a network of 1000 nodes having 9 zones in the network. The values are shown for 9 gateways per zone. Hence, the total number of gateways in the whole network becomes 81.

In case of 9 grids per zone with 9 zones in the network as shown in Figure 4.1, there are a maximum of 81 gateways present in the whole network. In order to compare both protocols, the number of nodes must be same in both ZHLS and LGHR. As mentioned earlier, in ZHLS, every node stores all the tables whereas in LGHR, only the leader and gateway nodes store their respective tables. Therefore, by taking the maximum number of gateways mean that every grid has at least one node. In such a case, the node would be a gateway node.

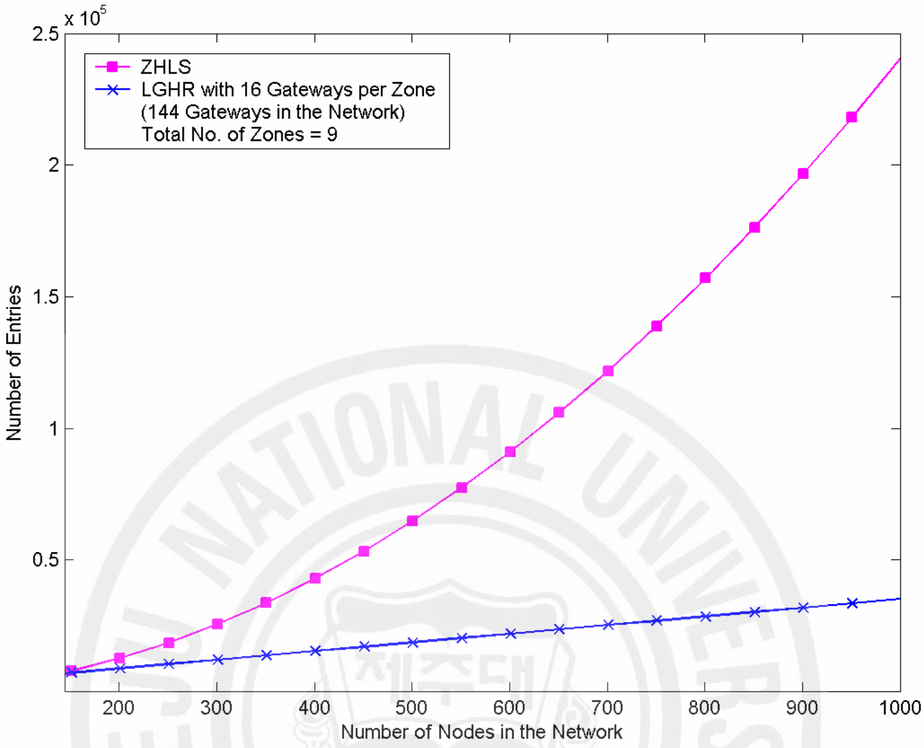


Figure 4.2: Comparison of LGHR with ZHLS in terms of number of entries stored for a network of 1000 nodes having 9 zones in the network. The values are shown for 16 gateways per zone. Hence, the total number of gateways in the whole network becomes 144.

The results shown are for the case of one gateway in each grid. Therefore, even if the numbers of nodes are increased in LGHR, there is a very minor increase in the number of entries stored, as the non-gateway nodes are not responsible for storing any tables; whereas in ZHLS, with increase in the number of nodes, every node has to store all the required entries and hence, there is a major increase in the storage overhead incurred by the protocol. In the figures, the effect on the storage overhead is shown from the point when the numbers of nodes in both protocols are same. In case of 9 gateways in a zone, there are 81 gateways in the whole network; therefore, the results are taken from this point onwards.

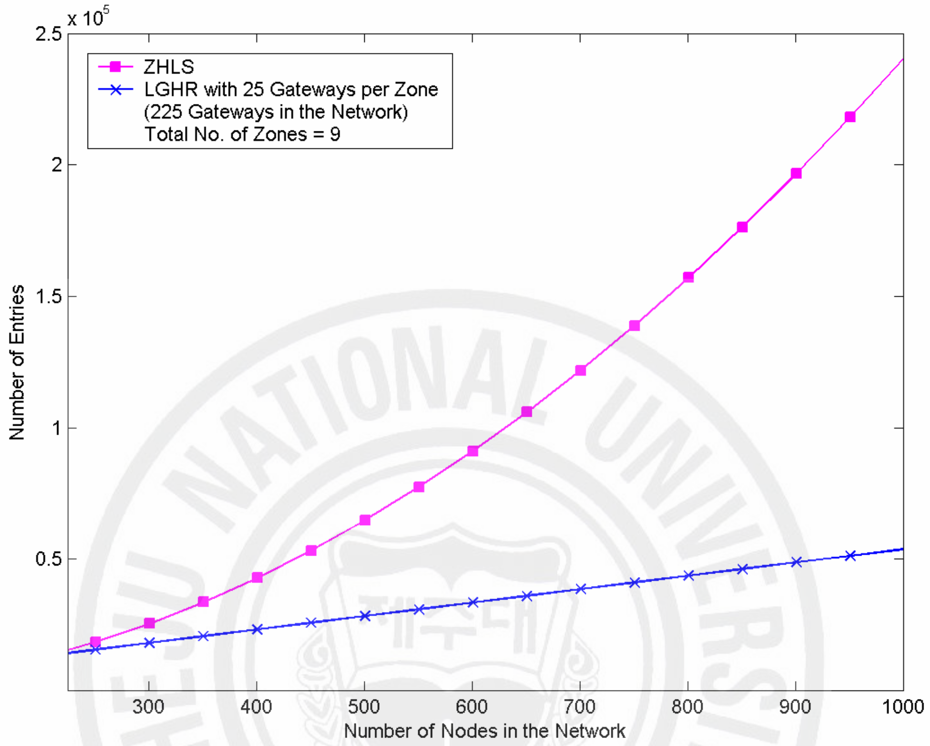


Figure 4.3: Comparison of LGHR with ZHLS in terms of number of entries stored for a network of 1000 nodes having 9 zones in the network. The values are shown for 25 gateways per zone. Hence, the total number of gateways in the whole network becomes 225.

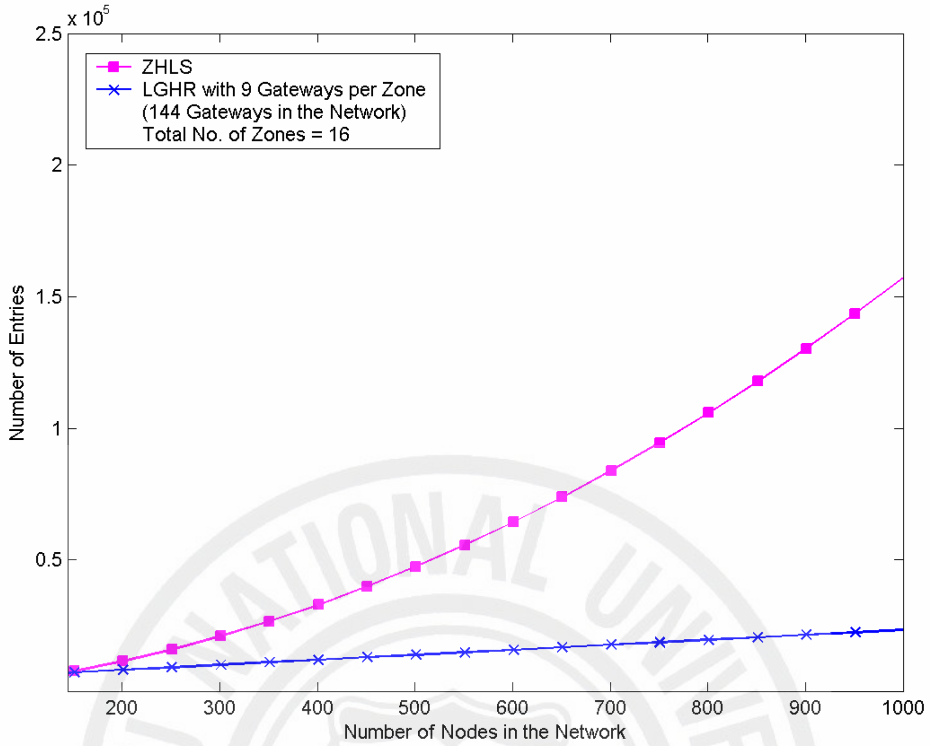


Figure 4.4: Comparison of LGHR with ZHLS in terms of number of entries stored for a network of 1000 nodes having 16 zones in the network. The values are shown for 9 gateways per zone. Hence, the total number of gateways in the whole network becomes 144.

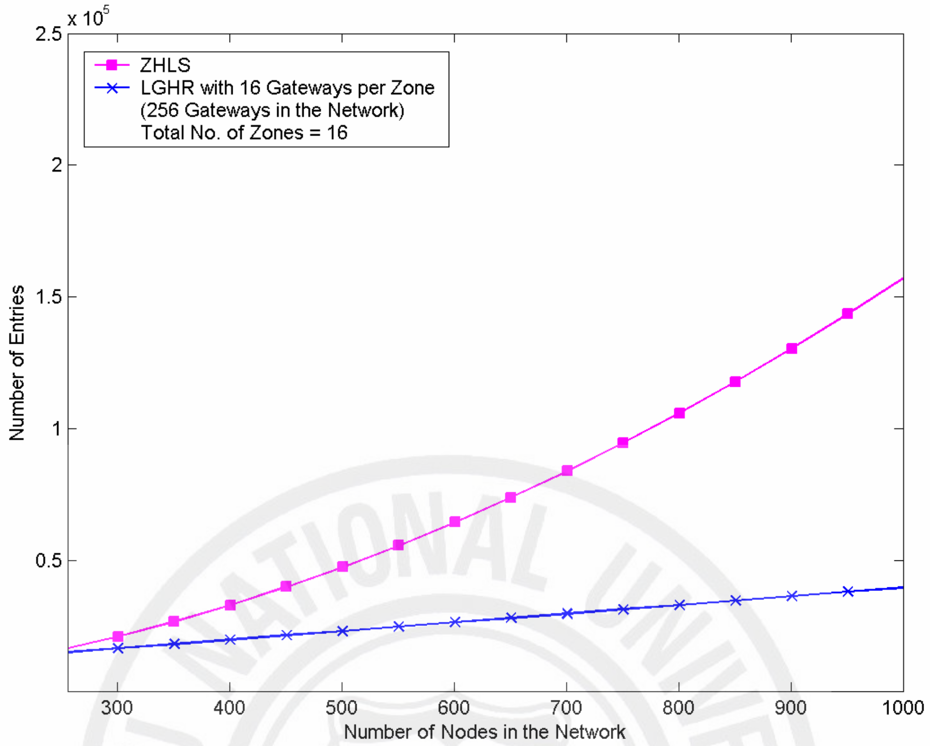


Figure 4.5: Comparison of LGHR with ZHLS in terms of number of entries stored for a network of 1000 nodes having 16 zones in the network. The values are shown for 16 gateways per zone. Hence, the total number of gateways in the whole network becomes 256.

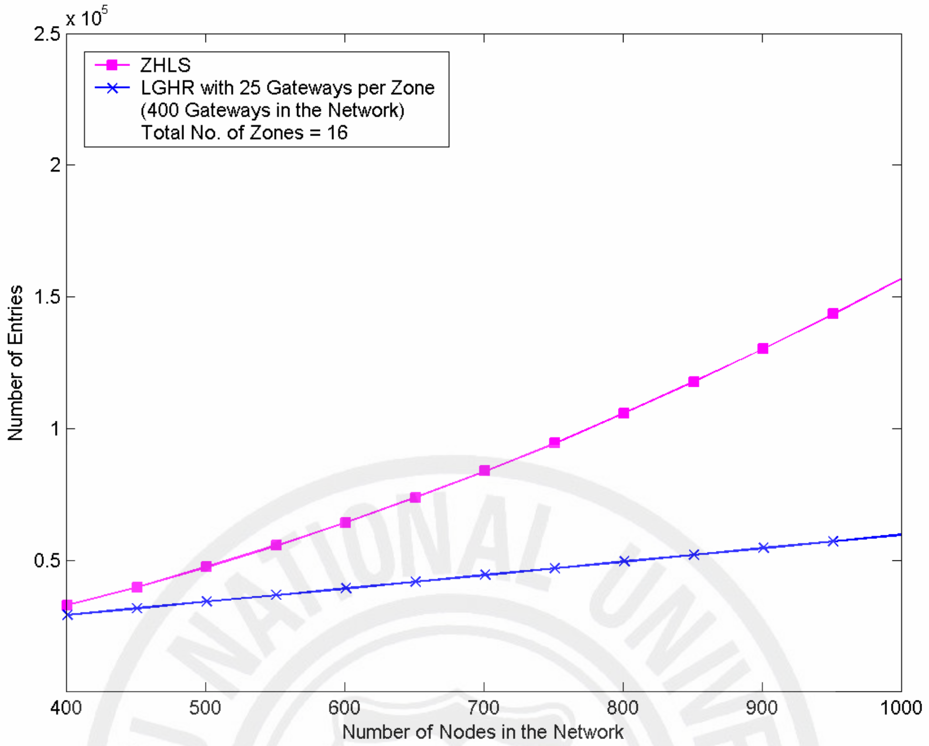


Figure 4.6: Comparison of LGHR with ZHLS in terms of number of entries stored for a network of 1000 nodes having 16 zones in the network. The values are shown for 25 gateways per zone. Hence, the total number of gateways in the whole network becomes 400.

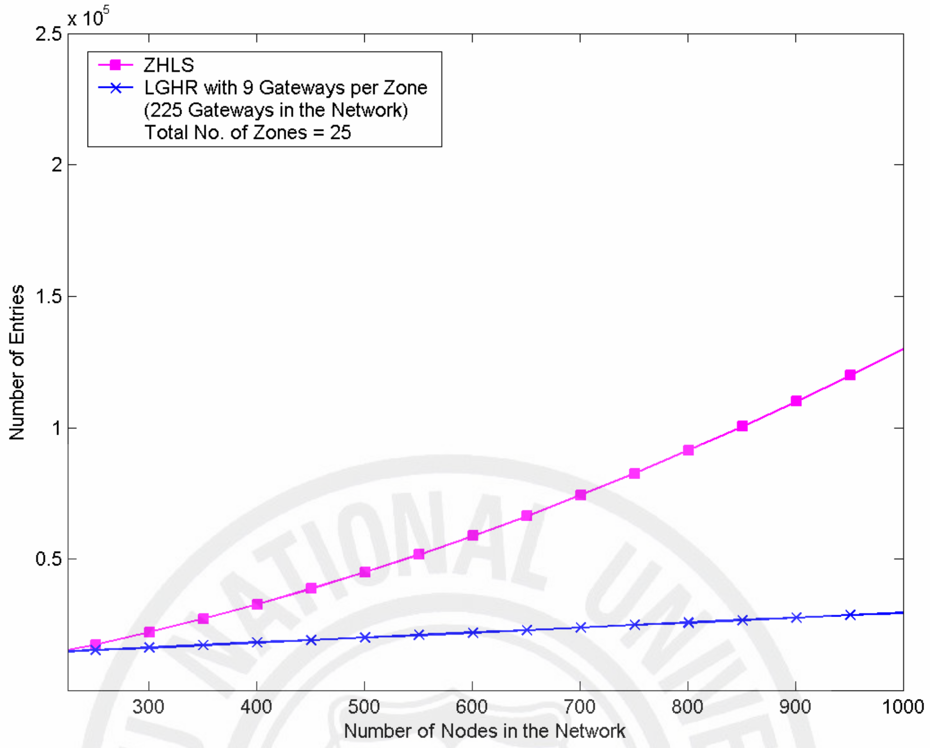


Figure 4.7: Comparison of LGHR with ZHLS in terms of number of entries stored for a network of 1000 nodes having 25 zones in the network. The values are shown for 9 gateways per zone. Hence, the total number of gateways in the whole network becomes 225.

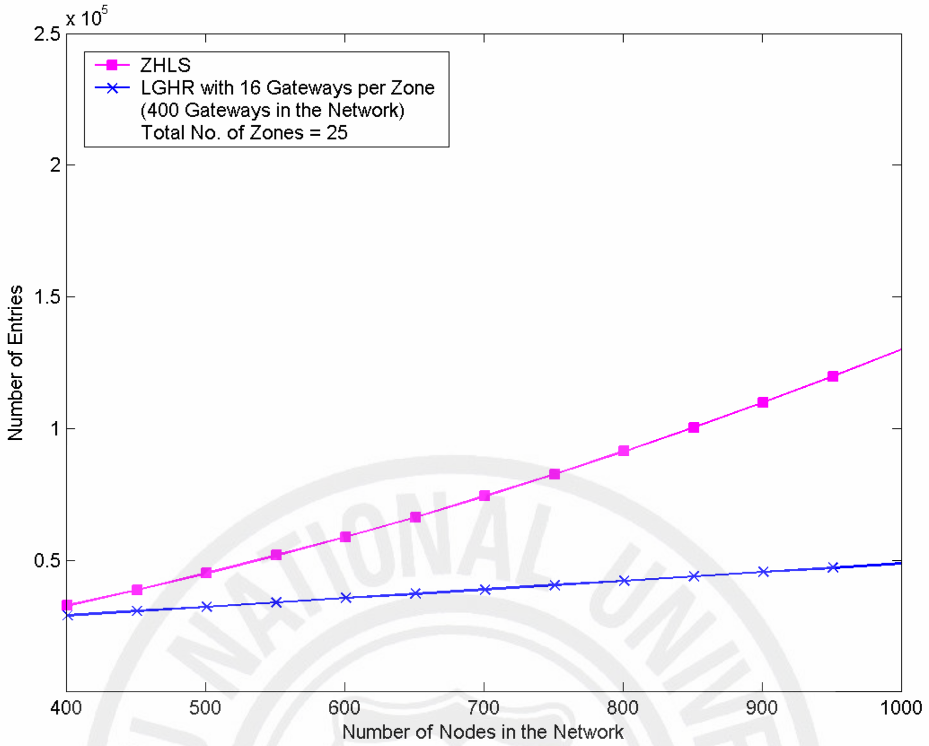


Figure 4.8: Comparison of LGHR with ZHLS in terms of number of entries stored for a network of 1000 nodes having 25 zones in the network. The values are shown for 16 gateways per zone. Hence, the total number of gateways in the whole network becomes 400.

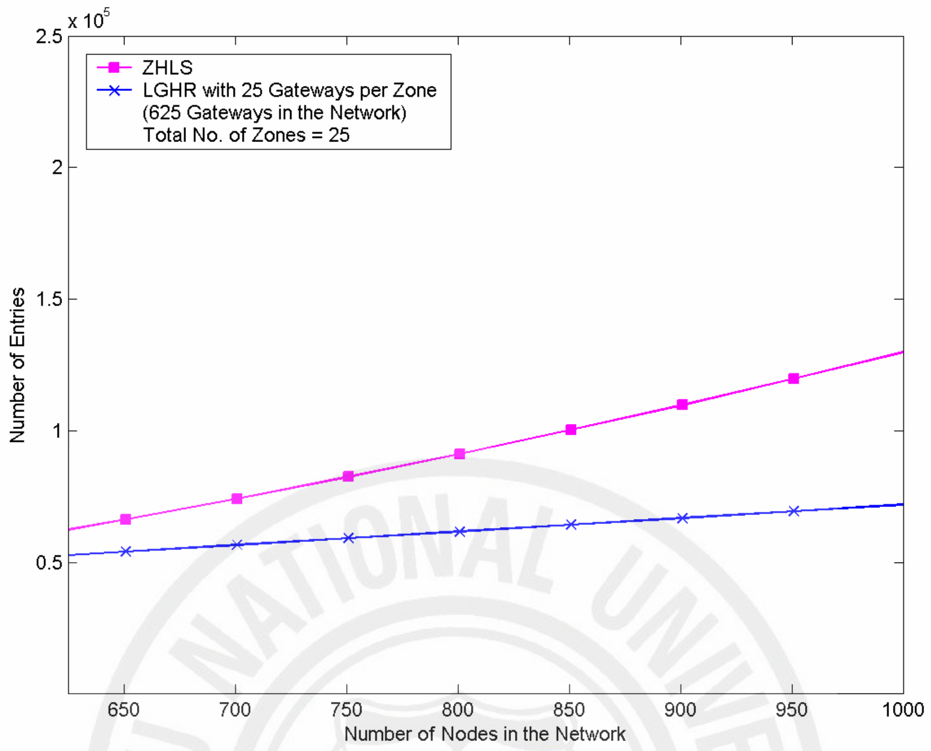


Figure 4.9: Comparison of LGHR with ZHLS in terms of number of entries stored for a network of 1000 nodes having 25 zones in the network. The values are shown for 25 gateways per zone. Hence, the total number of gateways in the whole network becomes 625.

These results clearly show that the Location-aware Grid-based Hierarchical Routing (LGHR) protocol performs better than ZHLS in all cases in terms of the storage overhead. In case of 25 zones and a maximum of 1000 nodes in the network, the overhead for LGHR increases by increasing the number of gateways in a zone whereas the values for ZHLS remain the same. However, if the numbers of nodes are increased to 2000, it is clearly shown in Figures 4.10 and 4.11 that the storage overhead for ZHLS increases drastically and the difference between the two protocols is still huge. The only major problem in LGHR is that the leader node has to carry a lot of burden which is sometimes unwanted. Since every node cannot take the responsibility of becoming a leader, and only eligible nodes can compete for it, it always has enough resources to handle all the responsibilities and therefore, avoids the possibility of carrying the whole topology information by other nodes as done in peer-to-peer based protocols such as ZHLS.

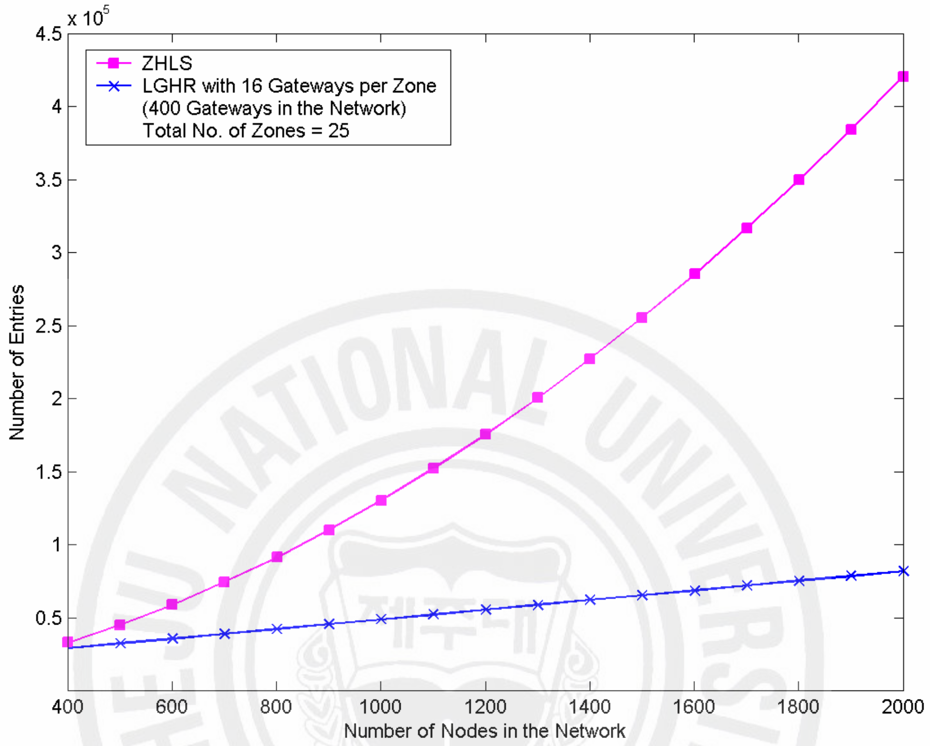


Figure 4.10: Comparison of LGHR with ZHLS in terms of number of entries stored for a network of 2000 nodes having 25 zones in the network. The values are shown for 16 gateways per zone. Hence, the total number of gateways in the whole network becomes 400.

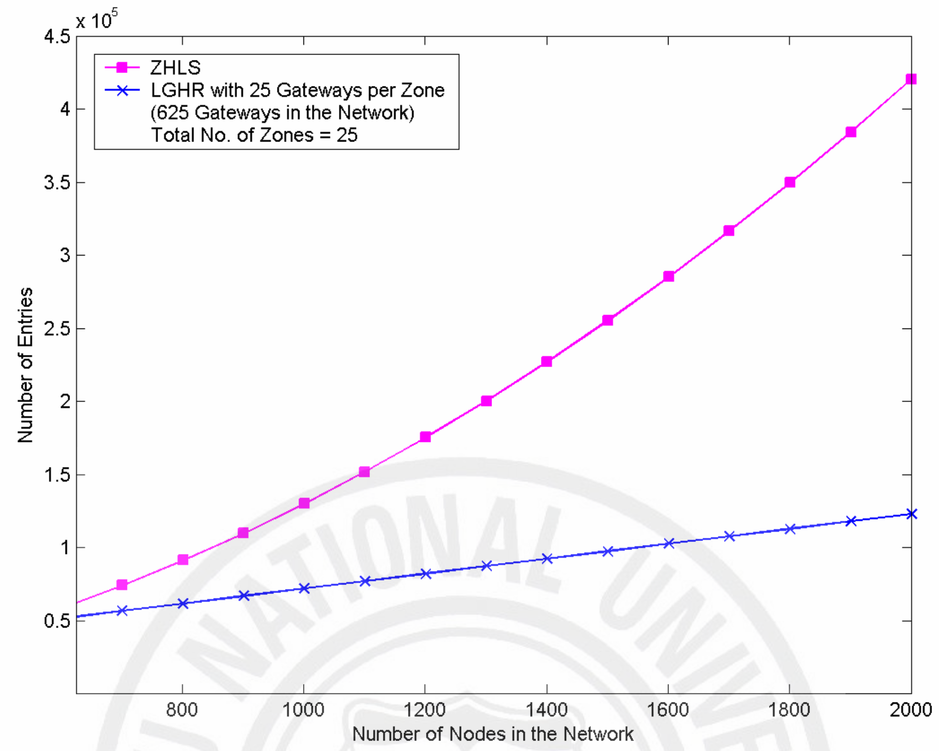


Figure 4.11: Comparison of LGHR with ZHLS in terms of number of entries stored for a network of 2000 nodes having 25 zones in the network. The values are shown for 25 gateways per zone. Hence, the total number of gateways in the whole network becomes 625.

4.1.2.2 Communication Overhead

The comparison for the communication overhead for topology creation for both ZHLS and LGHR protocols is shown in Figures 4.12, 4.13 and 4.14 based on the mathematical analysis. Figure 4.12 shows the difference between both protocols in case of 9 zones, Figure 4.13 shows the difference for 16 zones and Figure 4.14 shows the comparison for 25 zones in the network. In all cases, the communication overhead generated by LGHR is much smaller than ZHLS. The reason is that in ZHLS, all nodes send their node LSPs to all nodes in their zone. Similarly, each zone LSP is sent to all the nodes. In case of LGHR, the nodes in a zone are required to send their neighbor information to only the leader node. Similarly, the zone tables are also propagated to only leader nodes not to all nodes in the network. Moreover, the leader sends the respective routing tables to only the gateway nodes. Hence, the communication overhead for topology creation by LGHR is much smaller than the one generated by ZHLS.

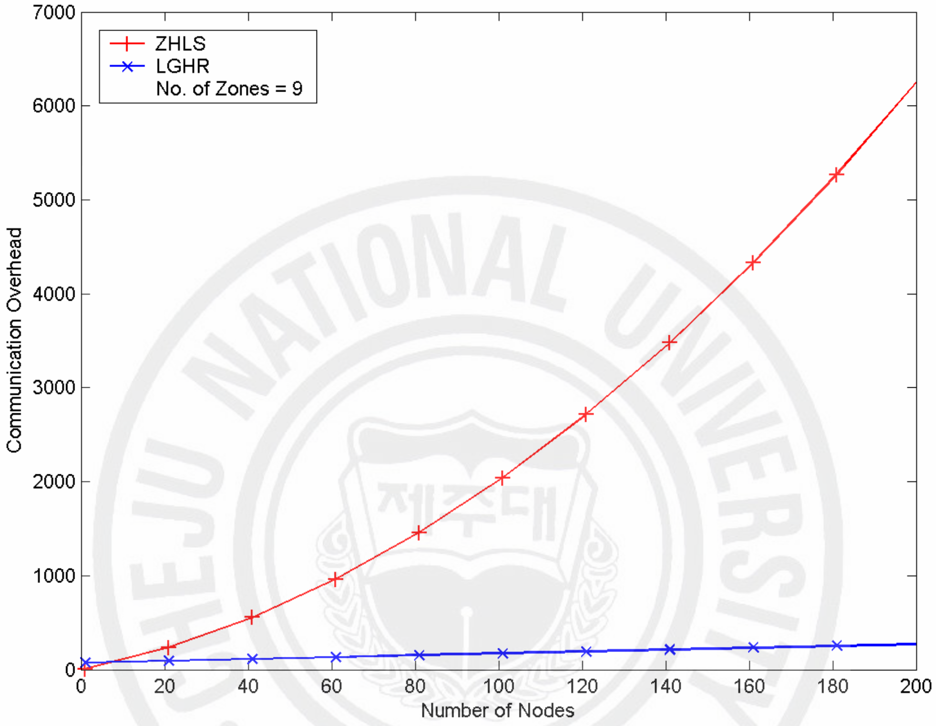


Figure 4.12: Communication overhead for topology creation generated by both LGHR and ZHLS protocols in case of 9 zones in the network.

Here, again the comparison of both protocols should be done from the point where the nodes in both protocols are same and the numbers of nodes in the network are more than total number of zones. This is because the average of total number of nodes in the network is taken for evaluation. Otherwise, the situation would be unrealistic. For realistic scenarios, LGHR always performs better than ZHLS in terms of communication overheard.

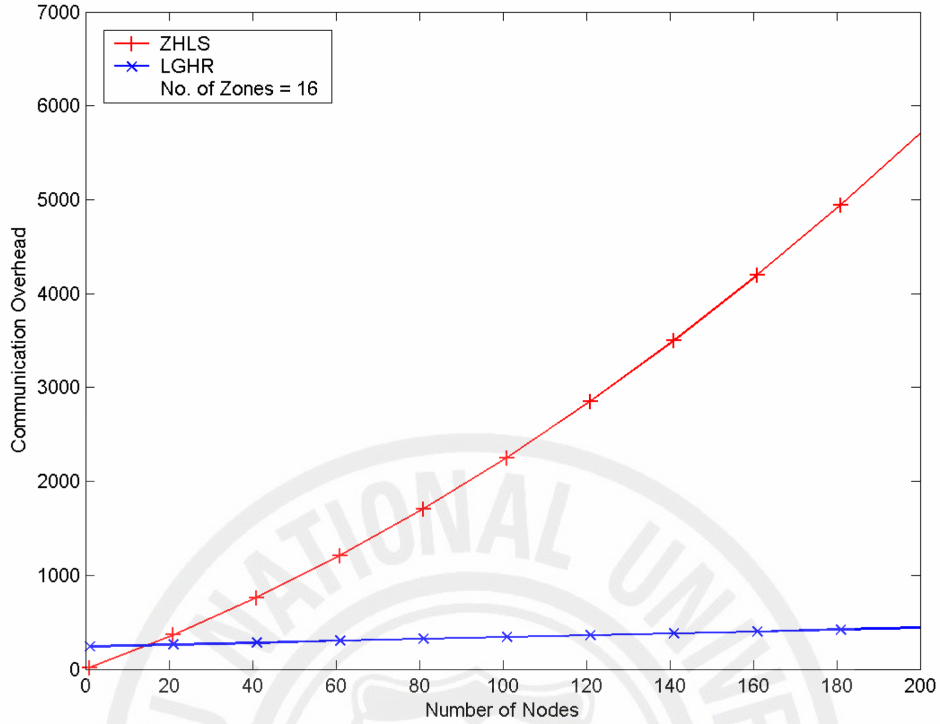


Figure 4.13: Communication overhead for topology creation generated by both LGHR and ZHLS protocols in case of 16 zones in the network.

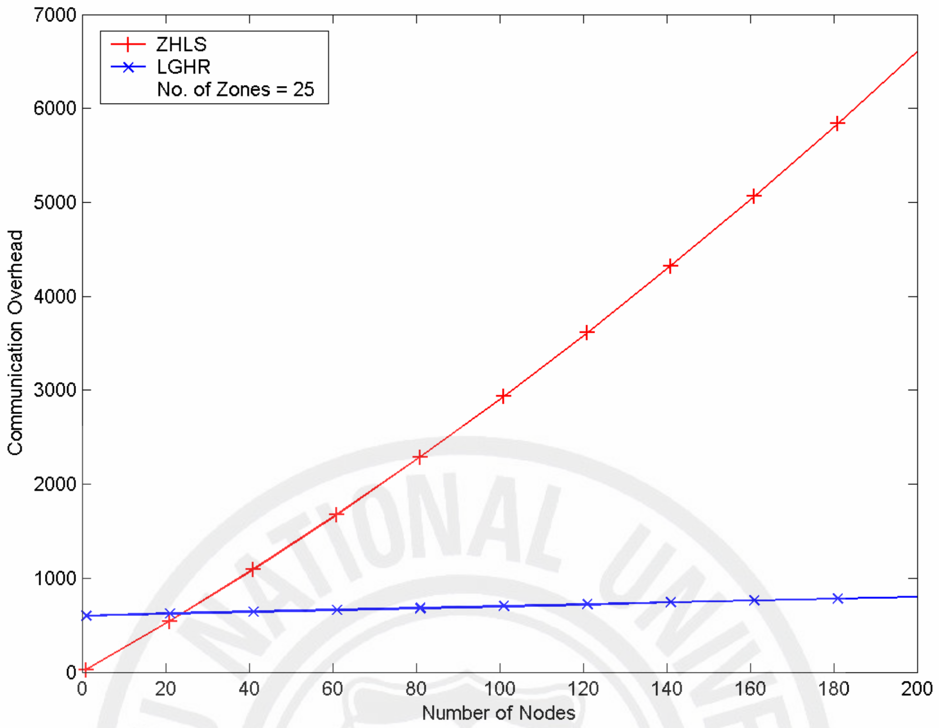


Figure 4.14: Communication overhead for topology creation generated by both LGHR and ZHLS protocols in case of 25 zones in the network.

4.2 Comparison with GRID Protocol

The comparison of LGHR is done with GRID protocol to analyze the stability of the protocol in terms of gateway election overhead. As mentioned earlier, in GRID protocol, the election mechanism considers only the distance of a node from the center of the grid. That is, a node is elected as a gateway if it lies at a shortest distance from the center of the grid. Once it is elected as a gateway, it starts functioning as a gateway until it leaves its grid. If a gateway goes out of the grid, a new election mechanism will start and another node would be elected as gateway.

In case of LGHR, not only the distance from the center of the grid is considered for electing a gateway, but the velocity of a node is also taken into consideration. This means that a node is elected as a gateway whose relative distance is minimum than other nodes. This distance is calculated by using the following formula:

$$dist_i = \sqrt{(X_i - X_c)^2 + (Y_i - Y_c)^2 + V_i^2} \tag{4.15}$$

The mechanism is already explained in detail in chapter 3. Since, in both protocols, the routing is performed by gateway nodes only and non-gateway nodes are not responsible for forwarding packets to other nodes, the gateway should be able to stay in the grid for longer periods of time. If the gateway moves out of the grid quite frequently, then each time a gateway moves out, a new election mechanism will be performed. In case of mobile nodes moving with higher velocities, the gateway nodes are more likely to leave the grid very frequently. Hence, that protocol will work in more stable manner in which the gateway election procedure is performed less frequently which means that the gateway stays inside the grid for more time. Using this criterion, the gateway election can be considered as a parameter for the stability of the routing protocol.

The comparison is done by performing simulations for both protocols. Since, only the frequency of gateway election mechanism is computed, the simulation code can be written in any programming language. In order to compare LGHR and GRID, the simulation environment is developed using Matlab 6.5 and the results are analyzed. The stability of both protocols is analyzed by examining the effect of several parameters on the frequency of gateway elections in a grid. The parameters are:

1. Velocity of nodes
2. Number of nodes in a grid
3. Size of the grid
4. Simulation time

For all simulations, the initialization angle is taken to be 150 degrees. The curve parameter α is taken to be 1. The nodes are generated and placed in a fixed-size grid and then are moved with given maximum velocities in random directions. Due to randomness of velocity and direction, the results can be different each time the simulation is performed. Therefore, each simulation is performed five times and then the average of all the values is taken.

4.2.1 Effect of Velocity

In order to analyze the effect of velocity, the simulations are performed with the following parameters:

Total Nodes = 30
Simulation time = 50 units
Grid size = 50 x 50

The results of keeping the number of nodes constant and increasing the velocity are shown in Figure 4.15. As shown in the figure, by increasing the velocity of mobile nodes, the number of elections for the gateway node also increases for both protocols. This is because, if the nodes are moving with higher velocity, there is a higher probability that the nodes will go out of the grid very frequently. Hence, there will be more elections for gateway nodes for both protocols. For the case of lower maximum velocity, both protocols perform almost the same. As the velocity is increased, the number of elections in case of GRID starts increasing. The reason is that in GRID protocol, there is no consideration of the velocity of mobile nodes and only the distance from the center of the grid is considered in order to elect a gateway. On the other hand, LGHR considers both the distance from the center of the grid as well as the velocity of the mobile nodes for electing a gateway node. This is because, in case the nodes are moving with higher velocities, the probability of performing the leader elections is also higher, since the nodes will tend to leave the grid very frequently. Therefore, in case of LGHR, those nodes are elected as gateways that have lower velocities and also they are not very far from the center of the grid, hence making the protocol more stable.

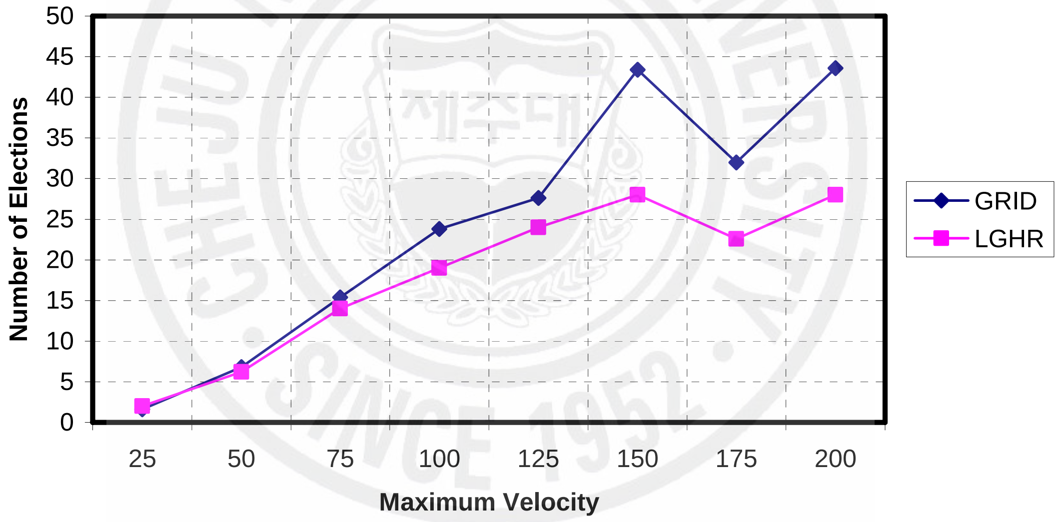


Figure 4.15: Comparison of LGHR and GRID in terms of velocity of mobile nodes.

4.2.2 Effect of Number of Nodes

For the second case, the following parameters are kept constant and the number of nodes is increased.

Maximum Velocity = 150 units

Grid Size = 50 x 50

Simulation Time = 30 units

Keeping the maximum velocity of nodes constant as 150 units and number of nodes is increased up to 100 nodes per grid. Figure 4.16 shows that by keeping velocity constant and increasing the number of nodes, LGHR performs better than GRID. For the case when nodes are equal to 100, the difference between both protocols is small. It is observed that if the numbers of nodes in the grid are small then the difference between both protocols is large. But as the numbers of nodes are increased in the grid, the difference becomes smaller between both protocols. Since a grid is a very small part of a zone, therefore, the numbers of nodes in a grid are likely to be few. Therefore, the proposed protocol LGHR performs better than GRID in that case. The results in the figure show that even though the difference between both protocols is small for 100 nodes, LGHR still performs better than GRID and is more stable even in this case.

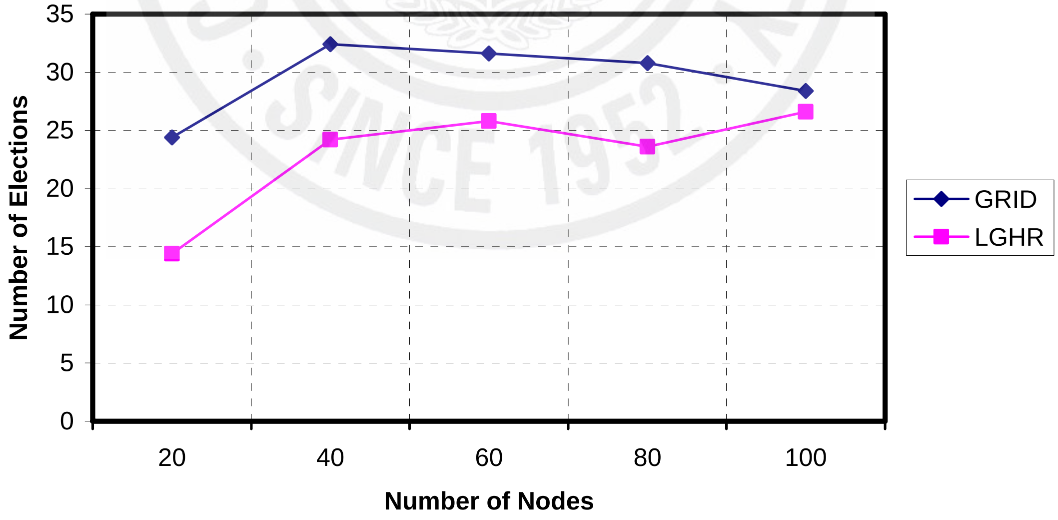


Figure 4.16: Comparison of LGHR and GRID in terms of number of nodes in a grid.

4.2.3 Effect of Grid Size

In order to analyze the effect of grid size in both LGHR and GRID protocols, the following parameters are kept constant.

Total Nodes in a grid = 30
Maximum Velocity = 150 units
Simulation Time = 20 units

Figure 4.17 shows that for smaller grid sizes, LGHR is more stable than GRID as it has less numbers of elections. As the grid size is increased, the performance of both protocols is similar which means that for larger grid sizes, both protocols work in almost the same manner. As mentioned earlier, the grid size is usually much smaller than the total size of a zone. Therefore, in the realistic scenarios, for smaller size of grid, LGHR works better than GRID. Another point to be noted here is that if the size of grid is small, more elections take place, which is clearly depicted in the figure. This is also due to the fact that if the grid is small, the nodes are more likely to go out of the grid very frequently. It can be seen that when the grid size is large, for example, in the case of 125 x 125 units, the gateway elections are performed less than five times in a given simulation time. The elections take place more frequently when the grid size is large.

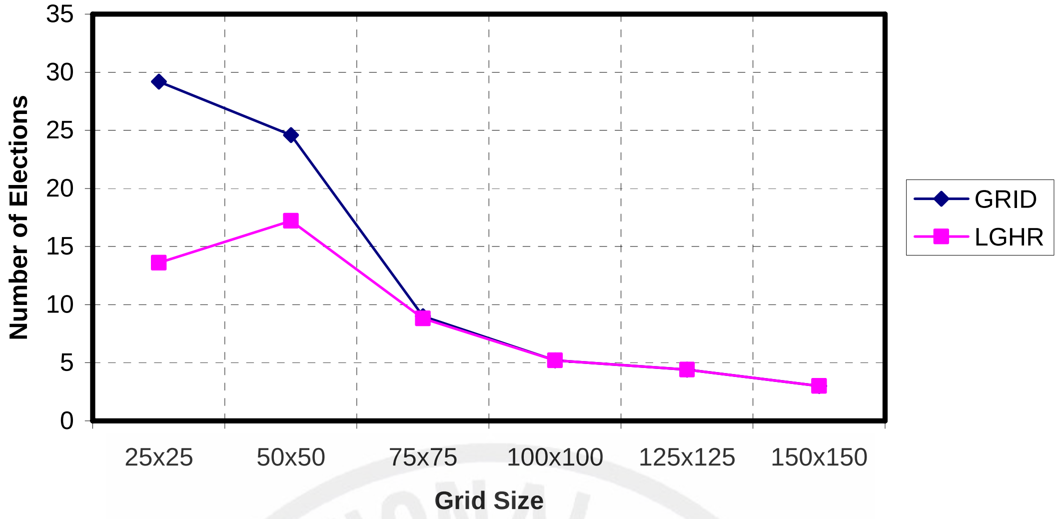


Figure 4.17: Comparison of LGHR and GRID in terms of grid size.

4.2.4 Effect of Simulation Time

It has been observed that the duration of the simulation also affects the frequency of gateway elections. For this analysis, the following parameters are kept constant:

Total Nodes in a grid = 30
Maximum Velocity = 150 units
Grid size = 50 x 50

From Figure 4.18, it is clear that the simulation time also affects the number of elections performed in a grid by both protocols. The simulations are performed by keeping the simulation time as 10 units and then increasing up to 50 units. It is observed that if the simulation time is increased, LGHR performs better than GRID. This is another indicator of the stable performance of LGHR in situations where nodes are likely to be present in the network for larger durations. The results clearly depict the superiority of the gateway election mechanism used in LGHR over the one used in GRID. Hence, the claim in LGHR is proved to be true in which the protocol works in a more stable manner if both the velocity and distance from the center of the grid are taken into consideration while electing the gateway node, instead of just the distance from the center.

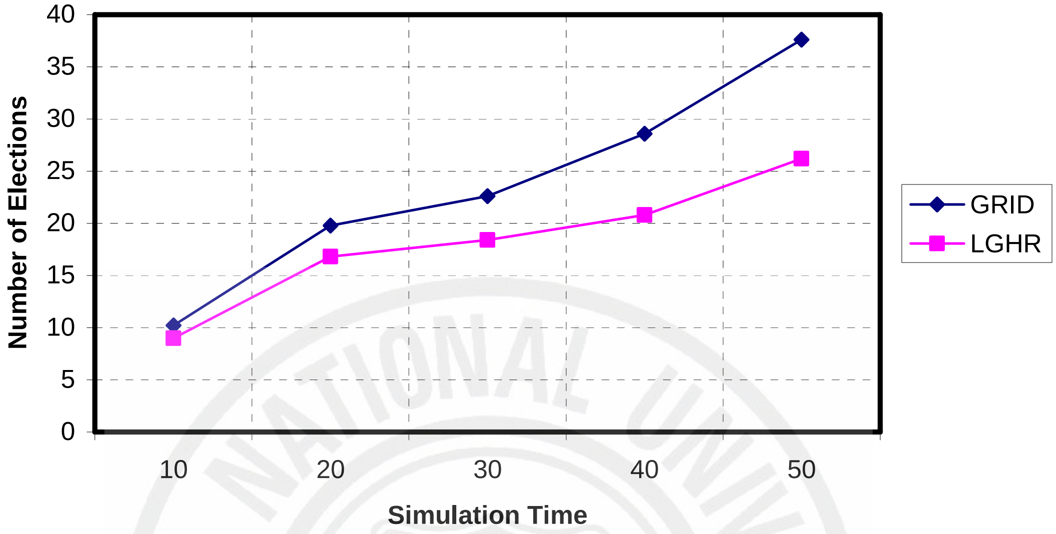


Figure 4.18: Comparison of LGHR and GRID in terms of simulation time.

4.3 Summary

The proposed protocol LGHR is compared with two other location-aware routing protocols, ZHLS and GRID. For comparison with ZHLS, the mathematical analysis is done and both ZHLS and LGHR are evaluated for storage overhead as well as communication overhead. Moreover, the effect of increasing the number of nodes as well as zones for both protocols is also analyzed. The analysis clearly indicates that LGHR performs better than ZHLS in terms of the storage overhead as well as communication overhead generated by all nodes. ZHLS uses a hybrid approach which may be suitable if there are small numbers of nodes in the network. But when the numbers of nodes are increased, ZHLS incurs huge communication overhead as all nodes in a zone proactively send their link state packets to all other nodes in that zone. Moreover, it has a reactive zone search mechanism which is initiated each time a destination lies in a different zone than that of the source node.

In LGHR, since only eligible nodes with sufficient resources can opt for becoming a leader, the possibility of a burden on the leader due to carrying the routing information of other nodes can be ignored. LGHR is also compared with GRID protocol in terms of stability. The proposed protocol is shown to be more stable than GRID due to considering the position of a node as well as its velocity for electing gateways in a grid. Simulations are performed for different parameters to check the stability such as the velocity, number of nodes, gird size and simulation time. In all cases, LGHR outperforms the GRID routing protocol and proves to work in a more stable manner.

Chapter 5

GEOCASTING IN WIRELESS AD HOC NETWORKS WITH GUARANTEED DELIVERY

In this chapter, the problem of delivering the geocast packets to all nodes inside the geocast region in an ad hoc network is addressed, where some of the nodes are not directly connected to one another. A geocast routing protocol is proposed called Grid-based Guaranteed Geocast (GGG or G3) which guarantees the delivery of geocast packets to all nodes inside a geocast region. In order to guarantee the delivery of packets to all nodes, the nodes outside the geocast region are used. The isolated groups of nodes inside the geocast region are named as islands. A grid-based approach is used for determining the islands as well as sending geocast packets to the geocast region. There can be several nodes outside the geocast region boundary that have direct connections with nodes in the islands. Out of these outer boundary nodes, one node is elected which is responsible for delivering the packets to the nodes inside the geocast region. Moreover, the concept of location server is also re-defined and is given the routing responsibilities as well. Analysis and simulations are performed to show that the proposed mechanism guarantees the delivery of geocast packets to all nodes in a geocast region.

5.1 Introduction

With the fast development and advancement of the Global Positioning System (GPS), it is now possible to route packets in a network on the basis of physical locations of wireless nodes. Especially, in case of wireless ad hoc networks where the location of nodes changes very rapidly, GPS can play a very important role in finding the positions of the moving nodes. Several location-based unicast as well as multicast routing protocols for ad hoc networks have been added into the literature for the past few years. Another concept called geocasting, which is a position-based variation of multicasting, has been seeking attention of researchers all over the world. Geocasting is a phenomenon in which a packet is supposed to be sent to all the nodes inside a physical region.

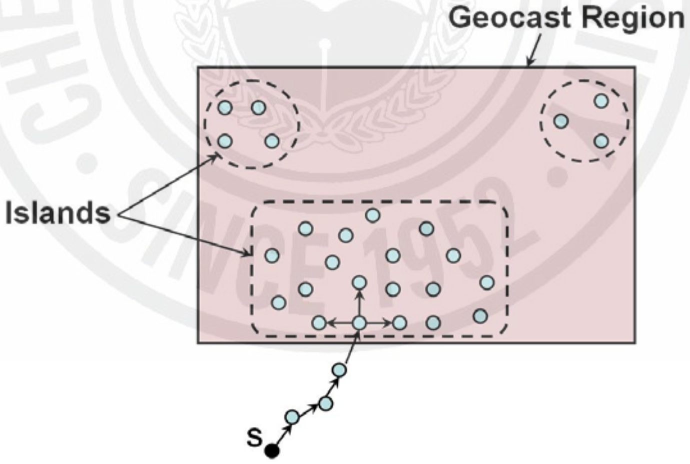
Several geocasting protocols have been proposed by various researchers (Camp and Liu, 2003; Ko and Vaidya, 1998; Ko and Vaidya, 2000b; Liao *et al.,* 2000; Seada and Helmy, 2004; Stojmenovic, 2004; Stojmenovic *et al.*, 1999). A detailed survey and analysis of geocasting protocols is presented in Maihöfer (2004). It is observed that most of the geocasting protocols at present are based on unicast routing protocols. In many cases, unicast protocols are enhanced to incorporate the geocasting features and then are transformed into a geocast routing protocol. For instance, LAR (Ko and Vaidya, 2000a) has been enhanced to make LBM (Ko and Vaidya, 1998), GRID (Liao *et al.,* 2001) has been modified to construct Geo-GRID (Liao *et al.,* 2000), Geo-TORA (Ko and Vaidya, 2000b) is the modified version of TORA (Park and Corson, 1999) and AODV (Perkins *et al.*, 2003) has been modified to work for geocasting (Schwingenschlogl and Kosch, 2002). Moreover, DSR (Johnson and Maltz, 1996) which is a unicast routing protocol, and ODMRP (Lee *et al.,* 1999) and CAMP (Garcia-Luna-Aceves and Madrga, 1999) which are multicast routing protocols, have been used as a basis for GAMER (Camp and Liu, 2003), which is a mesh-based geocast routing protocol. The concept of GPSR (Karp and Kung, 2000) has also been used for geocasting by several researchers (Bose *et al.,* 2001).

Mostly, the geocasting protocols like LBM, Voronoi Diagram based geocasting (Stojmenovic *et al.,* 1999), Geo-GRID and GAMER, all are based on directed or limited flooding whereas Geo-TORA is a protocol without flooding. This directed flooding is carried out before the packet enters the geocast region. Inside the geocast region, all the protocols use simple or smart flooding to deliver the packets to the nodes inside the geocast region. Apart from that, some protocols like in Seada and Helmy (2004) and Stojmenovic (2004) use different strategies to make it possible to route the packets to all nodes in a geocast region, even if they are not directly connected to one another from inside. In this case, nodes outside the geocast region are involved in order to guarantee the delivery of packets to all nodes in the region. Right hand rule traversals of nodes and face routing have been used in this case. Although, these algorithms attempt to deliver packets to all nodes inside the geocast region, they are more complex as they are face traversal-based algorithms and therefore, spend more time on traversing the nodes in different manners.

5.2 Motivation of Proposed Protocol

Various geocast routing protocols already exist in the literature but very few guarantee the delivery of geocast packets if there are multiple isolated regions in the geocast region. By isolated regions it is meant that there can be one or more groups of nodes that are not in direct connection from within the geocast region. They can have paths using nodes outside the geocast region but they are not directly connected to one another inside the geocast region. Hence, even if simple flooding is used inside in order to deliver the packets to all nodes, there are still certain nodes which are unable to receive geocast packets. These groups of nodes are named as islands. Nevertheless, by including some nodes from outside this region, the delivery of geocast packets can be guaranteed. The problem faced in this situation is that as in Figure 5.1, the nodes in the upper left and right corners of the geocast region are unable to receive the flooded packets, as they are not in the radio range of any node that receives the geocast packet.

Since recently, researchers have proposed a few approaches that guarantee the delivery of geocast packets to all nodes inside the geocast region. It is noted that these algorithms are mainly based on face routing and they use planer graphs for this approach. The problem with these approaches is that they are based on face traversal algorithms which are usually very slow and experience lots of extra traversals which result in higher cost and inefficiency (Leong, 2006). Some of these protocols are described in Seada and Helmy (2004) and Stojmenovic (2004). It is noted that blind flooding is a viable option to guarantee the delivery to all nodes in the geocast region if the network is sparse (Stojmenovic, 2004). But the problem with flooding is that it has a huge amount of overhead in terms of number of packets generated and forwarded. Apart from the face traversal based algorithms, other geocast protocols like LBM, Geo-Grid, and GAMER which are mainly based on restricted flooding do not completely guarantee the delivery of geocast packets to all nodes inside the geocast region. Only the Flooding-based GAMER protocol can guarantee but other schemes of GAMER like CORRIDOR or CONE do not guarantee the delivery. Similarly, in LBM, authors propose some optimizations for the definition of a forwarding zone by introducing a δ term. It is noted that the delivery cannot be guaranteed if the value of delta is small. Authors increase the value of delta from zero to 150 and observe that if the value of delta becomes 150, it behaves similar to the flooding based geocast. Therefore, it has a huge overhead in terms of number of packets generated by the protocol.



(a)

Figure 5.1: Nodes at top right and left corners are unable to receive geocast packets.

Here the point should be noted that the basic LBM scheme 1 and LBM scheme 2 do not guarantee the delivery. If the parameter δ is increased, the forwarding zone is increased and then the delivery can be guaranteed provided that the nodes are lying very near to the geocast region. And if the value of δ is kept on increasing, the protocol starts behaving in the same manner as flooding which has a huge overhead.

In this chapter, a geocasting protocol called Grid-based Guaranteed Geocast (GGG or G3) is proposed which guarantees the delivery of geocast packet to all nodes inside the geocast region. A grid-based approach is used with a hierarchical scheme to determine the connectivity of groups of nodes in the geocast region. Main point in the proposed approach is that the protocol is neither based on flooding nor it uses face traversals of planar graphs and yet it guarantees the delivery of geocast packets to all nodes in a geocast region.

The main problem with protocols which are not based on face traversals is that they do not have the prior information of how many islands are there in the geocast region. Since the geocasting is a phenomenon in which every source node can have its own geocast region, it is apparently impossible to find out the number of islands in the geocast region. For this purpose, a grid-based approach is introduced where the network is divided into several equal-sized squares or grids and each grid has a leader that maintains its connectivity information with all grids around it. The leader is elected based on a leader election mechanism. All leaders send periodic Hello messages to their neighboring leaders. On the basis of this Hello message, the leader determines the connectivity with other grids.

Moreover, the concept of a location server is introduced and its responsibilities are redefined unlike several existing location-based routing protocols. The location server is responsible for not only keeping the location information of all leader nodes but it also maintains the grid connectivity information taken from all leaders in the whole network. On the basis of this connectivity information sent by the leader nodes, the location server constructs the routing tables.

In the proposed mechanism, routing is performed in a grid-by-grid manner and packet is forwarded from leader of a grid to the leader of another grid. That is, a leader will send packet to its immediate neighboring grid leader and it will not "Jump" to another leader of a non-adjacent grid even if there is one is in its range. Since all nodes are not involved in the routing process and only the leader-to-leader routing is performed in a grid-by-grid manner, it does not put a great burden on the location server for maintaining the routing tables for all the leader nodes in the whole network. Whenever a node wants to send a geocast packet to a geocast region, the location server checks the co-ordinates of the geocast region and determines the number of islands in the geocast region on the basis of the connectivity map constructed based on the neighbor connectivity information supplied by the leader nodes. After determining the number of islands in the geocast region, it selects one leader node for each island and sends the source node the whole path from the source to these leader nodes. Upon receiving the path from the location server, the source node uses source routing by appending the path in the geocast packet. The source sends the geocast packet to each destination leader separately. Upon receiving the geocast packet, the destination leader floods the packet inside the geocast region to all the nodes in its island. Here, the point to be noted is that inside the geocast region, the packet is flooded to all nodes not to the leader nodes only. This is because the intention is to guarantee the geocast packet to all nodes in the geocast region.

5.3 Proposed Mechanism

First, a few terminologies are needed to be defined which will be used in the subsequent text.

An *island* is a group of connected wireless nodes making one entity, from which no node has a direct connection with other nodes in the geocast region.

Every grid has a *leader* which represents that grid and it is elected by other nodes in that grid. A grid can have zero, one or more nodes inside it.

An *Entry Point* is a node that lies outside the geocast region and is directly connected to one or more nodes inside the geocast region.

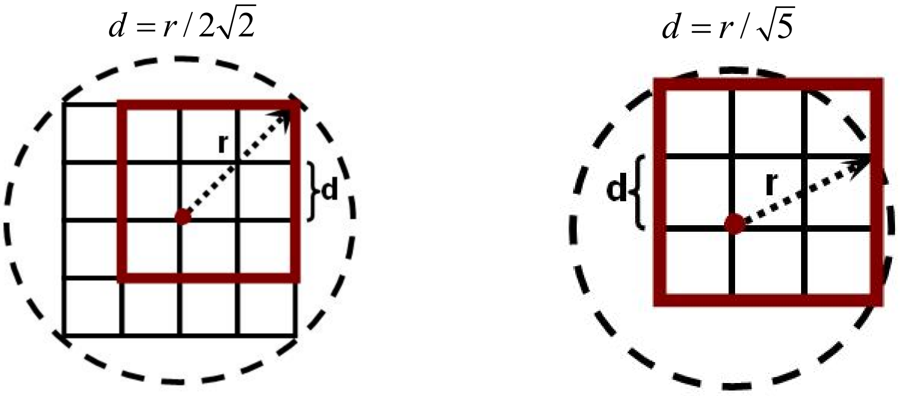
Main Entry Point (MEP) is a leader node which is responsible for delivering geocast packets to nodes inside geocast region. MEP is always a leader because the location server has the position information of only the leader nodes. Therefore, it sends the path based on leader-to-leader communication. MEPs are discussed in detail in section 5.3.4.

The concept of location server is redefined as it is used in other location-based routing protocols, and it is given the routing responsibilities as well. *Location server* is a node that stores the location of all the leaders in the network as well as their neighbor connectivity to other grids in the neighborhood. This information is sent to the location server by all the leaders. Based on this grid connectivity information, the location server constructs the routing tables for all the leader nodes. There can be more than one location servers in the network. It is assumed that each node knows its own position with the help of a GPS receiver.

5.3.1 Layout of the Network

The Network is divided into non-overlapping equal-sided squares called grids. The size of the grid is based on the radio range of the wireless nodes. It is assumed that the size of each side of the grid *'d'* is equal to $r/2\sqrt{2}$. The reason for taking this size is that if a node is anywhere inside a grid, it can still access all the nodes in its neighboring grids. The grid size based on the radio range *'r'* is shown in Figure 5.2.

The side length *'d'* of the grids can be $d = r/\sqrt{5}$. In that case, any node would be able to access all its horizontal and vertical neighbors from anywhere inside the grid, but it would not be able to access all nodes in the diagonal grids. Therefore, the size of the grid can be changed if desired. But, in Zhang and Mouftah (2005), authors show that diagonal routing such that the side length of grids having $d = r/2\sqrt{2}$ outperform protocols performing rectilinear routing such that $d = r/\sqrt{5}$. Therefore, the side length of the grids is assumed to be $d = r/2\sqrt{2}$ in the proposed geocasting mechanism. The network layout is shown in Figure 5.3.



(a) (b)

Figure 5.2: (a) The size of the each grid is such that a node from anywhere in the grid can access all its neighboring grids (b) A node is able to access all its horizontal and vertical neighbors from anywhere inside a grid, but it will not be able to access all nodes in the diagonal grids.

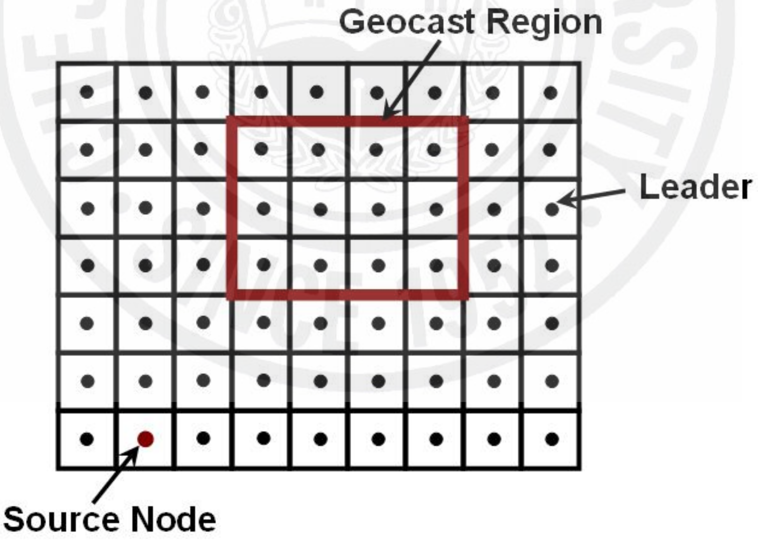


Figure 5.3: Layout of the network that is partitioned into equal-sided grids. Each grid has a leader node which maintains the connectivity information of all its neighboring grids.

5.3.2 Geocasting Mechanism

All leaders from each grid send their position and grid connectivity information to the location server (LS) to inform which grids are directly connected by them in their neighborhood. Based on this information, the location server makes the connectivity map of all the grids. Through this connectivity information, the location server makes the routing table for each leader.

When a source node wants to send a geocast message to a geocast region, it sends a request for the path to the location server. The location server checks the position co-ordinates of the geocast region and maps the position in order to know how many islands are there in the geocast region. If all nodes in the geocast region are connected with one another, then there is only one island. If some nodes are unreachable from other nodes in the geocast region, then there exists more than one island. The geocasting phenomenon in both single and multiple island cases is depicted in Figures 5.4 and 5.5 respectively.

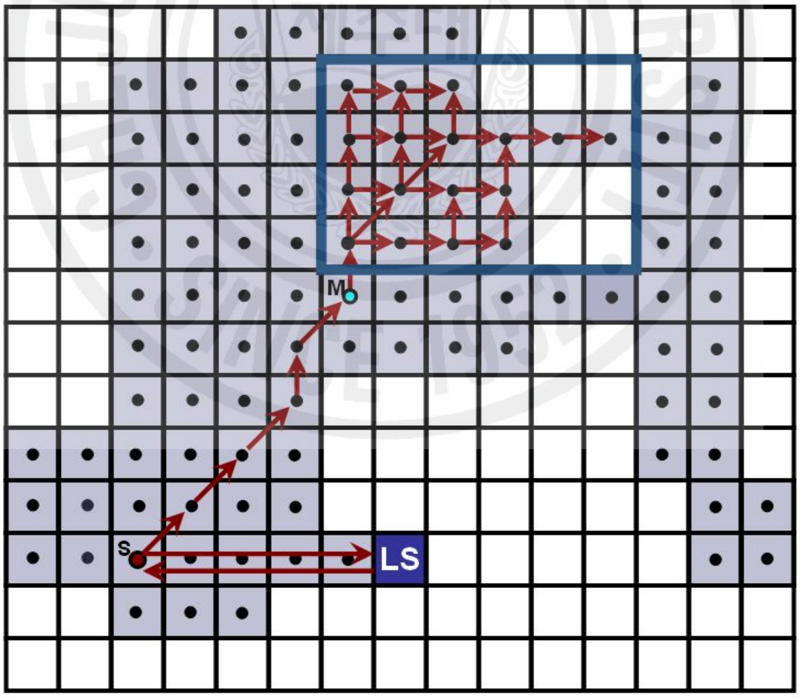


Figure 5.4: Geocasting mechanism with single island case. Node S is the source node whereas Node M is the MEP. Shaded grids show the connectivity among grids.

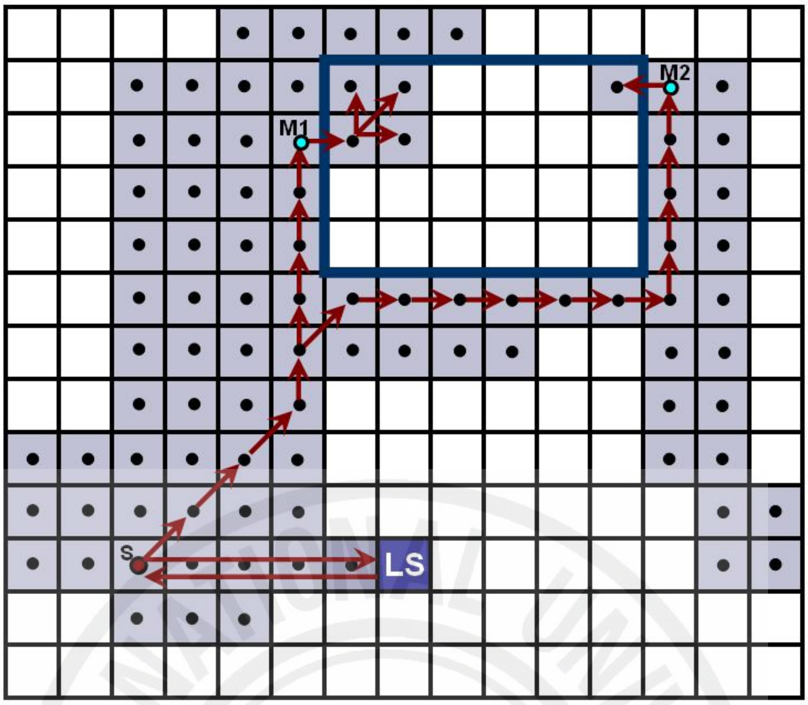


Figure 5.5: Geocasting mechanism with multiple islands case. Node S is the source node whereas Nodes M1 and M2 are two MEPs. Shaded grids show the connectivity among grids.

The location server (LS) selects one leader for each island from outside the geocast region. This leader is called as a Main Entry Point (MEP). This decision is made in such a way that a leader which has the shortest distance from the source node is selected out of all the candidate leaders. Upon receiving the request from the source node, the location server checks the routing table and constructs the path from the source node to each MEP separately. The path is made on the basis of shortest path algorithm based on number of hops. When the source node receives the path from the location server, it uses source routing to send the message to each MEP and the packet is transmitted as a separate unicast message individually. The MEPs then deliver the packet inside the geocast region. Once the packet reaches inside the geocast region, flooding is used to deliver it to all other nodes in the region.

Here, since only one leader is selected as MEP out of several candidate leaders outside each island, there are less duplicate packets transmitted into the geocast region as compared to LBM and Geo-Grid, where due to flooding, multiple entry points deliver the packet to the geocast region which causes extra packet overhead. In case of GAMER, multiple connections are established due to the mesh which also creates multiple connections. Also, since the routing is performed in a grid-by-grid manner where only the leader node is responsible for routing packets to the next leader of the neighboring grid, packet overhead is further reduced as compared to the case where the packet forwarding is done by all nodes. Moreover, in the proposed scheme, the overhead is further reduced by unicasting the geocast packet to the MEPs of each island instead of flooding it throughout the network.

5.3.3 The Leader Election

The nodes present in a grid elect one leader node which is responsible for maintaining the grid connectivity information sent by all nodes inside that grid. Any node within a grid can be a candidate to become a leader. The leader should be that node which is nearest to the center of the grid. A node that wants to become a leader sends a LEADER-ANNOUNCE packet to all reachable nodes in the grid. This packet contains the node-ID and its position and is shown in Figure 5.6. The Leader-Flag in the figure is set if a node wants to become a leader. If there is already a leader in the grid, it rejects its announcement by sending a REJECT packet. If the announcing node does not hear any other announcement from other nodes, it becomes the leader and sends a LEADER-CONFIRM packet to all the nodes in that grid. The leader then repeatedly sends the LEADER-CONFIRM packet after every pre-determined interval to tell other nodes about its existence. Once a node is elected as leader, it will remain a leader until it fails to work as a leader. In case of a leader failure, if a node does not hear any LEADER-CONFIRM packet from the leader for a certain predefined interval, the leader election procedure is re-initiated in the same manner. The nodes in all the grids choose their leaders in the same way.

Leader-Flag	Node ID	Position

Figure 5.6: LEADER-ANNOUNCE packet

5.3.4 Main Entry Points (MEPs)

There are several entry points for an island but there is only one Main Entry Point (MEP) which is responsible for delivering the packet to the geocast region. For simplicity, it is assumed that the geocast region is in the form of a square or a rectangle. The selection of the MEP is made by the location server based on the grid connectivity information. Upon the request of a source node, the location server sends the ID, location and path to reach each MEP to the source node. The Leader table stored by the location server is shown in Table 5-1.

Table 5-1: Leader table stored by the location server containing information about all the leaders and their connected grids.

Leader	Position	Connected Grids
L1	(x1,y1)	G2, G3, G4, G5
L2	(x2,y2)	G1, G6, G7
L3	(x3,y3)	G2, G8, G9
⋮	⋮	⋮

The proposed mechanism works in the following manner: In order to send a packet to the geocast region, a source node S first sends a request to location server asking it for the IDs of nearest MEPs outside the geocast region and their paths. The location server replies back with the IDs of one MEP per island and the paths to reach them. The source then unicasts the packet to all those MEPs based on source routing i.e. the whole path is sent with the packet to the destination MEP.

When a geocast packet arrives at one of the MEPs from the source node, it forwards it to the nearest internal boundary leader inside the geocast region. That node then floods the packet to all nodes inside that island. Here, only MEPs are used to deliver geocast packets to the islands because it is assumed that MEPs have enough resources than other nodes and are more stable. Moreover, there can be multiple location servers in the network and all the location servers collaborate with one another for keeping the updated information about all leader nodes. When MEP receives the geocast packet, it sends it to the leader of its adjacent grid inside the geocast region according to its neighbor table. The receiving node forwards the packet to all nodes inside the island using flooding.

The procedure for routing the packet from Source S to the MEPs is shown in the following steps:

Procedure:

1. Source S contacts location server for MEP-ID and path.
2. Server replies back with ID of the nearest MEP of each island and the path to reach them.
3. Source sends packet to each MEP based on source routing.
4. Upon receiving the packet, MEP delivers the packet to a node inside the geocast region.
5. That node then floods the packet to all nodes in its respective island.

As shown in Figure. 5.4, the source node S first contacts the location server to get the path information of the closest MEP of each island. After getting the path, it sends the geocast packet to all MEPs using source routing. When packet arrives at the MEP it sends it to an internal node in the geocast region. When the packet reaches that node, it floods the packet to all nodes inside its own island. The islands and MEPs are shown in Figure 5.7.

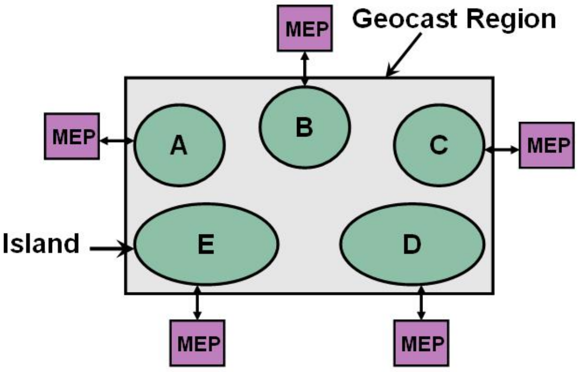


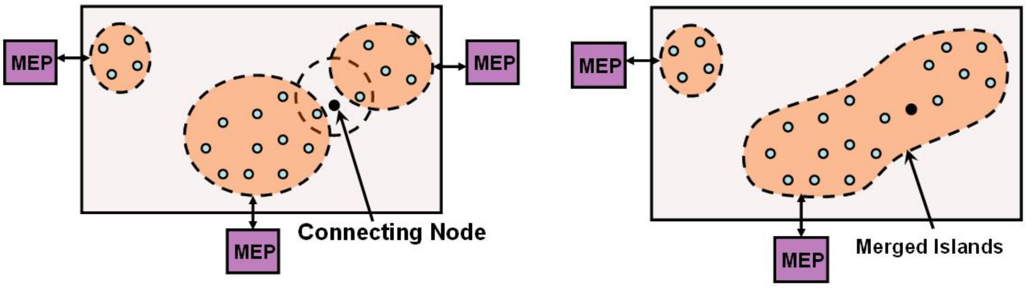
Figure 5.7: Each island A, B, C, D and E has one MEP which is responsible for delivering packets inside the geocast region.

5.4 Maintenance of Geocast Region

The maintenance of geocast region consists of merging and partitioning of islands in the geocast region, which is explained as follows:

5.4.1 Merging of Two Islands

When the connection between two islands is established, the merger of two islands takes place. In this case, two islands combine to become one. Since every island has its own MEP which represents the island, one MEP has to abandon its responsibilities from serving the island as MEP. Since the leaders regularly send their connectivity information to the location server, location server immediately notices that the merger of two islands has taken place. Once the location server comes to know about their merger, it sends a PATH-UPDATE message to the source node which contains the path of the new MEP. Generally, that MEP is selected from the two which is at a shorter distance from the source node. The distance is measured in terms of number of hops from a source to the destination. The merging process is shown in Figure 5.8.

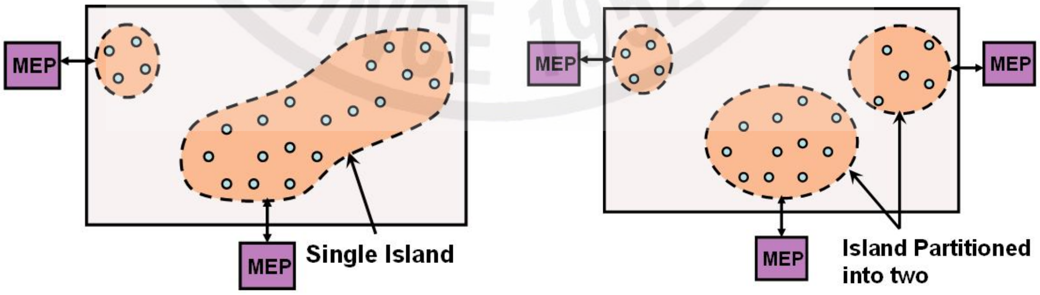


(a) (b)

Figure 5.8: Merging of two islands.

5.4.2 Partitioning of Islands

When the connection between two or more nodes of an island is lost in such a way that it separates them into two or more groups, the island is said to be broken. When an island breaks into two, one of the two islands will be left without an MEP. But because of the periodic connectivity information sent by the leader node, the location server immediately learns that the island has been partitioned into two. Therefore, it will select the nearest leader from the source node and send a PATH-UPDATE message to the source node. Upon receiving this path information, the source node will send the geocast message to this MEP separately. Figure 5.9 shows the partitioning mechanism.

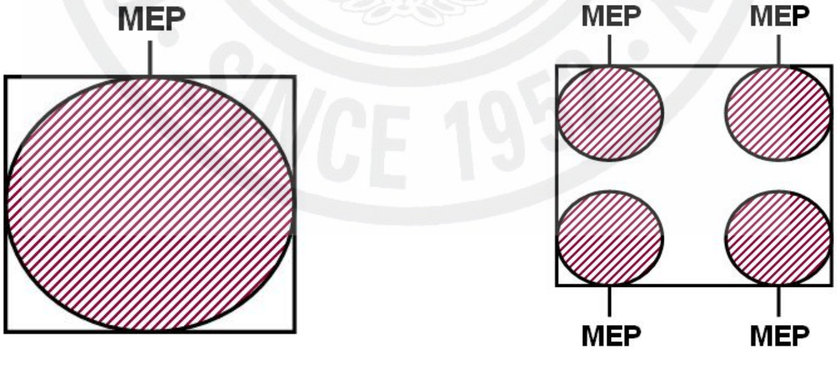


(a) (b)

Figure 5.9: Partitioning of an island into two.

5.5 Analysis and Discussion

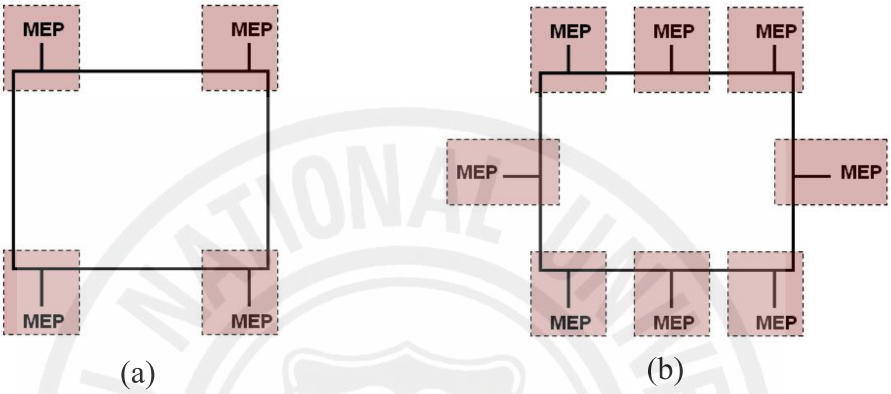
In the proposed mechanism, every island can have only one MEP. As mentioned earlier, the geocast region is assumed to be in rectangular form. But, for the purpose of better generalization of the system, the geocast region is considered to be a square. The system is analyzed from the very basic scenario of having one island in the geocast region to multiple islands. It is discussed how the system is affected by increasing or decreasing the number of nodes and number of islands in the geocast region. In order to analyze the system, consider the following scenarios as shown in Figure 5.10. In Figure 5.10 (a), there is one big island in the geocast region, which means that all nodes in the geocast region can receive geocast packets using simple flooding. Also, there is one MEP, through which the geocast packets are delivered from outside the geocast region. Figure 5.10 (b) shows four islands one at each corner of the geocast region each having one MEP. If the numbers of islands in the geocast region are increased, the number of MEPs also increases linearly. The maximum number of islands possible in a geocast region depends upon the size of the geocast region and the radio range of mobile nodes.



(a) (b)

Figure 5.10: (a) One island in the geocast region (b) Four islands in the geocast region each is having one MEP.

If the size of geocast region is big then more islands can be accommodated. Similarly, if the radio range of nodes is not so wide, more islands can be possible. It is observed that if the numbers of islands are kept on increasing in the geocast region, then at some point, the islands will start merging with each other when one or more nodes from one island enter the radio range of another island. This situation has been analyzed by increasing the number of islands in the geocast region. As shown in Figure 5.11, changing the number of islands will affect the number of MEPs for each region.



(a) (b)

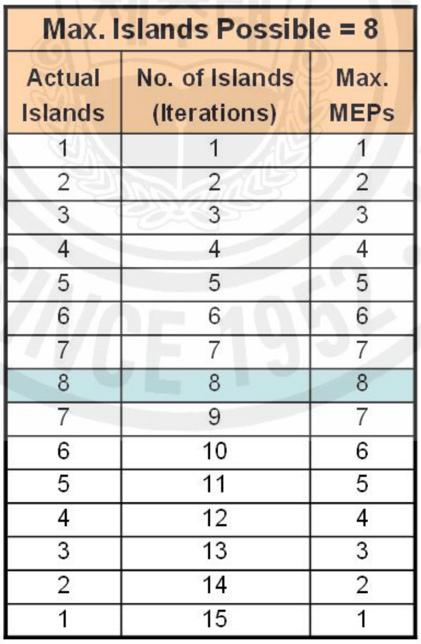
Figure 5.11: By increasing the number of islands result in increased number of MEPs until they start merging at some point. (a) 4 islands with 4 MEPs (b) 8 islands with 8 MEPs.

Tables 5.2 and 5.3 show that on increasing the number of islands in the geocast region, the numbers of MEPs also increase. But the increase in the number of MEPs stops at a certain point when there is no more room for another island. At this point, the number of MEPs is maximum. After this point, by increasing the number of islands would result in merging of islands and hence, the number of MEPs starts decreasing upon each merger. For example, in Table 5.2, the maximum number of MEPs for 4 islands is 4. After this point, the value decreases. The reason for the decrease in number of MEPs after the maximum value is reached is that when the maximum MEP threshold is crossed, the nodes in an island start having direct connection with the nodes in other islands. This merging causes the decrease in the number of MEPs.

Table 5-2: The effect of number of MEPs by increasing the number of islands in the geocast region. Maximum number of islands possible is 4

Max. Islands Possible = 4		
Actual Islands	No. of Islands (Iterations)	Max. MEPs
1	1	1
2	2	2
3	3	3
4	4	4
3	5	3
2	6	2
1	7	1

Table 5-3: The effect of number of MEPs by increasing the number of islands in the geocast region. Maximum number of islands possible is 8.



Max. Islands Possible = 8		
Actual Islands	No. of Islands (Iterations)	Max. MEPs
1	1	1
2	2	2
3	3	3
4	4	4
5	5	5
6	6	6
7	7	7
8	8	8
7	9	7
6	10	6
5	11	5
4	12	4
3	13	3
2	14	2
1	15	1

Figure 5.12 also shows that by increasing the number of islands in the geocast region, the number of MEPs also increases until it reaches some maximum value. After that maximum threshold value, the number of actual islands starts decreasing

by increasing the number of islands (iterations) until they become one island. Hence, the proposed mechanism performs better if there are large numbers of nodes in an island. In this case, the communication overhead decreases since for each island, the maximum numbers of MEPs are fixed, i.e., each island has one MEP. Therefore, even if the numbers of nodes increase, the maximum number of MEPs would remain the same. But, if the number of islands increases and the merger takes place, then the number of MEPs would decrease. This means that the communication overhead would be less in terms of number of packets generated.

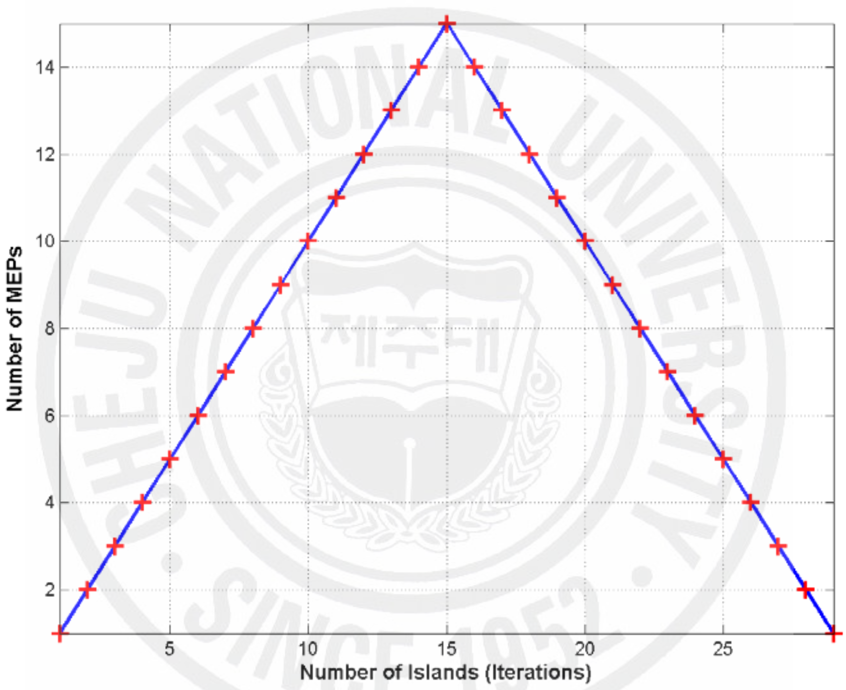


Figure 5.12: Effect on number of MEPs by increasing the number of islands.

5.6 Summary

A geocasting mechanism is proposed in which the problem of guaranteeing the delivery of geocast packets to all nodes inside the geocast region is discussed for an ad hoc network. The nodes in the geocast region may not be connected directly to one another, so for this purpose the nodes outside the geocast region are utilized to guarantee the delivery of packets to all nodes inside the geocast region. The isolated groups of nodes inside the geocast region are called islands. A grid-based approach is used for determining the islands as well as sending geocast packets to the geocast region. There can be several nodes outside the geocast region that have direct connections with nodes in the islands, however, one node is elected called Main Entry Point (MEP) which is responsible for delivering the packets to the nodes inside the geocast region. Moreover, the concept of location server is redefined and is given the routing responsibilities as well. The impact of increasing the number of nodes as well as number of islands in the geocast region is also analyzed and it is concluded that using the proposed mechanism; less communication overhead can be achieved among various MEPs and the nodes.

Chapter 6

EVALUATION OF GRID-BASED GUARANTEED GEOCAST PROTOCOL

In this chapter, the proposed Grid-based Guaranteed Geocast (G3) protocol is compared with other geocasting protocols by doing simulations. It is also shown that the proposed mechanism guarantees the delivery of geocast packets to all nodes in a geocast region.

6.1 Simulations

Simulations of the proposed geocasting protocol have been performed in NS-2 (Network Simulator). The proposed protocol called Grid-based Guaranteed Geocast (GGG or G3) is implemented and compared with some of the topology-based geocasting protocols. As mentioned in chapter 2, most of the topology-based geocasting protocols do not guarantee the delivery whereas some protocols based on face traversal algorithms guarantee the delivery. The main point in the proposed protocol here is that, although this protocol is neither a face traversal based algorithm nor it is based on flooding, it still guarantees the delivery of geocast packets to all nodes inside a geocast region.

For comparison, the LBM scheme 1 is used whereas GAMER is used with forwarding zones. The main difference between the proposed protocol and the other two is that both LBM and GAMER are based on restricted flooding. LBM sends the geocast packets in a rectangular request zone whereas GAMER uses a CORRIDOR and a CONE forwarding zones for establishing a mesh. The proposed mechanism does not use flooding, and it is based on a grid-based pro-active mechanism in which the network connectivity is determined by mapping the connectivity of grid leaders on a zone map. The main purpose of using this pro-active mechanism is to figure out how many islands are present in the geocast region. This is because, if the numbers of islands in the geocast region are unknown, there is no way to know whether the packets are delivered to all nodes in the geocast region. Moreover, by not using the flooding mechanism, the communication overhead can be reduced as well as the chances of duplicate packets in the network are decreased.

6.1.1 Simulation Model

For simulations, the nodes in the network are confined to an area of 800 x 600 units. The total numbers of wireless nodes are taken to be 40. Simulations are done for a total of three islands placed at different places in the geocast region. The number of nodes in island 1, island 2 and island 3 are 8, 2 and 1 respectively. It is assumed that the nodes know their current locations accurately and all nodes have the same transmission range. The transmission range is chosen to be 100 units. For the simulations, a sender is chosen randomly and the geocast region is predefined.

Table 6-1: Simulation parameters

Simulator	NS-2
Simulation area (wxh)	800 x 600 units
Total number of nodes	40
Total islands	3
Nodes in island 1	8
Nodes in island 2	2
Nodes in island 3	1
Transmission range	100 m
Simulation time	150 sec
Radio propagation model	Two-Ray Ground

Moreover, a Two-Ray Ground propagation model and omni-directional antenna is used. The simulations are run for a time period of 150 seconds. The parameters used are shown in Table 6-1.

6.1.2 Simulation Results

The simulations are carried out to show that the proposed geocasting protocol G3 guarantees the delivery of geocast packets in the geocast region whereas LBM and GAMER do not guarantee the delivery. Moreover, the throughput of all these three protocols has been analyzed and shown. The communication overhead and end-to-end delay is also computed for LBM, GAMER and the proposed protocol.

6.1.2.1 Delivery Guarantee

For simulations, three islands have been taken in the geocast region. The criterion is very simple; if the geocast packets reach nodes in all the islands then the protocol guarantees the delivery otherwise not. In order to show the delivery guarantee, the delivery of number of packets is shown in Table 6-2. The table shows that in case of island 1, LBM receives 123369 packets whereas GAMER receives 115365 packets. For both protocols, no packets are received by islands 2 and 3. In case of the proposed protocol, packets are successfully received by nodes of all the three islands. The reason behind not receiving packets by islands 2 and 3 in case of GAMER and LBM is that both protocols use forwarding zones and packets are forwarded only in the forwarding zones. In case of LBM, it uses a rectangular forwarding zone whereas GAMER uses two forwarding zone approaches i.e., CORRIDOR and CONE. Upon receiving the packet by nodes inside the geocast region, the packet is just flooded to all nodes in their islands. The packets cannot reach those parts of the geocast region that are not covered by the forwarding zones. Though, inside the geocast region, the protocol uses flooding, still the delivery of packets cannot be guaranteed if an island happens to lie on the other side of the geocast region that cannot be accessed from within the forwarding zone. The proposed protocol G3 guarantees the packets to be delivered to all nodes since the number of islands are figured out by using the proactive neighbor connectivity information sent by the leader nodes. Once the number of islands is known, the packet can be delivered to nodes in all the islands by using unicast routing.

Table 6-2: Packets received by all the three islands by the goeasting protocols

Delivery Guarantee			
Protocol	**Island 1**	**Island 2**	**Island 3**
GGG	166565	12274	24252
LBM	123369	0	0
GAMER	115365	0	0

6.1.2.2 Throughput

The throughput for all the three protocols is analyzed and shown in Figure 6.1. Throughput is defined as the number of packets received per unit time by the destination. Throughput of Grid-based Guaranteed Geocast protocol is compared with that of GAMER and LBM. The figure clearly shows that the throughput for the proposed protocol is higher than the other two protocols.

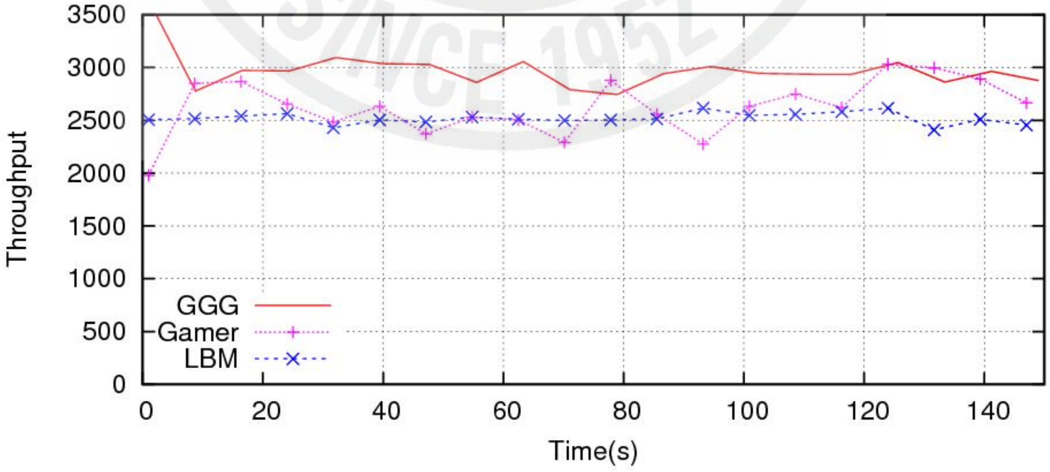


Figure 6.1: Comparative throughput for three protocols, LBM, GAMER and GGG.

6.1.2.3 Communication Overhead

The communication overhead analysis for geocast packets in case of the proposed protocol G3, GAMER and LBM is shown in Figure 6.2. The communication overhead is computed for the data packets only. Since the proposed protocol G3 is based on proactive connectivity information sent by leader nodes whereas LBM and GAMER use a reactive approach to establish paths, they cannot be compared on the basis of control packets generated. The proposed protocol and the other two protocols are different in the basic nature i.e., one is based on proactive mechanism and the other two are based on reactive strategy.

From the figure, it is clear that the proposed protocol has less communication overhead than the other two protocols i.e., LBM and GAMER. The overhead of LBM is the highest because LBM uses restricted flooding to send the geocast packets. Every node in the forwarding zone forwards the packet to every other node in its radio range; therefore, the total number of packets generated is much higher than the other two protocols. GAMER uses a mesh for sending the geocast packets. In case of GAMER, every node in the geocast region that lies at the boundary makes connection with the source node; hence a mesh is created between the source node and the internal boundary nodes of the geocast region. In case of G3, there is only one node called MEP which is responsible for delivering packet to each island even if there are more than one nodes present at the inner boundary of the geocast region. Therefore, the proposed protocol performs better than other two protocols in terms of communication overhead since it makes lesser number of connections with nodes in the geocast region than the other two protocols i.e., GAMER and LBM.

For these simulations, 8 nodes are kept in the first island, 2 in the second and 1 is present in the third island. Therefore, a total of 11 nodes are there in the geocast region. Moreover, all nodes are not placed at the boundary of the geocast region therefore; the total numbers of connections made by GAMER are not many. This is the reason that the difference between GAMER and G3 is not much in Figure 6.2. If there were more nodes present at the internal boundary of the geocast region, there would be more redundant connections for GAMER and hence the overhead generated by GAMER would have been much higher than the one in Figure 6.2.

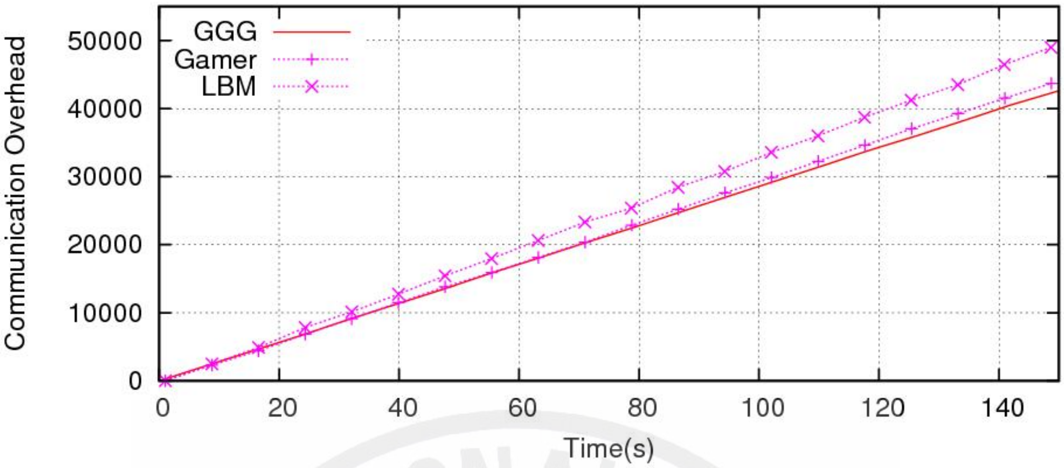


Figure 6.2: The communication overhead for LBM, GAMER and GGG.

6.1.2.4 End-to-End Delay

The end-to-end delay has also been computed for all the three protocols. The end-to-end delay is the delay experienced by a packet traveling from a source node to the destination. Here, the destination is the first node in an island in the geocast region that receives the geocast packet. The simulations show that the total end-to-end delay for the proposed protocol G3 is less than both protocols LBM and GAMER. This is because in G3, a single path is used by the source to deliver packets to the destination MEP of each island. Whereas in LBM and GAMER, multiple paths are used to forward geocast packets to the destination. Since, same packet is forwarded by multiple nodes, the packets can have collisions and hence, the delay can become larger because of resending the packets by the source nodes. The end-to-end delay experienced by all the three protocols is shown in Figure 6.3.

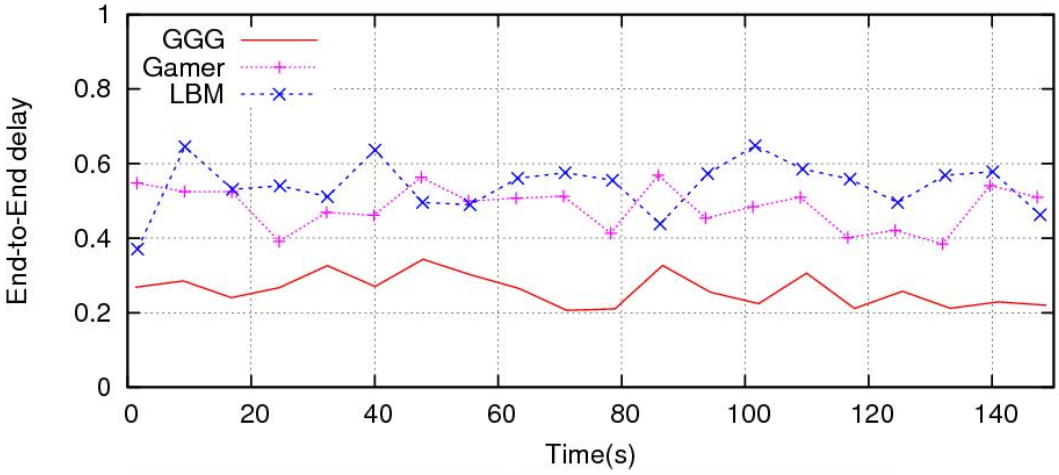


Figure 6.3: Total End-to-End delay experienced by LBM, GAMER and GGG.

6.1.2.5. Packet Delivery Ratio

The packet delivery ratio is also computed for all the three protocols. The packet delivery ratio is defined as the ratio of the number of packets received by the destination and the number of packets sent by the source node. The results of this ratio can be seen in Figure 6.4. Figure clearly shows that the packet delivery ratio of the proposed protocol is higher than LBM and GAMER. The reason behind this can be again the same i.e., in case of G3, the path is generated by the location server in advance, and there is only one path for each island from the source node to the destination. In case of LBM, flooding is used and hence, the possibility of collisions is higher. For GAMER also, there can be more redundant connections for each island. Therefore, the chance of packet loss due to collisions is also higher.

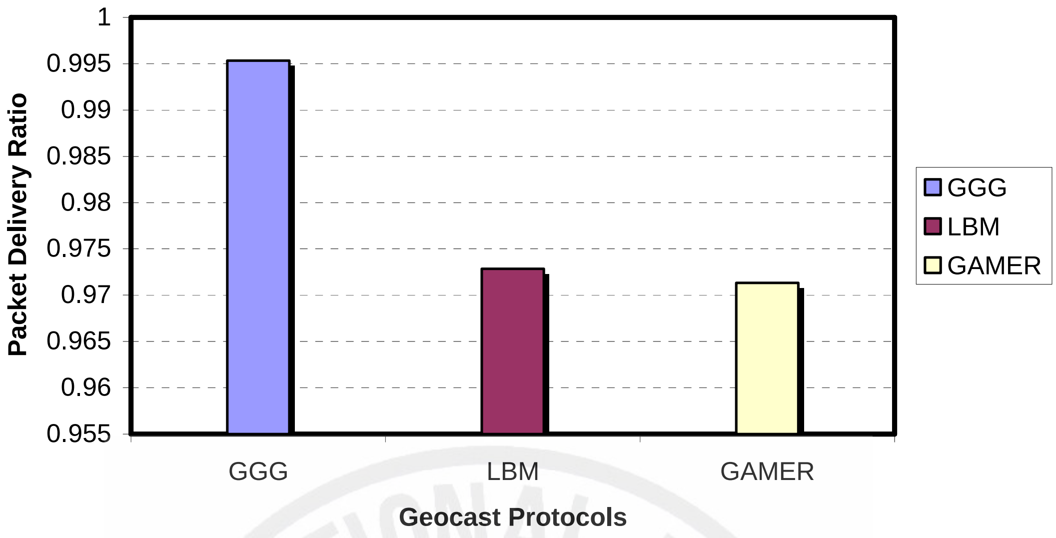


Figure 6.4: Packet delivery ratio for LBM, GAMER and GGG.

6.2 Summary

The simulations results were shown in this chapter for the proposed protocol G3. The protocol is compared with two other geocasting protocols, LBM and GAMER. Simulations results show that the proposed protocol guarantees the delivery of geocast packets to all nodes inside a geocast region. Moreover, it is shown that LBM and GAMER with forwarding zone do not guarantee the delivery of geocast packets. Throughput as well as communication overhead analysis is also done for LBM, GAMER and the proposed protocol. Moreover, the end-to-end delay and the packet delivery ratio are also computed for all the three protocols. The simulation results clearly show that in all cases, the proposed protocol performs better than the other two protocols LBM and GAMER.

Chapter 7

CONCLUSION AND FUTURE DIRECTIONS

In this work, two main issues have been addressed for wireless ad hoc networks. First, a new location-aware routing protocol called Location-aware Grid-based Hierarchical Routing (LGHR) protocol is proposed for mobile ad hoc networks. Secondly, the problem of guaranteeing the delivery of geocast packet to all nodes inside a geocast region for wireless ad hoc networks is addressed. For this purpose, a geocasting protocol called Grid-based Guaranteed Geocast (GGG or G3) is proposed that guarantees the delivery of geocast packets. In both the above protocols, a grid-based approach is used.

LGHR effectively utilizes the proactive link state routing by dividing the network into smaller manageable areas and at the same time, exploiting the location-aware capability for minimizing the possible overhead. In LGHR, the network is partitioned into non-overlapping zones. A hierarchy is made in such a way that the whole network is divided into zones and each zone is then further divided into grids. The role of a leader node is also introduced which is mainly responsible for making routing decisions. Both the intra-zone and inter-zone routing mechanisms are explained. The proposed protocol is compared with other location-aware ad hoc routing protocols such as Zone-based Hierarchical Link State (ZHLS) which is a hybrid routing protocol, and GRID which is a location-aware reactive routing protocol. ZHLS can perform well in scenarios where there are small numbers of nodes in a zone. But if the numbers of nodes in each zone are increased, huge overhead is occurred in ZHLS due to proactive peer-to-peer exchange of link state packets as well as reactive zone search mechanisms for each destination that is present in other zones.

For comparison, first the mathematical analysis and evaluation for ZHLS and LGHR is done. Analysis is also done for the effect of increasing the number of nodes as well as zones for both protocols. The analysis clearly indicates that the proposed protocol performs better than ZHLS in terms of the storage overhead as well as communication overhead generated by all nodes. Secondly, the proposed protocol is compared with GRID protocol in order to check the stability of the protocols. The stability factor is chosen on the basis of gateway election mechanisms. GRID uses only the distance from the center of the grid for electing a gateway whereas LGHR takes into account the velocity of a node along with the distance from the center of the grid. The simulation results clearly show that the proposed protocol LGHR is more stable than GRID especially in scenarios where the wireless nodes are moving with very high velocities.

With the rapid advancement in the wireless technology, large numbers of nodes would be present within a zone in future, as most of the currently wired devices would also become wireless. Therefore, LGHR would be a very useful candidate in such scenarios. Moreover, LGHR is suitable for vehicular networks since the stability of the protocol is taken into account due to the probability of nodes moving with very high velocities. The centralized approach in LGHR can also be modified to be used in wireless mesh networks. As a future work, the real world deployment of the proposed protocol LGHR is intended to be performed. The protocol can then be analyzed and evaluated based on the results obtained by the deployment.

In the proposed geocasting protocol Grid-based Guaranteed Geocast (GGG), a geocast routing mechanism is discussed in which the problem of guaranteeing the delivery of geocast packets to all nodes inside the geocast region is addressed for wireless ad hoc networks. The nodes in the geocast region may not be connected directly to one another, so for this purpose the nodes outside the geocast region are used to guarantee the delivery of packets to all nodes inside the geocast region. There can be several nodes outside the geocast region that have direct connections with the isolated nodes or islands, but one node is elected called Main Entry Point (MEP) which is held responsible for delivering the packets to the nodes inside the geocast region. By doing this, the numbers of connections for a geocast delivery are reduced as compared to other mesh-based protocols like GAMER, which uses multiple connections for geocast packet delivery causing a number of redundant packets to be delivered to the nodes in a geocast region. Also, the concept of location server is redefined and is also given the routing responsibilities as well. The impact of increasing the number of nodes as well as number of islands in the geocast region is analyzed. Simulations are performed for the proposed mechanism and other two geocasting protocols LBM and GAMER. All the three protocols are compared in terms of throughput, delivery guarantee, communication overhead, end-to-end delay and packet delivery ratio. The simulations prove that the proposed mechanism not only guarantees the delivery of geocast packets but also performs better than the other two protocols. The proposed mechanism has higher throughput, low end-to-end delay, higher packet delivery ratio and less communication overhead than the other two protocols, LBM and GAMER.

In case of the proposed geoasting mechanism, only static wireless nodes have been considered for simulations. Other face traversal based geocasting protocols that guarantee the delivery also consider static wireless nodes or sensor nodes. In future, the proposed protocol G3 will be tested for mobility scenarios as well. Moreover, the protocol can be deployed and tested in the real world scenarios.

BIBLIOGRAPHY

Abolhasan, M., Wysocki, T. and Dutkiewicz, E. 2004. A review of routing protocols for mobile ad hoc networks. *Ad Hoc Networks*, Vol. 2, Issue 1, pages 1-22

Basagni, S., Chlamtac, I., Syrotiuk, V. R. and Woodward, B. A. 1998. A distance routing effect algorithm for mobility (DREAM). In *Proceedings of the 4th annual ACM/IEEE international conference on Mobile computing and networking (MobiCom '98)*, New York, NY, USA, pages 76-84

Bellur, B., Ogier, R.G., Templin, F.L. 2003. Topology broadcast based on reverse-path forwarding routing protocol (TBRPF), In: *Internet Draft, draft-ietf-manet-tbrpf-06.txt,* work in progress

Bose, P., Morin, P., Stojmenovic, I. and Urrutia, J. 2001. Routing with guaranteed delivery in ad hoc wireless networks. *Wireless Networks*, 7(6): 609–616

Camp, T. and Liu, Y. 2003. An adaptive mesh-based protocol for geocast routing. *Journal of Parallel and Distributed Computing,* 63(2):196–213

Capkun, S., Hamdi, M. and Hubaux, J. 2001. GPS-Free Positioning in Mobile ad-hoc Networks. *In Proceedings of the 34th Annual Hawaii international Conference on System Sciences (Hicss-34)*-Volume 9, 9008

Caruso, A., Chessa, S., De, S. and Urpi, A. 2005. GPS free coordinate assignment and routing in wireless sensor networks. In *Proceedings of IEEE Infocom '05*, pages 150-160

Chang, C-Y., Chang, C-T. and Tu, S-C. 2003. Obstacle-free geocasting protocols for single/multi-destination short message services in ad hoc networks. *Wireless Networks,* 9(2):143–155

Fang, Q., Gao, J. and Guibas, L. J. 2004. Locating and bypassing routing holes in sensor networks. In *Proceedings of the 23rd IEEE Infocom'04.*

Fang, Q., Gao, J. Guibas, L. J., Silva, V. and Zhang, L. 2005. GLIDER: Gradient landmark-based distributed routing for sensor networks. I*n Proceedings of IEEE Infocom '05.*

Garcia-Luna-Aceves, J.J. and Madrga, E.L. 1999. A multicast routing protocol for ad-hoc networks, *In Proceedings of the Annual Joint Conference of the IEEE Computer and Communications Societies (Infocom'99)*, pages 784–792.

Garcia-Luna-Aceves, J.J. and Spohn, M. 1999. Source-Tree Routing in Wireless Networks , In *Proceedings of IEEE International Conference on Network Protocols (ICNP 1999),* Toronto, Canada, Pages 273-282

Giordano, S. and Stojmenovic, I. 2003. Position-based ad hoc routes in ad hoc networks. *The Handbook of Ad Hoc Wireless Networks,* CRC Press, Chapter 16, pages 287 - 300

Giordano, S. and Stojmenovic, I. 2004. Position based routing algorithms for ad hoc networks: A taxonomy. *Ad Hoc Wireless Networking*, Kluwer Academic Publishers, pages 103–136

Grewal, M.S., Weill, L. R. and Andrews, A. P. 2001. *Global Positioning Systems, Inertial Navigation and Integration.* John Wiley and Sons, Inc.

Haas, Z. J. and Pearlman, M. R. 1998. The performance of query control schemes for the zone routing protocol. In *Proceedings of ACM SIGCOMM Conference,* pages 167-177

Heissenbüttel, M. and Braun, T. 2003. A novel position-based and beacon-less routing algorithm for mobile ad-hoc networks. In *Proc. of the 3rd IEEE Workshop on Applications and Services in Wireless Networks (ASWN'03),* Bern, Switzerland, pages 197–209

Jacquet, P., Muhlethaler, P. and Qayyum, A. 2003. Optimized link state routing protocol, *RFC 3626.*

Jiang, M., Ji, J. and Tay, Y.C. 1999. Cluster based routing protocol, In: *Internet Draft, draft-ietf-manet-cbrp-spec-01.txt*, work in progress.

Jiang, X. and Camp, T. 2002. Review of geocasting protocols for a mobile ad hoc network. In *Proceedings of the Grace Hopper Celebration (GHC)*

Joa-Ng, M., Lu, I-T. 1999. A Peer-to-Peer Two-level Link State Routing Protocol for Mobile Ad hoc Networks. *IEEE Journal on Selected Areas in Communication*, Vol. 17, Issue 8, pp. 1415-1425

Johnson, D. B. and Maltz, D. A. 1996. Dynamic Source Routing in Ad Hoc Wireless Networks. *Mobile Computing,* Kluwer Academic Publishers, pages 152–181

Karp, B. 2000. Geographic Routing for Wireless Networks. *PhD thesis*, Harvard University, Cambridge, MA.

Karp, B. and Kung, H. T. 2000. GPSR: greedy perimeter stateless routing for wireless networks. In *Proceedings of the 6th Annual ACM/IEEE*

International Conference on Mobile Computing and Networking (MobiCom 2000), pages 243–254

Ko, Y. B. and Vaidya, N. H. 1998. Geocasting in mobile ad hoc networks: Location-based multicast algorithms. *Technical Report* TR-98-018, Texas A&M.

Ko, Y. B. and Vaidya, N. H. 2000a. Location-Aided routing (LAR) in mobile ad hoc networks. *Wireless Networks,* 6(4):307–321

Ko, Y. B. and Vaidya, N. H. 2000b. GeoTORA: A protocol for geocasting in mobile ad hoc networks. *Technical report,* Texas A&M.

Lee, S.-J., Gerla, M. and Chiang, C.-C. 1999. On-demand multicast routing protocol, *In Proceedings of IEEE Wireless Communications and Networking Conference (WCNC'99)*, pages 1298–1302.

Leong, B. Liskov, B. and Morris, R. 2006. Geographic routing without planarization. *In Proceedings of the 3rd USENIX/ACM Symposium on Networked Systems Design and Implementation (NSDI '06)*

Leong, B. 2006. New techniques for Geographic Routing, *PhD thesis,* MIT

Lian, J., Naik, K., Liu, Y. and Chen, L. 2006. Virtual Surrounding Face Geocasting with Guaranteed Message Delivery for Ad Hoc and Sensor Networks, In *Proceedings of IEEE ICNP'06*, Santa Barbara, California, USA

Liao, W.-H., Tseng, Y.-C., Lo, K.-L. and Sheu, J.-P. 2000. GeoGRID: A geocasting protocol for mobile ad hoc networks based on grid. *Journal of Internet Technology*, 1(2):23–32

Liao, W.-H., Tseng, Y.-C., and Sheu, J.-P. 2001. Grid: A fully location-aware routing protocol for mobile ad hoc networks. *Telecommunication Systems,* 18(1), 37-60

Maihöfer, C. 2004. A survey of geocast routing protocols. *IEEE Communications Surveys and Tutorials,* 6(2):32–42

Mauve, M., Widmer, J. and Hartenstein, H. 2001. A survey on position-based routing in mobile ad hoc networks. *IEEE Network Magazine,* 15(6):30–39

Network Simulator, (http://www.isi.edu/nsnam/ns/)

Ni, S-Y., Tseng, Y-C., Chen, Y-S. and Sheu, J-P. 1999. The Broadcast Storm Problem in a Mobile Ad Hoc Network, In *Proceedings of ACM/IEEE International Conference on Mobile Computing and Networking,* IEEE Press, Piscataway, N.J., pages 151-162

Nikaein, N., Labiod, H., and Bonnet, C. 2000. DDR: Distributed Dynamic Routing algorithm for mobile ad hoc networks, In *Proceedings of the 1st ACM international symposium on Mobile ad hoc networking (MobiHoc '00)*, Boston, USA pages 19-27

Park, V. D. and Corson, M. S. 1999. Temporally-ordered routing algorithm (TORA), *IETF Internet Draft.*

Perkins, C. E. and Bhagwat, P. 1994. Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers. In *Proceedings of ACM SIGCOMM'94 Conference*, pages 234-244

Perkins, C. E., Belding-Royer, E. M. and Das, S. 2003. Ad hoc on-demand distance vector (AODV) routing. *IETF RFC 3561*

Priyantha, N. B., Miu, A., Balakrishnan, H. and Teller, S. 2001. The cricket compass for context-aware mobile applications. In *Proceedings of the 7th ACM International Conference on Mobile Computing and Networking (MobiCom '01)*

Rao, A., Papadimitriou, C. H., Shenker, S. and Stoica, I. 2003. Geographic routing without location information. In *Proceedings of the 9th ACM International Conference on Mobile Computing and Networking (MobiCom '03)*, pages 96-108, San Diego, CA

Schwingenschlogl, C. and Kosch, T. 2002. Geocast Enhancements of AODV for Vehicular Networks" *Mobile Computing and Communications Review,* Volume 6, Issue 3

Seada, K., Helmy, A. and Govindan, R. 2004. On the effect of localization errors on geographic face routing in sensor networks. In *Proceedings of the 3rd International Symposium on Information Processing in Sensor Networks (IPSN'04)*, pages 71-80

Seada, K., Helmy, A. 2004. Efficient Geocasting with Perfect Delivery in Wireless Networks, *IEEE Wireless Communications and Networking Conference WCNC,* Atlanta, Georgia, USA

Stojmenovic, I., Ruhil, A. P. and Lobiyal, D.K. 1999. Voronoi Diagram and Convex Hull Based Geocasting and Routing in Wireless Networks, *University of Ottawa,* TR-99-11

Stojmenovic, I. 2004. Geocasting with guaranteed delivery in sensor networks. *Wireless Communications*, 11(6):29–37

Stojmenovic, I. 2006. Geocasting in ad hoc and sensor networks. *Theoretical and Algorithmic Aspects of Sensor, Ad Hoc Wireless and Peer-to-Peer Networks*, Auerbach Publications, pages 79–97

P. Yao, E. Krohne, and T. Camp, Performance Comparison of Geocast Routing Protocols for a MANET, In *Proceedings of the 13th IEEE International Conference on Computer Communications and Networks (IC3N)*, pp. 213-220, 2004.

Zhang, B. and Mouftah, H. T. 2005. Efficient Grid-Based Routing in Wireless Multi-Hop Networks, In *Proceedings of 10th IEEE Symposium on Computers and Communications (ISCC'05)}*, Washington DC, USA