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**ADAPTIVE ROUTING FOR GROUP COMMUNICATIONS IN MULTI-HOP
AD-HOC NETWORKS**

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by

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Contents

List of Figures

List of Tables

Abstract

Adaptive Routing for Group Communications in Multi-Hop Ad-hoc Networks

by

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In recent years, Mobile Ad Hoc networks (MANETs) have been extensively studied as an alternative to infrastructure networks because of their ease of deployment. The targeted environments for ad hoc networks are typically inhospitable regions where it is difficult to set up infrastructure or environments where the existing infrastructure has collapsed temporarily or permanently. MANETs maintain dynamic interconnection between mobile users through multi-hopping. MANET nodes may be highly mobile or stationary and may vary widely in terms of their capabilities and applications. All these features pose serious challenges to routing.

Since group-oriented services are one of the key classes of applications targeted by MANETs, several multicast protocols have been proposed by the ad-hoc network community. In this dissertation, we propose techniques to provide seamless, integrated multicast service whereby a single multicast group can span different network types (e.g., fixed, fixed mobile, and different types of MANETs). Our goal is to develop an integrated, adaptive framework whereby nodes can communicate across various ad-hoc clouds running different multicast protocols. This will allow a given host to partake in multicast communication regardless of the underlying routing protocol and may require hosts to adaptively switch routing mechanisms as they move from one network to another. To our knowledge, there is little or no experience

in the network research community in multicast protocol interoperation or adaptation (albeit, some proposals have been floated in the IETF) [1–3].

As a first step, we have studied both mesh based and tree based protocols and evaluated their performance relative to flooding. Our study shows that, although these protocols perform well under very specific scenarios of mobility, traffic load and network conditions no single protocol is optimal in all scenarios. In particular, we investigate the performance of On-demand Multicast Routing Protocol (ODMRP) and Multicast Ad Hoc On-demand Distance Vector (MAODV) and compare the performance with baseline flooding. Based on an extensive comparative study we also propose two flooding variations i.e *scoped flooding* and *hyper flooding* as means to reduce overhead and increase reliability respectively. An important contribution from this initial study was a qualitative and quantitative comparison of mesh and tree based protocols and the proposed flooding variations.

Given that no single multicast protocol is optimal for all ad hoc scenarios, we investigated adaptive routing protocols in which nodes can change routing mechanisms based on their perception of current network conditions. More specifically, we developed an adaptive flooding protocol in which nodes can dynamically switch among different flooding variations, namely *scoped-*, *plain-*, or *hyper* flooding. We employ relative velocity and perceived network load as the criteria nodes use to switch among protocols. Simulation results comparing our adaptive protocol against two of the better performing MANET multicast protocols, namely ODMRP [4] and MAODV [5], show considerable performance benefits, under various MANET scenarios. We thus argue that the proposed protocol can be used as the basis for developing adaptive, integrated routing techniques for the integrated media networks of the

future.

It is quite likely that future internetworks may interconnect numerous MANET clouds, each running different routing mechanisms. This could be primarily dictated by administrative constraints or different functional and performance requirements. Yet, nodes belonging to different MANET clouds running different routing mechanisms may wish to communicate with one another. Interoperability is also an important aspect of any adaptive routing mechanism in which nodes can actively switch between different routing protocols based on their functional requirements. As explained previously one of the primary objectives of this thesis is to propose techniques to provide seamless, integrated multicast service whereby a single multicast group can span different network types. To this end, we introduce two interoperability techniques, namely flooding based- and facilitator-assisted interoperability and investigate random facilitator selection as well as adaptive facilitator selection.

One feature common to MANETs, is the need to flood control messages network-wide during the route acquisition and maintenance process. Flooding of control messages may result in redundant broadcasts and cause serious contention and collision problems in large MANETs consisting of several thousand mobile nodes. To analyze the impact of flooding in ad hoc networks, we have developed an analytical model to study the performance of plain- and probabilistic flooding in terms of its *reliability* and *reachability* in delivering packets. *Reliability* is a measure of the total number of packets received by network nodes whereas *reachability* refers to the total number of unique nodes reached by the flooding process. Our proposed model can also be extended to analyze other broadcast techniques in MANETs such as scoped flooding etc.

The random waypoint model is one of the most widely used mobility models in the evaluation of MANET protocols. However, this model has serious drawbacks as concluded by a recent paper [6] which shows that average node speed tends to zero in the steady state. Another contribution of this dissertation was to develop a novel statistical model that captures speed decay over time using maximum speed and terrain size as input parameters. A Bayesian approach to model fitting is employed to capture the uncertainty due to unknown parameters of the model. The resulting posterior predictive distributions of quantities of interest (i.e, average node speed) can be used to formally address the fit of the statistical model. Since our statistical model can help characterize the average node speed as a function of time, it offers an efficient alternative to obtaining an estimate of how long simulation experiments using the random waypoint model take to "warm-up". Simulation data from the "warm-up" period can then be discarded to obtain accurate protocol performance results.

Keywords: Ad-hoc networks, group communications, multicast, wireless, on-demand protocols, mobility model, adaptive routing

Acknowledgements

To my dear wife Menaka and my Parents

Chapter 1

Introduction

Group communications or one to many communications form an important class of applications targeted by Mobile Ad-hoc Networks or MANETs. Several approaches to group communications or multicast [7] have been proposed in the MANET community. In this chapter we provide background information on MANETs, discuss the challenges in routing and introduce existing MANET multicasting strategies. We then present the problem statement, i.e, the problems and challenges addressed by this thesis and overview our proposed solutions. We also highlight the main contributions and provide an outline for this dissertation.

1.1 Wireless Ad-Hoc Networks

Mobile multi-hop ad hoc networks, or MANETs, are characterized by the lack of fixed network infrastructure. Unlike traditional wireless networks there is no concept of base stations. All network components of a MANET can be mobile. Moreover, there is no distinction between a host and a router since all nodes can be sources as well as forwarders of traffic.

1

Applications such as conferences, group sessions, crowd management, disaster recovery and control and battlefield scenarios are some of the best known MANET applications. In such cases, MANETs (which are the successor of packet radio networks [8–10]) comprising of mobile nodes equipped with radios can be deployed without the need for fixed infrastructure. MANETs differ from traditional, fixed-infrastructure mobile networks, where mobility occurs only at the last hop. In such networks, although issues such as address management arise, they do not affect core network functions, most importantly, routing. In contrast, MANETs require fundamental changes to conventional routing and packet forwarding protocols for both unicast and multicast communication. Conventional routing mechanisms are based on routers maintaining distributed state about the network topology. These mechanisms were designed for wired networks and work well in fixed-infrastructure mobile networks. However, topology changes in MANETs can be very frequent making conventional routing mechanisms both ineffective and expensive.

1.2   Challenges in Routing and Group Communications in MANETs

Routing in MANETs have to contend with several limitations such as scarce bandwidth and energy, presence of unidirectional links and dynamically changing topologies [11]. In addition, packet radios have limited transmission range depending upon environmental conditions such as interference and fading effects. Since MANET nodes can continuously move, wireless links between nodes can be disrupted. The underlying routing mechanism has to be capable of constructing and maintaining routes in a timely manner. The routing mechanism has to accomplish this without generating excessive control overhead given the bandwidth and

2

energy limitations.

The popularity of group-oriented applications such as video-conferencing, multi-player games etc had led to the development of several multicast protocols. Multi-point communications [12] is important for MANETs since typical applications require nodes to work together in groups to accomplish certain tasks. Multicast protocols for wireline networks such as Distance Vector Multicast Routing Protocol (DVMRP) [13] and Multicast Open Shortest Path First (MOSPF) [14] build source based multicast trees while Protocol Independent Multicast (PIM) [15] builds source based as well as shared trees for maintaining connectivity among group members. However these approaches cannot be readily adopted for MANETs on account of the dynamically changing topology. This changing topology triggers frequent routing table updates which results in excessive channel overhead and slow convergence. Hence MANETs require different techniques for creating and maintaining efficient and durable routes.

1.3 Problem Statement

We propose to study adaptive routing strategies for group communications in MANETs. As it became clear that group-oriented services are one of the primary classes of applications targeted by MANETs, a number of multicast routing protocols for MANETs have been developed. The On Demand Multicast Routing protocol (ODMRP) [16] Multicast-Ad hoc On Demand Distance Vector (MAODV) [5], Core Assisted Mesh Protocol (CAMP) [17] and Protocol for Unified Multicasting through Announcements (PUMA) [18] are examples of *on-demand* multicast routing protocols where a route is established only when a source has data to

send. Although these protocols are known to perform well in constrained mobility MANETs, it has been shown that their performance degrades under more stringent network conditions such as high mobility and traffic load [19].

In general, we believe that no single multicast protocol is optimal for all MANET scenarios given the diversity of MANETs. To address this issue, we investigate adaptive routing protocols in which nodes can change routing mechanisms based on their perception of current network conditions. More specifically, we developed an adaptive flooding protocol in which nodes can dynamically switch among different flooding variations, namely *scoped-*, *plain-*, or *hyper* flooding. We also argue that the proposed protocol can be used as the basis for developing adaptive, integrated routing techniques for the integrated media networks of the future.

Although MANETs have typically been considered as isolated, stand-alone networks with no connection to the Internet, it is quite likely that future internetworks may interconnect numerous MANET clouds, each running different routing mechanisms. This could be primarily dictated by administrative constraints or different network functional and performance requirements and can result in scenarios where nodes belonging to different MANET clouds running different routing mechanisms may wish to communicate with one another. Interoperability is also an important aspect of any adaptive routing mechanism in which nodes can actively switch between different routing protocols based on their functional requirements. In this thesis we propose techniques to allow interoperability of various multicast routing protocols in MANETs. In particular we investigate two different interoperability techniques i.e flooding based and facilitator assisted interoperability.

4

Our research goal is to provide seamless, integrated multicast service whereby a single multicast group can span all network types (fixed, fixed mobile, and different types of MANETs). This will allow a given host to partake in multicast communication regardless of the underlying routing protocol. Our work will enable hosts to dynamically switch routing protocols based on current network conditions and also allows for interoperability among different routing protocols.

1.4 Contributions

Our main contributions which are further elaborated in the remainder of this thesis are as follows:

- Performance evaluation of mesh-based (ODMRP) and tree-based (MAODV) protocols with baseline flooding. Based on our analysis and simulation results, introduced two variations of flooding i.e *Scoped Flooding* and *Hyper Flooding* as means to reduce overhead and increase reliability respectively.

- Development of an adaptive flooding mechanism in which nodes can dynamically change routing modes based on their perception of the network conditions. We evaluated two different switching criteria used by nodes to adaptively change routing mechanisms, namely relative velocity based switching and network load based switching.

- Performance evaluation of the adaptive routing strategy under "synthetic" as well as "realistic" ad-hoc network conditions such as disaster-recovery and conference scenarios which were generated using the scen-gen [20] tool.

5

- Development of an analytical model to evaluate the reliability and reachability of broadcast mechanisms in MANETs. We also extended the model to compare probabilistic flooding techniques and characterize the lower overhead of probabilistic flooding in terms of the saved re-broadcasts compared to plain flooding.

- Development of a framework to allow interoperability of various multicast routing protocols in MANETs. We proposed and evaluated two different interoperability techniques, namely flooding based and facilitator assisted interoperability.

- Development of a statistical model to characterize the speed decay of nodes utilizing the random waypoint mobility model. The proposed model provides an efficient alternative to obtaining an estimate of how long simulation experiments using the random waypoint model take to "warm-up". The model helps researchers design simulation experiments and obtain accurate results by running simulations past the warm-up period.

1.5 Publications

- Understanding the Random Waypoint Model: A Statistical Approach, Kumar Viswanath, Katia Obraczka, Athanasios Kottas and Bruno Sansó, Under submission.

- Modeling the Performance of Flooding in MultiHop Ad Hoc Networks (Extended Version), Kumar Viswanath and Katia Obraczka, Computer Communications Journal (CCJ 2005).

- Interoperability of Multicast Routing Protocols in Wireless Ad-Hoc Networks, Kumar Viswanath and Katia Obraczka, Wireless Communications and Mobile Computing

6

(WCMC) Special Issue 2004.

- Modeling the Performance of Flooding in Wireless Multi-Hop Ad-Hoc Networks , Kumar Viswanath and Katia Obraczka, International Symposium on Performance Evaluation of Computer and Telecommunication Systems, (SPECTS 04).

- Exploring Mesh- and Tree Based Multicast Routing Protocols for MANETs, Kumar Viswanath, Katia Obraczka and Gene Tsudik, Transactions of Mobile Computing (TMC 2004).

- An Adaptive Approach to Group Communications in Multi-Hop Ad hoc Networks, Kumar Viswanath and Katia Obraczka, International Conference on Networking (ICN 2002), Atlanta, Georgia, August 2002.

- An Adaptive, Integrated Approach to Reliable Group Communications in Multi-Hop Ad hoc Networks, Kumar Viswanath and Katia Obraczka, IEEE Symposium on Computers and Communications (ISCC 2002), Taormina, Italy, July 1-4.

- Pushing the Limits of Multicast in Ad Hoc Networks , Katia Obraczka, Gene Tsudik, Kumar Viswanath , International Conference on Distributed Computing Systems (ICDCS-21), Phoenix, Arizona, April 2001, pp. 719-722.

- Flooding for Reliable Multicast in Multi-Hop Ad Hoc Networks (extended version), Christopher Ho, Katia Obraczka, Gene Tsudik and Kumar Viswanath, Wireless Networks (WINET 2001), vol 7(6), pp. 627-634

- Flooding for Reliable Multicast in Multi-Hop Ad Hoc Networks, Christopher Ho, Katia

7

Obraczka, Gene Tsudik and Kumar Viswanath, MobiCom Workshop on Discrete Algorithms and Methods for Mobility (DialM '99), Seattle, WA, August 1999, pp. 64-71.

1.6 Thesis Outline

The remainder of the thesis is organized as follows. Chapter 2 summarizes prior research done in the context of multicast routing in ad-hoc networks. In Chapter 3 we describe our work comparing mesh and tree-based protocols with flooding based protocols. Chapter 4 details our contributions in adaptive routing techniques and introduces two different switching criteria, namely relative velocity based switching and network load based switching. We also evaluate the performance of the proposed adaptive routing mechanism for "synthetic" as well as "realistic" MANET scenarios. In Chapter 5, we motivate the need for interoperability of multicast routing protocols in MANETs and propose two different interoperability mechanisms, namely flooding based interoperability and facilitator assisted interoperability. In Chapter 6, we introduce our analytical model for studying the performance of flooding in MANETs and extend the model to evaluate the performance of probabilistic flooding techniques. Chapter 7 details the statistical model for characterizing the speed decay of nodes using the random waypoint mobility model. Finally in Chapter 8 we summarize our contributions and provide some possible future work directions.

Chapter 2

Review of Multicast Routing

Strategies

In this chapter, we look at the classification of MANET routing protocols and review some of the prior research work done in the context of multicast routing in MANETs.

2.1 Classification of Routing Protocols

MANET routing protocols can be classified according to their routing strategy as Distance Vector [21] or Link State [22]. Traditional distance vector protocols such as Bellman-Ford [23] are inefficient in MANETs because of their slow convergence and counting to infinity problems. However modified versions of the distance vector protocol such as Destination Sequence Distance Vector (DSDV) [24] and Wireless Routing Protocol WRP [25] have been proposed. Protocols such as Optimized Link State Routing (OLSR) [26] and Source Tree

Adaptive Routing (STAR) [27] on the other hand are based on link state routing.

In addition, MANET protocols can also be classified according to how they acquire/maintain routes. Reactive (or on-demand) protocols acquire routes only when required and do not maintain routes to all destinations in a network. The process of establishing a route involves a *Route Discovery* phase in which a *Route Request* packet is flood network-wide. When the destination receives the request it chooses the best possible route according to certain metrics (such as hop count or sequence number) and sends a *Route Reply* packet back to the source along the newly chosen route. The advantage of on-demand protocols is that control messages are greatly reduced since they do not require periodic exchange of route updates. Dynamic Source Routing(DSR) [28], Temporally Ordered Routing Algorithm (TORA) [29], Ad-hoc On demand Distance Vector (AODV) [30] are examples of on-demand protocols. Proactive protocols such as Destination Sequenced Distance Vector (DSDV) [24], Optimized Link State Routing (OLSR) [26] and Source Tree Adaptive Routing Protocol (STAR) [27] on the other hand maintain routes continually to all possible destinations.

There are also hybrid protocols which combine the best features of both proactive and on-demand approaches. For example, protocols such as Zone Routing Protocol (ZRP) [31] use a proactive approach to maintain routes to nodes within a specific zone and a reactive approach to maintain routes to nodes outside the zone. These protocols are particularly useful for those scenarios in which ad-hoc networks may be connected to the outside world through gateway nodes. In such cases member nodes requiring connectivity to the wired network may have to maintain routes to the gateway nodes at all times. Pro-actively maintained routes would be more efficient as compared to reactive routing mechanisms in

10

these scenarios.

There is another class of protocols known as geographic routing protocols which make use of the location information through Global Positioning System (GPS). Knowledge of node position can help to make routing more effective at the cost of the overhead required to exchange the location information. Examples of such protocols are Location Aided Routing (LAR) [32], Zone-Based Hierarchical Link State (ZHLS) [33] and Distance Routing Effect Algorithm for Mobility (DREAM) [34].

2.2   Multicast Routing Protocols

Many different protocols for multicasting have been proposed in recent years. Acharya and Badrinath [35] were among the first to address the issue of multicast communications in wireless networks. Subsequently a number of multicast protocols have been proposed and evaluated [36], [34], [37], [5], [4], [17], [38], [39].

MANET multicast protocols can be classified according to how they propagate data as tree-based or mesh-based. While tree-based protocols propagate data over a tree spanning all multicast group members, in mesh-based protocols a subset of network nodes (the mesh) is responsible for forwarding data to all multicast receivers. On-demand Multicast Routing Protocol (ODMRP) [4], Core Assisted Mesh Protocol (CAMP) [17], Protocol for Unified Multicasting through Announcements (PUMA) [18], Forwarding Group Mesh Protocol (FGMP) [40] and Dynamic Core-Based Multicast Routing Protocol (DCMP) [41] are examples of mesh based protocols. Protocols such as Multicast Ad-hoc On demand Distance Vector (MAODV) [5], Ad-Hoc Multicast Routing Protocol using Increasing Id-numbers

11

(AMRIS) [37], Ad-hoc Multicast Routing (AMRoute) [36] and Preferred Link Based Multi-cast Protocol (PLBM) [42] are examples of tree-based protocols. In the following sections we describe some of these protocols in greater detail.

2.2.1 Forwarding Group Mesh Protocol (FGMP)

Forwarding Group Mesh Protocol was one of the earliest protocols to use the notion of a mesh for multicast in ad-hoc networks. The basic idea of FGMP was to scope the effect of broadcasting data packets in the network by only allowing certain nodes (forwarding group members) to re-broadcast the data. Unlike traditional techniques like DVMRP which keep track of links, FGMP keeps track of a group of nodes that participate in the data packet forwarding. Each multicast group in the network has associated with it a *forwarding group* FG. All nodes in FG are responsible for forwarding data packets for the group G. When a forwarding group member for a particular group G receives a data packet, it checks to see if it is a duplicate. If not, then the forwarding group member will further re-broadcast the packet. This scheme can be envisioned as *limited scope flooding*.

2.2.2 On-demand Multicast Routing Protocol (ODMRP)

The On-Demand Multicast Routing Protocol (ODMRP) [4] falls into the category of on-demand protocols since group membership and multicast routes are established and updated by the source whenever it has data to send. Unlike conventional multicast protocols which build a multicast tree (either source-specific or shared by the group), ODMRP is mesh-based. It uses a subset of nodes, or *forwarding group*, to forward packets via scoped flooding.
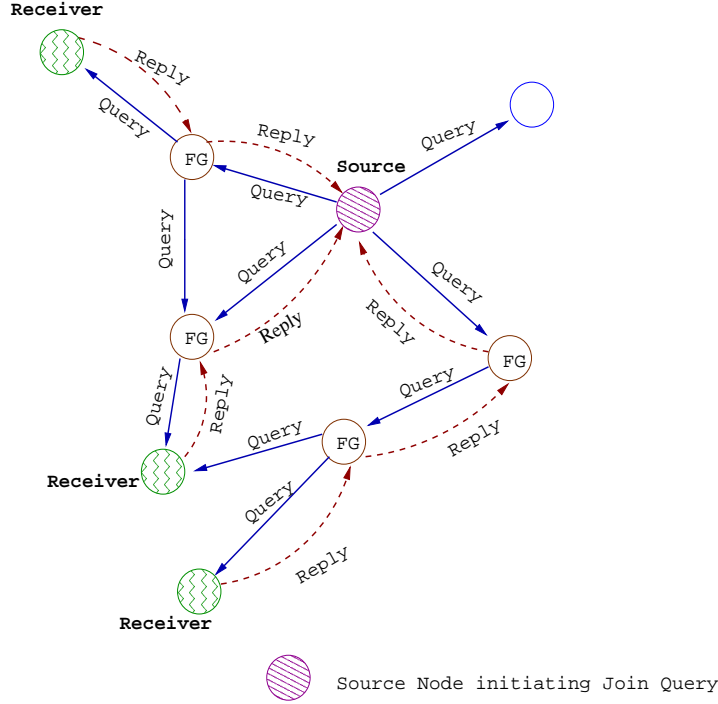
Figure 2.1: Mesh Formation in ODMRP

ODMRP borrows the notion of the forwarding group from FGMP.

Similar to other reactive protocols, ODMRP consists of a request phase and a reply phase. When a multicast source has data to send but no route or group membership information is known, it piggybacks the data in a `Join-Query` packet. When a neighbor node receives a unique `Join-Query`, it records the upstream node ID in its *message cache*, which is used as the node's routing table, and re-broadcasts the packet. This process' side effect is to build the reverse path to the source. When a `Join-Query` packet reaches the multicast receiver, it generates a `Join-Table` packet that is broadcast to its neighbors. The `Join-Table` packet contains the multicast group address, sequence of (source address, next hop address) pairs, and a count of the number of pairs. When a node receives a `Join-Table`,

it checks if the next node address of one of the entries matches its own address. If it does, the node realizes that it is on the path to the source and thus becomes a part of the forwarding group for that source by setting its *forwarding group flag*. It then broadcasts its own `Join-Table`, which contains matched entries. The next hop IP address can be obtained from the message cache. This process constructs (or updates) the routes from sources to receivers and builds the forwarding group. Membership and route information is updated by periodically (every `Join-Query-Refresh` interval) sending `Join-Query` packets. Nodes only forward (non-duplicate) data packet if they belong to the forwarding group or if they are multicast group members. By having forwarding group nodes flood data packets, ODMRP is more immune to link/node failures (e.g., due to node mobility). This is in fact an advantage of mesh-based protocols. Figure 2.1 illustrates how the mesh is created in ODMRP.

2.2.3   Core Assisted Mesh Protocol (CAMP)

Core Assisted Mesh Protocol extends the receiver initiated approach used in Core Based Trees (CBT) [43] for the formation of multicast meshes. In CAMP all nodes in the network are responsible for maintaining a membership table and routing information. The nodes are classified as either *simplex* or *duplex* members. Simplex members are used to create connections between nodes that function as only senders and the multicast mesh whereas duplex members are full members. One the main advantages of CAMP is its use of a *Core* to restrict the scope of the *Join Request* packets.

When a node wishes to join a multicast mesh it first checks it table to see if any of its neighbors are already members of the mesh. In this case, it advertises its membership

CORE

Node wants to join group

Group Members
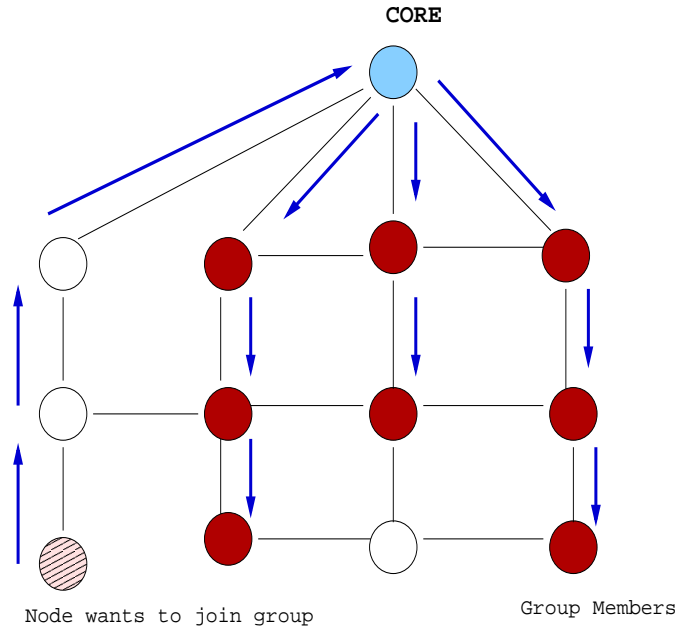
Figure 2.2: Mesh formation in CAMP

with the help of a update message. Otherwise it propagates a *Join Request* towards one of the designated cores for the multicast group. It is assumed that each node has at least one path through which it can reach the core. Any duplex member of the group can respond with a *Join Ack* which is propagated back to the source. Periodically, nodes send out *Heartbeat* messages toward the source on the reverse shortest path. This helps to ensure that the mesh contains reverse shortest path from all receivers to all sources.

One possible disadvantage of CAMP is that it relies on an underlying unicast routing protocol such as WRP [25] for unicast routes to all destinations in the network.
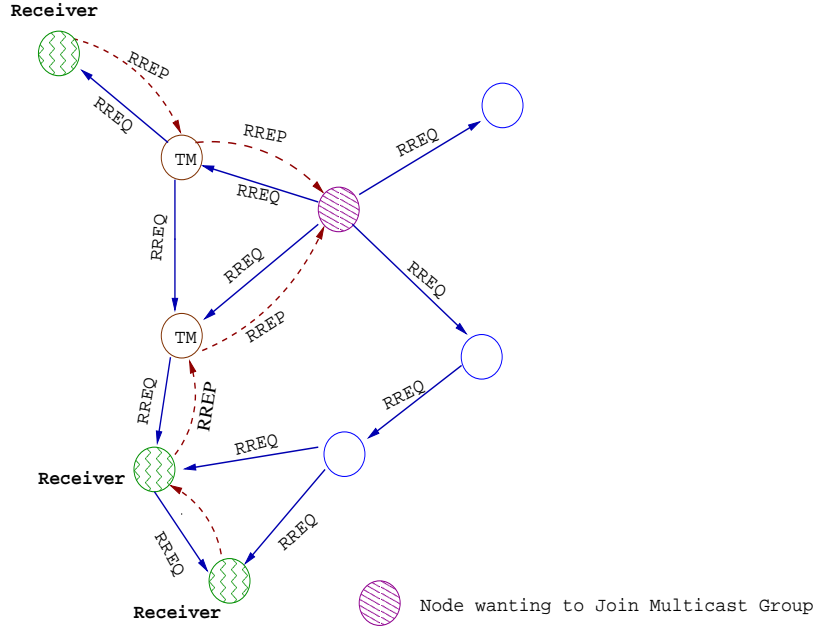
Figure 2.3: Tree Creation in MAODV

2.2.4 Multicast Ad-hoc On demand Distance Vector (MAODV)

MAODV is an example of a tree-based multicast routing protocol (Figure 2.3 illustrates MAODV tree formation). Similar to ODMRP, MAODV creates routes on-demand. Route discovery is based on a route request Rreq and route reply Rrep cycle. When a multicast source requires a route to a multicast group, it broadcasts a Rreq packet with the join flag set and the destination address set to the multicast group address. A member of the multicast tree with a current route to the destination responds to the request with a Rrep packet. Non members rebroadcast the Rreq packet. Each node on receiving the Rreq updates its route table and records the sequence number and next hop information for the source node. This information is used to unicast the Rrep back to the source. If the source node receives multiple replies for its route request it chooses the route having the freshest sequence number or the

least hop count. It then sends a multicast activation message `Mact` which is used to activate the path from the source to the node sending the reply. If a source node does not receive a `Mact` message within a certain period, it broadcasts another `Rreq`. After a certain number of retries (`Rreq-Retries`), the source assumes that there are no other members of the tree that can be reached and declares itself the *Group Leader*. The group leader is responsible for periodically broadcasting group hello (`Grp-Hello`) messages to maintain group connectivity. Nodes also periodically broadcast `Hello` messages with *time-to-live = 1* to maintain local connectivity.

2.2.5 Ad-Hoc Multicast Routing Protocol using Increasing Id-numbers (AM-RIS)

AMRIS is an on demand protocol that creates a shared delivery tree. The main idea that differentiates AMRIS from other protocols is the use of a multicast session member id *msm-id*. The *msm-id* is an indicator of the logical height of the node in the multicast delivery tree and is used to direct the flow of data. The root of the tree has the smallest *msm-id* among all member in the group.

Initially, a special node called Sid broadcasts a *New-Session* packet containing the Sid's *msm-id*. Neighboring nodes on receiving the *New-Session* packet generate their own *msm-id* by computing a number that is greater than the advertised *msm-id* but not consecutive. The intermediate id's are utilized for local repairs. This process is then repeated by the neighbor nodes so that the *msm-id's* get larger as they propagate away from the Sid. Any node wishing to join the multicast session, unicast's a *Join-Req* packet to its potential parent

17

which has a smaller *msm-id*. The node receiving the *Join-Req* then responds with a *Join-Ack* if it is already a member of the group. Otherwise, it generates a *Join-Req-Passive* packet and forwards it to its potential parents. If the initiator of the *Join-Req* does not receive a *Join-Ack* within a pre-defined time-interval or receives a *Join-Nak* it initiates *Branch-Reconstruction*. This phase is executed in an expanding ring fashion till the node succeeds in joining the multicast group.

AMRIS uses a beaconing mechanism to detect link breakages. If no beacons are heard within a certain time-interval the node has to join the tree by sending out a new *Join-Req*. Data forwarding is only handled by nodes on the tree. So link breakages are expensive causing data packets to be dropped till the tree is re-configured.

2.2.6 Ad-hoc Multicast Routing (AMRoute)

The Ad-hoc Multicast Routing Protocol (AMRoute) is a shared tree multicast protocol that uses multicast trees and dynamic logical cores. It creates a bi-directional, shared tree for data distribution using only group senders and receivers as tree nodes. Unicast tunnels are used as tree links to connect neighbors on the user-multicast tree. The advantage of using unicast tunnels is that network nodes that are not interested/capable of multicast need not participate in the routing mechanism, and group state cost is incurred only by group senders and receivers. Another advantage of the tunnels is that the tree structure does not change even in case of a dynamic network topology. This helps reduce the signaling traffic and packet loss. AMRoute does not require a specific unicast routing protocol; therefore, it can operate seamlessly over separate domains with different unicast protocols.

18

In AMRoute certain tree nodes are designated as logical cores. The cores are responsible for initiating and managing the signaling component of AMRoute, such as detection of group members and tree setup. The logical cores of AMRoute differ significantly from those in CBT and PIM-SM, since they are not a central point for data distribution and can migrate dynamically among member nodes. Initially, each member of a group declares itself as a core for the group. The cores periodically flood *Join-Req* in an expanding ring fashion to discover mesh segments for the group. When a group member receives a *Join-Req* from a core of the same group, it responds with a *Join-Ack* and marks the node as its mesh neighbor. Similarly the node sending out the *Join-Req* also marks the receiver as its mesh neighbor. After the mesh has been created the cores for each group periodically transmit *Tree-Create* packets to build a shared tree. Nodes, that do not wish to be a part of the multicast group can transmit a *Join-Nak* packet to their neighbors and stop forwarding data packets for the group.

2.2.7 Flooding

Although flooding is normally used for broadcast in MANETs, it can also be used for multicast especially if the receiver group is quite dense. Our implementation of routing by flooding is quite standard: when a node receives a packet, it broadcasts the packet except if it has seen that packet before. Nodes keep a cache of recently received packets; older packets are replaced by newly-received ones. A node only re-broadcasts a packet if that packet is not in the node's cache.

We use a well-known randomization technique to avoid collisions: when a node receives a packet it waits a random time interval between 0 and `flooding interval`

before it rebroadcasts the packet.

Chapter 3

Performance Evaluation of ODMRP, MAODV and Flooding

One of the main challenges presented by multicast routing in MANETs is the need to achieve robustness in the presence of universal mobility and frequent node outages and failures. We observe that key features of MANETs make them attractive for deployment in critical environments, such as military or civilian emergency operations. Since in any critical environment, robustness and high quality of service are very important, multicast routing and packet forwarding algorithms (which may be attractive otherwise) that cannot provide high delivery guarantees may be inadequate for mission-critical, highly dynamic MANETs.

As a first step towards our research objective we investigated the performance of ODMRP and MAODV which are two of the best performing multicast routing protocols among the currently proposed pool. Although, similar studies [16] have shown the benefits of mesh-based protocols over tree-based protocols, those studies were restricted to very

specific, "synthetic" ad-hoc scenarios. One of the main differences in our study was the attempt characterize the merits of mesh-based and tree-based protocols under a wide range of network conditions and realistic scenarios. To this end, we conducted extensive simulations employing a wide range of mobility and traffic load conditions, as well as different multicast group characteristics (e.g., number of sources and number of receivers).

Based on our analysis we also provided recommendations on the suitability of the protocol for specific types of networks. The On-Demand Multicast Routing Protocol (ODMRP) [4] was chosen to represent mesh-based protocols since it has been shown to the best performer among a recently proposed protocol pool [16]. Multicast Ad Hoc On-Demand Distance Vector (MAODV) [5] was chosen to represent tree-based protocols. Both protocols belong to the reactive category. As a yardstick in our comparisons, we use flooding, arguably the simplest and oldest mesh-based routing technique. Despite the hefty overhead, it provides the best delivery guarantees for unicast, multicast and broadcast in wired networks. However, in flooding redundant broadcasts may cause serious contention and collision problems in MANETs.

At the time of our performance evaluation, ODMRP was shown to be the best performer in the comparative study reported in [16] and hence was chosen representative of mesh based protocols. [1]. In fact, [16] compares the performance of ODMRP and CAMP [17] as mesh-based protocols against AMRoute [36] and AMRIS [37], representing tree-based mechanisms. Our comparative performance study differs from [16] in a number of ways. First, we use MAODV as representative of tree-based multicast routing since it does not exhibit the

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[1]Recently, mesh-based protocols such a PUMA have been proposed which fare better than ODMRP under a variety of scenarios

Protocol	Configuration	Loop Free	Periodic Messaging	Control Packet Flooding
Flooding	Mesh	Yes	No	No
ODMRP	Mesh	Yes	Yes	Yes
MAODV	Tree	Yes	Yes	Yes

Table 3.1: Protocol Summary

limitations of AMRoute and AMRIS, both of which rely on an underlying unicast routing protocol. Additionally, AMRoute is susceptible to transient routing loops. Another distinguishing feature of our study is that it investigates a wider range of MANET scenarios subjecting the protocols under consideration to more stringent network conditions including higher mobility and traffic load, as well as a variety of multicast group characteristics (e.g., number of traffic sources, group size and density). Finally, besides synthetic MANET environments, our study also considers more realistic scenarios such as conferencing and emergency response operations. Table 3.1 summarizes key characteristics of the three protocols.

3.1   Simulation Environment and Methodology

We used the network simulator ns-2 for our simulations. ns was originally developed at Lawrence Berkeley National Laboratory (LBNL) [44]. Currently it is being extended as part of the VINT project [45] involving USC/ISI, Xerox PARC, LBNL, and UC Berkeley. ns is a discrete-event simulator which started as a simulation environment for wired networks and has been extended to simulate mobile wireless environments. In particular, we use the CMU Monarch group extensions that enable ns version 2 (ns-2) to simulate MANETs [46]. Some of the MANET scenarios we use in our simulations were generated using a scenario generator for ad hoc networks [20] and will be described in greater detail in Section 3.4.2.

23

3.1.1 MANET Scenarios

We use two types of MANET scenarios in our simulations. In "synthetic" scenarios, parameters such as mobility, multicast group size, traffic sources, and number of multicast groups are varied over an arbitrary range of values. We also define more "concrete" environments reflecting specific MANET applications, namely impromptu teleconferencing and disaster relief/battlefield scenarios. The scenario generator [20] was used to generate conferencing and rescue scenarios for our experiments.

For the synthetic scenarios, 50 nodes are placed in a 1000 m^2 field. Each node transmits a maximum of 1000 packets (256 bytes each) at various times during the simulations. Nodes's channel bandwidth is set to 2 Mbit/sec and their transmission range is 225 meters.

3.1.2 Mobility Model

The mobility model used is a modified version of the *random-waypoint* model also known as the *bouncing ball* model. In this model, nodes start off at random positions within the field. Each node then chooses a random direction and keeps moving in that direction till it hits the terrain boundary. Once the node reaches the boundary it chooses another random direction and keeps moving in that direction till it hits the boundary again. An important aspect of our modified mobility model is that we always set *Vmin* to be non-zero. In fact we set *Vmin = Vmax* for most of our simulations. Hence the bouncing ball model does not suffer from the drawbacks of the random mobility model as shown in [6].

3.1.3 Traffic Model

A constant bit rate (CBR) traffic generator was used for synthetic scenarios. The data payload size was fixed at 256 bytes. Senders were chosen randomly among network nodes. Network traffic for different sender populations was maintained constant at 50 Kbps by adjusting the inter-packet interval for the CBR sources. For concrete scenarios we also used the ON-OFF traffic generator. Each source transmitted at 5 Kbps with a burst period of 3 secs and idle time of 3 secs.

3.1.4 Metrics

We use the following metrics in evaluating the performance of the different multicast routing protocols.

- **Packet delivery ratio** is computed as the ratio of total number of unique packets received by the receivers to the total number of packets transmitted by all sources times the number of receivers.

- **Routing overhead** is the ratio between the number of control bytes transmitted to the number of data bytes received. In ODMRP, control bytes account for `Join-Query` and `Join-Table` packets. It also includes data packet header bytes forwarded by forwarding group members. In MAODV, control bytes account for the `Rreq`, `Rrep`, `Mact`, `Hello`, and `Grp-Hello` packets. It also includes the data packet headers forwarded by intermediate nodes. In flooding, control bytes include all data header bytes forwarded by network nodes. We also account for the length of the IP header in

25

Parameter	Value
flooding-interval	25 ms

Table 3.2: Flooding Parameter Values

Parameter	Value
Join Query refresh interval	3 secs
Forwarding Group Timeout	3 secs
Route Timeout	5 secs
Data Rebroadcast interval	25 ms

Table 3.3: ODMRP Parameter Values

Parameter	Value
Group Hello Interval	5 secs
Hello Interval	1 sec
Mtree Build	3 secs
Route Discovery Timeout	3 secs

Table 3.4: MAODV Parameter Values

our calculation of routing overhead.

- **Group reliability** is a measure of the effectiveness of the routing protocol in delivering packets to all receivers. We compute group reliability as the ratio of number of packets received by **all** multicast receivers to number of packets sent. Thus, for this metric, a packet is considered to be received only if it is received by every member of the multicast group.

Other Parameters

Table 3.2 summarizes flooding parameters while, 3.3, and 3.4 list protocol-specific parameters.

26

3.2 Simulation Results

In this section, we report simulation results comparing ODMRP, MAODV, and flooding. In these simulations, we use synthetic MANET scenarios, in which we subject the protocols to a wide range of mobility, traffic load, and multicast group characteristics (i.e., group size and number of sources). We ran each simulation (keeping all parameters constant) five times, each time using a different seed value. Each data point in the graphs below, represents the average across all five runs. The error-bars shown in the graphs represent a confidence interval (CI) of 95% [2].

In our simulations the senders are chosen at random from the multicast group. All nodes join as members at the start of the simulations and remain members throughout the duration of the simulation.

3.2.1 Effect of Mobility

The mobility experiment consisted of 5 traffic sources and 20 receivers chosen randomly. Each source transmitted 10 Kbps and thus the overall network load was 50 Kbps. Average node speed was varied between 0 and 150 kms/hr. Speeds of 150 kms/hr might at first seem too high. However, we claim that such high speed is very reasonable whenever a MANET includes fast-moving nodes, such as: helicopters, fixed-wing aircraft as well as police, military and other emergency vehicles.

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[2]Although we calculated the 95% CI for all graphs, we only show error-bars in graphs where they do not impact readability

Packet Delivery Ratio

Figure 3.1 shows how protocol reliability varies with mobility (node speed).

Packet Delivery Ratio Vs Mobility : 5 Senders 20 Receivers: 50kbps
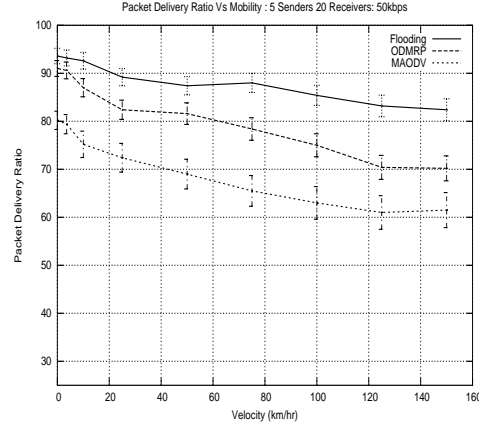
Figure 3.1: Packet delivery ratio as a function of node mobility

The general trend we observe from Figure 3.1 is that, especially at high mobility, flooding performs better than ODMRP which in turn performs better than MAODV.

Comparing flooding to ODMRP, we notice that – at lower speeds – the difference in packet delivery ratio is between 5% and 7%. This result agrees with what was observed in [16]. However, at higher speeds the gap in packet delivery ratio starts widening. In the case of ODMRP, increased mobility requires that forwarding group members be updated more frequently. However, the frequency at which routes are refreshed (using periodic `Join-Queries`) remains constant, i.e., does not change with node speed. One way to address this problem is to update forwarding group members more often through more frequent *Join-Queries*. This of course would result in higher control overhead and possibly greater packet loss due to contention.

Comparing ODMRP with MAODV, we observe that ODMRP exhibits better (by

28

roughly 10%) packet delivery ratios. Since ODMRP maintains meshes, it has multiple re-dundant paths to receivers and is not affected by mobility as greatly as MAODV. Increased mobility causes frequent link changes and requires MAODV to reconfigure the multicast tree more frequently to prevent stale routing information. This in turn requires higher control traf-fic which can have a negative effect of increased packet loss due to contention and hidden terminals.

Routing Overhead
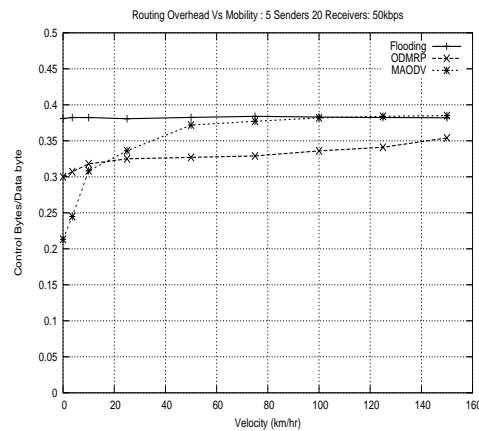
Figure 3.2: Routing overhead as a function of node mobility

Figure 3.2 plots control overhead per data byte transferred as a function of mobility. Note that flooding's overhead does not change with mobility as only data header packets contribute to overhead. In ODMRP, the *Join-Query* interval was fixed at 3 seconds and hence control overhead remains fairly constant with node mobility. The slight increase in overhead at higher speeds (around 55 km/hr) is due to the fact that the number of data bytes delivered decreases with increased mobility. In the case of MAODV, increased mobility causes frequent

29

link breakages and data packet drops; link outages also generate repair messages increasing control overhead.

Group Reliability

Since MANETs often target mission-critical applications, scenarios that require data transmission to be received by **all** multicast group members in a timely fashion are quite common. While a reliable transport protocol would repair losses detected by the communication end points, having the highest possible delivery rate from the underlying routing protocol improves the system's overall efficiency, including response time. Our group reliability metric tries to capture the effectiveness of routing protocols in delivering packets to all group members.
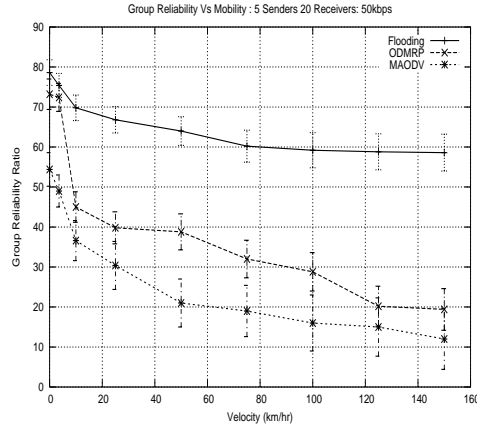
Figure 3.3: Group reliability as a function of node mobility

Figure 3.3 plots group reliability as a function of node speed. From the figure it can be seen that flooding is most effective in delivering packets to all group members (as expected). Moreover, flooding is able to keep group reliability fairly constant even at higher

30

speeds.

Both ODMRP and MAODV exhibit poor performance even at low mobility (group reliability lower than 50% for speeds higher than 10 km/hr) . However, as expected, ODMRP exhibits better group reliability than MAODV. Although ODMRP can maintain multiple routes to receivers, the mesh connectivity is largely dependent on the number of senders and receivers. In case of 5 senders, mesh connectivity is insufficient to ensure packet delivery to all group members (especially, with node mobility) resulting in low group reliability.

Since MAODV delivers packet along a multicast tree, a single packet drop upstream can prevent a large number of downstream multicast receivers from receiving the packet. The absence of redundant routes affects performance greatly as node mobility results in frequent link breakages and packet drops.

3.2.2 Effect of Multicast Group Size

In this set of experiments, we focus on the influence of group size (the number of receivers) on multicast routing performance. The number of senders was fixed at 10, node mobility at 75 kms/hr, and traffic load at 50 Kbps. Group size was varied from 10-40 receivers in increments of 5.

Packet Delivery Ratio

Figure 3.4 shows the variation in protocol reliability as a function of group size. Note that flooding is able to keep its delivery ratio fairly constant and close to 90% for different group sizes. Compared to ODMRP, flooding's delivery ratio is around 10% higher at a

Packet Delivery Ratio Vs Multicast Group Size : 10 Senders: 50kbps
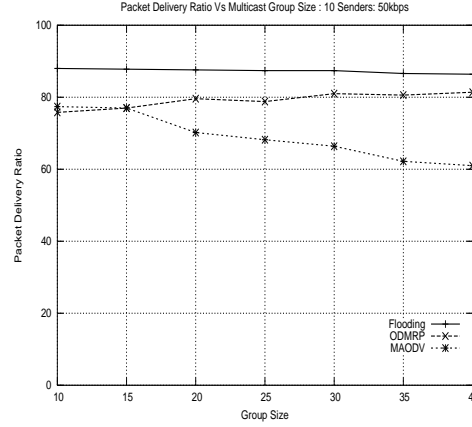
Figure 3.4: Packet delivery ratio as a function of multicast group size

group size of 10 and around 6% higher as multicast group size increases to 40. Interestingly, ODMRP delivery ratio increases as group size increases. This is indeed consistent with the way mesh-based protocols operate. For instance, in ODMRP the mesh is formed as a result of the `Join-Query` - `Join-Table` process. As the number of receivers increase, the number of `Join-Tables` sent out in response to `Join-Queries` increases. This causes a larger number of nodes to be incorporated into the mesh as *forwarding group* members, increasing mesh connectivity and redundancy. Hence, packet delivery ratio tends to increase with increase in multicast receivers.

In case of MAODV, packet delivery ratio decreases as group size increases (it is around 77% for 10 receivers and lowers to approximately 62% for 40 receivers). One reason for the decrease is that, as previously mentioned, a packet loss upstream affects a larger set of receivers. The increased group size also results in a greater number of control messages transmitted which can result in greater packet loss due to collisions.

32
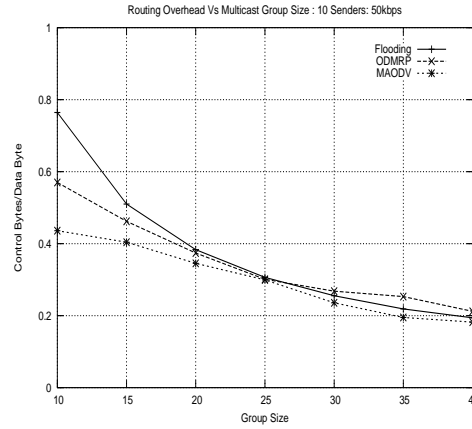
Routing Overhead

Figure 3.5: Routing overhead as a function of group size

Figure 3.5 shows how control overhead varies with group size. At low values of group size, flooding exhibits the highest routing overhead among all protocols for groups with up to 25 receivers. Flooding's overhead decreases with increasing group size. This is because all nodes rebroadcast data packets irrespective of group size. However, rebroadcast packets become more effective as group size increases since they now count towards packets delivered to multicast receivers. For this particular scenario, ODMRP's routing overhead is the highest among all three protocols for group sizes above 25. This is due to the large number of `Join-Tables` being transmitted and greater redundancy as number of group members increases. In case of MAODV, increased group size results in larger number of `Repair` messages. However data packets do not have to travel over multiple redundant paths, resulting in a lower overall routing overhead for MAODV as compared to ODMRP and flooding.

33
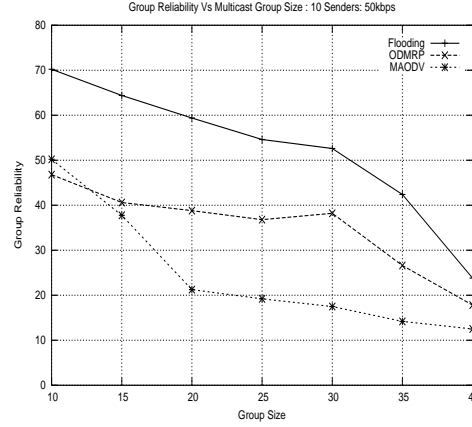
Figure 3.6: Group reliability as a function of group size

Group Reliability

Figure 3.6 shows how group reliability varies with group size. As expected, group reliability of all protocol degrades for larger multicast group size. This can be explained by the fact that, as the number of receivers increase, the probability of at least one receiver not receiving the data packet also increases.

From the graph it is seen that the trend is similar to that observed in section 3.2.1

3.2.3   Effect of Number of Traffic Sources

In this set of experiments we vary the number of multicast sources from 10 to 30 in steps of 5, keeping number of receivers fixed at 30 and node mobility fixed at 75 kms/hr. For each value of number of senders, overall traffic load is maintained constant at 50 Kbps by changing the CBR sources' inter-packet interval.
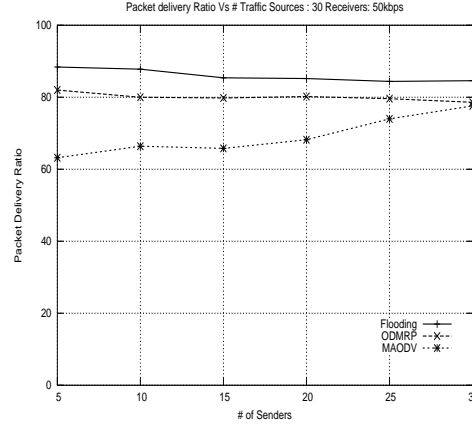
Figure 3.7: Packet delivery ratio as a function of number of traffic sources

Packet Delivery Ratio

Figure 3.7 shows packet delivery ratio as a function of number of senders. Note that both flooding and ODMRP packet delivery ratio remain fairly constant with number of senders; thus they do not suffer from increased contention except at higher number of sources where a slight drop off can be observed and is attributed to data packet loss due to collisions. An interesting and counter-intuitive result is that in the case of MAODV, delivery ratio increases with increase in number of traffic sources. This is due to the fact that, in MAODV, the shared tree is formed as a result of the Rreq - Rrep process. As the number of senders increases, a greater number of intermediate nodes (on the path from the sender to the multicast tree) are grafted as part of the tree. This helps to increase redundancy along certain links due to the presence of multiple downstream neighbors who can potentially forward data along the tree. Hence packet delivery ratio tends to increase with increase in number of sources. However, MAODV packet delivery ratio is consistently lower than that of ODMRP and flooding.

35
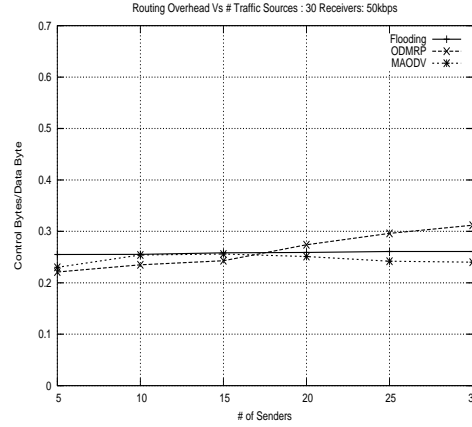
Routing Overhead

Figure 3.8: Routing overhead as a function of traffic sources

Figure 3.8 depicts how control overhead varies with number of traffic sources. Flooding does not transmit any control messages and hence its routing overhead remains constant with number of senders. For ODMRP, increased sender population results in a larger number of `Join-Reqs` and `Join-Tables`. `Join-Tables` in particular can result in large byte overhead since they carry next-hop information for multiple sources. Similarly, larger sender population results in larger number of MAODV control messages being transmitted. However, as discussed in section 3.2.3, the number of data bytes received also increases. Hence, MAODV's overall ratio of control bytes/data byte delivered remains fairly constant.

Group Reliability

Figure 3.9 shows how group reliability varies with number of traffic sources. It is interesting to notice how the different reliability metrics capture different protocol behav-
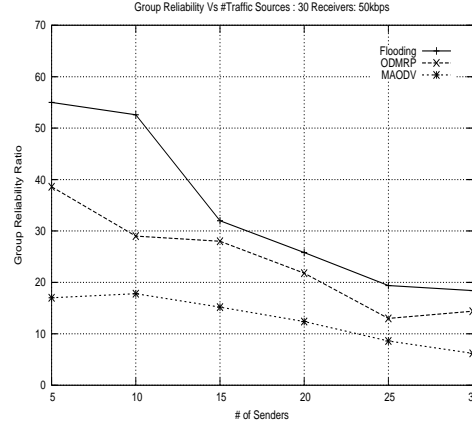
Figure 3.9: Group reliability as a function of traffic sources

ior. According to the packet delivery ratio metric, both flooding and MAODV exhibit fairly high delivery ratios (above 80%); MAODV delivers around 65% of the packets for up to 20 senders, but increases its reliability (close to 80%) for 30 receivers as shown in Figure 3.7. However, the group reliability metric, as depicted in Figure 3.9, shows a completely different behavior. Even though the relative performance among the protocols remains the same (i.e., $flooding >> ODMRP >> MAODV$, where $>>$ denotes "performs better"), we observe that group reliability degrades considerably for larger number of senders. This effect is mainly due to increased contention as larger number of senders results in more number of packets transmitted. As a result a greater number of packets are dropped due to collisions.

3.2.4 Multiple Multicast Groups

The goal of these experiments is to evaluate how multiple multicast groups impact the performance of mesh- and tree-based multicast routing. For the multi-group simulations, two separate multicast groups are used, each of which having 5 sources and 10 receivers.

37

Protocol	Pkt Delivery Ratio	Routing Overhead	Group Reliability
Flooding (1 Group)	87.6	0.383	59.42
Flooding (2 Groups)	86.8	0.764	70.41
ODMRP (1 Group)	79.6	0.374	38.80
ODMRP (2 Groups)	71.8	0.328	36.27
MAODV (1 Group)	70.2	0.345	21.25
MAODV (2 Groups)	68.2	0.352	23.52

Table 3.5: Performance with multiple multicast groups

Average node speed and overall traffic load are fixed at 20 Km/hr and 50 Kbps, respectively. For the single-group simulations, we use 10 senders and 20 receivers. The same node mobility and overall traffic load are used, i.e., 20 Km/hr and 50 Kbps, respectively.

Table 3.5 compares the performance of the protocols when operating in a multi-group environment against single multicast group operation. We observe that flooding's performance is the most affected by multiple multicast groups. Although, delivery ratio remains fairly similar, routing overhead almost doubles. This is due to the fact that, since flooding does not maintain group membership information, nodes rebroadcast every packet irrespective of the group.

In the case of ODMRP, mesh connectivity depends on the number of receivers. Since in the multiple group case, the number of receivers for each group is halved (as compared to single group case) the mesh is not as rich as before, resulting in lower packet delivery ratios. Routing overhead decreases since nodes can piggyback the `Join-Tables` for multiple groups. The performance of MAODV is not significantly affected by multi-group operation.

3.2.5   Effect of Network Traffic Load

In this section, we evaluate the impact of increasing traffic load on protocol performance. The number of senders was fixed at 10 and number of receivers at 20 respectively. Node mobility was set at 75 kms/hr. The overall network load was increased from 10 Kbps to 50 Kbps in steps of 5 Kbps. This is achieved by increasing the sending rate of each source from 1 Kbps to 5 Kbps. The data traffic introduced into the network is CBR traffic.

Packet Delivery Ratio
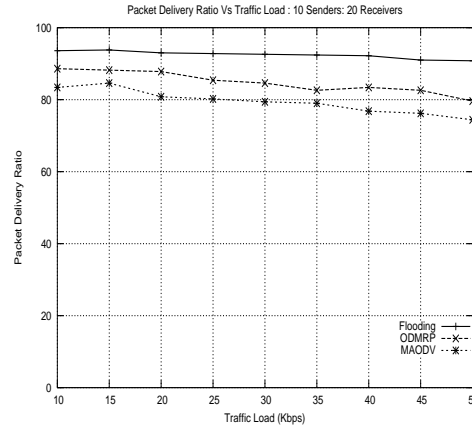
Figure 3.10: Packet delivery ratio as a function of traffi c load

Figure 3.10 shows packet delivery ratio as a function of traffic load. It is observed that all protocols are affected by the increase in network traffic. Increased network traffic results in greater contention and packet loss due to higher collisions and buffer overflow. For the traffic loads considered, flooding still outperforms ODMRP and MAODV in terms of delivery ratios. However we expect the performance of flooding to deteriorate more rapidly then ODMRP and MAODV as traffic load increases on account of the greater number of

redundant transmissions.

Routing Overhead

Routing Overhead Vs Traffic Load : 10 Senders: 20 Receivers
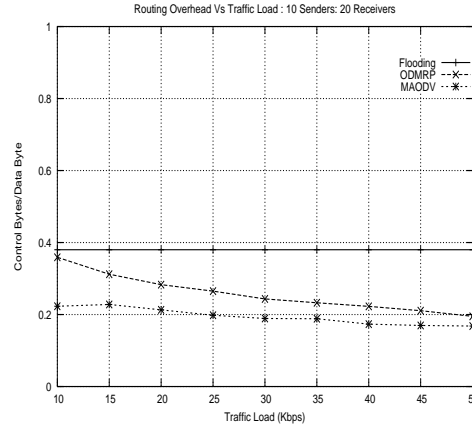
Figure 3.11: Routing overhead as a function of traffic load

Figure 3.11 depicts the control overhead per data byte delivered as a function of traffic load. It can be seen that flooding's control overhead remains almost constant with increasing load. Flooding does not transmit any control packets and all packets received by a node are retransmitted exactly once resulting in almost constant control overhead. The high routing overhead seems to suggest that flooding can be quite expensive at higher traffic loads and hence not scalable with increased traffic loads.

In case of ODMRP and MAODV, routing overhead decreases with increase in traffic load. As network load increases, the total number of data bytes received by ODMRP and MAODV receivers also increases. However control data transmitted, remains fairly constant with increased network load thereby reducing the routing overhead. (Note that routing overhead is calculated as ratio of control bytes/data byte received). In this experiment, ODMRP

has a greater routing overhead than MAODV on account of the mesh structure but the gap

reduces as network load increases. As traffic load increases both ODMRP and MAODV are

affected by packet losses on account of contention. Since ODMRP maintains multiple routes

to destinations, receivers can possibly receive data packets from other routes. This increases

the total number of data bytes received by ODMRP receivers as compared to MAODV re-

ceivers which helps to reduce the routing overhead.
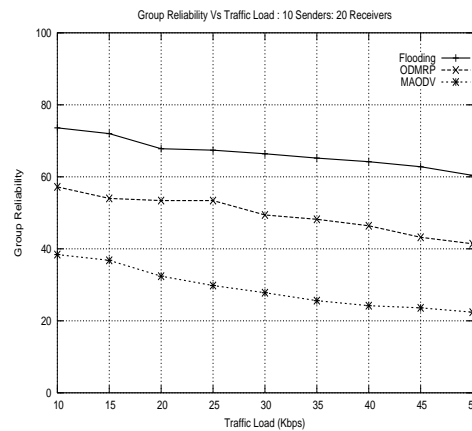
Group Reliability

Figure 3.12: Group reliability as a function of traffic load

Figure 3.12 plots group reliability as a function of traffic load. From the figure it

can be seen that, group reliability for all protocols decreases with increase in traffic load as

expected. Flooding, has the highest group reliability among the three protocols as before. All

protocols exhibit almost similar decrease in group reliability (about 16-18 %) as traffic load

increases. In case of flooding and ODMRP the increased redundancy is offset by the increase

in collisions which degrades the reliability. In case of MAODV, performance degrades on

Protocol	Route setup overhead	Route maintenance overhead	Forwarding overhead	Reliability	Traffic Conc:	Scalability
Flooding	Low	Low	High	High	Low	Low
ODMRP	Moderate	Moderate	Moderate	High	Low	Low
MAODV	High	Highest	Low	Low	Highest	High

Table 3.6: Qualitative comparison of ODMRP, MAODV and flooding

account of increased collisions and buffer overflow as traffic load increases.

3.2.6 Qualitative comparison of protocols

Table 3.6 provides a qualitative comparison of the protocols based on our simulation analysis in the preceding sections.

Flooding requires no resources for route initialization since there is no setup associated with establishing routes to multicast group members. In the case of ODMRP, nodes have to transmit Join-Query messages to establish routes to multicast group members. Group members and forwarding group nodes reply with Join-Tables. MAODV's route initialization consists of leader selection for the group followed by a Rreq-Rrep route discovery phase. The sender has to then send out a Mact message to activate a particular route among various possible routes. Thus, MAODV incurs the highest overhead for route setup.

In terms of data forwarding, as observed from the simulation results, flooding has the highest overhead for most scenarios. Hence bandwidth resources used by flooding in delivering data to receivers is greatest among the protocols considered. MAODV has lowest forwarding overhead whereas forwarding resources used by ODMRP is moderate.

As expected, flooding delivers the highest reliability (both in terms of packet delivery ratio and group reliability). Since ODMRP maintains a mesh structure and has multiple

routes to multicast group members it exhibits better reliability than MAODV, but lower than that of flooding. MAODV, on the other hand, maintains a shared tree structure and is susceptible to frequent link changes due to mobility. This has a considerable effect on MAODV's reliability.

In flooding, data is re-broadcast by all nodes and does not travel along certain paths, resulting in low traffic concentration on any given link. On account of the mesh structure in ODMRP, data is routed through multiple paths. In case of MAODV, data has to be forwarded along the tree and can lead to traffic concentration along certain tree links.

Flooding is not very scalable with increase in number of nodes on account of the excessive broadcasts and forwarding overhead. In case of ODMRP, routing overhead can get prohibitive as number of sender increases. MAODV is most scalable in terms of number of network nodes and multicast senders.

3.3 Flooding Variations

The results from section 3.2 show that flooding performs considerably well compared to ODMRP and MAODV, especially, at high mobility. However, one major drawback of flooding is that it results in redundant broadcasts which increases the routing overhead. Redundant broadcasts are particularly damaging in ad hoc networks where nodes are often bandwidth- and energy-constrained. In this section, we introduce *scoped flooding*, a variation of flooding that aims at restricting redundant broadcasts. It does so based on different heuristics, which are discussed in detail below. Several other broadcast techniques [47–49] for reducing the redundant transmission of plain flooding have been proposed in parallel to

our work. The differentiating factor is the heuristic applied to reduce the retransmissions. In [50], Williams and Camp have categorized the broadcast techniques into four main categories.

It is also possible to envisage scenarios that require higher delivery guarantees beyond what plain flooding can provide. To achieve these more stringent delivery guarantees, we propose a technique called *hyper flooding*. The basic principle of hyper flooding is to force nodes to re-broadcast data packets more than once based on certain criteria. This helps to ensure maximum packet delivery at the cost of overhead. We argue that mission critical applications may be willing to pay the price of higher overhead in exchange for highest possible delivery guarantees. Below, we describe scoped- and hyper flooding in detail.

3.3.1 Scoped Flooding

The basic principle behind scoped flooding is the reduction of re-broadcasts to avoid collisions and minimize overhead. Scoped flooding is suitable for constrained mobility environments (e.g., conference scenarios) where nodes do not move much and thus plain flooding will likely yield unnecessary redundant re-broadcasts. In fact, S. Ni et. al. [51] show that the coverage area of subsequent retransmissions reduces drastically and drops down to 0.05% when the number of retransmissions is greater than 4.

Different heuristics can be used in deciding whether to re-broadcast a packet. In our scoped flooding implementation, each node periodically transmits *hello* messages which also contain the node's neighbor list. Nodes use *hello* messages to update their own neighbor list and add received lists to their neighbor list table. When a node receives a broadcast, it compares the neighbor list of the transmitting node to its own neighbor list. If the receiving

node's neighbor list is a subset of the transmitting node's neighbor list, then it does not re-broadcast the packet. In our simulations we did not require neighbor lists to be strict subsets of one another. An 85% overlap was considered sufficient to prevent re-broadcasts and this was obtained after extensive simulation-based analysis of scoped flooding.

3.3.2 Hyper Flooding

Hyper flooding is suitable for highly mobile scenarios where high reliability is required. The price to pay for the additional reliability is of course higher overhead.

Similar to both plain and scoped flooding, nodes in hyper flooding exchange periodic `hello` messages. When a node receives a `hello` message from a neighbor, it adds the identity of `hello` message originator to its neighbor list (if the list does not already contain that node). As in plain flooding, when a node receives a new data packet, it simply re-broadcasts the packet and queues it in its packet cache. Additionally, re-broadcasts are triggered by two other events: receiving a data packet from a node which is not in the current neighbor list or receiving a `hello` message from a new neighbor. In these cases, nodes transmit all packets in their cache. The rationale behind re-broadcasts is that "newly acquired" neighbors could have missed the original flooding wave on account of their mobility. This increases overall reliability by ensuring that new nodes entering the transmission region of a node receive data packets which they otherwise would have missed. Nodes periodically purge their packet cache to prevent excess re-flooding of older packets.

3.4 Performance of Flooding Variations

We conducted extensive simulations to compare the performance of the proposed flooding variations against plain flooding, ODMRP, and MAODV. One novel feature of our study is that, in addition to the synthetic environments described in Section 5.4, we also use concrete MANET scenarios, namely conferencing and emergency response/rescue operations (described in detail in Section 3.4.2 below). We start with the simulation results for synthetic MANET scenarios.

3.4.1 Synthetic scenarios

Similarly to the scenarios described in Section 5.4, for these simulations, 150 nodes are randomly placed in a 1500 m^2 field. Each node transmits a maximum of 1000 packets (256 bytes each) at various times during the simulation. Nodes' channel bandwidth is set to 2 Mbit/sec and their transmission range is 225 meters. Senders are chosen randomly from the multicast group members. All member nodes join at the start of the simulations and remain members throughout the duration of the simulation. Total network traffic was kept constant at 50 Kbps. Each data point was obtained by averaging across five runs with different seed values.

Figure 3.13 shows how packet delivery ratio varies with mobility and number of traffic sources. Surprisingly for these scenarios hyper flooding does not exhibit the highest delivery ratio among all protocols as expected. Given the larger node density for these particular scenarios, rebroadcasting multiple times seems counter-effective resulting in a lot of packets being drops due to collisions. It is seen that flooding has the best delivery ratio, out-

<div align="center">

Packet Delivery Ratio Vs Mobility : 10 Senders 50 Receivers: 50kbps   Packet Delivery Ratio Vs Mobility : 20 Senders 100 Receivers: 50kbps

</div>
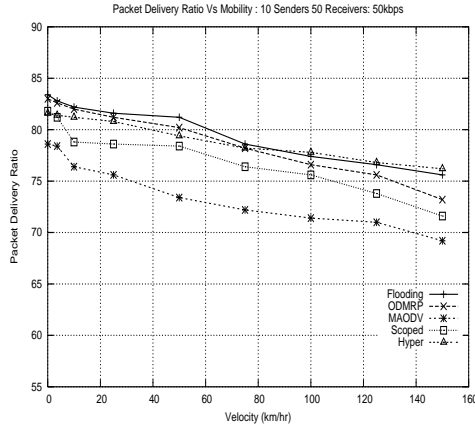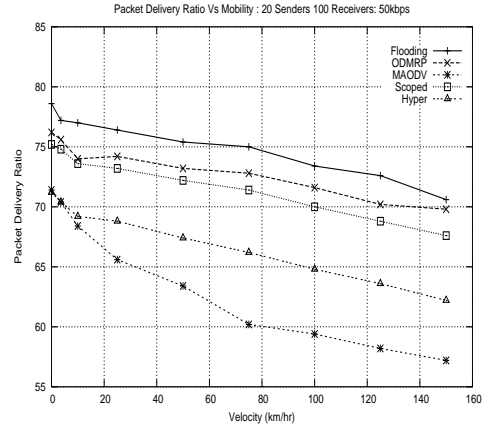
(a) 10 Senders 50 Receivers   (b) 20 Senders 100 Receivers

Figure 3.13: Packet delivery ratio as a function of node mobility

performing ODMRP by 2-3%.

However this increase in reliability is obtained at the cost of routing overhead as evident from Figure 3.14. Another interesting observation is that the delivery ratio of scoped flooding is very similar to ODMRP. However this reliability is obtained at a much lower routing overhead. Both ODMRP and scoped flooding have multiple redundant routes to destinations. However, in the case of scoped flooding, the number of redundant broadcasts is optimized by using forwarding nodes with non-overlapping neighbors. Another factor contributing to scoped flooding outperforming ODMRP is that scoped flooding does not have to transmit any control messages which can potentially result in medium contention and higher packet loss due to collisions.

Figure 3.15 plots group reliability as a function of node speed. From the figure it can be seen that the protocols perform quite poorly in terms of delivering packets to all

Routing Overhead Vs Node Mobility: 10 Senders 50 Receivers | Routing Overhead Vs Node Mobility: 20 Senders 100 Receivers
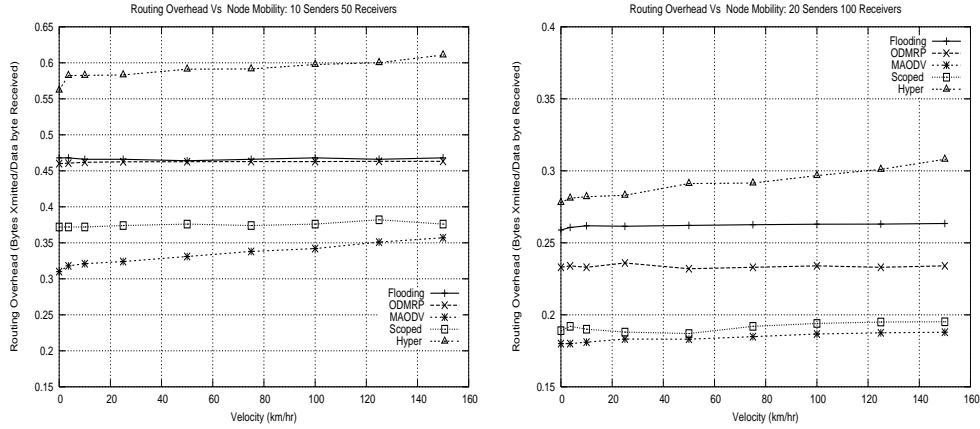
(a) 10 Senders 50 Receivers   (b) 20 Senders 100 Receivers

Figure 3.14: Control overhead as a function of node mobility

group members, especially at high mobility. The group reliability for all protocols drops to about 10-15% at speeds of 150 kms/hr with MAODV having the lowest group reliability. For these scenarios, ODMRP has the highest group reliability among the protocols evaluated. In these experiments, given the large node density and receiver population, flooding and hyper are severely affected by packet losses due to collision and contention. ODMRP and scoped flooding perform the best under these conditions because of their limited rebroadcasts as compared to flooding and hyper flooding. Since MAODV maintains a shared tree structure it is susceptible to frequent link breakages due to mobility. This has a severe effect on MAODV's group reliability performance.

(a) 10 Senders 50 Receivers   (b) 20 Senders 100 Receivers
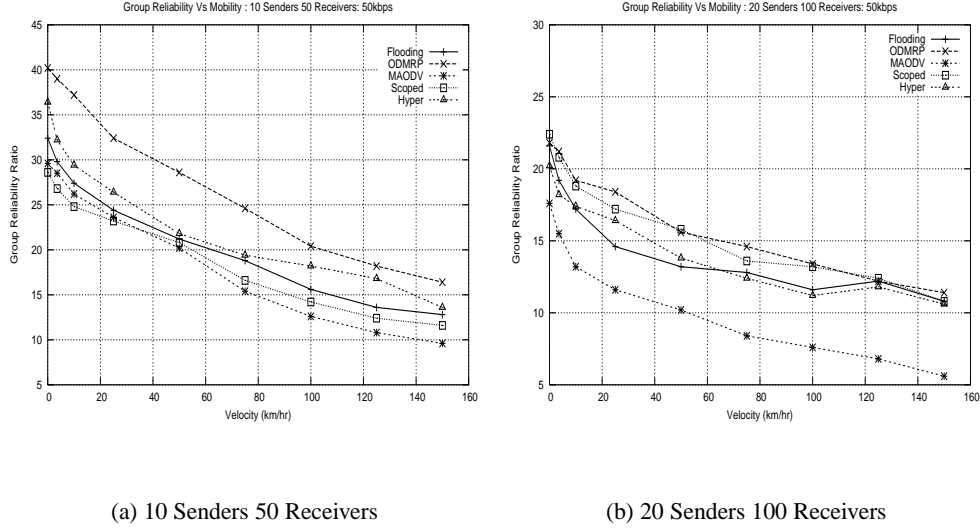
Figure 3.15: Group reliability as a function of node mobility

3.4.2   Concrete scenarios

We also use "typical" MANET scenarios such as conferencing and rescue operations to compare the performance of the protocols under investigation. Such scenarios were generated using the scenario generator for ad hoc networks [20] and are described in greater detail below.

Conferencing

The conference scenario consists of a total of 50 nodes in a 1000 m^2 field with one *speaker* node and three *audience* groups, i.e., *audience1*, *audience2* and the *wanderers*. Both *audience1* and audience2 consist of 20 members moving at low speeds (between 2-5 m/s) with pause time between 0-2 secs. The movement of the speaker was modeled using brownian motion whereas the movement of the audience groups was modeled using random waypoint

49

motion and node movement was restricted to a limited area within the field. *Wanderers* consist

of 9 nodes who were capable of moving over the entire topology. The speeds for these nodes

were randomly chosen between 1-5 m/s with pause times between 0-1 sec. *Wanderers* move

according to the random waypoint model. The *speaker* node and 20 randomly chosen audience

nodes acted as sources of data.

Both CBR and ON-OFF traffic were used. In CBR, each source transmitted 2.5 Kbs,

while the traffic rate was set to 5 Kbs for ON-OFF traffic with a burst period of 3 secs and idle

time of 3 secs. Figure 3.16 depicts the conference scenario setup.

Table 3.7 summarizes simulation results for the conferencing scenario in decreasing

order of packet delivery ratio. Scoped flooding is the best performer for both CBR- and ON-

OFF traffic. In particular, for ON-OFF traffic, scoped flooding's delivery ratio is around 10%

higher than ODMRP and around 14% higher than MAODV, yet its overhead is lower than

ODMRP and only slightly higher than MAODV. Flooding and hyper flooding exhibit lower

delivery ratio than ODMRP and MAODV for CBR traffic. The low mobility of nodes coupled

with sufficiently high node density and high traffic load results in large number of collisions

especially for flooding and hyper flooding. The high overhead incurred by both protocols also

contribute to increased medium contention.

Emergency response scenario

For the emergency response scenario, we use a 2000 m^2 field with a total of 75 nodes

divided into the following categories: two helicopters, two rescue teams of ground personnel

and two teams on ground vehicles. The helicopters move with speeds ranging between 0-50

Conference scenario			
	Protocol	Delivery ratio %	Routing overhead (Bytes Xmitted/data bytes recvd)
CBR Traffic	Scoped flooding	84.2	0.114
	ODMRP	81.4	0.136
	MAODV	76.8	0.081
	Hyper flooding	71.2	0.145
	Flooding	70.6	0.137
ON-OFF Traffic	Scoped flooding	76.4	0.126
	ODMRP	67.3	0.128
	Flooding	64.5	0.154
	MAODV	63.5	0.084
	Hyper flooding	60.4	0.172

Table 3.7: Conference scenario

m/s according to the random waypoint model. The first vehicle team consists of 25 nodes while the second team consisted of 8 nodes. Members of both vehicle teams move according to the random waypoint model with speeds ranging between 5-15 m/sec. The team of ground personnel consists of 20 nodes moving with speeds ranging between 0-5 m/s and pause times between 0-2 secs. Each team covers well-defined areas within the field with sufficient overlap
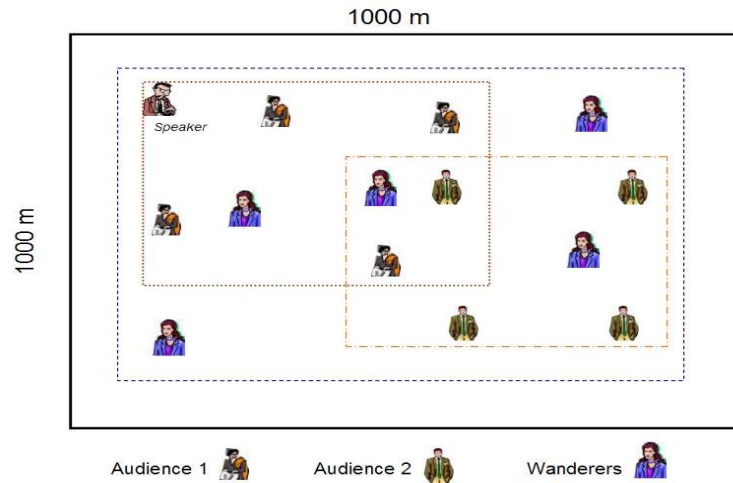
Figure 3.16: Conference scenario setup

51
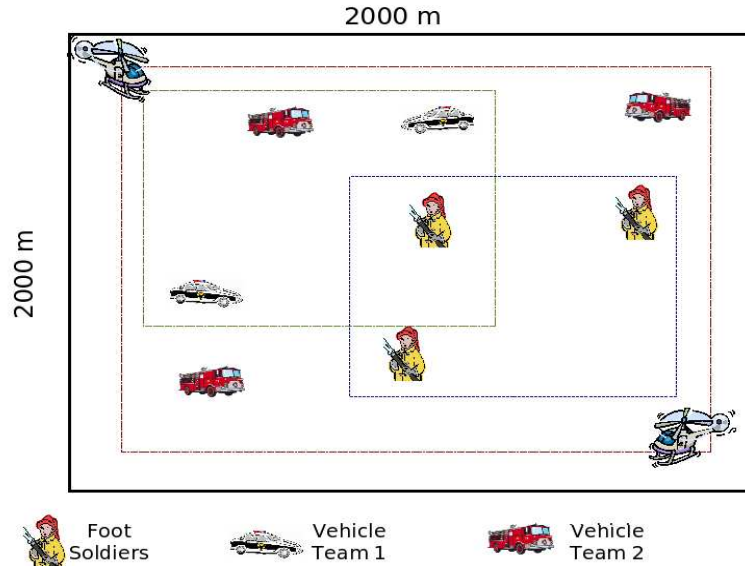
Figure 3.17: Emergency Response Scenario setup

Emergency response scenario			
	Protocol	Delivery ratio %	Routing overhead (Bytes Xmitted/data bytes recvd)
CBR Traffic	Hyper flooding	80.2	0.148
	Flooding	76.4	0.132
	Scoped flooding	75.2	0.116
	ODMRP	67.4	0.126
	MAODV	60.2	0.091
ON-OFF Traffic	Hyper flooding	78.4	0.165
	Flooding	73.2	0.141
	Scoped flooding	69.8	0.122
	ODMRP	60.36	0.129
	MAODV	56.2	0.093

Table 3.8: Emergency response scenario

to ensure that information could be relayed among the different teams. Two helicopters and 20 other randomly chosen nodes act as data sources for this scenario.

Figure 3.17 depicts the emergency response scenario setup. From Table 3.8, which summarizes simulation results for the emergency response scenario, we observe that flooding

variations achieved considerably better packet delivery ratio than ODMRP or MAODV for both CBR- and ON-OFF traffic. Even though we ensure that different "mobility" groups have sufficient overlap to relay data among groups, in the case of ODMRP only forwarding group members can relay data, whereas in MAODV only multicast tree members can forward data traffic. At route setup time, nodes in the overlap region are incorporated as forwarding group members (ODMRP) or multicast tree members (MAODV). However, node mobility may cause forwarding group members and multicast tree members to move outside the overlap region resulting in a large number of packet drops until the route is refreshed at the end of the *Active-Route-Interval*. This effect is more severe for bursty traffic as compared to CBR traffic. In the case of flooding and its variations, all nodes can forward data traffic, and thus achieve better reliability. In particular, scoped flooding achieves close to 10% higher delivery ratio than ODMRP at lower overhead; when compared to MAODV, scoped flooding delivers close to 15% more packets at slightly higher overhead. Hyper flooding improves reliable delivery even further: for both CBR- and ON-OFF traffic, it achieves between 20-22% better reliability than MAODV incurring approximately 50% overhead increase. When compared to ODMRP, hyper flooding's reliability improvement are also quite substantial at slightly higher routing overhead.

Although, in our simulations we use CBR and on-off traffic, from our simulation studies it can be extrapolated that flooding and its variations are particularly well suited for voice based applications. Due to the nature of voice traffic, the delay jitter has to be minimal and packets arriving after a certain bounded delay cannot be constructively used by the application. Flooding provides the best delay guarantees for small sized networks since one of the

	Scenario Type	Recommendation
Low Average Mobility < (10 m/s)	Low Sender/Receiver Populations	Scoped Flooding or ODMRP
	Low Bandwidth Requirement	MAODV
	Conference/ Exhibition	Scoped Flooding
High Average Mobility > (20 m/s)	High Reliability	Flooding or Hyper Flooding
	Large Multicast Group Size	ODMRP Scoped Flooding
	Disaster/ Recovery	Scoped Flooding

Table 3.9: Choice of Routing Protocol for Specific Scenarios

paths from the source to the receiver is likely the shortest path. This makes flooding and its variations particularly attractive for applications with stringent delay requirement.

Table 3.9 provides an overview of the results obtained and recommendations on the choice of the protocols for specific network conditions and mobility.

3.5 Conclusions

In this chapter, we reported on simulation-based experiments evaluating two different approaches to multicast communication in mobile ad hoc networks (MANETs), namely mesh- and tree-based multicast. One of the chief contributions of this work is our objective analysis of these two multicast routing protocol categories in order to characterize their behavior under a wide range of MANET scenarios, including different mobility and traffic load conditions as well as multicast group characteristics (e.g., size, number of sources, multiple multicast groups, etc.). Another contribution of this work is the use of realistic MANET scenarios, such as conferencing and emergency response in evaluating routing protocols. These

54

MANET scenarios were generated using the scenario generator tool [20].

Our simulation results demonstrate that even though the performance of all multicast protocols degrade in terms of packet delivery and group reliability as node mobility and traffic load increases, mesh-based protocols (e.g., flooding and ODMRP) perform considerably better than tree-based protocols (e.g., MAODV). The general conclusion from the comparative analysis was that flooding, which is the simplest routing mechanism provides higher delivery guarantees than ODMRP and MAODV for most scenarios considered. ODMRP exhibits decent robustness on account of its mesh structure. MAODV did not perform as well as the other protocols in terms of packet delivery ratio and group reliability but has the lowest routing overhead among the protocols considered.

A well-known drawback of flooding is its inherent overhead in the form of redundant broadcasts. This is particularly evident in the case of multiple multicast groups, where flooding's overhead increases with number of groups. To limit flooding's excessive overhead we proposed *scoped flooding*, a variation of flooding which attempts to minimize re-broadcasts by using neighbor information. Simulation results show that scoped flooding can reduce overhead by around 20% compared to flooding and 15% compared to ODMRP at comparable delivery ratios. One interesting observation was the performance of scoped flooding in conference scenarios, where it exhibited stellar performance in delivering data at low routing overhead.

In order to address the issue of reliability at high node speeds we also investigated other flooding variation referred to as *hyper flooding*. Simulations results indicate that hyper flooding, indeed provides the best delivery guarantees under more stringent conditions (e.g.,

high mobility, traffic load) but this is achieved at greater overhead (about 10% in the case of our emergency response scenarios) than flooding. However, we believe that hyper flooding can be justified in those MANET scenarios demanding highest possible guarantees of reliable (yet timely) delivery, regardless of costs.

One of the conclusions from our study is that given the diversity of MANETs, it is impossible for any one routing protocol to be optimal under all scenarios and operating conditions. One possible solution would be to develop specialized multicast solutions for each type of network and the means for integrating those solutions. We believe that an adaptive, integrated approach to routing may be the best means to tackle this problem. In this approach nodes can dynamically switch routing mechanisms based on their perception of the network conditions. However such an adaptive approach presents various challenges such as:

(1) Interoperability and integration issues.

(2) Mechanisms for active, on-the-fly switching among different multicast routing mechanisms as a mobile host changes the network type it is part of. We address some of the above mentioned issues in Chapter 4.

Chapter 4

Adaptive Routing Techniques for

MANETs

In this chapter, based on our simulation studies from Chapter 3, we motivate the need for adaptive routing and introduce an adaptive flooding mechanism in which nodes can dynamically switch routing strategy based on their perspective of the current network conditions.

4.1   Motivation and Background

The diverse nature of MANETs makes it almost impossible for any one routing protocol to perform well under a wide range of operating conditions. This fact is further reinforced by our simulation results and analysis from chapter 3. It is also very likely that future internetworks will be composed of numerous ad-hoc networks each running different mechanisms for group communications, either due to administrative concerns or current net-

work requirements. Our main research goal is to provide seamless integrated multicast service whereby a single multicast group can span all network types (fixed, fixed mobile, and different types of MANETs). This would allow a given host to partake in multicast communication regardless of the underlying network type. Therefore, hosts will have to dynamically switch among different multicast routing mechanisms as they move from one network to another. To our knowledge, there is little or no experience in the network research community in multicast protocol interoperation or adaptation.
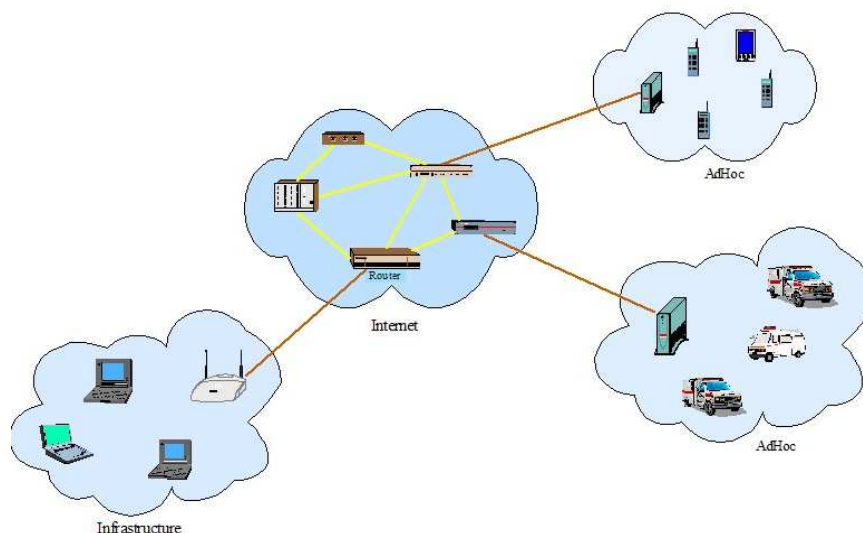
Figure 4.1: Internetwork with Infrastructure and Ad-hoc Networks

4.2   Adaptive Protocol Overview

The routing protocol we propose, integrates scoped-(Section 3.3.1), plain-, and hyper flooding (Section 3.3.2) into a single adaptive protocol. Nodes switch among flooding

variations based on their own perception of current network conditions. The primary motivation to use flooding as the basis for our adaptive, integrated multicast routing framework, is that flooding and its variations perform considerably better than other protocols such as MAODV and ODMRP [19] over a wide range of mobility and traffic load conditions. Another factor is that flooding and its variations interoperate easily. However, we note that adaptive flooding may not necessarily be most suited for all MANET scenarios. We propose flooding variations as the first step in investigating the merits of adaptive protocols over non-adaptive routing mechanisms. One of our objectives it to investigate other adaptive routing mechanisms which are not based on flooding.

Each node running our adaptive, integrated multicast routing protocol is capable of operating in any of the three modes: *scoped-*, *plain-*, and *hyper*. Individual nodes dynamically switch among the different operating modes according to their own perspective of the current network conditions. The different criteria for switching between modes is explained below in section 4.2.1.

4.2.1 Switching Among Protocols

One fundamental issue in the design of adaptive integrated multicast is deciding when a node should switch protocols and which protocol to switch to. Every node needs to make its own decision based on its perception of current network conditions.

For the current version of adaptive flooding, we chose *relative velocity* and *network load* as the preliminary criteria nodes use to switch among the different flooding variations. The rationale for using relative velocity and network load in deciding when to switch operating

modes is due to the high dependence of multicast routing protocol performance on mobility and network traffic load [19]. It should be noted that, nodes presently use only one switching criteria for current version of the adaptive protocol.

The proposed relative-velocity based switching criterion works as follows. Nodes send velocity (speed and direction) information as part of *hello* messages. Each node is then able to compute its velocity relative to all its neighbors. We use only immediate neighbor information to calculate a node's relative velocity. Each node maintains a running average, as well as the minimum and maximum value of relative velocity up to the current time window. Based on the current value of relative velocity and its past history, each node adaptively chooses a *low-threshold* and a *high-threshold* value for the current time window. If the current value of relative velocity is higher than *high-threshold*, the node switches to hyper flooding mode. If the relative velocity is below *low-threshold*, scoped flooding is used. Otherwise, the node switches to plain flooding.

We want to point out that the basic objective of the relative velocity based switching criteria is to get a measure of the rate of change of a nodes neighborhood. One way to implicitly estimate the the change in the neighborhood is through mac layer transmissions. We can also use other heuristics such as rate of link changes etc., as the switching criteria and obtain similar results. Another observation is that, although we explicitly transmit velocity information along with hello messages it is also possible to infer velocity of neighbor nodes based on position information alone. However, this would require a node to store the past and current position information for all its neighbors.

Switching modes based on network load uses MAC-layer collisions as an indicator

of network traffic. We chose collisions instead of nominal network load because it is possible that certain nodes may have very sparse neighbor sets, allowing those nodes to communicate even at high loads with low collision. In this switching method each node computes the total number of collisions that have occurred in the current time window. However, in case of real MAC implementations it may be difficult to differentiate between real collisions and interference from other wireless sources (e.g., microwaves operating at the 2.4 GHz range). In such cases, we can use other indicators of network traffic such as the state of MAC queue at neighbor nodes. In this alternate scheme, all nodes can transmit their current MAC queue state along with the hello messages and this information can be used for the switching criteria.

Similar to the velocity criterion, each node adaptively computes a *low-threshold* and a *high-threshold* value for the current time window. If the current number of collisions is lower than *low-threshold*, the node switches to the hyper flooding mode. If the number of collisions is greater than *high-threshold*, scoped flooding is selected. For collision values in between the low and high thresholds, nodes switch to plain flooding. Setting the threshold adaptively, based on current and past values helps to provide hysteresis to the switching operation and prevents nodes from changing routing protocols rapidly in each time window. This helps avoid oscillatory behavior.

Although, we have implemented a simple threshold estimator, we can obtain better granularity by using a weighted average of the relative velocity or number of collisions from the past and current time windows, similar to the TCP round trip timeout estimator.

61

4.3   Simulation Environment and Methodology

We used the network simulator `ns-2` for our simulations as described in section 3.1. In the following simulation analysis we compare the performance of our adaptive flooding mechanism with ODMRP and MAODV under "synthetic" as well as realistic scenarios described in section 3.4.2.

4.4   Results

4.4.1   Relative Velocity Based Switching

The graphs in Figure 4.2 show how protocol reliability varies with node mobility which is expressed in terms of average relative velocity. The average relative velocity is computed as follows. The relative velocity of each node with respect to its neighbors is calculated throughout the duration of the simulation and is then averaged over all nodes.

It can be observed from Figure 4.2 that packet delivery ratio decreases with increase in relative velocity. The increased mobility of the nodes causes them to move outside the radio range of their neighbors more frequently resulting in lower packet reception. In case of the adaptive flooding protocol, nodes rely on neighbor information to decide if they retransmit packets. Neighbor information may become stale as the mobility of the nodes increases resulting in lower packet delivery ratio at higher speeds. It can be seen from the graphs that adaptive flooding performs better than ODMRP or MAODV in terms of packet delivery ratios delivering around 90% of the packets at a relative velocity of 50 m/s. At lower speeds adaptive flooding switches to scoped flooding mode in an attempt to reduce redundant retransmissions.

62
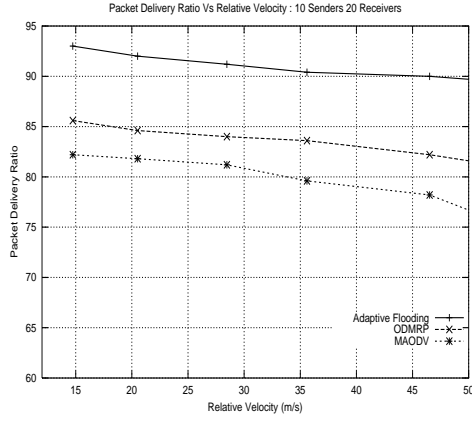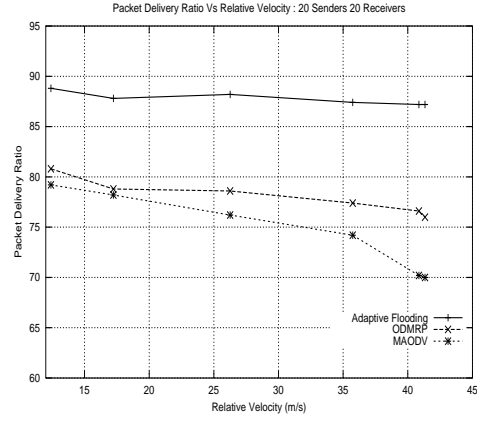
(a) 10 Senders 20 Receivers   (b) 20 Senders 20 Receivers

Figure 4.2: Packet Delivery Ratio as a function of Node Mobility

As the relative velocity increases it switches to flooding and hyper flooding modes resulting in consistent packet delivery ratios. Comparing adaptive flooding to ODMRP we notice that at lower speeds the difference in packet delivery ratio is only within 5%. However at higher speeds the difference in packet delivery ratio starts widening. For instance, in the case of 20 senders and 20 receivers we observe packet delivery ratio differences of up to 12% in favor of adaptive flooding. This is because with increased mobility the forwarding group members need to be updated more frequently. This requires that sources send out *Join-Requests* more frequently resulting in higher control overhead and greater packet loss due to contention.

Comparing ODMRP with MAODV we observe that ODMRP has better packet delivery ratios (around 7-10%) at higher speeds. Since ODMRP maintains meshes, it has multiple redundant paths to receivers and is not affected by mobility as greatly as MAODV. In the case of MAODV increased mobility causes frequent link changes and requires tree reconfig-

uration to prevent stale routing information. This in turn requires higher control traffic which can result in greater packet loss due to contention.

(a) 10 Senders 20 Receivers   (b) 20 Senders 20 Receivers
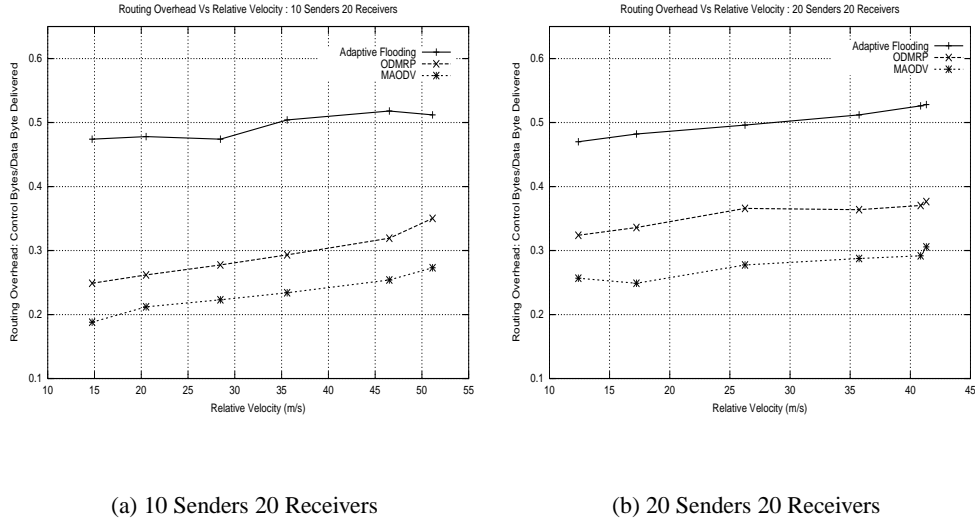
Figure 4.3: Routing Overhead as a function of Node Mobility

The graphs in Figure 4.3 plot control overhead per data byte delivered as a function of node mobility. It can be seen from the graphs that the routing overhead/data byte delivered increases with increase in node mobility. This is due to the fact that the routing overhead remains almost constant with increase in mobility but fewer data packets are delivered. Adaptive flooding has the highest overhead among the protocols on account of the redundant transmissions. At high velocities, adaptive flooding switches to the hyper flooding mode in an attempt to increase reliability, thereby increasing the routing overhead.

4.4.2 Network Load Based Switching

In this section we present results for adaptive flooding based on the network load switching criteria. The graphs in Figure 4.4 show how the reliability varies with network load. Although we ran simulations for different node velocities we only include results for node speeds of 20 m/s (72 km/hr). An ON-OFF traffic generator was used for the simulation results presented below. The overall traffic rate was obtained by averaging the data rate of all senders.

(a) 10 Senders 20 Receivers   (b) 20 Senders 20 Receivers
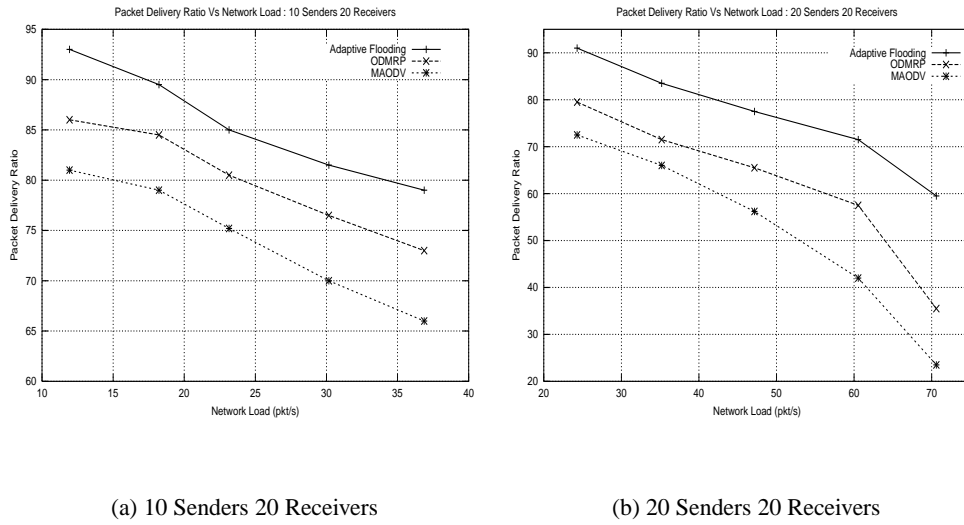
Figure 4.4: Packet Delivery as a function of Network Load

From Figure 4.4 it can be observed that for the 20 sender, 20 receiver case ODMRP and MAODV deliver around 40-60% packets at network load of 60 packets/sec. Both ODMRP and MAODV are affected to a greater extent, than adaptive flooding. As the network load increases, adaptive flooding switches to the scoped flooding mode in an attempt to reduce collisions. In case of adaptive flooding, the losses are mostly due to collisions. In case of ODMRP and MAODV, node mobility results in stale routing information. The bursty nature

Conference Scenario			
	Protocol	Delivery Ratio %	Routing Overhead (Bytes Xmit/Data byte recvd)
CBR Traffic	Adaptive Flooding (NL)	86.32	0.138
	ODMRP	81.38	0.136
	MAODV	79.87	0.081
ON-OFF Traffic	Adaptive Flooding (NL)	81.41	0.140
	ODMRP	67.78	0.112
	MAODV	64.58	0.087

Table 4.1: Conference Scenario: Network Load (NL)

Disaster Scenario			
	Protocol	Delivery Ratio %	Routing Overhead (Bytes Xmit/Data byte recvd)
CBR Traffic	Adaptive Flooding (RV)	82.47	0.170
	ODMRP	65.24	0.164
	MAODV	60.81	0.108
ON-OFF Traffic	Adaptive Flooding (RV)	76.79	0.180
	ODMRP	60.56	0.147
	MAODV	56.47	0.101

Table 4.2: Disaster Scenario: Relative Velocity (RV)

of the traffic causes a large number of packet drops before the routes are refreshed.

4.4.3   Conference and Rescue Scenarios

Tables 4.1, 4.2 and 4.3 present results for the conference and disaster rescue scenarios using relative velocity and network load as switching criteria.

For the conference scenario, adaptive flooding (using network load as the switching criterion) performs better than ODMRP and MAODV for both CBR and ON-OFF traffic. In particular, for ON-OFF traffic, adaptive flooding's delivery ratio is around 14% higher than ODMRP and around 17% higher than MAODV. In this scenario, node density was sufficiently large and average node mobility was quite low. The low mobility of nodes coupled with

Disaster Scenario			
	Protocol	Delivery Ratio %	Routing Overhead (Byte Xmit/Data byte recvd)
CBR Traffic	Adaptive Flooding (NL)	81.73	0.150
	ODMRP	65.24	0.164
	MAODV	60.80	0.108
ON-OFF Traffic	Adaptive Flooding (NL)	76.44	0.150
	ODMRP	60.56	0.147
	MAODV	56.47	0.101

Table 4.3: Disaster Scenario: Network Load (NL)

high traffic load results in a large number of collisions. This triggers adaptive flooding to mostly operate in the scoped flooding mode in an effort to reduce re-transmissions. However, in case of ODMRP the number of forwarding group members was quite large, resulting in a large number of redundant transmissions. This effect is compounded in the case of bursty traffic resulting in lower packet delivery ratios for ON-OFF traffic. Adaptive flooding's routing overhead is comparable to ODMRP in case of CBR traffic and slightly higher than ODMRP in case of ON-OFF traffic.

For the disaster scenario, both versions of adaptive flooding performed considerably better, delivering around 16-22% more data packets than ODMRP or MAODV. This scenario consisted of several groups of nodes which were restricted to move within a subset of the total topology. The groups had sufficient overlap to ensure that data packets could be relayed from one group to another. In case of ODMRP only forwarding group members can relay data, whereas in MAODV only multicast tree members can forward data traffic. At the time of route setup, nodes in the overlap region are incorporated as forwarding group members (ODMRP) or multicast tree members (MAODV). However node mobility causes the forwarding group members and multicast tree members to move outside the overlap region resulting in a large

number of packet drops until the route is refreshed at the end of the *Active-Route-Interval*. This effect is more severe for bursty traffic as compared to CBR traffic. However in the case of adaptive flooding all nodes can forward data traffic and thus adaptive flooding delivers around 20% more data than ODMRP or MAODV. Applications that require high delivery guarantees will likely trade adaptive flooding's slightly higher overhead for its considerably higher delivery rate.

4.5   Conclusions

Our study shows that the diverse nature of MANETs make it impossible for any one protocol to be be optimal under all scenarios and operating conditions. This calls for specialized multicast solutions for each type of network and the means for integrating those solutions. In this chapter we have proposed an adaptive approach to routing where nodes dynamically switch routing mechanisms based on their perception of current network conditions. Using the proposed adaptive protocol, which incorporates different variations of flooding, nodes can switch from one mode of flooding to another using relative velocity and traffic load as switching criteria.

Our simulation results compare the adaptive protocol with ODMRP and MAODV for "synthetic" as well as "realistic" MANET scenarios. The results demonstrate that the adaptive protocol performs consistently well in terms of both packet delivery ratio and routing overhead. For the disaster-rescue scenario, adaptive flooding's delivery ratio was about 15-20% higher than ODMRP and MAODV for CBR and ON-OFF traffic, which was achieved at a comparable routing overhead. In case of the conference scenario, adaptive flooding's

delivery ratio was 15-17% higher than ODMRP and MAODV for ON-OFF traffic. The routing

overhead in this case was comparable to ODMRP and slightly higher than MAODV.

The main emphasis from this study is that given the diversity of MANETs, adaptive

protocols are capable of providing consistent performance benefits over a wide range of oper-

ating conditions. The simulation results presented in this chapter highlight these performance

benefits and lay the foundations for other adaptive routing mechanisms which are not based

on flooding.

Chapter 5

Interoperability of Multicast Routing Protocols in Wireless Ad-Hoc Networks

Typically, MANETs have always been considered to be isolated, stand-alone networks with no connection to the Internet. However, we envision that future internetworks will consist of a wired backbone and a collection of wired, fixed-infrastructure mobile, and ad hoc networks as leaves as illustrated in Figure 4.1. We believe that a "global" routing solution for future internets will include specialized solutions for each type of network, as well as mechanisms for integrating these solutions. The choice of routing mechanism could be primarily dictated by administrative constraints, application requirements, operating conditions, or even by varying implementations available from network providers. For example, commercial deployments available from NovaRoam [52] use AODV [30] and TORA [29] as routing protocols, whereas

70

MANET products available from Firetide [53] use TBRPF [54] as the routing mechanism.

Based on these observations, our premise is that, in future internets, different routing mechanisms will coexist and thus calls for mechanisms that allow different protocols to interoperate so that nodes in different *routing domains* can communicate. Our main focus is on multicast communication, in particular, enabling a single multicast group span different MANET clouds and consequently, routing domains. Further, mobility may cause nodes to migrate from one cloud to another. Node mobility not only raises interoperability and integration issues, but also calls for mechanisms to actively, switch on-the-fly among different multicast routing mechanisms as a mobile node moves across MANET clouds.
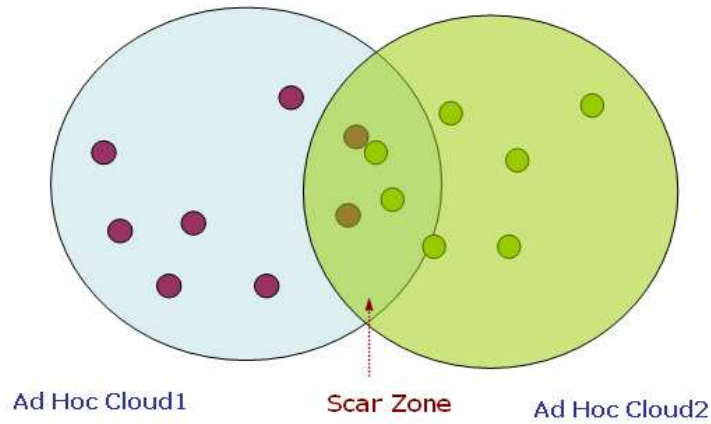
Figure 5.1: Interoperability of two Ad Hoc domains

Figure 5.1 depicts a scenario where two different ad hoc domains, running different multicast routing protocols come together on account of mobility. The overlap region is referred to as the *Scar Zone* [55]. It is quite possible that nodes in the scar zone may wish to commmunicate with other members of the multicast group. This requires some means of

71

"healing" the scar zone and an interoperability mechanism that will facilitate communication between nodes from different domains. One simple solution to address this interoperability issue is for all nodes in one domain to implement and switch to the routing protocol in another domain. This approach although easy to implement has several drawbacks:

- All nodes will have to implement multiple routing protocols and will require means to actively switch from one protocol to another.

- Any existing routing information established by the current routing mechanism will be lost. Any on-going intra domain communication will have to dropped and reestablished after the nodes have switched routing protocols.

- The choice of the new routing protocol may be suboptimal for certain nodes.

Based on the above observations, we argue the need for an interoperability mechanism that is lightweight and extensible and can be used over existing routing mechanisms without major modifications to the underlying protocol. We believe that our proposed interoperability mechanism provides the right balance of scalability, extensibility and can be easily implemented on top of most MANET multicast routing protocols. We address these design concerns in greater detail in Section 5.2.

In this chapter, we focus primarily on interoperability issues in internets consisting of several MANET clouds running different multicast routing mechanisms. To our knowledge, there is little or no experience in the wireless network research community in multicast (or unicast) routing protocol interoperation or adaptation (although, some proposals have been floated in the IETF in the context of wired networks [1–3]). We introduce two different inter-

72

operability mechanisms and evaluate their effectiveness for different MANET environments, including scenarios motivated by typical MANET applications. In particular we investigate flooding based interoperability and facilitator assisted interoperability approaches. The initial simulation results indicate that the flooding based interoperability mechanism is best suited for scenarios involving infrequent communication between different routing domains and when group membership is dense due to flooding's inherent redundancy whereas the facilitator assisted approach is best suited for data intensive applications such as video-conferencing.

5.1   Design Goals

Analogous to wired internets, we define *routing domain* (or *cloud*) as a collection of MANETs under a single administrative control running the same routing protocol. When designing the proposed interoperability mechanisms, the main goals to address include:

- **Scalability**: state that needs to be maintained at nodes and exchanged across domains to allow interoperation should be minimal and scalable with the number of nodes.

- **Prevention of routing loops**: Assuming that the intra-domain routing protocol is loop-free, the interoperability mechanism should ensure that the routes across domains are loop free as well.

- **Generality**: The interoperability mechanism should be allow interoperation of various multicast routing techniques. This not only includes interoperability **among** different mesh- (e.g., [4], [40] [17]) and tree-based protocols (e.g., [5], [37]), but also interaction **between** mesh- and tree-based routing. In other words, a domain running a

73

mesh-based protocol should be able to communicate with a domain running a tree-based protocol, and vice-versa.

- **Minimal impact on intra-domain routing**: Each routing domain should be able to choose the routing technique best suited to meet the requirements of its driving applications and network conditions, independently of other domains. Further, the interoperability mechanism should have a minimal effect on the operation of intra-domain routing protocols.

5.2   Interoperability Mechanisms

In this section we provide an overview of the proposed interoperability mechanisms. Some of the principles that guided our design, which are outlined in Section 5.1 above, are often conflicting. In particular, if the design favors protocol efficiency and scalability, it will sacrifice protocol generality. This tradeoff led to the development of two interoperability mechanisms, namely (1) flooding-based and (2) facilitator-assisted interoperability. We review these two techniques below.

5.2.1   Flooding-Based Interoperability

The basic premise of this approach is to use simple flooding to route data across routing domains. The main advantage of such flooding-based interoperability is its simplicity and the fact that it requires no cross-domain route establishment. Furthermore, it is quite easy to prevent routing loops (usually by adding sequence number and a maximum hop count information to packets). Another key benefit of flooding-based interoperability is that it is

simple enough to allow interoperation of most routing protocols. However, the main draw-back, which is inherent of flooding-based approaches in general, is that it results in excessive redundant transmissions, sacrificing scalability for generality.

Given these features, flooding-based interoperability is suitable for scenarios where receiver groups are quite dense and communication across domains is intermittent. An example where this approach would be beneficial is in the case of emergency response/natural disaster type scenarios. In such circumstances, the rescue operation may consist of several ad-hoc clouds of fire-fighters, medical, search and recover personnel, etc. A major part of the communication in these circumstances is expected to be intra-domain with less frequent inter-domain exchanges (e.g., to obtain feedback and situation appraisal from the co-ordinating stations). Considering that inter-domain communications are most likely to be short-lived, the expense of cross domain route establishment and maintenance (which is the approach taken by the other proposed interoperability scheme) may be unjustified.

5.2.2 Facilitator-Assisted Interoperability

This approach to interoperability is motivated by scenarios involving frequent inter-domain communications such a video conferencing since flooding-based interoperability mechanisms can prove to be quite expensive for such applications. Facilitator-assisted interoperability requires extra functionality to be assigned to a small set of nodes in each domain referred to as *facilitators*. These special nodes are similar in functionality to Multicast Border Routers (MBRs) [2] in wired networks. In wired networks, MBRs are responsible for connecting two multicast routing domains by sharing their forwarding caches. The multicast protocol

running on each MBR sends its forwarding table entries to a shared cache. The shared cache functions as the bridge between multicast trees in neighboring domains. Analogous to MBRs, facilitators in each domain act as entry and exit points for all cross-domain communication. They can also function as normal nodes (i.e, sources, multicast receivers or forwarding group members) in the context of their own routing domain. Facilitators in each domain are essentially responsible for creating and maintaining links between neighboring domains through the use of periodic signalling.

Facilitator-assisted interoperability favors scalability since it uses the existing structure created by the underlying routing protocols to forward data, avoiding global flooding. However, in order to do so, it sacrifices generality as it may require changes to the underlying routing protocol. For example, in sender initiated protocols (e.g., ODMRP), facilitator nodes also have to act as "dummy" senders to establish group membership.

5.3   Protocol Description

One key modification required by our interoperability mechanisms is the addition of a *composite header* for all routing layer messages. The *composite header* ensures that nodes in different routing domains running different routing mechanisms have some minimal knowledge about cross-domain routing messages. The information carried by the composite header include:

- `Protocol   Type   (`*proto*`)`: Specifies the type of the protocol e.g MAODV, ODMRP, AM-RIS etc.

- `Message   Type   (`*mtype*`)`: Specifies the type of message e.g request, reply, data

76

- Source Address (*srcAddr*): Address of node initiating the message

- Destination Address (*dstAddr*): Address of destination node or multicast group

- Next Hop (*nextAddr*): Next hop towards destination

- Sequence Number (*seq_number*): Required to detect duplicate messages

The use of the different fields will become clear in the following sections as we illustrate the operation of the interoperability mechanisms through examples.

5.3.1 Flooding-Based Interoperability

In the flooding based approach, when nodes receive routing messages, they first check the composite header for the *proto* field. If protocol types are the same, the packet is handled by the default routing operation. However, if the protocol types are different, then nodes check the *mtype* field to determine the message type. All routing messages (i.e., route requests, replies etc.) are dropped silently. However, if the *mtype* field indicates a data packet, then the node re-broadcasts the packet to its immediate neighbors. Nodes also cache packet headers to prevent looping and unnecessary retransmissions. The basic operation of the protocol is illustrated through example below.

Figure 5.2 illustrates the initial route setup across two different MANET clouds using flooding-based interoperability. The domain on the right runs a tree-based multicast routing protocol while the left domain employs a mesh-based protocol. When nodes receive routing messages from neighboring domains these routing messages are not forwarded and dropped silently.

77
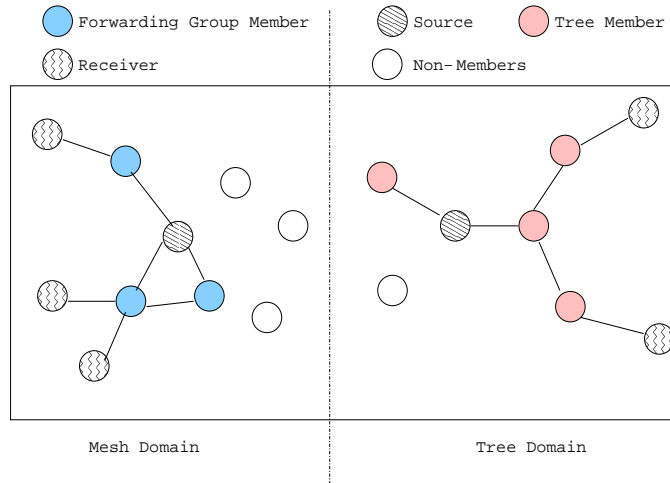
Figure 5.2: Flooding-based interoperability: initial route setup across two routing domains.
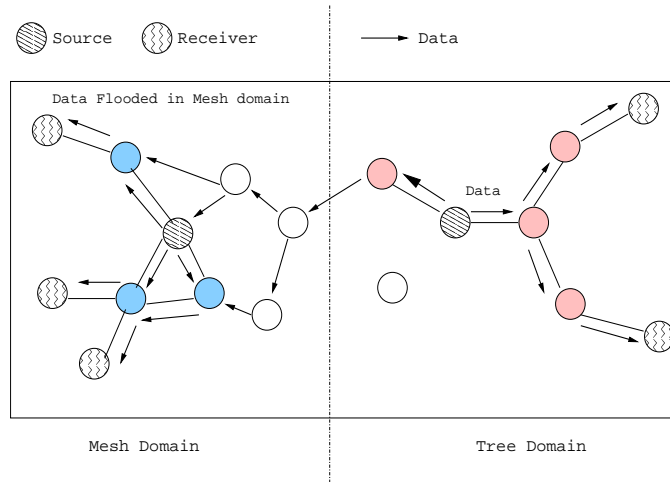
Figure 5.3: Flooding of data in mesh routing domain

Data forwarding across domains is illustrated in Figure 5.3. In this particular example, the source is in the tree domain. Data packets are handled normally in the tree domain in accordance with the underlying routing protocol. However, when the packets are received in the mesh domain, nodes first add the relevant information to their packet caches and broadcast the data to their immediate neighbors. Each node that receives the data packet essentially does

78

a one-hop broadcast after recording the packet header in its cache leading to flooding of data in the mesh domain.

The pseudo-code corresponding to our implementation of flooding-based interoperability is shown below.

```
case:  Non  Member   of  Multicast    Group
 if   (proto   != my_proto)    {

   if (mtype   == data)  {

       Add  packet    header   to  cache

       Rebroadcast    Data  Packet

       }

     else  if  (mtype   != data)

       drop  packet

  }


case:  Member   of  Multicast    Group
 if   (proto   != my_proto)    {

   if   (mtype   == data)  {

       Add  packet   header   to  cache

       Send  packet   to  transport   layer

       Rebroadcast    Data  Packet

       }

     else  if  (mtype    != data)

           drop  packet

  }
```

Using a variation of the simple flooding approach, it may be possible to further reduce the number of redundant retransmissions. The idea is to use *scoped flooding* [56] which employs different heuristics to decide whether a packet should be re-broadcast. In our scoped flooding implementation, each node periodically transmits `hello` messages which also contain the node's neighbor list. Nodes use `hello` messages to update their own neighbor list. When a node receives a data packet it compares the neighbor list of the transmitting node to its own neighbor list. If the receiving node's neighbor list is a subset of the transmitting node's neighbor list, it does not re-broadcast the packet. The assumption is that if there is significant overlap in the neighborhood of the two nodes, it is likely that the packet has already been received by the neighbors.

5.3.2 Facilitator-Assisted Interoperability

As mentioned in Section 5.2.2, facilitators in each domain maintain links to facilitators in neighboring domains through a signaling protocol consisting of two types of messages: (1) `fac-request` and (2) `fac-reply`. Fac-requests are periodically initiated by all facilitators for inter-domain link creation and maintenance. Facilitators of neighboring domains respond to Fac-requests by sending Fac-replies towards the source of the request.

The following example illustrates the sequence of operations and protocol interactions involved in facilitator-assisted interoperability. Figure 5.4 depicts a scenario in which a multicast group spans two different routing domains, each running a different multicast routing protocol. More specifically, the domain on the right employs a tree-based routing protocol while the domain on the left a mesh-based protocol. The initial route setup in each domain is
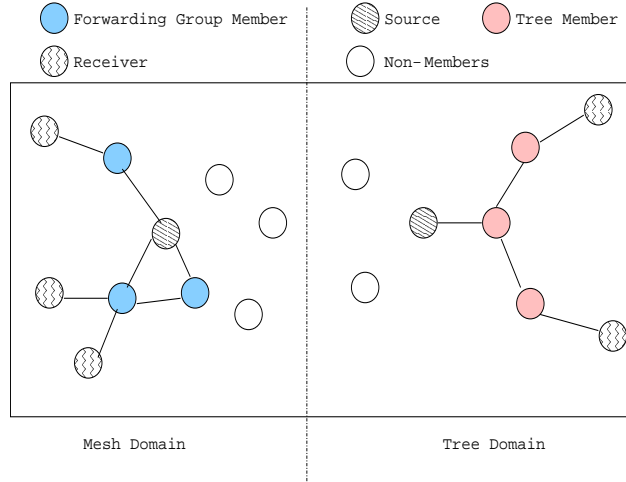
Figure 5.4: Facilitator-assisted interoperability: initial route setup across two routing domains

shown in Figure 5.4.
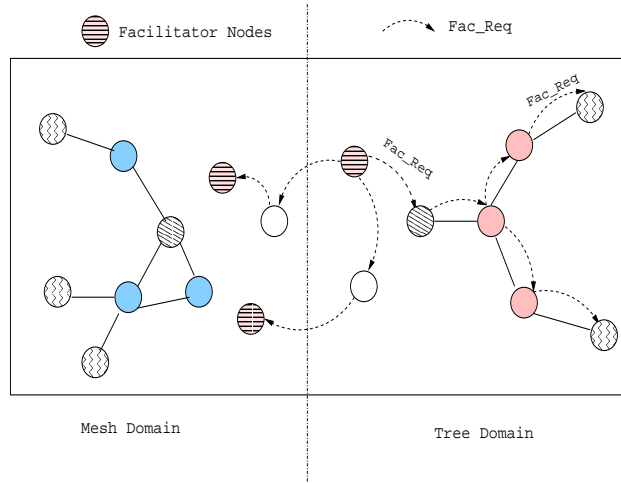
Figure 5.5: Facilitator request

As shown in Figure 5.5, certain nodes in each domain are selected as facilita-tors [1]. For the purpose of this discussion, we assume that facilitators are randomly se-lected. When a node is selected to be a facilitator for a domain, it first checks whether

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[1] We discuss facilitator selection in greater detail in Section 5.3.3.

it is a member of the multicast group. If it is not a member, it sends out a join group message which is specific to the underlying multicast protocol used in its domain. This is required to ensure that all facilitators have routes to multicast groups in their own domain. As shown in Figure 5.5, a facilitator in the tree domain broadcasts a fac-request message. The composite header for this message is of the form < `proto _type  tree`, `msg _type  FAC _REQ`, `srcAddr`, `mcastAddr`, `seqNumber  #1` >. When nodes in the tree domain receive the fac-request, they add the request to their fac-request table, set up reverse routes to the source of the request, and forward the request. Similarly, when nodes in the mesh domain receive the fac-request, they add the request to their fac-request table, set up reverse routes to the source of the request, and forward the request. Thus the fac-request is propagated till it is received by a facilitator in the mesh domain. As shown in Figure 5.6, after ensuring that the request is not a duplicate, the facilitator in the mesh-domain sends out a fac-reply to the next-hop towards the source of the request. The composite header for this message is: < `proto _type  mesh`, `msg _type  FAC _REP`, `srcAddr`, `mcastAddr`, `next-hop`, `seqNumber  #1` >. The next-hop, on receiving the fac-reply, after ensuring that the reply is not a duplicate, checks to see if it is already a member of the mesh. If it is not a mesh member, it becomes one and forwards the packet along the reverse route towards the source of the fac-request. All intermediate nodes along the path to the source in both tree and mesh domains are incorporated as members for the tree or mesh. The forwarding group status for the incorporated nodes is periodically refreshed by the fac-requests. The effect of the fac-request - fac-reply exchange is to create links between facilitators in each domain.
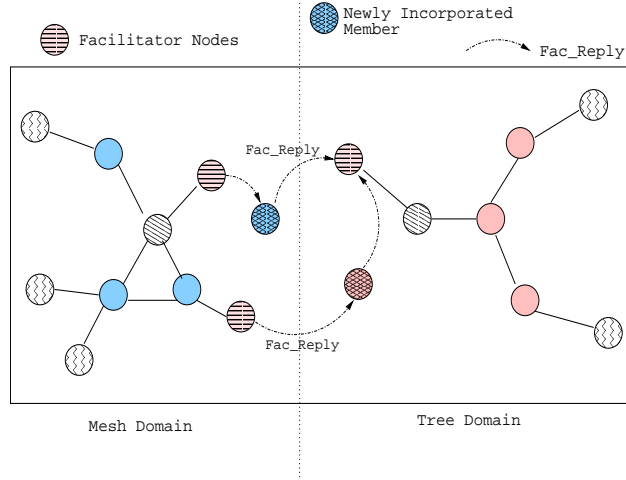
Figure 5.6: Facilitator reply
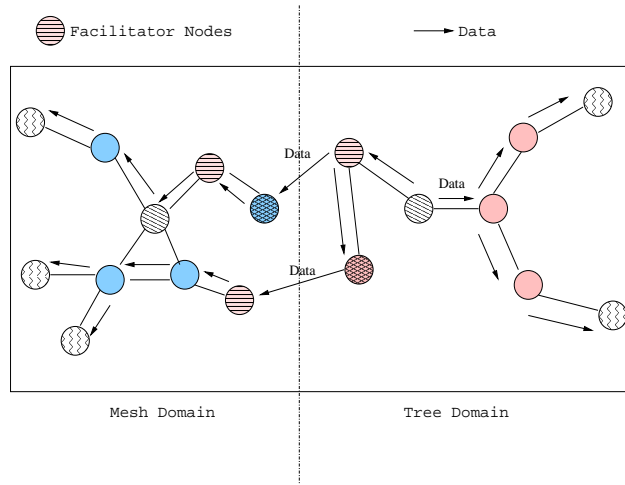
Figure 5.7: Forwarding data

Figure 5.7 depicts the traversal of data across neighboring domains. In each domain, data is forwarded according to the underlying protocol along the existing tree or mesh. The only difference is that certain nodes that are incorporated as part of the tree or mesh due to the fac-request - fac-reply exchange are also responsible for forwarding data.

The pseudo-code corresponding to our implementation of facilitator-assisted inter-

operability is shown in figure 5.8.

5.3.3 Facilitator Selection

As explained above facilitators are responsible for enabling cross-domain communications by creating and maintaining mesh links across domains. Hence, the choice of facilitators can impact the performance of group communications both within and across domains. When selecting facilitators, one of the essential requirements is that all facilitators be members of the multicast group. In receiver-initiated multicast routing (e.g., MAODV), this ensures that facilitators have routes to the multicast group within their own domain. However, in case of sender-initiated routing protocols (e.g., ODMRP), facilitators also act as "dummy" senders for the group to ensure that they have paths to multicast receivers within their own domain.

In scenarios where MANET clouds are wireless extensions of the internet, certain nodes are typically assigned special functionality (e.g., gateways, DNS service providers, proxies, web caches, etc.). These nodes naturally lend themselves to be elected as facilitators. The number of facilitators in each domain is another important factor in determining performance. In scenarios where nodes are mobile, it is necessary that each domain has sufficient number of facilitators to ensure redundant links to neighboring domains. However, increasing number of facilitators can also potentially degrade performance on account of the increase in facilitator-related control messages. The number of facilitators should be typically assigned based on the requirements of the network in terms of control overhead and data delivery guarantees. We have conducted a preliminary study of the impact of facilitator selection on the performance of facilitator-assisted interoperability and present our results in Section 5.5.

```
case: Facilitator Node                       case: Regular Nodes


Proc Init-Fac-Node:                          Proc Recv-Packet:
if (!member of multicast group) {            if (proto != my_proto) {
  Join_Group                                   if (mtype == FAC-REQ) {
  }                                               Add Req to Fac Req Table
  Send Periodic Fac_Request                       Set Reverse Path to Source of Req
                                                  Forward Fac Req
Proc Fac-Node-Recv-Packet:                      }
if (proto != my_proto) {                        if (mtype == FAC-REP) {
  if (mtype == FAC-REQ) {                          if (nextAddr == my_addr) {
      Add Req to Fac Req Table                        if (!member of group)
      Send-Fac-Reply                                     Set as Forwarding Group Member
      }                                               Add to Fac Rep Table
  if (mtype == FAC-REP) {                             Forward along reverse path to Source
     if (!initiator of Request)                     }
        forward along reverse path to source     }
         Add Rep to Fac Rep Table              if (mtype == DATA) {
      }                                            if (forwarding member  of group)
  if (mtype == DATA) {                                 One hop broadcast to neighbors
      One hop broadcast to neighbors              else drop packet
      }                                           }
}                                              }
                                             if (proto == my_proto) {
                                               if (mtype == FAC-REQ) {
if (proto == my_proto) {                          Add Req to Fac Req Table
  if (mtype == FAC-REQ) {                          Set Reverse Path to source of Req
     Add Req to Fac Req Table                      Forward Fac Req
     Set Reverse Path to source                  }
     Forward Fac Req                            if (mtype == FAC-REP) {
     }                                             if (nextAddr == my_addr) {
  if (mtype == FAC-REP) {                             if (!member of group)
     Add Rep to Fac Rep Table                            Set as Forwarding Group Member
     Forward along reverse path to source            Add to Fac Rep Table
     }                                           Forward along reverse path
  if (mtype == DATA) {                             }
     One hop broadcast to neighbors            }
     }                                          if (mtype == DATA) {
}                                                 if (forwarding member  of group)
                                                      One hop broadcast to neighbors
                                                   else drop packet
                                                   }
                                             }
```

Figure 5.8: Pseudo Code for Facilitator Assisted Interoperability

5.4 Simulation Setup

We used `Qualnet`   [57] as the simulation platform. The simulation setup essentially consisted of two routing domains, one running a tree-based routing protocol and the other a mesh-based protocol. MAODV [5] was chosen as representative of tree-based routing while ODMRP [4] was chosen to represent mesh-based routing techniques. It should be noted that MAODV is a receiver initiated protocol, i.e, receivers send explicit join messages to graft themselves to the multicast tree. However, ODMRP is sender initiated, i.e, the multicast mesh is formed by join queries transmitted by senders prior to data transmission. Thus, in the ODMRP domain, facilitators had to function as "dummy" senders to ensure that they had routes to multicast groups in their own domain.

We use two type of MANET scenarios in our simulations. In "synthetic" scenarios, parameters such as mobility, number of facilitators, traffic sources, and number of multicast receivers are varied over an arbitrary range of values. We also define more "concrete" environments reflecting specific MANET applications, namely exhibition/symposium and emergency rescue scenarios. These scenarios were generated using the scenario generator presented in [20] and is described in detail in section 5.5.4.

In our simulations, each domain consists of 50 nodes randomly placed in a 1000 m^2 field. The domains had sufficient overlap to enable communications from one domain to another. Nodes' channel bandwidth was set to 11 Mbit/sec and their transmission range is 225 meters. All member nodes join at the start of the simulation and remain members throughout the experiment.

Random waypoint was used to model node mobility nodes. For our simulations,

nodes were restricted to move only within their own domains. Each source had a constant bit rate (CBR) traffic generator generating 5Kbps. The data payload size was fixed at 256 bytes.

We use the following metrics in evaluating the performance of the different interoperability mechanisms.

- **Packet delivery ratio** is computed as the ratio of total number of packets received by the nodes to the total number of packets transmitted times the number of receivers.

- **Routing overhead** is the ratio between the number of control bytes transmitted to the number of data bytes received. In ODMRP, control bytes account for `Join-Query` and `Join-Table` packets. It also includes data packet header bytes forwarded by forwarding group members. In MAODV, control bytes account for the `Rreq`, `Rrep`, `Mact`, `Hello`, and `Grp-Hello` packets. It also includes the data packet headers forwarded by intermediate nodes.

  For the flooding-based interoperability approach, in addition to the underlying routing protocol overhead, control overhead also includes all data header bytes forwarded by network nodes and overhead due to the `composite header`.

  In the case of facilitator-based interoperability, the routing overhead includes fac-requests, fac-replies and also accounts for the `composite header` in the data forwarding process.

87

5.5   Simulation Results

In this section, we report simulation results comparing the different interoperability approaches. We ran each simulation (keeping all parameters constant) five times, each time using different seed values. Each data point in the graphs below, represents the average across five runs.

5.5.1   Effect of Mobility

For the mobility experiment, 10 nodes from the tree-domain were randomly chosen as traffic sources. Each source transmitted 5Kbps and thus the overall network load was 50Kbps.The multicast group comprised of 20 receivers in each domain. Further, 5 nodes from each domain were randomly assigned as facilitators for the facilitator-based approach. Average node speed was varied from 3.6 to 100 kms/hr.

Figure 5.9 depicts the reliability performance of the two interoperability approaches as a function of node mobility.
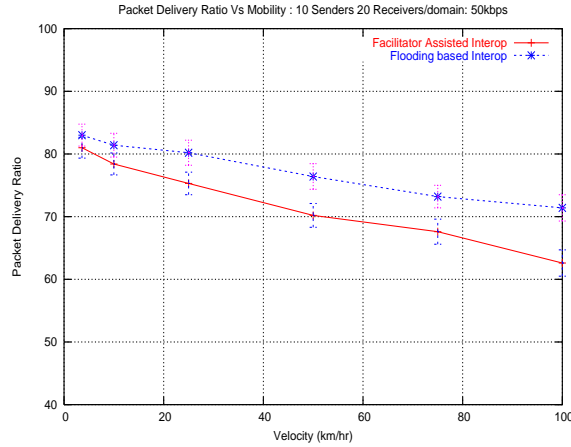
Figure 5.9: Packet delivery ratio as a function of node mobility

We observe that flooding-based interoperability exhibits higher reliability than the facilitator assisted approach. The difference in delivery ratio is around 10% at 100km/hr. This trend is quite intuitive since flooding based approaches are more resilient to link failures. In the facilitator assisted approach, node mobility may cause links between facilitators in the mesh and tree domain to frequently go down. Hence no cross-domain communication can occur until the links are refreshed by new `fac_requests`. Further it can be seen that delivery ratio for both approaches decreases with increase in mobility. This decline in the delivery ratio can be attributed to the behavior of the underlying routing protocol. Increased mobility causes frequent link changes and requires MAODV to reconfigure the multicast tree more frequently to prevent stale routing information. A number of data packets in the tree domain are dropped due to route failures and hence never transmitted to the mesh domain.
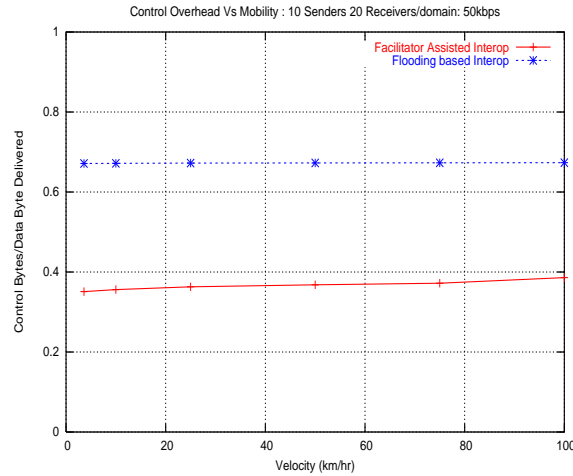
Figure 5.10: Control overhead as a function of node mobility

Figure 5.10 plots control overhead per data byte transferred as a function of mobility and shows that control overhead for both approaches increases with node mobility. As average

89

node speed increases, link failures in the tree-domain triggers route-error messages and causes frequent tree configuration. This increases the flow of control messages thus increasing the overhead. However, the key result from the figure is that the routing overhead of the flooding based approach is almost twice that of the facilitator approach. As mentioned earlier, the flooding based approach results in a large number of redundant transmissions in the mesh-domain which considerably increases the overhead.

5.5.2 Facilitator Selection: Random Placement

As mentioned in section 5.3.3 the selection of facilitators can significantly affect the performance of group communications both within and across domains. Intuitively, we can expect the performance to increase as we increase number of facilitators since the mesh links between facilitators in different domains becomes richer. This provides greater redundancy and resilience to link failures and node mobility. In this set of experiments 10 randomly selected nodes act as sources generating CBR traffic at a rate of 5Kbps. The number of multicast receivers in each domain was increased to 40 and node mobility was fixed at 10 kms/hr. The number of facilitators is varied from 5-40 and we observe its impact on the performance metrics.

Figure 5.11 shows the impact of number of facilitators on packet delivery ratio. As discussed earlier packet delivery ratio increases as number of facilitators increase. However when the number of facilitator is greater than 20 the delivery ratio starts decreasing. For this particular setup, increasing the number of facilitators up to 20 strengthens the connectivity between facilitators in the tree and mesh domain. This makes the interoperability mecha-
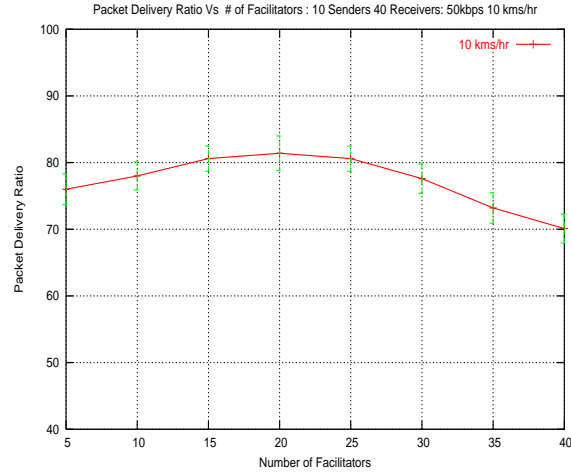
Figure 5.11: Packet delivery ratio versus number of facilitators

nism more resilient to link failures. However, increasing the number of facilitators also has the negative effect of increasing the control overhead due to greater cross-domain facilitator exchanges. Data packets have to contend with facilitator control messages which results in greater channel contention and packet drops due to collisions.
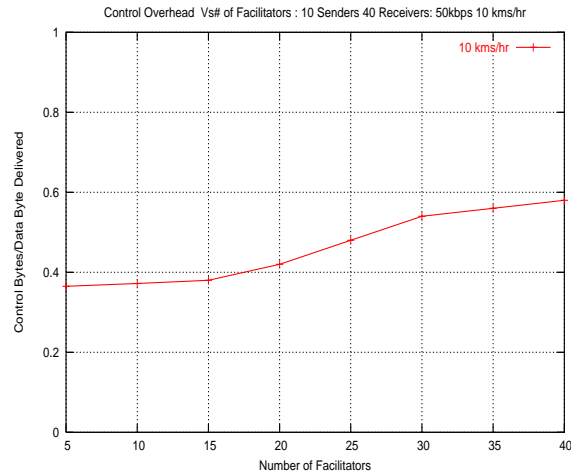
Figure 5.12: Control overhead versus number of facilitators

Figure 5.12 shows the impact of number of facilitators on routing overhead. As

91

expected the control overhead increases with increase in number of facilitators. One subtle

side-effect is that a larger number of non-member nodes in the tree and mesh domains are also

incorporated as members to forward data due to facilitator exchanges. Although this increases

redundancy it also results in larger number of redundant data retransmissions.

We have also investigated the impact of mobility and traffic load on the facilitator

selection process. In these experiments, 10 nodes were chosen as traffic sources and 40 nodes

in each domain were chosen as multicast receivers. Node mobility and traffic load was varied

over arbitrary values and the impact on the overall performance is depicted in the graphs

below.
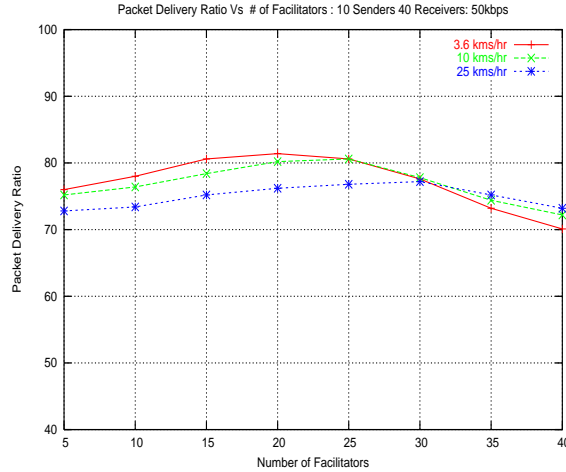
Figure 5.13: Packet delivery ratio versus number of facilitators for different node mobility

Figures 5.13 and 5.14 indicate that the optimum value of the facilitators for a partic-

ular scenario is dependent on node mobility and traffic load. From Figure 5.13 it is observed

that as node mobility increases, the interdomain links between facilitators are more prone to

failures. In high mobility scenarios, increasing the number of facilitators increases the overall
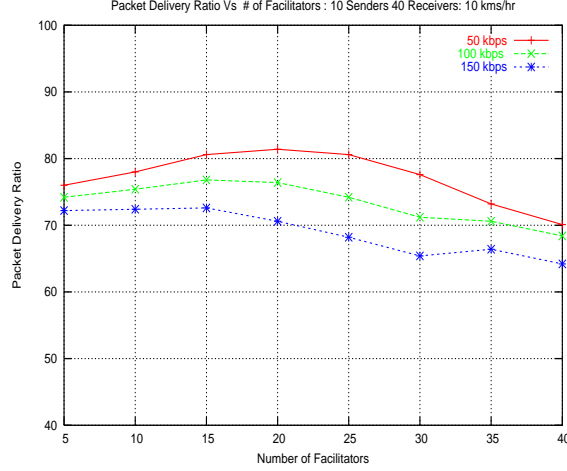
Figure 5.14: Packet delivery ratio versus number of facilitators with varying traffic load

packet delivery ratio by providing higher number of redundant links. Similarly, Figure 5.14 indicates that for a traffic load of 50 kbps the optimum number of facilitators is around 20. However, the optimum number of facilitators decreases to 15 as traffic load is increased to 150 kbps. As noted earlier, increasing number of facilitators increases the control traffic. It also has the side-effect of incorporating a larger number of non-member nodes to participate in the data forwarding process which results in higher packet contention and data loss due to collisions.

5.5.3 Facilitator Selection: Adaptive Placement

One key observation from the above experiments, is that the performance of the interoperability mechanism is heavily dependent on the facilitator selection criteria. This requires that facilitators be chosen adaptively, based on the underlying network conditions. In this section we investigate adaptive techniques for facilitator election process. An important

factor in the adaptive technique is the observation that the critical links are those links that bridge the different ad hoc clouds or domains. Based on this observation, the logical extension is to choose nodes that are one hop away from neighbor nodes of another domain as facilitators. The adaptive facilitator selection algorithm is outlined below:

- All nodes send periodic *Hello* messages with a *ttl* of one hop. The hello messages contain the nodes *NwId's* which are obtained as part of the bootstrap process and are same for all nodes of a particular domain.

- When a node receives the hello message it can determine if the message originated from its own domain or a different domain based on the NwId. If the hello message was from a neighboring domain then the node begins the process to join the group as a facilitator. The node has to first establish group membership (if it is already not a member) by using the Join-Group primitives for its specific routing protocol.

- After joining the multicast group, the potential facilitator broadcasts a one hop *Fac-Req* message for the multicast group along with its NwId. Any node from the neighboring domain (one hop away) which receives the fac-request will respond to the source of the request with a *Fac-Reply*. The node then uses the Join-Group primitives for its specific routing protocol to become a member of the group and thus establishes a data forwarding path from its domain into the neighboring domain.

- Nodes that receive the Fac-Reply message for their requests will elect themselves as Facilitators and are responsible for sending Fac-Request messages every *Fac-Request-Interval* to reestablish links across domains.

94

- If facilitator nodes do not receive hello messages from the neighboring domain within the *Fac-Refresh-Interval* they relinquish the role of facilitator and can leave the multicast group (unless they were already group members prior to being elected as facilitators). Similarly, nodes from the neighbor domain which get selected as facilitators can stop functioning as facilitators if the state is not refreshed by periodic Fac-Requests from the neighbor domain.

One important aspect of this adaptive scheme is that all nodes can potentially function as facilitators and no special purpose nodes are required for this scheme. One main difference between the random facilitator selection process and the adaptive facilitator selection process is the fact that nodes elected as facilitators do not necessarily have to function as facilitators for the entire duration of network operation. In the adaptive scheme as nodes move away from the neighboring domain they stop functioning as facilitators. The onus of providing facilitator services rests only on those nodes which are one hop away from neighbor domains. From our preliminary simulation results, we observed that the adaptive facilitator selection scheme performs quite well compared to the random placement scheme in terms of packet delivery ratio for the simulation setup described in 5.4. In particular, the adaptive facilitator selection scheme delivered 78% of the total transmitted packets. The routing overhead for the adaptive selection scheme is lower than that of the random selection scheme since facilitator messages are not broadcast network-wide.

Exhibition scenario		
Interoperability Mechanism	Delivery ratio %	Routing overhead (Bytes Xmitted/data bytes recvd)
Flooding	80.2	0.57
Facilitator	72.4	0.34

Table 5.1: Exhibition Scenario

5.5.4 Realistic MANET Scenarios

In this experiment we evaluate the performance of flooding based and facilitator assisted interoperability in realistic MANET scenarios.

Exhibition/Symposium Scenario

The scenario consisted of 75 nodes in a 1000 m^2 field in each domain. The nodes were divided into the following categories: 20 stationary *exhibition booths*, 20 *audience* nodes and 35 *wanderer* nodes. The exhibition booths were randomly distributed within their respective domains and were assigned as facilitators for the facilitator assisted mechanism. The members of the audience group moved with speeds ranging from 2-5 m/s and their movement was modeled using brownian motion. The movement of the audience group was restricted to a limited area inside their own domains. The wanderer nodes moved according to the random-waypoint model with speeds ranging from 1-5 m/s. Unlike the audience group, wanderers were capable of moving throughout their entire domain. The receiver group consisted of 50 nodes randomly selected in each domain. All exhibition booths in both domains functioned as traffic sources, generating CBR traffic at the rate of 5Kbps.

Table 5.1 summarizes simulation results for the exhibition scenario.

96

Emergency Rescue Scenario		
Interoperability Mechanism	Delivery ratio %	Routing overhead (Bytes Xmitted/data bytes recvd)
Flooding	75.4	0.64
Facilitator	64.2	0.47

Table 5.2: Rescue Scenario

Emergency Rescue Scenario

For the emergency response scenario, we use a 2000 m^2 field in each domain with 125 nodes divided into the following categories: two helicopters, two rescue teams of ground personnel and two teams on ground vehicles. The helicopters move with speeds ranging between 0-50 m/s according to the random waypoint model. The first vehicle team consists of 35 nodes while the second team consisted of 38 nodes. Members of both vehicle teams move according to the random waypoint model with speeds ranging between 5-15 m/sec. The team of ground personnel consists of 25 nodes each, moving with speeds ranging between 0-5 m/s and pause times between 0-2 secs. Each team covers well-defined areas within the field with sufficient overlap to ensure that information could be relayed among the different teams. Two helicopters and 20 other randomly chosen nodes act as data sources, generating CBR traffic at the rate of 5Kbps. The receiver group consisted of 50 nodes randomly selected in each domain.

Table 5.2 summarizes simulation results for the emergency rescue scenario. Similar to the results from our prior experiments the flooding based approach had a higher packet delivery ratio as compared to facilitator assisted interoperability mechanism. However, the control overhead was about 60% higher compared to the facilitator based approach.

97

5.5.5 Discussion

Our simulation results confirm that flooding based interoperability is more reliable but incurs significantly higher routing overhead. However, in cases where generality is important (e.g pre-deployed MANETs) then flooding based interoperability approaches may be the only choice. In general, flooding based approaches are best suited for infrequent communications between different domains. On the other hand for data intensive multicast applications such a video-conferencing the facilitator assisted approach is better suited. Facilitator assisted approaches require minor modifications to the intra-domain routing protocol and hence trade-off reliability for scalability.

An important observation from our simulations, is that the performance of the interoperability mechanism is heavily dependent on the facilitator selection criteria. In this thesis we have investigated random facilitator selection as well as an adaptive facilitator selection algorithm in which facilitator signaling messages are used to select certain nodes as facilitators. The main criteria used in the proposed scheme is that only nodes that are one hop away from neighboring domain are chosen as facilitators.

Other adaptive criteria for choosing facilitators can be based on node mobility. In this method, all nodes monitor the relative mobility of their one-hop neighborhood through periodic hello messages. If the relative mobility of the one-hop neighborhood is below a certain threshold (over a time window) then the node can choose to elect itself as a facilitator. This ensures relatively robust intermediate links between the facilitators across domains increasing the overall performance of the interoperability mechanism. Investigation of such adaptive schemes can be the subject of future work.

5.6 Related Work

To our knowledge, there has been very little experience in the wireless network research community in multicast (or unicast) routing protocol interoperation or adaptation. However, interoperability issues in the context of wired networks have been addressed in some detail and several proposals have been floated in the IETF. Hierarchical DVMRP (HD-VMRP) [58] which was proposed as an inter-domain routing protocol aims to interconnect multiple domains by flooding data packets to boundary routers. HDVMRP divides the flat routing region into non-overlapping regions. DVMRP [13] is used as the multicast routing protocol within domains and also as the intra-domain routing protocol between different regions. The Border Gateway Multicast Protocol (BGMP) architecture [59] addresses the scaling problems of approaches such as HDVMRP. BGMP consists of two complementary protocols for inter-domain multicasting. The Multicast Address Set Claim (MASC) proposes an hierarchical address allocation scheme for dynamic address allocation to domains. The Border Gateway Multicast Protocol (BGMP) builds bidirectional shared trees across domains without interfering with the intra-domain routing protocols. Hierarchical Multicast Routing (HIP) [60] was also motivated by the scalability problems of DVMRP and provides means for routing across heterogeneous domains. HIP uses the concept of virtual routers (VRs) to organize all border routers of a domain so that they appear as a single router to the higher level tree. Ordered Core Based Trees [61] is used for inter-domain routing. RFC 2715 [2] addresses interoperability requirements for multicast protocols in wired networks. The proposed framework attempts to provide efficient interoperability among different multicast routing protocols such as DVMRP [13], MOSPF [14], CBT [43] etc.

5.7   Conclusions

In this chapter, we introduced interoperability techniques to facilitate seamless multicast communication between nodes spanning heterogeneous domains. In particular we proposed two different interoperability techniques, i.e, flooding-based and facilitator assisted interoperability. The flooding-based interoperability technique has the advantage of being simple in terms of implementation and requires no explicit cross-domain route establishment protocol. This is beneficial in situations where it may be difficult to change the existing network infrastructure but interoperability is still desired. The facilitator based approach, on the other hand, requires the addition of special functionality to a small subset of nodes in each domain. The functionality of facilitators is quite similar to that of Multicast Border Router's (MBRs) in wired domains. This approach is well suited for scenarios involving frequent inter-domain communications such a video conferencing since flooding-based interoperability mechanisms can prove to be quite expensive for such applications. However, the side-effect of flooding-based approaches is better reliability on account of the redundant transmissions. The facilitator based approach on the other hand favors scalability as opposed to generality since it requires minor modifications to the underlying routing protocol behavior.

One of the factors affecting the performance of the facilitator based interoperability mechanism is the facilitator selection process. Our simulation analysis shows that the performance is quite sensitive to the choice and number of facilitators. An area of future work is to analyze distributed algorithms suited to the facilitator election process and evaluate the impact of these algorithms on overall performance.

Chapter 6

Modeling The Performance Of

Flooding in Ad Hoc Networks

In this chapter, we develop an analytical model to characterize the reachability and reliability

of flooding in multi-hop ad hoc networks. The main contribution of this work is that the

proposed analytical framework can be extended to evaluate the performance of other broadcast

mechanisms such as probabilistic and scoped flooding.

6.1   Introduction

In chapter 2 we overviewed different routing strategies in ad-hoc networks and clas-

sification of the routing strategies. We also pointed out benefits of on-demand protocols com-

pared to table-driven or proactive protocols as shown by previous studies [16].

One feature common to on-demand protocols like DSR [28], AODV [30] and ODMRP [4]

is the need to broadcast control messages during the *Route Request Phase* in order to obtain routes to reach potential receivers. *Route Request* is typically carried out by using a broadcast mechanism such as flooding. Broadcast in MANETs is also necessary for applications such as

- Sending commands to a group of nodes (e.g., alarm signals).

- Paging Mobile Hosts

- Sending location updates for routing.

The most common mechanism for broadcast is through flooding. However, one drawback of flooding is that it may result in redundant broadcasts. These re-broadcasts can cause serious contention and collision problems, especially in resource-constrained (e.g., power, bandwidth) MANETs. Several flood protocols have been proposed in an effort to reduce the redundant messages in normal flooding based on probabilistic approaches, location or neighbor information [62], [63], [64], [65], [49].

We should point out that significant work has been done in analyzing the performance of packet radio networks [66] in terms of its delay characteristics, optimum transmission radius (e.g., [67]), etc. However, to our knowledge, little work has been done in characterizing the reliability of routing protocols based on analytical models. We also use simulations to validate our model and validation results look quite promising.

One of the longer-term goals of this thesis is to propose variants of flooding that achieve delivery ratios similar to flooding at considerably lower overhead and study their performance analytically and through simulations. To this end, we introduce an analytical

model to evaluate the performance of flooding in MANETs and argue that this model can be used as a framework for analyzing the performance of other flooding based approaches to broadcast in wireless ad hoc networks.

6.2 Probability of Successful Transmissions

In MANETs, packet losses can occur either due to node mobility or collisions arising from exposed sources and hidden terminals. It should be noted that since we are using flooding, we assume that data is broadcast at the MAC layer and there is no RTS-CTS exchange to prevent exposed sources from transmitting at the same time. Thus, the behavior of the MAC layer is essentially similar to CSMA for broadcast. Given this similarity, the analysis of CSMA's successful transmission probability can be extended to determine the probability of successful reception by nodes in the flooding regime. However, the difference is that in flooding, nodes can possibly receive the same packet multiple times.

In the remainder of this section, we revisit the CSMA analysis presented by Varshney and Wu [68] including their network model, assumptions, and key results. These results are then used in Section 6.3 to derive the probability of successful reception by nodes in flooding.

Network Model and Assumptions

Figure 6.1 shows the hearing regions of nodes A and B, where r is the distance between A and B, and R is their transmission radius. The following multi-hop network model was assumed in the analysis presented in [68].

- The node distribution within the topology is a two-dimensional Poisson point process with parameter λ, i.e,

$$P(k \text{ nodes within Tx region of radius } R)$$
$$= \exp(-\lambda \pi R^2)\frac{(\lambda \pi R^2)^k}{k!} \tag{6.1}$$

- The transmission time T (or packet length) is assumed to be the same for all nodes. Transmission time is divided in slots of duration α, where α is the one way propagation delay. τ is defined to be $\frac{T}{\alpha}$. Nodes can transmit only at the beginning of each slot.

- All nodes always have packets waiting to be transmitted and nodes transmit at the beginning of a slot according to a Bernoulli process with parameter p, where $0 < p < 1$. Although the probability of a node transmitting varies from slot to slot, the model assumes a steady state probability p. This assumption has also been used by Kleinrock and Takagi [69] in deriving the optimum transmission range for packet radio networks.

- The receiver is chosen randomly from any one of the transmitter's neighbors.

- The system is independent from slot to slot during the idle period, i.e., whenever there is a packet waiting to be sent, it is equally likely that this packet will be destined to any node no matter whether it is a new– or retransmitted packet.

- The re-transmission of a packet by neighbor nodes is assumed to be independent of one another. Although, this is not strictly the case for flooding mechanisms this assumption makes the problem more tractable. In our simulation comparison, we can approximate this assumption by enforcing a random jitter period before nodes can retransmit a re-

104

ceived packet. The independence assumption is also be reinforced by the contention backoff behavior exhibited by 802.11 systems before acquiring the channel. In our simulation experiments, we also use multiple sources of traffic to strengthen the above assumption.
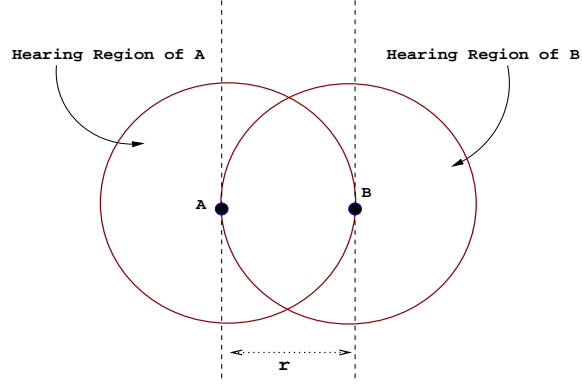
Figure 6.1: Hearing Region

CSMA Probability of Successful Transmission

Even though a node may be ready to transmit, the actual transmission in a slot depends on collision avoidance and also on the state of the channel. In [68], the authors have shown that the probability p' that a node actually transmits in a time slot is given as

$$
\begin{aligned}
p' &= p * \text{P}(\textit{channel is idle in given slot}) \\
&= \frac{\alpha p}{1 + \alpha - e^{p'N}}
\end{aligned}
\tag{6.2}
$$

where α is the one way propagation delay and N is number of nodes within transmission region of radius R.

Using the assumptions and network model described in section 6.2, it has also been

shown in [68] that the probability of a successful transmission from a A to B is given as

$$P_s = \frac{2p'(1-p')}{\alpha + p'} e^{-(2\tau+1)p'N} \int_0^1 e^{\frac{4p'N\tau}{\pi}q(\frac{r}{2})} r\,dr \qquad (6.3)$$

where $q(r) = \arccos(r) - r\sqrt{1-r^2}$ and $N = \lambda\pi R^2$

6.3 Reliability and Reachability Analysis of Flooding

In this section, we build upon the results from Section 6.2 to compute flooding's reachability and reliability in MANETs. We also analyze the reliability and reachability of probabilistic flooding. We first start by defining these metrics.

Definitions

- **Reachability** is the number of nodes in the network that can receive at least one copy of a source's transmission.

- **Reliability** is the ratio of number of nodes that receive the source's transmission to the total number of nodes in the network.

Note that these are important metrics when studying the performance of MANET routing mechanisms. In fact, these performance metrics are key to achieve our goal of designing protocols that are as reliable as flooding but incur less overhead (e.g., in terms of number of retransmissions).

6.3.1 Flooding's Probability of Successful Reception

We extend the analysis presented in Section 6.2 for determining CSMA's probability of success in the case of multi-hop transmissions via flooding. Our approach is to estimate the probability of successful reception by nodes as the flooding wave passes through the network. If we assume that the flooding wave terminates after each packet has been retransmitted a maximum of l hops (which can be determined from the network diameter), we can sum the number of nodes reached by each retransmission to obtain flooding's *reachability*.
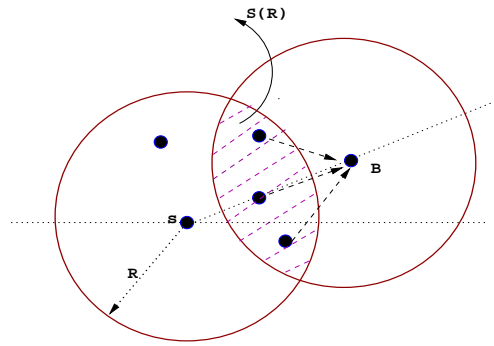
Figure 6.2: Intersection region for second level retransmissions

In Figure 6.2, S is the source of the flooding packet. The average number of nodes within S's transmission region is N. The probability of a successful transmission from source S to any of its neighbors is P_s, as given by Equation 6.3.

Let N_s be the number of neighbors that receive the transmission from source S.

$$P(N_s) = \binom{N}{N_s} P_s^{N_s} (1 - P_s)^{N-N_s} \tag{6.4}$$

$$\bar{N}_s = E[N_s] = P_s N \tag{6.5}$$

Each of these $\bar{N}_s$ neighbors will further retransmit the packet. As shown in Figure

107

6.2, at the second level of re-transmission, nodes in the $S(R)$ region are the ones which can forward the packet to node B. The number of nodes in region $S(R)$ is given by

$$
\begin{aligned}
N_b &= \frac{S(R)}{\pi R^2} \bar{N}_s \\
&= \frac{P_s N}{\pi R^2} \left(2R^2 \mathrm{acos}(\frac{r}{2R}) - r\sqrt{R^2 - \frac{r^2}{4}} \right) \quad (6.6)
\end{aligned}
$$

The expected value of the number of nodes in region $S(R)$ can be obtained by unconditioning on r and θ (θ is the angle made by the line joining the centers of node S and B with the X axis).

$$
\begin{aligned}
E[N_b] &= \bar{N}_b \\
&= \int_0^{2\pi} \int_0^R \frac{PsN}{\pi R^2} \frac{rdrd\theta}{\pi R^2} \left(2R^2 \mathrm{acos}(\frac{r}{2R}) - r\sqrt{R^2 - \frac{r^2}{4}} \right) \\
&= P_s N \frac{2}{\pi R^2} \int_0^R \left(2\mathrm{acos}(\frac{r}{2R}) - \frac{r}{R^2}\sqrt{R^2 - \frac{r^2}{4}} \right) rdr \quad (6.7)
\end{aligned}
$$

The probability that any node B at the second level of retransmission receives at least one copy of the source's packet successfully is

$$
\begin{aligned}
P_b &= \text{P (}B \text{ receives at least 1 copy/ } \bar{N}_b \text{ nodes Tx)} \\
&= 1 - \text{P (}B \text{ receives no copy/ } \bar{N}_b \text{)} \\
&= 1 - (1 - P_s)^{\bar{N}_b} \quad (6.8)
\end{aligned}
$$

Similarly, the probability of successful reception at any retransmission level is also P_b.

6.3.2 Determining Flooding's Reachability
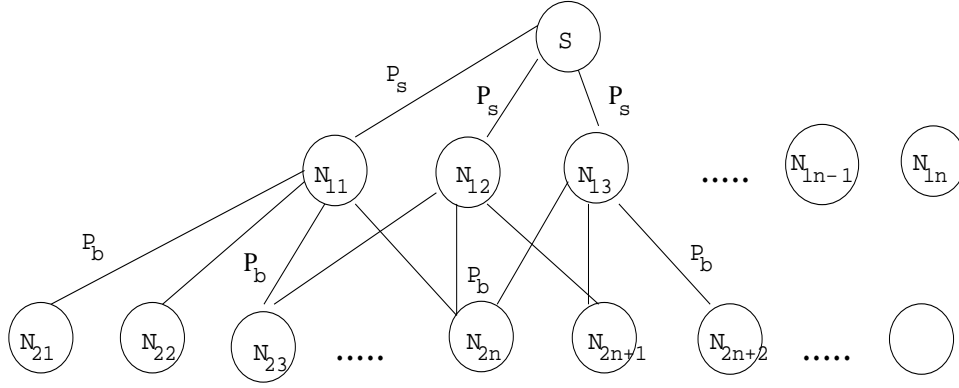
Figure 6.3: Reachability of flooding

We generalize the previous analysis to l retransmission levels (assuming each packet is retransmitted a maximum of l hops). Figure 6.3 schematically represents the first two retransmission levels, where S is the source of transmissions. At the first level, the number of nodes reached, or N_1 is given by

$$N_1 = P_s N \tag{6.9}$$

In [62], it was shown that the area of coverage from the second retransmission significantly overlaps with the original transmission area. The expected increase in the coverage area achieved by the second retransmission (β) is around 41% of the original transmission. Hence, the number of nodes reached by the second level, N_2, is

$$
\begin{aligned}
N_2 &= \beta P_s N P_b N \\
&= \beta P_s N \left(1 - (1 - P_s)^{\bar{N}_b}\right) N
\end{aligned}
\tag{6.10}
$$

109

where β is the percentage increase in the coverage area. Similarly, at retransmission level l, N_l is

$$
\begin{aligned}
N_l &= P_s N (P_b N)^{l-1} \beta^{l-1} \\
&= P_s N \left(\left(1 - (1 - P_s)^{\bar{N}_b}\right) N \right)^{l-1} \beta^{l-1}
\end{aligned}
\tag{6.11}
$$

Assuming the flooding wave terminates after l hops, then flooding's reachability is measured by the total number of nodes receiving S's transmission N_T and is given as

$$
\begin{aligned}
N_T &= P_s N + P_s N \sum_{i=1}^{l-1} P_b{}^i N^i \beta^i \\
&= P_s N + P_s N \left(\sum_{i=0}^{l-1} P_b{}^i N^i \beta^i - 1 \right) \\
&= P_s N \frac{(P_b N \beta)^l - 1}{P_b N \beta - 1}
\end{aligned}
\tag{6.12}
$$

6.3.3 Determining Flooding's Reliability

If N_R is the total number of nodes in the network, then reliability of flooding can be estimated as

$$
\begin{aligned}
\text{Reliability factor} &= \frac{N_T}{N_R} \\
&= \frac{1}{N_R} \left(P_s N \frac{(P_b N \beta)^l - 1}{P_b N \beta - 1} \right)
\end{aligned}
\tag{6.13}
$$

110

6.4 Reliability and Reachability Analysis for Probabilistic Flooding

Recall that in plain flooding, each node always forwards packets it receives to all its neighbors. In probabilistic flooding, however, a node forwards packets according to some probability $p \leq 1$ (when $p = 1$ probabilistic flooding behaves exactly similar to plain flooding). By varying p, we can control the degree of flooding while maintaining the connectivity of the network. However, the main challenge in probabilistic flooding is to determine the critical probability p_c which ensures that the network is statistically connected. For instance, in [70], the phase transition phenomena from percolation theory was used to determine p_c. Our premise is that, by adjusting p as a function of the conditions of the underlying network, we can achieve reliability similar to flooding at lower cost.

6.4.1 Determining Probabilistic Flooding's Reachability

We consider that all nodes receiving the packet retransmit it with probability P_{tx} where $P_{tx} \leq 1$. With reference to Figure 2, in case of probabilistic flooding, out of the $\bar{N}_s$ neighbors that receive the packet from source S, only $\bar{N}_s P_{tx}$ will further retransmit the packet. Hence by similar analysis to equation 3.5, we can determine the probability that any node B at the second level of retransmission receives at least one copy of the source's packet successfully is

$$P_b \;=\; \text{P}\,(\textit{B receives at least 1 copy/ } \bar{N}_b P_{tx} \textit{ nodes Tx})$$

$$= 1 - \mathrm{P}\,(B\ \textit{receives no copy}/\ \bar{N}_b P_{tx}\,)$$

$$= 1 - (1 - P_s)^{\bar{N}_b P_{tx}} \tag{6.14}$$

With reference to Figure 6.3.2, we assume each packet is retransmitted a maximum of l hops. At the first level, the number of nodes reached, or N_1 is given by

$$N_1 = P_s N \tag{6.15}$$

Out of the $P_s N$ nodes reached only $P_{tx} P_s N$ will retransmit the packet. Hence, the number of nodes reached by the second level of transmission, N_2, is

$$N_2 = \beta P_{tx} P_s N P_b N$$

$$= \beta P_{tx} P_s N \left(1 - (1 - P_s)^{\bar{N}_b P_{tx}}\right) N \tag{6.16}$$

where β is the percentage increase in the coverage area as explained in section 6.3.2. Similarly, at retransmission level l, N_l is

$$N_l = P_s N (P_b N P_{tx})^{l-1} \beta^{l-1}$$

$$= P_s N \left(\left(1 - (1 - P_s)^{\bar{N}_b P_{tx}}\right) N P_{tx}\right)^{l-1} \beta^{l-1} \tag{6.17}$$

Hence for probabilistic flooding, the total number of nodes receiving S's transmission is N_T and is given as

$$
\begin{aligned}
N_T &= P_s N + P_s N \sum_{i=1}^{l-1} P_{tx}{}^i P_b{}^i N^i \beta^i \\
&= P_s N + P_s N \left(\sum_{i=0}^{l-1} P_{tx}{}^i P_b{}^i N^i \beta^i - 1 \right) \\
&= P_s N \frac{(P_{tx} P_b N \beta)^l - 1}{P_{tx} P_b N \beta - 1}
\end{aligned}
\tag{6.18}
$$

6.4.2 Determining Probabilistic Flooding's Reliability

If N_R is the total number of nodes in the network, then reliability of probabilistic flooding can be estimated as

$$
\begin{aligned}
\text{Reliability factor} &= \frac{N_T}{N_R} \\
&= \frac{1}{N_R} \left(P_s N \frac{(P_{tx} P_b N \beta)^l - 1}{P_{tx} P_b N \beta - 1} \right)
\end{aligned}
\tag{6.19}
$$

6.5   Validation and Simulation Results

In this section we validate our model using results obtained from a network simulator. We used ns-2 as the simulation platform. Table 6.1 summarizes the simulation parameters used.

In our simulations, 10 nodes are selected as data sources. The mobility model chosen was a modified version of the random waypoint model referred to as the bouncing ball model. In this mobility model, nodes start off at random positions within the field. Each node then chooses a random direction and keeps moving in that direction till it hits the terrain

Parameter	Value	Description
num-packets	250	packets sent by a node
bandwidth	2 Mbit/s	node's bandwidth
simulation-time	500 s	simulation duration
node-placement	random	node placement policy
propagation-func	Free-Space	propagation function
mac-protocol	802.11	MAC layer
transport-protocol	UDP	transport layer

Table 6.1: Simulation parameters

boundary. Once the node reaches the boundary it chooses another random direction and keeps moving in that direction till it hits the boundary again. All nodes moved with speeds between $v\_min = 2m/sec$ and $v\_max = 5m/sec$.

While in our analytical model, we assume that nodes are constantly transmitting, in the simulations we do not require that all nodes be traffic sources. Recall that in the flooding regime, all nodes re-broadcast data packets that they receive for the first time. If we assume that re-broadcasts by neighboring nodes are independent, we can treat these re-broadcasts as data transmissions. The assumption of independence can be somewhat justified by introducing a random jitter value between the time the nodes receive a data packet and the time they re-broadcast the packet.

A CBR traffic generator was attached to the sources and the data rate was varied from 0.5Kb/s to 10Kb/s. We implemented a simple *hello* message scheme to compute the average node neighborhood for each node. The average neighbor information and the average number of hops from the simulator were then used in the analytical model for comparison. Each point in the graph represents the average of 10 different seed values. We used 50 different traffic patterns to generate data points from the simulator.

It should be noted that the field size and total number of network nodes were chosen to ensure that the model and the simulator setup were matched as closely as possible. In the case of the simulator, fixing the total number of network nodes places an arbitrary upper bound on the reachability. However, this upper-bound may not necessarily be the same as reported by the model. Hence the total number of nodes and field size for the simulations are chosen to match the upper-bound on the total nodes reached, as obtained from the model for a particular field size.

6.5.1 Results for Normal Flooding

Figure 6.4 shows the results obtained for a field size of $1150x1350m^2$ comprising of 75 nodes, Figure 6.5 shows results for a field size of $1250x1250m^2$ containing 100 nodes and Figure 6.6 shows results obtained for 150 nodes in a field size of $1500x1750m^2$. The field sizes and the node speeds considered in the simulations could be typical of collaborative computing in an airport concourse environment or in emergency/disaster rescue scenarios. Although, we tried to vary the packet transmission probability p' by varying the packet size and the traffic rate, it is seen that typically the operating region for the simulator lies between 10^{-3} and 10^{-2}. This can be explained by the fact that the packet transmission probability is dependent on the rate at which traffic is being sourced into the network and also on the behavior of the 802.11 [71] MAC layer. As the traffic rate increases, the increased contention causes channel access algorithm of the MAC layer to stabilize the system by reducing the actual transmission probability. From our simulations we observed that the operating region was between 10^{-3} and 10^{-2}.
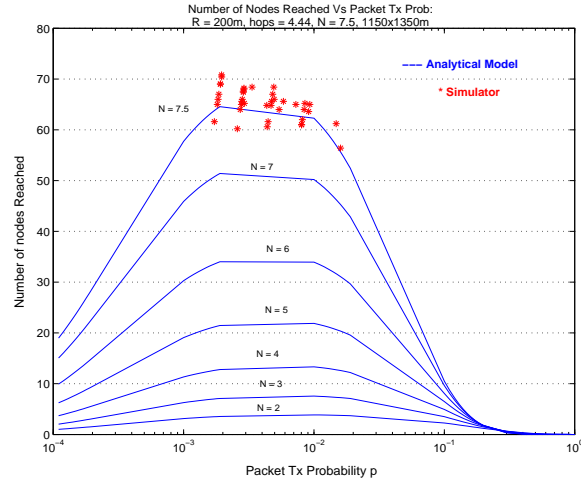
(a) Reachability
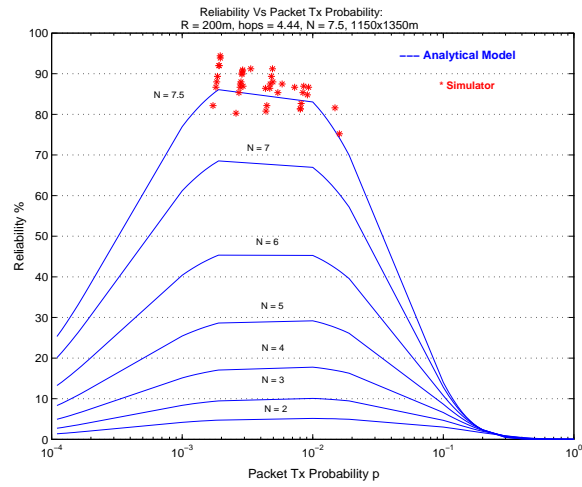
(b) Reliability
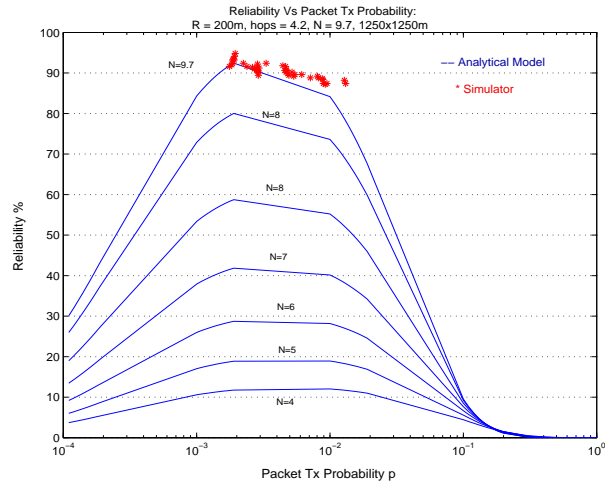
Figure 6.4: Flooding's reliability and reachability: 75 Nodes, $1150\text{x}1350m^2$

From Figures 6.4(a), 6.5(a) and 6.6(a), it is observed that the simulated values for *reachability* seem to correspond to values obtained from the model. One difference between

116
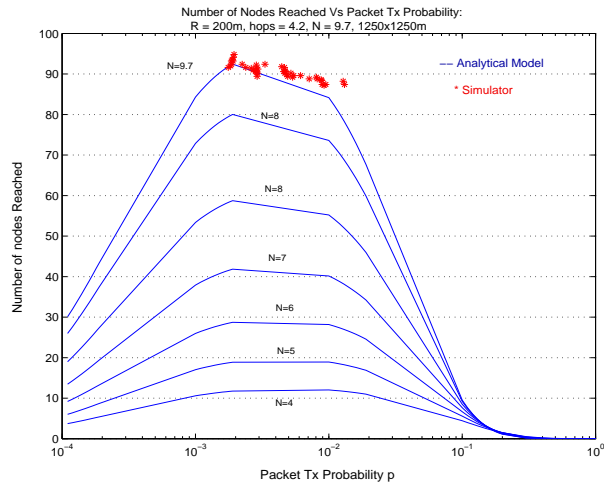
(a) Reachability

(b) Reliability

Figure 6.5: Flooding's Reliability and Reachability: 100 Nodes, 1250x1250m^2

the simulator and the model is that in our implementation of flooding, we use a jitter mechanism to stagger re-broadcasts to prevent unnecessary collisions. However, the model assumes that after nodes receive a data packet they re-broadcast the packet immediately. This can result in the model having a conservative estimate of the probability of successful reception (P_b) as compared to the simulator.

Figures 6.4(b), 6.5(b) and 6.6(b) plot *reliability* as a function of the packet transmission probability.

The results from the simulator and model suggest that the reliability of flooding is dependent on the number of network nodes and total number of hops. In general as number of hops increases, the reliability of flooding decreases. This result is quite intuitive since data packets that are dropped at each hop on account of contention or collision are not propagated further. The downstream neighboring nodes may never receive a copy of the data packet and hence cannot forward it to their own downstream neighbors, reducing the inherent redundancy of the flooding mechanism. This effect accumulates over multiple hops, causing nodes which are farthest away from sources to receive a smaller number of packets as compared to nodes which are closer.

Another observation from the results is that reliability increases as number of neighbors increases, since nodes can potentially receive each packet from a larger set of neighbors. From the model it is seen that the maximum value of reliability is obtained when the packet transmission probability is between 0.01 and 0.001. The reliability starts decreasing with further increase in the packet transmission probability p'. As packet transmission rate increases there is a greater chance for contention and collision among nodes, reducing the probability
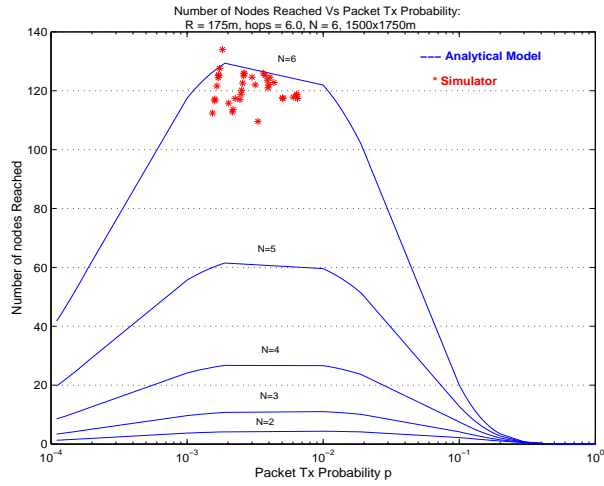
(a) Reachability
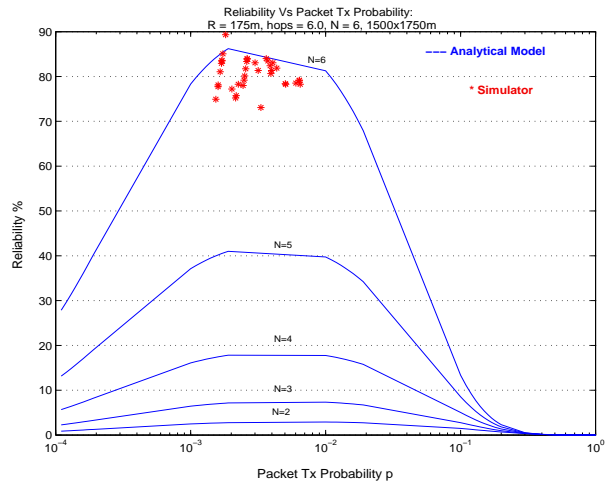
(b) Reliability

Figure 6.6: Flooding's Reliability and Reachability: 150 Nodes, $1500\text{x}1750m^2$

of successful reception and also the total number of nodes that can be reached.

6.5.2 Results for Probabilistic Flooding

The simulation setup for this set of experiments was similar to that of normal flooding. However, in this set of experiments the packet transmission probability p_{tx} was varied between 0.5 and 1 We present results for $p_{tx} = 0.75$ and $p_{tx} = 0.85$.
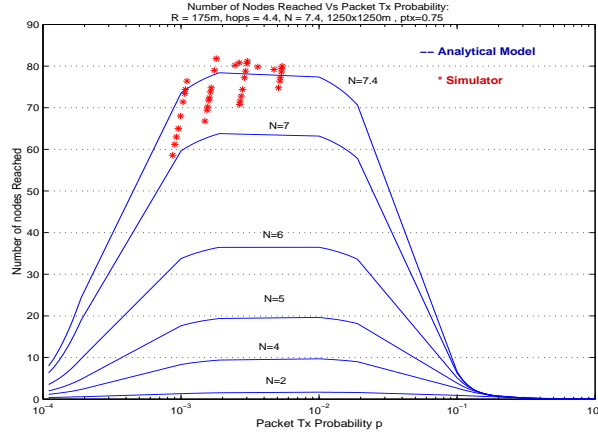
(a) Reliability: $p_{tx} = 0.75$
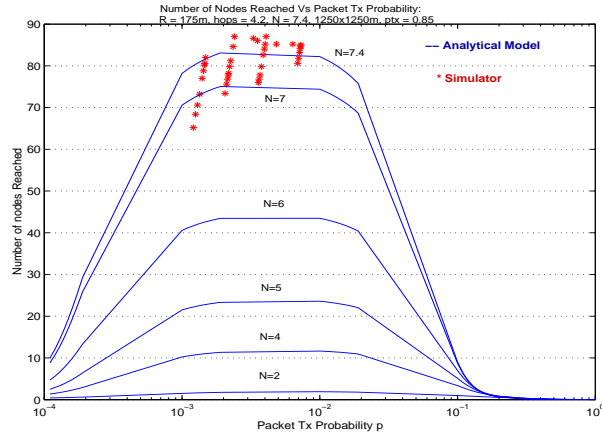
(b) Reliability: $p_{tx} = 0.85$

Figure 6.7: Reachability of Probabilistic Flooding : 100 Nodes, $1250\text{x}1250m^2$

Figures 6.7(a) and 6.7(b) show the results obtained for a field size of $1250\text{x}1250m^2$ comprising of 100 nodes for $p_{tx} = 0.75$ and $p_{tx} = 0.85$ respectively. Similar to the results from section 6.5.1, it is observed that the simulated values for *reachability* seem to correspond to values obtained from the model. One interesting observation from the results was that the average number of hops decreased slightly with the increase in the transmission probability p_{tx}. As p_{tx} increases, a greater number of intermediate nodes re-transmit packets. Hence it is more likely that packets reach destinations through more optimal paths resulting in a decrease in the average hop-count. Comparing the results of probabilistic flooding with normal flooding we see that the reachability of probabilistic flooding is quite similar to that of plain flooding. However, it should be noted that this reliability is obtained at a lower overhead. An interesting extension to this study would be to characterize this overhead in terms of the number of saved re-broadcasts and we are currently working on this aspect.

6.6   Conclusions

In this chapter, we have developed an analytical model for determining the *reachability* and *reliability* of flooding protocols in MANETs. We also extended the basic CSMA analysis presented in [68] to derive the probability of successful reception in multihop flooding. A network simulator was also used to provide some preliminary simulation results to validate the model. Our initial tests seem to indicate that the results for the analytical model correspond quite closely to those obtained from the simulator.

As mentioned previously, most MANET routing protocols have to flood network-wide during the route acquisition phase. Flooding is also used for signaling purposes such as

paging mobile hosts, sending alarm signals and for location updates in routing. One major drawback of flooding is that it results in redundant broadcasts causing serious contention and collision problems and increasing routing overhead. This is especially harmful in resource-constrained MANETs. One technique to reduce the impact of network-wide flooding is to use scoped flooding [72] or probabilistic flooding [70]. In this chapter we proposed an analytical model for determining the reachability and reliability of probabilistic flooding. Our preliminary simulation results indicate that probabilistic flooding can provide similar reliability and reachability guarantees as plain flooding at a lower overhead (saved re-broadcasts). One interesting extension to this work would be to characterize the lower overhead of probabilistic flooding in terms of the saved re-broadcasts compared to plain flooding. Scoped flooding [72] is another technique to reduce the number of re-broadcasts based on neighbor discovery. In [70] Sasson et al. have proposed a probabilistic form of flooding based on percolation theory. The analysis of these flooding variants using the proposed framework can be the subject for further analytical work.

Chapter 7

Understanding the Random Waypoint

Model: A Statistical Approach

Packet-level network simulators (e.g., ns-2 [73], GloMoSim [74], QualNet [57], OPNET [75])

have been widely used as platforms for evaluating wireless network protocols. There are clear

advantages to using simulations when evaluating network protocols, including the ability to

reproduce experiments and subject protocols to a wide range of network topologies and con-

ditions, including mobility patterns. Topology, number of network nodes and node mobility

are important parameters that can significantly affect the performance of the protocols being

evaluated. Hence results obtained with unrealistic mobility models may not represent the true

performance of protocols.

Most existing network simulators employ random waypoint mobility to model how

nodes move on a terrain [28]. Nodes in the random waypoint regime move according to the

following rules: (1) each node picks a destination randomly within the simulation area and

also picks a speed v that is uniformly chosen between v_{min} and v_{max}. Each node then moves toward the destination over a straight line with speed v. (2) upon reaching the destination, a node pauses for some *pause-time*; (3) the node then picks the next destination and the process re-starts. Typically, the values of v_{min}, v_{max}, and *pause-time* are parameters of the simulation and are selected according to the requirements and operating environment of the application at hand.

Recently, it has been reported that the random waypoint model exhibits some originally unforeseen anomalous behavior. More specifically, it has been shown that, under the random waypoint model, the average node speed decays with time [6]. It has also been shown that the nodes moving according to the random waypoint model tend to concentrate in the middle of the simulation region, resulting in non-uniform node spatial distribution. In the specific case where $v_{min} = 0$, as time $t \rightarrow \infty$, node speeds tend to zero, resulting in a stationary system. One important effect of this behavior is that, if simulations using the random waypoint model do not run for sufficiently long periods beyond the initial steep decay, the corresponding simulation results will not be accurate. In fact, variations of up to 40% in ad hoc routing performance over a 900-second simulation have been detected [6].

From the above discussion, one important consideration is how long does it take for the system to converge to steady state. Given this information, one easy "fix" to the random waypoint model is to run simulations long enough to guarantee that protocol performance evaluation is conducted after steady state is reached. In this study, we introduce a novel approach to study the behavior of the random waypoint regime which uses a statistical model to predict average node speed (through both point and interval estimates) as a function of input

124

parameters v_{max} and field size. Since our model also characterizes average node speed as a function of time, it also offers an efficient alternative to obtaining an accurate estimate of how long simulation experiments take to "warm-up". Simulation data from the "warm-up" period can then be discarded to obtain accurate protocol performance results.

Our model considers as input terrain size and maximum node speed. One key observation that helped to simplify model formulation was the implicit relationship between terrain size and number of nodes used in simulation experiments. For a given transmission range, the terrain size chosen normally dictates the minimum number of nodes required to ensure that the network is connected [1]. Hence our model implicitly accounts for number of nodes through the "field-size" parameter, which is defined as the 2-dimensional region within which nodes can move.

7.1 Background and Related Work

Mobility models are an important component of network simulators and are one of the key factors affecting the performance of ad-hoc network protocols. A number of mobility models for ad-hoc networks have been proposed and evaluated ([76–79]). One of the most widely used mobility models is the random waypoint model ([16, 28, 80]) described earlier. This model is implemented in a number of current network simulation platforms such as `ns-2` [73], `GloMoSim` [74], and `Qualnet` [57].

However, it has been shown in [6] that under the random waypoint regime, the average node speed decays with time before reaching steady state and the settling time to

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[1]Node mobility can cause the network to be disconnected at certain times

reach steady state increases as the minimum speed parameter v_{min} of the model decreases. In particular, the default random waypoint models distributed with `ns-2` and `GlomoSim` use $v_{min} = 0$ which causes the average node speed to steadily decrease over time. In [6], the impact of this speed decay on ad-hoc routing protocols like DSR [28] and AODV [30] was also investigated. It was shown that speed decay can result in performance variations of around 40% over simulation times typically used in the study of ad-hoc network protocols. One suggested solution was to use non-zero minimum speed or to discard results from the "burn-in" period, i.e., the simulation period during which speed decay is most dramatic.

There have been several other bodies of work such as [81–83] which have investigated the spatial node distribution for the Random Waypoint model.

In [84], a framework for analyzing the speed decay of mobility models was proposed; additionally, based on this framework, a technique to obtain the stationary equivalent to mobility models that exhibit the speed decay behavior was introduced. Essentially, the proposed strategy is to choose initial speeds from the stationary distribution and subsequent speeds according to the original distribution.

We propose a novel approach to study the behavior of the Random Waypoint model which uses a statistical model to characterize speed decay. Our model is able to predict average node speed (through both point and interval estimates) as a function of input parameters v_{max} and field size. Our model also offers an efficient alternative to obtaining accurate results from simulations using the original Random Waypoint model [2]. More specifically, as it will become clear in Section 7.4.2, using our statistical model, one can obtain the speed decay as a function

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[2] Note that the alternative is to run pre-simulations of the mobility model for different combinations of parameters of interest.

126

of time (as well as the input parameters). This allows protocol designers running simulations to plan their experiments accordingly so as to discard results from the "warm-up" period and hence perform accurate protocol performance evaluation.

7.2   Methodology

We used `GloMoSim` [74] as the simulation platform for the initial mobility experiments. The simulation setup consisted of 150 nodes moving according to the random waypoint model with v_{max} from the set { 2, 3, 4, 5, 7.5, 10, 12.5, 15, 17.5 , 20 } m/s and $v_{min} = 0$. The pause-time was set to 0 for all experiments. The field-size was varied in the range { 500, 1000, 1500, 2000, 2500, 3000 } m^2. Hence we ran mobility simulations for 60 different combinations of v_{max} and field-size with each run averaged over 10 different seed values. The total duration of the mobility experiments was set to 20,000 secs and we captured the average node speed as reported by the simulator every 5 secs. As noted previously the values were averaged over 10 different runs using different seed values. The data obtained from these mobility experiments was used as "input data" for our statistical model.

Figure 7.1 is a pictorial representation of the speed decay suffered by nodes using the Random Waypoint mobility model. Note that, the average initial speed of the nodes is $(v_{max} - v_{min})/2$ as expected and then starts decaying with time. This is similar to the results observed in [6].
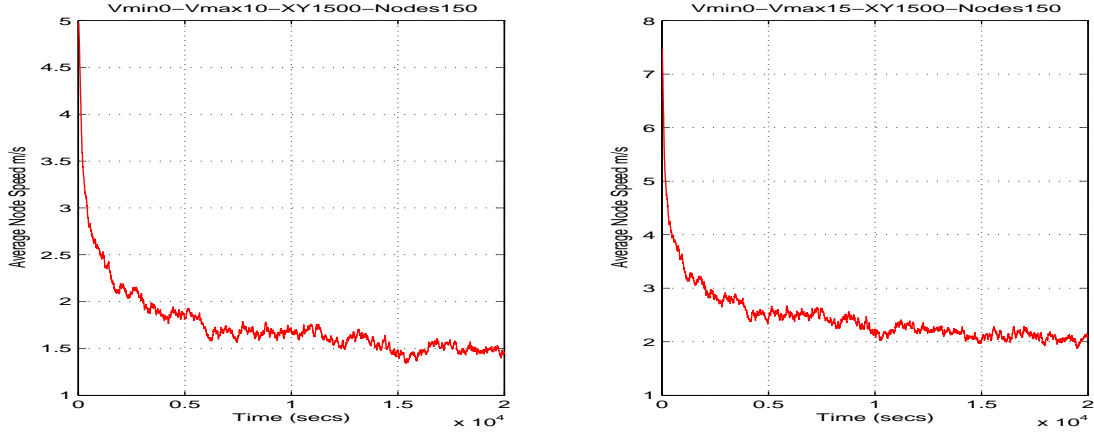
127

Figure 7.1: Speed decay under the random waypoint model

7.3 Statistical Model

We fitted a statistical model to observations on average node speed, obtained from the simulator as discussed in section 3, for 10 different choices of v_{max} and 6 different field sizes. In what follows we use the notation v for v_{max}, f for field-size, t for time in seconds, and y_t for the average node speed at time t. We started by considering the non-linear regression model

$$y_t = \frac{c}{(1 + b(t/1000))^a} + \varepsilon, \tag{7.1}$$

where ε is a random error term, for each of the 60 combinations of v_{max} and field-size. We fitted these models using least squares and obtained a set of 60 triplets corresponding to the fitted values of a, b and c. By exploring the dependence of these values on v and f, we were able to generalize model (7.1) making the coefficients a, b and c dependent on v and f. Hence we obtain a model for the average node speed corresponding to any combination of v and f

128

given by $y_t(v, f) = g(t, v, f; \mathbf{a}, \mathbf{b}, \mathbf{c}) + \varepsilon$, where

$$g(t, v, f; \mathbf{a}, \mathbf{b}, \mathbf{c}) = \frac{c(v, f)}{(1 + b(v, f)(t/1000))^{a(v,f)}} \tag{7.2}$$

with

$$a(v, f) = \exp\{a_1 + a_2 \log(f/v) + a_3 \log(\log(f/v)) + a_4 \log(\log((v/f) + 1)) + a_5 \log(\log(v + 0.5))\}$$

$$b(v, f) = \exp\{b_1 + b_2 \log v + b_3 \log f + b_4 \log(\log(f/v)) + b_5 \log(\log f) + b_6 \log(\log(v + 0.5))\}$$

and

$$c(v, f) = \exp\{c_1 + c_2 \log v + c_3 \log f\}.$$

Here $\mathbf{a} = (a_1, \ldots, a_5)$, $\mathbf{b} = (b_1, \ldots, b_6)$ and $\mathbf{c} = (c_1, c_2, c_3)$ denote the vectors of the unknown coefficients. These can be estimated from the data. A critical advantage of this formulation is that, once the 14 unknown parameters are estimated, one can estimate the average node speed for any combination of field-size and v_{max}, and for any time.

The estimation of the parameters in the model was performed by assuming that the error term follows a normal distribution with zero mean and variance σ^2. Therefore, given the data $Y = \{y_t(v_i, f_j); t = 1, \ldots, T; i = 1, \ldots, 10; j = 1, \ldots, 6\}$, we obtain the likelihood for the parameter vector, which is denoted by $\boldsymbol{\theta} = (\mathbf{a}, \mathbf{b}, \mathbf{c}, \sigma^2)$, as

$$L(\boldsymbol{\theta}|Y) = \prod_{t,i,j} (2\pi\sigma^2)^{-1/2} \exp\left\{-\frac{1}{2\sigma^2}(y_t(v_i, f_j) - g(t, v_i, f_j; \mathbf{a}, \mathbf{b}, \mathbf{c}))^2\right\}.$$

We estimate $\boldsymbol{\theta}$ using a Bayesian approach. This is based on exploring the posterior distribution $p(\boldsymbol{\theta}|Y)$. We consider a non-informative prior $p(\mathbf{a}, \mathbf{b}, \mathbf{c}, \sigma^2) \propto 1/\sigma^2$. Thus $p(\boldsymbol{\theta}|Y) \propto 1/\sigma^2 L(\boldsymbol{\theta}|Y)$. Under squared error loss, the optimal estimator is given by the posterior expectation $E(\boldsymbol{\theta}|Y)$.

129

Given the difficulties involved in describing, integrating or maximizing $p(\boldsymbol{\theta}|Y)$, which is a 15-dimensional function, we resort to Markov chain Monte Carlo (MCMC) to obtain samples from $p(\boldsymbol{\theta}|Y)$. The idea of MCMC methodology is to construct a Markov chain that is easy to sample from and such that its equilibrium distribution is $p(\boldsymbol{\theta}|Y)$ [85]. Before we describe the Markov chain that we used, we note that $p(\mathbf{a}, \mathbf{b}, \mathbf{c}, \sigma^2|Y) = p(\sigma^2|\mathbf{a}, \mathbf{b}, \mathbf{c}, Y)p(\mathbf{a}, \mathbf{b}, \mathbf{c}|Y)$, where

$$p(\mathbf{a}, \mathbf{b}, \mathbf{c}|Y) \propto A^{-60T/2} \quad \text{and} \quad p(\sigma^2|\mathbf{a}, \mathbf{b}, \mathbf{c}, Y) \propto (\sigma^2)^{-(60T+2)/2} \exp\{-A/(2\sigma^2)\},$$

with $A = \sum_{t,i,j}(y_t(v_i, f_j) - g(t, v_i, f_j; \mathbf{a}, \mathbf{b}, \mathbf{c}))^2$. Thus we recognize $p(\sigma^2|\mathbf{a}, \mathbf{b}, \mathbf{c}, Y)$ as the density of an inverse gamma distribution with shape $60T/2$ and scale $A/2$.

To obtain samples from the posterior $p(\boldsymbol{\theta}|y)$ we follow the steps:

1. Set initial values $\boldsymbol{\theta}_0$ and total number of iterations K

2. Loop for $k = 1, \ldots, K$

3. At iteration k, denote the current samples with the super-index k, and sample a vector of candidates $(\mathbf{a}^*, \mathbf{b}^*, \mathbf{c}^*)$ from a normal distribution with mean $(\mathbf{a}^k, \mathbf{b}^k, \mathbf{c}^k)$ and covariance matrix $\mathbf{V}$.

4. Calculate $\alpha = \min\{1, r\}$ where

$$r = \frac{p(\mathbf{a}^*, \mathbf{b}^*, \mathbf{c}^*|Y)}{p(\mathbf{a}^k, \mathbf{b}^k, \mathbf{c}^k|Y)}$$

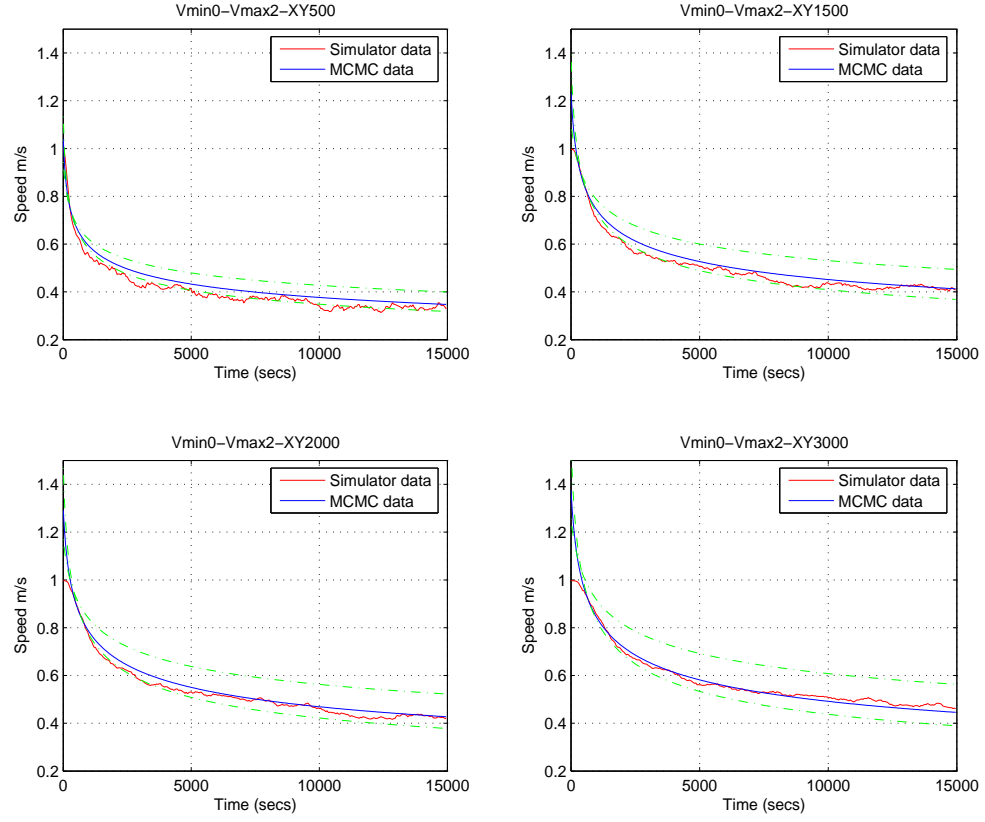5. Sample u from a uniform distribution on (0,1).

Figure 7.2: Inference: v_{max} 2 m/s

6. If $u < \alpha$ then sample $(\sigma^2)^*$ from an inverse gamma distribution with shape $60T/2$ and

   scale $A^*/2$, where A^* denotes the evaluation of A at the candidate values $(\mathbf{a}^*, \mathbf{b}^*, \mathbf{c}^*)$.

   Let $(\mathbf{a}^{k+1}, \mathbf{b}^{k+1}, \mathbf{c}^{k+1}) = (\mathbf{a}^*, \mathbf{b}^*, \mathbf{c}^*)$, $(\sigma^2)^{k+1} = (\sigma^2)^*$ and cycle.

7. If $u > \alpha$, let $(\mathbf{a}^{k+1}, \mathbf{b}^{k+1}, \mathbf{c}^{k+1}) = (\mathbf{a}^k, \mathbf{b}^k, \mathbf{c}^k)$, $(\sigma^2)^{k+1} = (\sigma^2)^k$ and cycle.

   After an initial burn-in period, the results from this chain yield a sequence of sam-

ples $\boldsymbol{\theta}^k$ whose distribution is approximately $p(\boldsymbol{\theta}|Y)$. These posterior samples can be used to

obtain inference for $\boldsymbol{\theta}$.

7.4 Results

In this section we present results obtained from the statistical model and assess its performance using mobility data obtained from the simulator. As explained in section 7.3, we ran a Markov Chain Monte Carlo (MCMC) algorithm in MATLAB to obtain samples from the posterior distribution for $p(\boldsymbol{\theta}|Y)$. These samples were then used to estimate $a(v, f), b(v, f)$ and $c(v, f)$ for different combinations of v_{max} and field-size. The estimates thus obtained were then used to evaluate for each combination of (v, f) the posterior mean of y_t as given in equation (7.4.2) for 4000 time-points upto 20,000 secs. Note that for each combination of (v, f) we obtain samples from the entire posterior distribution for equation (7.4.2). We present both point estimates and interval estimates (denoted by dashed lines in the subsequent figures) based on 5% and 95% quantiles of the posterior samples.

As seen from these figures, the statistical model produces good fits as compared to the mobility data from the simulator. The interval estimates tend to capture the variability of the original data as well. One minor discrepancy is the tendency of the statistical model to overestimate the actual values of the average node speed at t close to 0.

7.4.1 Model Validation

In order to verify the accuracy of the proposed estimator we also ran some validation tests. In these tests we fitted the statistical model to simulator data not originally used in developing the model from section 7.3. We used two different values of v_{max}, i.e, $\{8, 25\}$, keeping all other simulator parameters constant. Note that one of the v_{max} values, i.e, 8 m/s is within the data range originally considered while the other value, i.e, 25 m/s is outside the
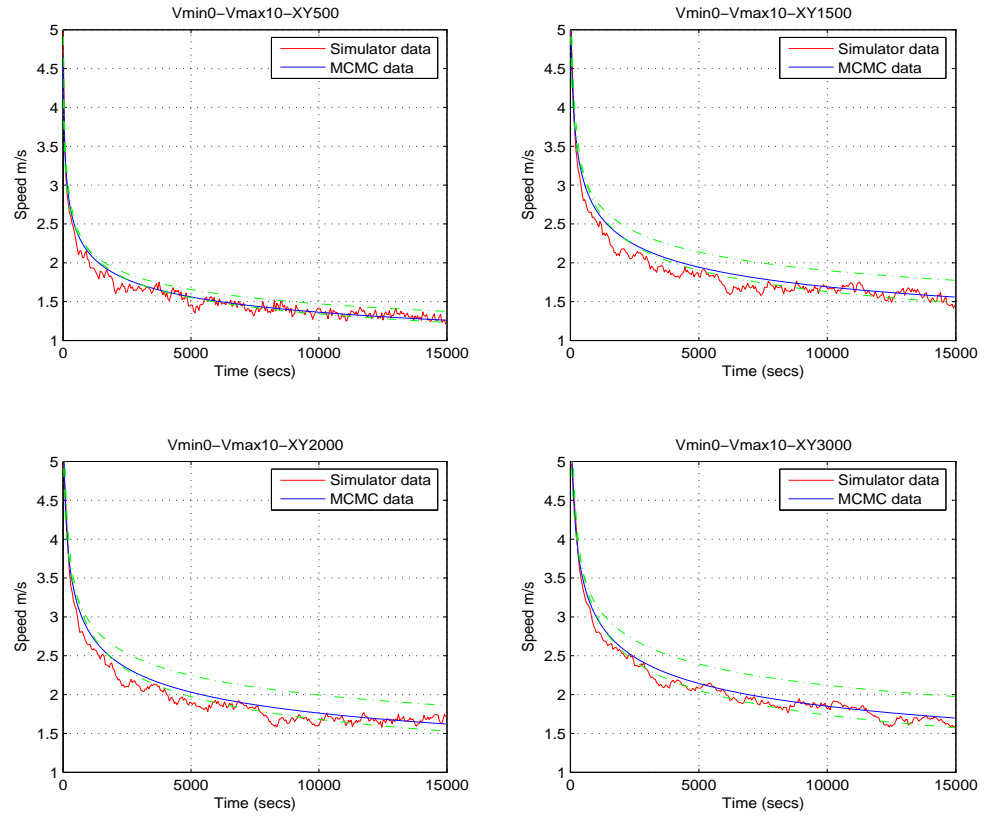
Figure 7.3: Inference: v_{max} 10 m/s

Figure 7.2 depicts the comparison between the simulator data and posterior point and interval estimates based on the statistical model for $v_{max} = 2$ m/s, while figures 7.3 and 7.4 show the comparison for $v_{max} = 10$ m/s and 20 m/s, respectively. Note that, in the figures we only present model fits up-to 15,000 secs for the sake of clarity as the behavior beyond 15,000 seconds is very similar.
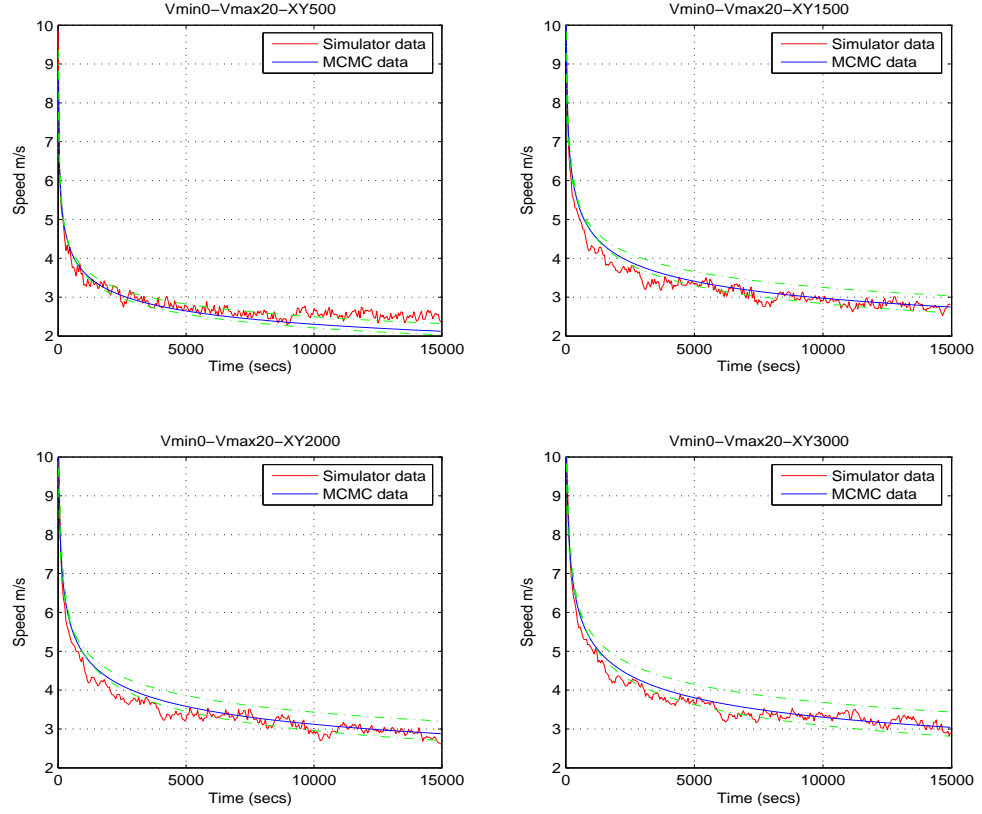
Figure 7.4: Inference: v_{max} 20 m/s

data range used to formulate the statistical model. Figures 5 and 6 illustrate that the statistical

model provides good fits for the new simulator data as well.

7.4.2 Discussion

The main contribution of this work is the ability of the statistical model to predict the

average node speed (through both point and interval estimates) as a function of input param-

eters v_{max} and field-size. One of the recommended techniques to obtain accurate simulation
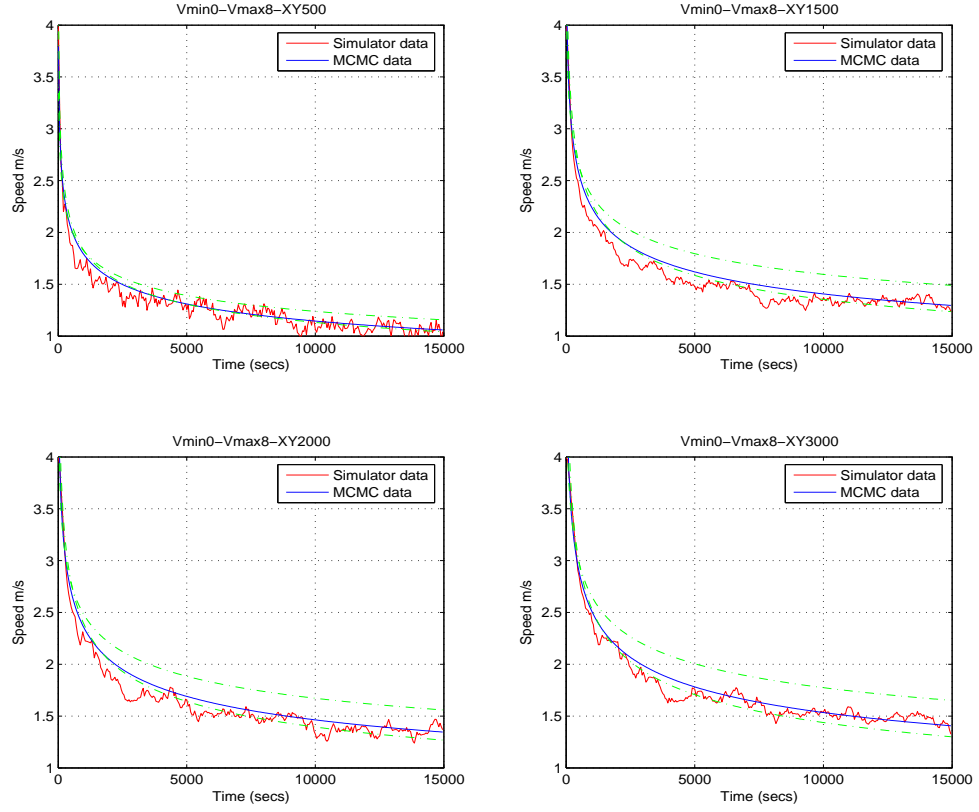
Figure 7.5: Validation v_{max} 8 m/s

results using the random waypoint model is to discard results from the "warm-up" period during which average node speed is still decaying. The proposed statistical model is useful in providing inference for the "warm-up" period for a specific simulation using the following equation

$$t_{warm-up} = 1000.b^{-1}\{(c/y_t)^{a^{-1}} - 1\},$$

where y_t is the required value for the speed decay and a, b and c are functions of v_{max} and field-size as defined in section 7.3. Hence we can obtain the entire posterior

135
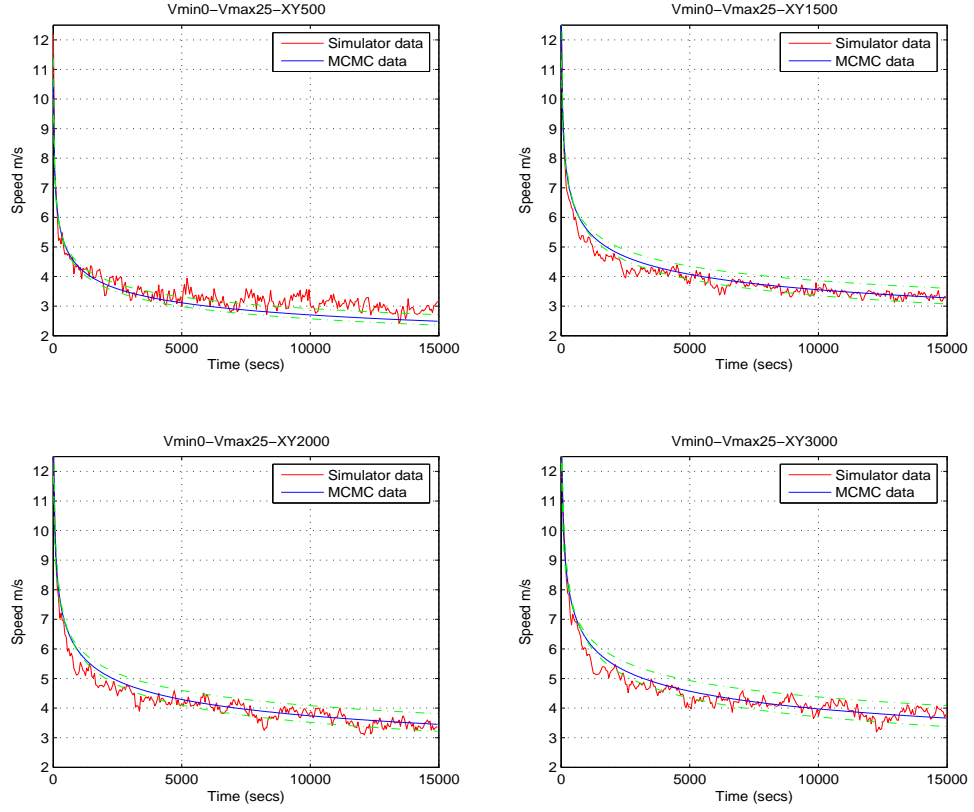
Figure 7.6: Validation v_{max} 25 m/s

distribution for $t_{warm-up}$ as a function of v_{max} and field-size for different values of speed decay y_t.

Figure 7.7 represents the point estimates of the "warm-up" period for a grid (of size 1250) over a range of commonly used combinations of v_{max} and field-size for 2 different values of y_t.

To put these results in perspective, the alternative approach would require running pre-simulations of the mobility model. For the 1250 different combinations of v_{max} and field-

size considered above this would take approximately 65 hrs for 10 different seed values on a sufficiently fast simulation machine, whereas our approach required approximately 20 minutes of computing time.

7.5   Conclusions

In this study we introduced a novel statistical model to characterize the behavior of the Random Waypoint mobility regime. Our model captures speed decay over time using maximum speed and terrain size as input parameters. A Bayesian approach to model fitting is employed to capture the uncertainty due to unknown parameters of the model. The resulting posterior predictive distributions of quantities of interest (i.e, average node speed) can be used to formally address the fit of the statistical model.

One of the main contributions of our statistical model is that, since it characterizes average node speed as a function of time, it also offers an efficient alternative to obtaining accurate results from simulations employing the original Random Waypoint model. More specifically, using our model, protocol designers using the Random Waypoint model can obtain an accurate estimate of how long simulation experiments take to "warm-up". Simulation data from the "warm-up" period can then be discarded to obtain accurate protocol performance results. We present results obtained from the model and evaluate its accuracy by validating it against data obtained from the simulator.

One direction of future work is to use a similar statistical approach to extend the current model to consider non-zero minimum speeds ($v\_min \neq 0$).
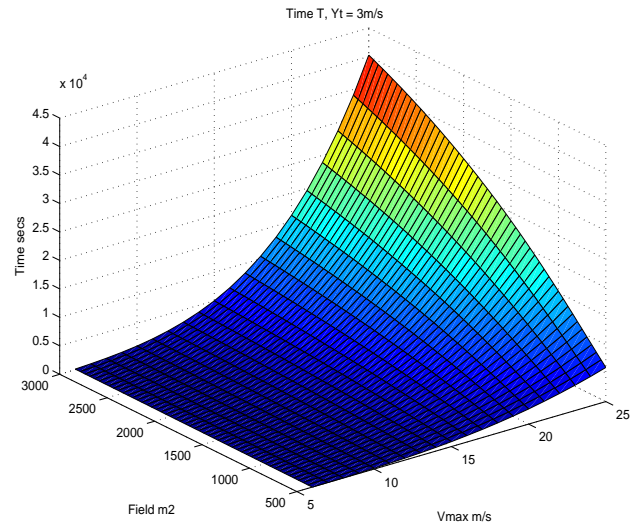
(a) Warm-up times for speed decay of $Y_t = 3$ m/s
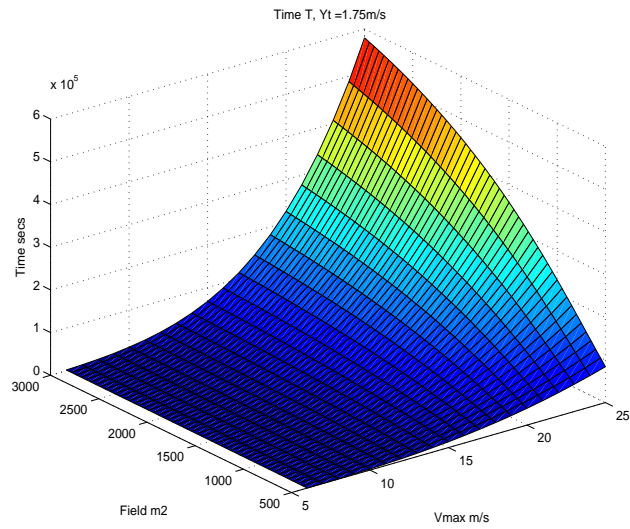
(b) Warm-up times for speed decay of $Y_t = 1.75$ m/s

Figure 7.7: Point Estimates of $t_{warm-up}$ as a function of v_{max} and field size

Chapter 8

Conclusions and Future Work

Mobile multi-hop ad hoc networks, MANETs differ from traditional, fixed-infrastructure mobile networks, where mobility occurs only at the last hop. In such networks, although issues such as address management arise, they do not affect core network functions, most importantly, routing. In contrast, MANETs require fundamental changes to conventional routing and packet forwarding protocols for both unicast and multicast communication. Conventional routing mechanisms are based on routers maintaining distributed state about the network topology. These mechanisms were designed for wired networks and work well in fixed-infrastructure mobile networks. However, topology changes in MANETs can be very frequent making conventional routing mechanisms both ineffective and expensive. These limitations pose serious challenges to routing in ad hoc networks. Recently, as it became clear that group-oriented services are one of the primary classes of applications targeted by MANETs, a number of multicast routing protocols for MANETs have been proposed.

In this thesis we first evaluated two well known multicast routing protocols, namely,

On Demand Multicast Routing protocol (ODMRP) and Multicast-Ad hoc On Demand Distance Vector (MAODV) under a wide range of network conditions and realistic scenarios. To this end, we conducted extensive simulations employing a wide range of mobility and traffic load conditions, as well as different multicast group characteristics (e.g., number of sources and number of receivers). We also compared the performance of these two protocols with baseline flooding. Based on our simulation analysis we proposed two different variations of flooding, i.e, scoped and hyper flooding. One of the main contributions of this work was the qualitative comparison of the different routing mechanisms and their usefulness under different MANET scenarios. One of the primary results from this initial study was that no multicast routing protocol is optimal under all MANET scenarios.

This initial simulation study provided the background and motivation to investigate adaptive routing techniques in which nodes can actively switch routing mechanisms based on their perception of current network conditions. It is also very likely that future internetworks will be composed of numerous ad-hoc networks each running different mechanisms for group communications, either due to administrative concerns or current network requirements. Therefore, hosts will have to dynamically switch among different multicast routing mechanisms as they move from one network to another. In this thesis we also presented an adaptive flooding scheme which integrates scoped, plain and hyper flooding into a single adaptive protocol. We also proposed two different switching criteria, namely, relative velocity based switching and network load based switching as techniques for the adaptive mechanism to decide what protocol to switch to and when. Our simulation results comparing the adaptive protocol with ODMRP and MAODV for "synthetic" as well as "realistic" MANET scenarios

demonstrate that the adaptive protocol performs consistently well in terms of both packet delivery ratio and routing overhead. The main emphasis from this study is that given the diversity of MANETs, adaptive protocols are capable of providing consistent performance benefits over a wide range of operating conditions. The simulation results presented in chapter 4 highlight these performance benefits and lay the foundations for other adaptive routing mechanisms which are not based on flooding.

We envision that future internetworks will consist of a wired backbone and a collection of wired, fixed-infrastructure mobile, and ad hoc networks as leaves. We believe that a "global" routing solution for future internets will include specialized solutions for each type of network, as well as mechanisms for integrating these solutions. The choice of routing mechanism could be primarily dictated by administrative constraints, application requirements, operating conditions, or even by varying implementations available from network providers. Interoperability is also an important issue for any adaptive routing scheme. In this thesis, we introduced interoperability techniques to facilitate seamless multicast communication between nodes spanning heterogeneous domains. In particular we proposed two different interoperability techniques, i.e, flooding-based and facilitator assisted interoperability. The flooding-based interoperability technique has the advantage of being simple in terms of implementation and requires no explicit cross-domain route establishment protocol. This is beneficial in situations where it may be difficult to change the existing network infrastructure but interoperability is still desired. The facilitator based approach, on the other hand, requires the addition of special functionality to a small subset of nodes in each domain. The functionality of facilitators is quite similar to that of Multicast Border Router's (MBRs) in wired domains. This approach is

141

well suited for scenarios involving frequent inter-domain communications such a video conferencing since flooding-based interoperability mechanisms can prove to be quite expensive for such applications. However, the side-effect of flooding-based approaches is better reliability on account of the redundant transmissions. The facilitator based approach on the other hand favors scalability as opposed to generality since it requires minor modifications to the underlying routing protocol behavior.

One feature common to on-demand protocols like DSR AODV and ODMRP is the need to broadcast control messages during the *Route Request Phase* in order to obtain routes to reach potential receivers. *Route Request* is typically carried out by using a broadcast mechanism such as flooding. Broadcast in MANETs is also necessary for applications such as

- Sending commands to a group of nodes (e.g., alarm signals).

- Paging Mobile Hosts

- Sending location updates for routing.

The most common mechanism for broadcast is through flooding. However, one drawback of flooding is that it may result in redundant broadcasts. These re-broadcasts can cause serious contention and collision problems, especially in resource-constrained (e.g., power, bandwidth) MANETs. Several flood protocols have been proposed in an effort to reduce the redundant messages in normal flooding based on probabilistic approaches, location or neighbor information. However, to our knowledge, little work has been done in characterizing the reliability of routing protocols based on analytical models. In this thesis we also develop an analytical model for charactering the reliability of broadcast mechanisms in ad hoc

networks. As part of the analysis we also extended the basic CSMA analysis presented in [68] to derive the probability of successful reception in multihop flooding. A network simulator was also used to provide simulation results to validate the model. Our tests seem to indicate that the results for the analytical model correspond quite closely to those obtained from the simulator. The main contribution of this work is that the model can be used as a framework to evaluate other flooding based approaches to broadcast in wireless ad hoc networks which offer similar reliability as flooding at a lower overhead.

Packet-level network simulators (e.g., ns-2, GloMoSim, QualNet, OPNET) have been widely used as platforms for evaluating wireless network protocols. There are clear advantages to using simulations when evaluating network protocols, including the ability to reproduce experiments and subject protocols to a wide range of network topologies and conditions, including mobility patterns. Many contemporary researchers in the wireless field including our thesis have made extensive use of packet level simulators to provide insight and evaluate the performance of protocols that have been proposed for MANETs. Topology, number of network nodes and node mobility are important parameters that can significantly affect the performance of the protocols being evaluated. Hence results obtained with unrealistic mobility models may not represent the true performance of protocols. Most existing network simulators employ random waypoint mobility to model how nodes move on a terrain. Recently, it has been reported that the random waypoint model exhibits some originally unforeseen anomalous behavior. More specifically, it has been shown that if simulations using the random waypoint model do not run for sufficiently long periods beyond the initial steep decay, the corresponding simulation results will not be accurate. In fact, variations of up to

143

40% in ad hoc routing performance over a 900-second simulation have been detected. From the above discussion, one important consideration is how long does it take for the system to converge to steady state. Given this information, one easy "fix" to the random waypoint model is to run simulations long enough to guarantee that protocol performance evaluation is conducted after steady state is reached. In this thesis, we introduce a novel approach to study the behavior of the random waypoint regime which uses a statistical model to predict average node speed (through both point and interval estimates) as a function of input parameters v_{max} and field size. Since our model also characterizes average node speed as a function of time, it also offers an efficient alternative to obtaining an accurate estimate of how long simulation experiments take to "warm-up". Simulation data from the "warm-up" period can then be discarded to obtain accurate protocol performance results.

We summarize the contributions of this thesis below:

- Evaluated the performance of mesh-based (ODMRP) and tree-based (MAODV) protocols with baseline flooding. Based on our analysis and simulation results, introduced two variations of flooding i.e *Scoped Flooding* and *Hyper Flooding* as means to reduce overhead and increase reliability respectively.

- Developed an adaptive flooding mechanism in which nodes can dynamically change routing modes based on their perception of the network conditions. Introduced two different switching criteria used by nodes to adaptively change routing mechanisms i.e relative velocity based switching and network load based switching

- Evaluated the performance of the adaptive routing strategy under "realistic" ad-hoc net-

work conditions such as disaster-recovery and conference scenarios which were generated using the scen-gen [20] tool.

- Developed an analytical model to evaluate the reliability and reachability of broadcast mechanisms in ad-hoc networks. Extended the model to compare probabilistic flooding techniques and characterize the lower overhead of probabilistic flooding in terms of the saved re-broadcasts compared to plain flooding.

- Proposed a framework to allow interoperability of various multicast routing protocols in MANETs. Evaluated two different interoperability techniques i.e flooding based interoperability and facilitator assisted interoperability.

- Developed a statistical model to characterize the speed decay of nodes utilizing the random waypoint mobility model. The statistical model provides an efficient alternative to obtaining an estimate of how long simulation experiments using the random waypoint model take to "warm-up".

8.1   Future Directions

Some of the future research directions related to this body of work include:

- Investigate adaptive routing protocols in greater detail and more specifically study adaptive routing mechanisms which are not based on flooding.

- Study the interoperability of different routing protocols in an adaptive routing scheme and their interaction with the interoperability techniques.

- As seen from our studied one of the factors affecting the performance of the facilitator based interoperability mechanism is the facilitator selection process. An area of future work would be to analyze distributed algorithms suited to the facilitator election process and evaluate the impact of these algorithms on overall performance.

- Extend our work on facilitator based interoperability approaches for unicast communications in MANETs.

- Extend the model for studying the reliability of flooding mechanisms as proposed in this thesis for analyzing scoped flooding. An interesting extension to our work would be to characterize the lower overhead of probabilistic flooding in terms of the saved re-broadcasts as compared to plain flooding.

- The statistical model presented in our thesis offers an efficient alternative to obtaining accurate results from simulations employing the original Random Waypoint model. One direction of future work is to use a similar statistical approach to extend our current model to consider non-zero minimum speeds ($v\_min \neq 0$).

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152

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