

MASTER THESIS
**EVALUATION OF GROUP COMMUNICATION
APPROACHES FOR DISCONNECTED MOBILE
AD HOC NETWORKS**

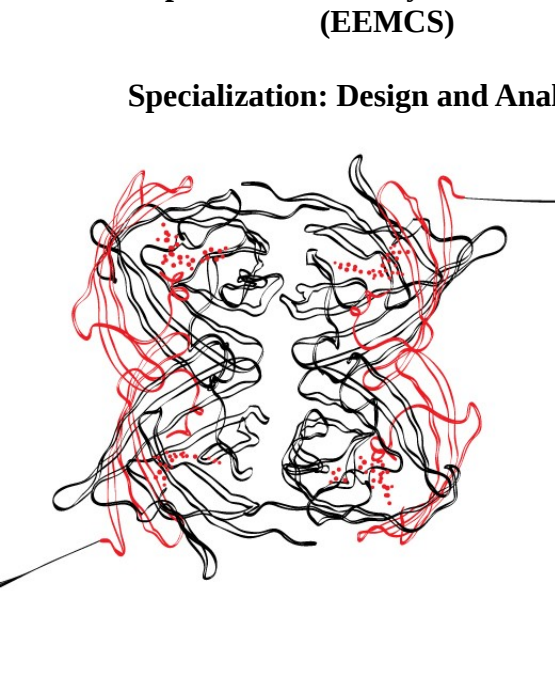
Dawit Alemayohu Kahsay

Supervisors:

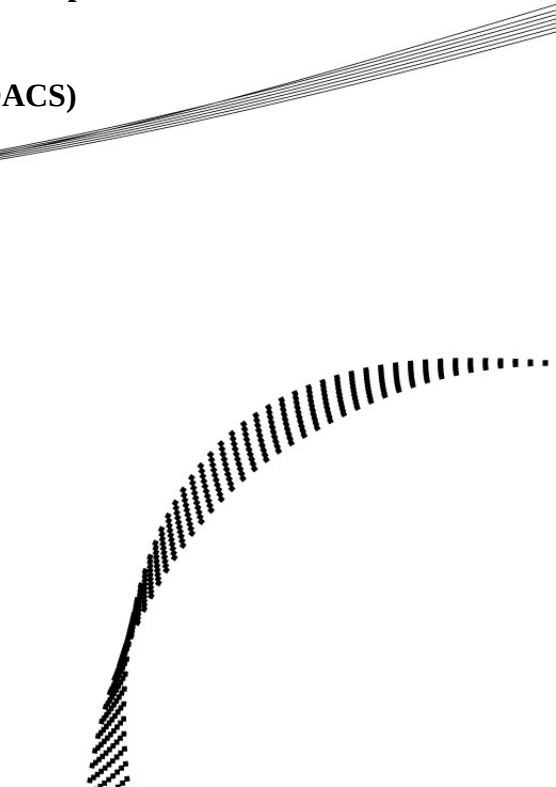
Prof. Hans Van den Berg (University of Twente)
Dr. Ir. Maurits de Graaf (University of Twente)
Dr. Ir. Geert Heijenk (University of Twente)
Dr. Ir. Gerard Hoekstra (Thales)

**Department: Faculty of Electrical Engineering, Mathematics and Computer Science
(EEMCS)**

Specialization: Design and Analysis of Communication Systems (DACS)



August 2015



UNIVERSITY OF TWENTE.

Abstract

Ad-hoc networks in tactical or emergency response operations may get partitioned into different groups of mobile nodes that have different tasks and movement patterns. Hence a tactical network can be both ad hoc and disrupted at the same time in different parts of the network. It will be difficult to maintain optimal communication using only conventional mobile ad hoc network Mobile Ad hoc Network (MANET) routing schemes. It leads to high packet loss as there are often no end-to-end connections in the network between sources and destinations. Thus, an optimum routing algorithm is needed that integrates Disruption/Delay Tolerant Network (DTN) routing schemes with conventional MANET routing schemes for efficient data dissemination among disconnected mobile ad hoc networks.

In this thesis we first provide an extensive overview of existing work on hybrid MANET-DTN routing and proposals for implementation of two group routing approaches. Next, we extended NS2 to support DTN functionality along side the existing MANET functionality and then we examine and compare two group routing approaches that can be used for disconnected mobile ad hoc networks using simulation. The first approach is, to store messages at the group leader only. The group leader coordinates and controls all inter-group communication with other disconnected groups of mobile nodes. The second approach is to store all messages contained by a group in all member nodes of the group. In this approach, member nodes communicate with nodes of adjacent groups independent of each other. We evaluate the performance of the two approaches for different scenarios using four performance metrics, namely delivery ratio, average delay, number of duplicate messages, and average buffer size.

Acknowledgements

I would never have been able to finish my thesis without the help and guidance of my supervisors, support from family and friends.

I would like to express my genuine gratitude to Prof. Hans Van den Berg and Dr. Ir. Maurits de Graaf for their daily support, patience, critical feedback, motivation, and immense knowledge. Their committed guidance helped me in all the time of research and writing of this thesis. I would also thank Dr. Ir. Geert Heijenk for the inspiring discussion and support. I could not have imagined having better advisors and supervisors for my thesis. They were able to bring me back to the right track when I was lost in a problem. I doubt that I will ever be able to convey my appreciation fully, I am so deeply grateful for all their time and vast knowledge.

Last but not the least, I would also like to thank my family, friends for supporting me and encouraging me with their best wishes.

Contents

Abstract	1
Acknowledgements	2
1 Introduction	1
1.1 Background	1
1.2 Research questions	3
1.3 Document Structure	3
2 MANETs and DTNs	5
2.1 Mobile Ad hoc Network (MANET)	5
2.1.1 Main characteristics	5
2.1.2 MANET routing schemes	6
2.2 Disruption Tolerant Network (DTN)	7
2.2.1 Main characteristics	7
2.2.2 DTN routing schemes	7
2.3 Mobility models	9
2.4 Performance metrics	11
3 State-of the-art of hybrid MANET–DTN routing schemes	12
3.1 Overview of hybrid MANET–DTN routing schemes	12
3.1.1 Hybrid DTN-MANET Routing for Dense and Highly Dynamic Wireless Networks	12
3.1.2 Routing strategy in disconnected mobile ad hoc networks with group mobility	14
3.1.3 Leader Based Group Routing with Group Mobility	15
3.1.4 Group Based Routing in Disconnected Ad Hoc Networks	16
3.1.5 Using group structures for efficient routing in delay tolerant networks	16
3.1.6 Island Hopping: Efficient Mobility-Assisted Forwarding in Partitioned Networks	17
3.1.7 Efficient Adaptive Routing in Delay Tolerant Networks	19
3.1.8 CAR: Context-aware Adaptive Routing for Delay Tolerant Mobile Networks	21
3.1.9 Adaptive Routing in Mobile Opportunistic Networks	21
3.1.10 Integrating DTN and MANET Routing	22
3.1.11 STAR: Storage Aware Routing Protocol for Generalized Delay Tolerant Networks	23
3.1.12 A Mobile Ad Hoc and Disruption Tolerant routing protocol for tactical networks	24
3.1.13 Trust Based Algorithm for Candidate Node Selection in Hybrid MANET-DTN	24
3.1.14 Combining on-demand and DTN routing for intermittently connected networks	25
3.2 Comparison of hybrid MANET-DTN routing schemes	26
3.2.1 Performance metrics and mobility models	26
3.2.2 Group-based hybrid MANET-DTN routing schemes	28
3.2.3 Hybrid routing schemes that don't apply explicit grouping of mobile nodes	33
3.3 Summary	34
4 Group communication approaches	36
4.1 Group Mobility	36
4.2 Intra Group Routing	37
4.3 Proposed group communication approaches for inter group routing	37

4.3.1 Leader Based Group Routing	38
4.3.2 Distributed Group Routing	42
4.3.3 Buffer Management	46
5 Set-up of simulation experiments	47
5.1 Simulation Methodology	47
5.1.1 DTN mechanisms	48
5.1.2 MANET routing	48
5.1.3 Traffic generation	48
5.1.4 Simulation parameters	49
5.2 Scenarios	49
5.3 Simulation parameters	51
6 Performance results	52
6.1 Low mobility environment	52
6.1.1 Source-destination pairs chosen randomly from different groups (5 groups)	52
6.1.2 Source-destination pairs chosen randomly from different groups (10 groups)	56
6.1.3 When only one group generates traffic	60
6.1.4 Only one destination group scenario	64
6.2 High mobility environment	68
6.2.1 Source-destination pairs chosen randomly from different groups (5 groups)	68
6.2.2 Source-destination pairs chosen randomly from different groups (10 groups)	72
6.2.3 When only one group generates traffic	75
6.2.4 Only one destination group scenario	78
7 Conclusions and Future Work	83
7.1 Summary	83
7.2 Revisiting the Research Questions	84
7.3 Future work	87
Appendix A	89
References	109

List of Acronyms

ACK	Acknowledgement
AODV	Ad-hoc on-Demand Distance Vector Routing
CAR	Context-aware Adaptive Routing
CP	Concentration Point
DSDV	Destination-Sequenced Distance-Vector routing
DSR	Dynamic Source Routing
DTN	Disruption Tolerant Networking
EAR	Efficient Adaptive Routing
GER	Group Epidemic Routing
GID	Group Identifier
GSV	Group Summary Vector
HYMAD	Hybrid DTN-MANET Routing for Dense and Highly Dynamic Wireless Networks
MANET	Mobile Ad hoc Network
ORWAR	Opportunistic Routing with Window Aware Replication
PDU	Packet Data Unit
PRoPHET	Probabilistic Routing Protocol using History of Encounters and Transitivity
RAPID	Resource Allocation Protocol for Intentional DTN routing
RPGM	Reference Point Group Movement
RREP	Request Reply
RREQ	Route Request
RWMM	Random Waypoint Mobility Model
ZRP	Zone Routing Protocol
TC	Topology Control
NS2	Network Simulator - 2
SDR	Speed Deviation Ratio
ADR	Angle Deviation Ratio

Chapter 1

Introduction

In this chapter, we present an introduction to the research carried out. Once this is done the main research question is defined. Finally, a short structure of the report is given to guide the reader.

1.1 Background

Conventionally, wireless communication networks have always been supposed to be connected all or most of the time. A connected network means there is always an end-to-end connection between any pair of nodes in the network. When partitions/disruptions occur, they are considered temporary failures and core network functions such as routing try to solve these failures by searching alternate paths. Even in mobile ad hoc networks (MANETs), where links are more unstable due to wireless channel impairments and mobility, partitions are still considered as exceptions and assumed uncommon and short lived.

The conventional MANET routing schemes do perform quite good for efficient communication in dense and stable networks. However in critical scenarios, it is common to have long-lived disruptions, connection breaks, and partitions of the network into disconnected (isolated) clusters due to random movements, different tasks, and energy exhaustion of mobile nodes. In such cases finding an alternative path is not possible.

Tactical or emergency response operations need highly synergistic efforts which involves different hierarchical structures. Establishing and maintaining optimal communication among intermittently connected and separated “islands” of well-connected nodes are critical tasks in order to create situational awareness and establish a common operational picture. For instance, different search and rescue teams may be separated from each other as they move out of communication range. Due to the mobility of the rescue workers, as well as link and device failures, the network topology and connectivity characteristics of the network will constantly change. Hence it will be difficult to maintain optimal and synergistic communication using only conventional MANET routing schemes.

On the other hand, a Disruption/Delay Tolerant Network (DTN) is designed to handle lengthy network disruptions. DTN routing schemes provide routing by implementing store-carry-forward mechanism together with different replication strategies among intermittently connected mobile nodes in an opportunistic environment. Store-and-forward routing allows nodes in different network partitions to exchange data, even if there are no end-to-end connections. At the same time, DTN routing schemes introduce also communication and storage overheads. Moreover, DTN routing doesn't provide real-time services which are critical tasks in tactical (emergency) scenarios.

Thus mobile networks in critical scenarios can be both ad hoc and disrupted, and they can work in MANET and DTN modes at the same time in different parts of their networks. Hence an optimum routing algorithm is needed that integrates DTN routing schemes with conventional MANET routing schemes for efficient data dissemination among disconnected mobile ad hoc networks.

In this research, first we study several hybrid MANET-DTN routing schemes that combine MANET with DTN mechanisms.

Different researches have been carried out on combining MANET and DTN routing protocols for providing optimal communication in opportunistic environments. Different hybrid MANET-DTN routing schemes apply different combination of MANET and DTN routing protocols for routing among disconnected mobile nodes of a network. Basically, these different hybrid routing schemes apply MANET communication when there is an end-to-end connection between source and destination nodes, and they apply DTN communication when there are arbitrarily long-lived connectivity interruptions, and /or delays along the path to an intended recipient.

During critical task operations, different groups of vehicles or rescue workers may move in different directions to execute their missions. Members of a group act as a unit when they move together or when they communicate with other adjacent groups during random encounter times. Thus, routing strategies have to literally represent the real communication scenarios and they should maximize communication means during repeated disconnection challenges (or network disruptions) so as to provide optimal communication mechanism in critical scenarios.

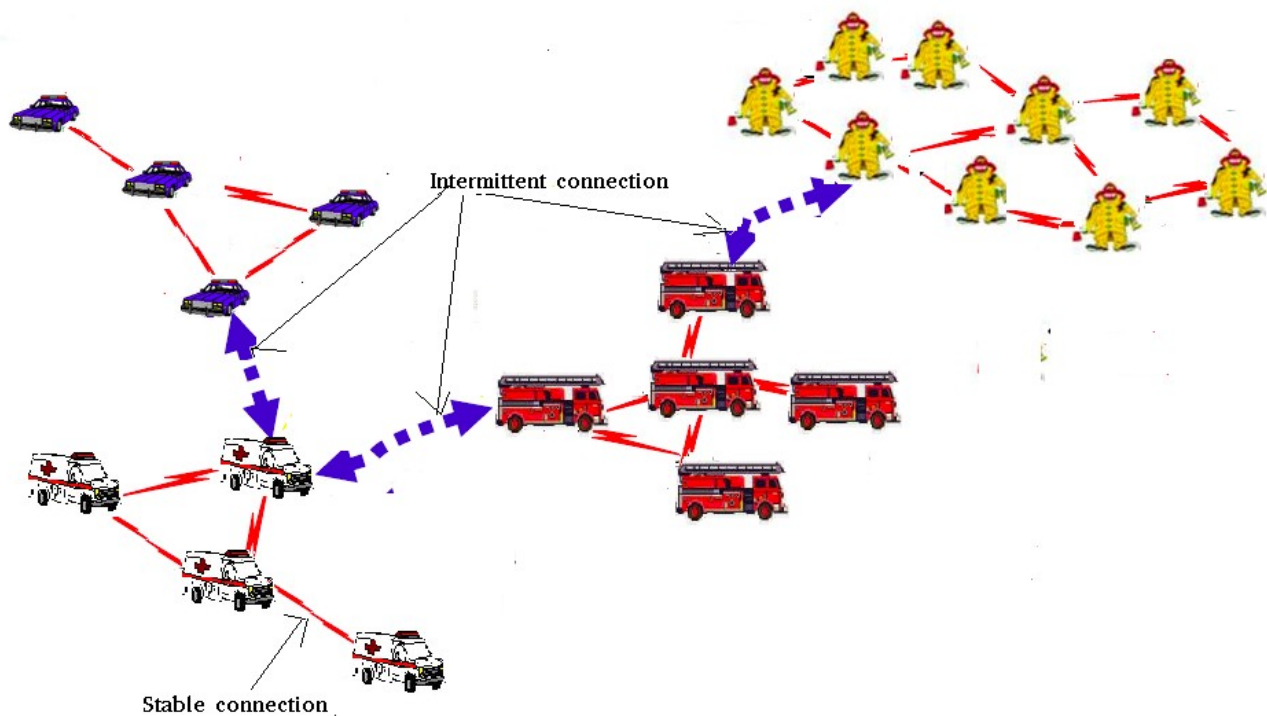


Figure 1: Network of disconnected subnets in emergency scenario

As in critical task (emergency response) operations the main challenge is, to provide optimum routing among intermittently connected groups of mobile nodes. Next, we examine and compare two group routing approaches that can be used for disconnected mobile ad hoc networks in critical scenarios.

The first approach is a leader based group routing where group leader coordinates the asynchronous communication with other disconnected groups of mobile nodes and ordinary members serve as requesters/forwarders of messages to/from their group leader. Members of a group move as a unit with group mobility. This routing scheme represents leader-centric group communication. This approach is heavily dependent on the group leader. If communication with the group leader fails, there will be no communication with other groups which might severely affect critical tasks. Moreover, the group leader can be the bottleneck of inter-group communication when there are more than one parallel communications among adjacent groups. This can also limit the number of messages exchanged during contact time of adjacent groups.

The second approach is distributed group routing where all members of a group have all messages contained by their group. In this approach, all member nodes have the same role and they communicate with other nodes of adjacent groups independently. A message that is received by any member of a group from a node of an other group has to be disseminated to all other member nodes. This approach is more robust at the cost of higher overhead.

These two routing approaches consider group as an individual node for inter-group communication. In both group routing approaches intra-group communication is performed via MANET routing, whereas inter-group communication is achieved via DTN routing. These two approaches have their own pros and cons under different scenarios.

Thus, our study compares the performance of both approaches in different scenarios using simulation in order to uncover their performance and therefore their suitability to different scenarios.

1.2 Research questions

The aim of our research is to examine and compare two group routing approaches introduced above that can be used for hybrid MANET-DTN networking. In particular, our main research question is refined as follows:

How does a leader based group routing perform compared to a distributed group routing in hybrid MANET-DTN networking?

In order to answer the main research question, the following sub-questions have been formulated.

1. What is the state-of -the art of hybrid MANET-DTN routing ?

This subquestion aims at exploring how different hybrid MANET-DTN routing schemes implement grouping of mobile nodes, replication mechanisms, and integration of MANET and DTN routing protocols.

2. How is inter-group routing among randomly moving groups of mobile nodes coordinated in the two approaches?

This subquestion seeks answer on how inter-group routing is coordinated both at group level and node level in both group routing approaches.

3. What are the pros and cons of using each approach?
4. How do the two approaches perform under different scenario?

This questions how each approach performs with respect to common performance metrics in scenarios that present different challenges.

1.3 Document Structure

The remainder of this document is structured as follow:

Chapter 2 provides preliminary knowledge about ad hoc networks (MANETs and DTNs), mobility models and performance metrics of ad hoc networks which is used throughout the rest of this document.

Chapter 3 provides an extensive overview of researches conducted on hybrid MANET-DTN routing schemes. Extensive study of existing work on hybrid MANET-DTN routing schemes has been one of the goals of this thesis. In Section 3.1 comprehensive discussion is provided on how the different hybrid routing schemes proposed in literature have implemented grouping of mobile nodes, intra group and inter group routing. Then in Section 3.2, we compare the different hybrid MANET-DTN routing schemes based on performance metrics, group formation and management of mobile nodes. At last, it sums up with a summary.

Chapter 4 describes how the two approaches (leader based group routing and distributed group routing) work used for our study. Specifically, Section 4.1 and 4.2 respectively, explain the group mobility and intra-group routing used in our study. Section 4.3 provides description of the two proposed group routing approaches,i.e. leader based group routing and distributed group routing. Then Section 4.4 discusses the buffer management in both approaches.

Chapter 5 provides complete explanation of the simulation methodology and the scenarios that are used in our research.

Chapter 6 presents and discusses the performance analysis results for both leader based and distributed group communication approaches in terms of delivery ratio, average delay, duplicate messages and average buffer metrics using results obtained from simulations. The performance of the two approaches has been studied in low and high mobility environment for different scenarios.

Chapter 7 provides the summary, conclusion and topic ideas for future work.

Finally, Appendix A gives detailed tables of the simulation results obtained for each scenario used in our study.

Chapter 2

MANETs and DTNs

This chapter is a background study on MANET and DTN routing schemes of ad hoc networks of mobile nodes intended to help reader with the basic concepts, so that he /she gets a clear picture of the intention of the research. It also includes the definition and explanation of common performance metrics and mobility models that are used in ad hoc networks.

2.1 Mobile Ad hoc Network (MANET)

2.1.1 Main characteristics

A MANET is an infrastructure-less network of wireless mobile devices. Each mobile node in a MANET is connected to other nodes in the network either in the form of direct, or relayed end-to-end connectivity. MANETs consist of a peer-to-peer, self-forming, self-healing network¹. Since mobile nodes can move independently in a random direction, it is challenging to maintain stable MANET network and thus link disruptions (breaks), variable wireless link quality, propagation path loss, fading, multiuser interference, power expended, hidden terminal problem, exposed terminal problem, limited bandwidth, security threats, and topological changes are common challenges of mobile ad hoc networks.

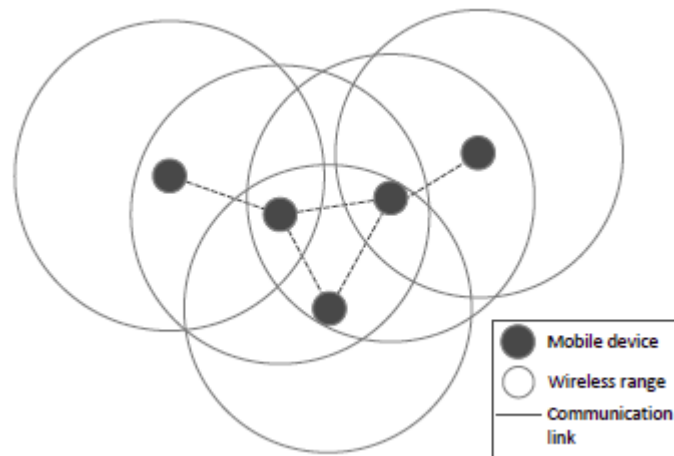


Figure 2: MANET network

In the following section we will focus on routing protocols that deal with the highly dynamic nature of MANETs.

¹ https://en.wikipedia.org/wiki/Mobile_ad_hoc_network

2.1.2 MANET routing schemes

MANETs have to determine in a distributive way network organization, link scheduling, and efficient routing. Different MANET routing protocols have been proposed over years. MANET routing protocols can be categorized into proactive, reactive and hybrid protocols.

Proactive (table-driven) protocols maintain up to date routing information for all nodes of a network in advance of actual communication and updates of any changes of network are propagated throughout the network. Each node maintains route information to every other node in the network prior to any data exchange.

Reactive protocols build an end-to-end route between source and destination nodes on demand. Source node initiates route discovery to a destination node when it needs to forward message to the destination node. Hybrid protocols apply both table-driven and on-demand routing protocols. An overview of some typical examples of these different protocol types is presented below.

Destination-Sequenced Distance Vector routing (DSDV) [6] is a table-driven routing protocol based on Bellman–Ford algorithm. Each node maintains hop count metric, next hop, and sequence number generated by destination node in its route table entries for each destination. The sequence number generated by destination node is used to distinguish old and new route information.

Optimized Link State Routing Protocol (OLSR) [8] is an optimized proactive link state protocol for MANET. Each mobile node builds its local route table based on local information base (set of actual links for one hop neighbors), neighbor information base (information about one and two hop neighbors), and topology information base that are gathered by hello and topology control (TC) messages.

Ad-hoc on-Demand Distance Vector Routing (AODV) [17] is a reactive routing protocol that applies destination sequence numbers to discover recent path to a given destination. A source node discovers route towards a given destination when it needs to transmit messages. A source node broadcasts Route Request (RREQ) packet to the network and intermediate nodes send Route reply (RREP) back to the source node if they have valid route to the destination or rebroadcast the Route Request (RREQ) packet. This way on-demand route is built between source and destination nodes. If any error is encountered along the route, intermediate nodes forward route error (RERR) packet to the source node.

Dynamic Source Routing (DSR) [5] is a type of reactive routing protocol that applies source routing. Like AODV routing, source node broadcasts Route Request (RREQ) packet to the network but the intermediate nodes don't send Request reply (RREP) packets they simply insert their addresses to the RREQ packet and forward it towards the destination node. The destination node then sends back a Request reply (RREP) packet to the source node based on the route record on the Route Request packet.

Zone Routing Protocol (ZRP) [6] is a hybrid routing protocol that aims to provide efficient routing on-demand with a limited search cost. In ZRP each node has a routing zone that consists of nodes within k -hops of the node. ZRP applies any one of the proactive routing protocol if the destination node is within the routing zone of the source node. But if the destination node is in a different zone, the source node sends a route request to the border nodes that are k -hops away from it. Each border node checks if the destination node is in its routing zone and if it is not member of its zone, it adds its address to the route request packet and sends it to its own border nodes. But if the destination node is a member of its routing zone, the border node sends route reply packet back to the source node. Then the source node uses information stored in the route reply to send packets to the destination.

2.2 Disruption Tolerant Network (DTN)

2.2.1 Main characteristics

A delay/disruption tolerant network is a network of intermittently connected MANETs. Unlike a conventional MANET network, in DTN there might not be an end-to-end connection between source and destination nodes. In DTN, mobility of mobile nodes is used as a means for transmitting messages among the intermittently connected parts. DTN routing schemes implement a Store-Carry-Forward mechanism together with different replication strategies to enable communication among intermittently connected mobile nodes. To implement the Store-Carry-Forward mechanisms on top of the Internet protocols, the DTN architecture introduces a new transmission protocol called the bundle protocol between the application layer and transport layer.

The bundle protocol binds together lower protocols to facilitate communication between DTN nodes across lower-level protocols under conditions that involve long network delays or disruptions. The bundle protocol implements node-to-node retransmission using an optional custody transfers. When the current custodian sends a bundle to the intended next custodian, it will set a timer. If it doesn't receive custodial-acceptance acknowledgement from the intended custodian, it will retransmit the bundle. In addition to custody transfers, the bundle protocol applies return receipt confirmation message from the destination to the source entity to provide end-to-end assurance of delivery. QoS can also be provided by generating bundles with different priority.

In DTN mobility, storing, sending, receiving and dis-connectivity consume more energy than conventional routing technique. Thus optimal dtn routing strategy is a major challenge in addition to the delay and disruption challenges.

In the next section, we will discuss common DTN routing schemes.

2.2.2 DTN routing schemes

A number of classification schemes have been proposed for DTN routing protocols. The common method of classification is according to deterministic approaches, and stochastic approaches.

Deterministic approaches make use of known mobility patterns to schedule transmission of bundle along time-varying links ahead of time to the intended destination.

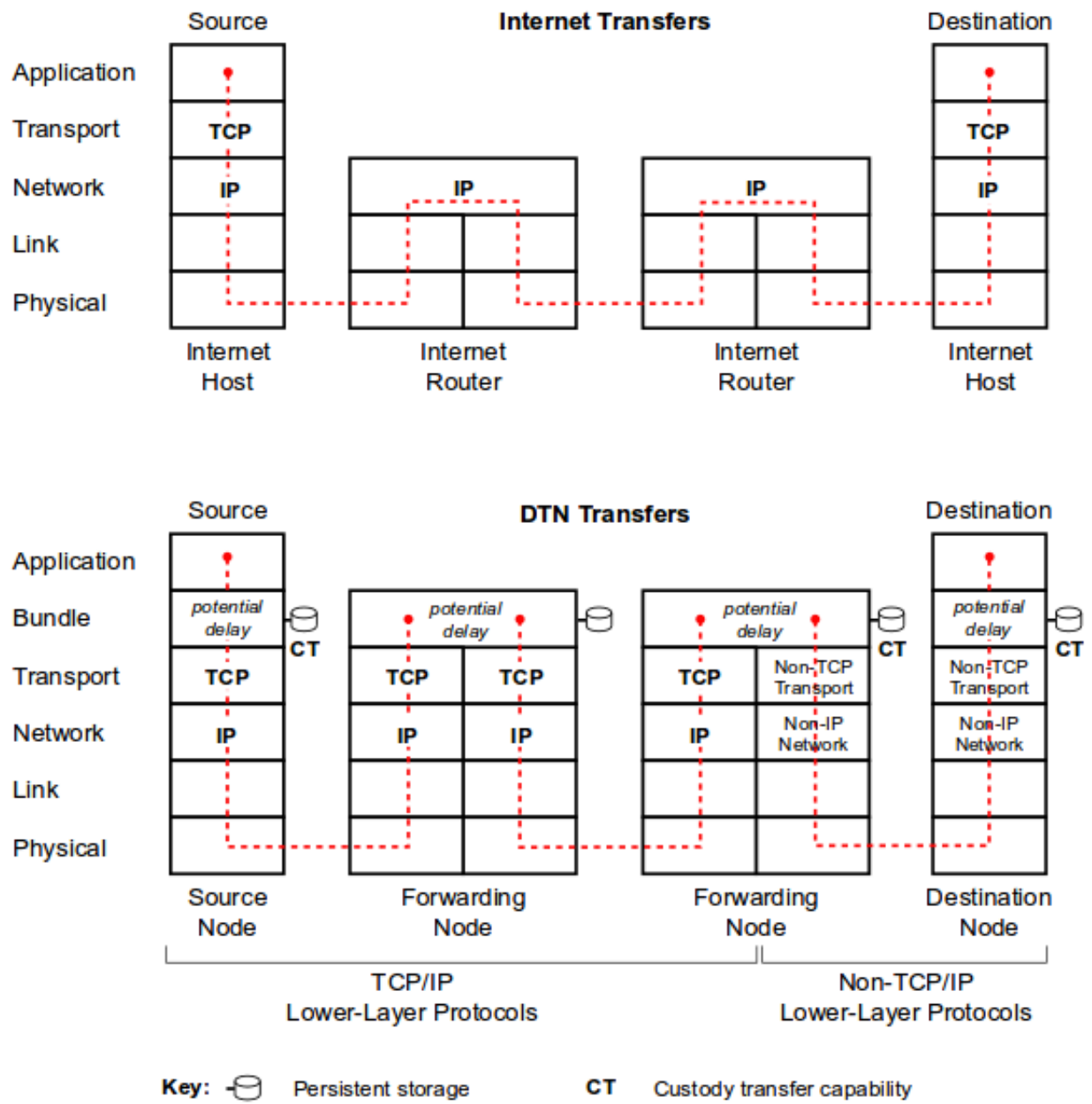


Figure 3: IP routing Vs DTN routing

In stochastic approaches, the DTN network of mobile nodes is assumed as an opportunistic environment and DTN routing schemes implement different routing strategies to secure optimal way of message transmissions to intended parts. An overview of some of the DTN routing schemes that are proposed for random mobility behavior is presented below.

Epidemic [26] is the simplest routing approach where a given node with a replicated message forwards a copy to every node it meets. This routing scheme achieves highest delivery ratio but with highest overhead. This scheme is very expensive in terms of resource consumption.

Spray and wait [23] limits the maximum number of replicas of a message in a network. In this protocol, a source node forwards k copies to the first k distinct nodes it encounters. Then all k nodes wait until they encounter the destination node.

Binary spray and wait [23, Def.3.2] is a modified version of spray and wait protocol. Given an

initial k replicas of a message, a source node forwarding $\lfloor k/2 \rfloor$ of copies to the first node it encounters, keeping $\lfloor k/2 \rfloor$ copies to itself. In this scheme, each node with copies of a given message keeps forwarding $\lfloor \text{number of current copies}/2 \rfloor$ of copies when it comes in contact with any node that doesn't have a copy until it is left with one copy of the given message. Nodes with only 1 copy keep their copies until they encounter the destination node.

PROPHET algorithm [13] limits flooding of replicas based on delivery probabilities of mobile nodes to a given destination. Mobile nodes update delivery probabilities of each other every time they meet. This way, the PROPHET algorithm applies history of encounters and transitivity to calculate delivery probabilities of nodes to a given destination. A node with a copy of a given message forwards a copy if it encounters a node with higher delivery probability to a given destination.

MaxProp [4] focuses on vehicle-based DTNs with short contact durations. Packets are forwarded or dropped based on their path likelihood, which depends on history of encounters. Nodes that did not meet frequently in the past have low link likelihood. Nodes exchange estimated node -meeting likelihood vectors they have with other nodes so as to have complete view of path likelihood to a given destination.

RAPID [2] strives to optimize a routing metric given constraints on both storage and bandwidth. It implements per-packet utility-driven replication mechanisms. Each packet is replicated based on its utility to optimize a given routing metric. Mobile nodes exchange meta data using an in-band control channel to track the effect of replication of each packet on the routing metric to be optimized. RAPID mainly focuses on minimizing average delay, minimizing worst-case delay, and maximizing the number of packets delivered before a deadline.

ORWAR [21] focuses on optimal usages of transmission powers, bandwidth and memories of mobile nodes by reducing the probability of partially transmitted messages. It also provides differentiation of services by introducing three different priority (low, medium, high) classes. ORWAR limits the number of initial replicas of a given message based on its class. ORWAR reduces the likelihood of partial transmission of messages by estimating the maximum message size that can be transmitted during the contact time of two nodes. The contact time is estimated according to the velocities, directions and transmission ranges of the mobile nodes. Then if any one of the nodes has a copy of a message with size less than the maximum transmittable message ($S_{\max}$), it forwards $\lfloor \text{number of current copies}/2 \rfloor$ of the message copies and keeps the remaining for itself. The nodes keep exchanging copies of messages until the remaining time is estimated to be too short to allow for complete message transmission. Moreover, ORWAR introduces utility /bit metric for buffer management. Messages are queued in decreasing utility/ bit value order. When the message queue is full, messages at the lower tail of the queue are deleted first.

2.3 Mobility models

In order to evaluate the performance of any protocol for ad hoc networks, researchers use traces of mobility patterns from real-life networks or synthetic mobility models that mimic the movements of real mobile nodes. Different MANET and /or DTN routing schemes are evaluated by different mobility models that represent the real life mobility patterns of mobile nodes. Mobility models broadly can be categorized into *group mobility* models that represent mobile nodes whose movements are dependent on each other and *entity mobility* models that represent mobile nodes whose movements are independent of each other. The most common mobility models that are used for research of ad hoc networks are presented below:

Random walk (Brownian motion) mobility model [20] is an entity mobility model where a mobile node moves independently by randomly choosing a speed and direction from pre-defined ranges, [speed min, speed max] and $[0, 2\pi]$ respectively. The future speed and direction of a node is independent of its current speed and direction. Hence this mobility model can generate unrealistic movements such as sudden stops and sharp turns.

Random way point mobility model (RWMM) [1] is a modified version of random walk mobility model. In this mobility model, each mobile node chooses randomly its next destination and moves with a randomly chosen speed from the uniform distribution of $(0, V_{\max})$ of speed values. At its next stop it pauses for some time, and chooses randomly its new next stop and speed. The process continues until the end of the simulation time. Most of the MANET and /or DTN routing schemes implement this mobility model.

Reference Point Group Movement (RPGM) [11] is a group mobility model where nodes with the same interest (mission) follow the logical center (group leader) of the group. The group leader chooses a destination randomly and each member of the group determines its speed and direction deviation in random way from the speed and direction of the group leader. Thus mobile nodes move as a group. Reference point group movement can represent some real group movements scenarios.

$$\begin{aligned} |V_{member}(t)| &= |V_{leader}(t)| + \text{random}() * \text{SDR} * \text{max_speed}, \\ |\theta_{member}(t)| &= |\theta_{leader}(t)| + \text{random}() * \text{ADR} * \text{max_angle}. \end{aligned}$$

Where, SDR is the speed deviation ratio, ADR is the angle deviation ratio, $0 < \text{SDR}, \text{ADR} < 1$.

Community based mobility model [15] mimics the natural movement of human beings. In real life, people spend most of their time with their community, and their movement is strongly influenced by their social ties. Likewise, in community based mobility model mobile nodes that are geographically collocated and socially coalited form a community (group). Hence in this mobility model, any mobile node first randomly chooses its destination inside its community and then it can move to any community that exerts high social attractiveness to the mobile node. Thus mobile nodes can commute between communities based on their popularity and social ties. Like RPGM, this mobility model represents a group mobility model and it is popular for networks build among smart devices carried by people.

In addition to the mobility models described here, some MANET and DTN routing schemes also use mobility traces collected from real world networks. An overview of some examples of mobility traces of ad-hoc networks is presented below.

Rollernet trace [27] is a dense and highly dynamic wireless connectivity trace of 62 participants of the regular Sunday afternoon roller blading tour in Paris, France. The participants comprises of groups of friends, members of roller blading associations and staff operators. The network topology evolves extremely quickly and it alternates between expanding to several separate connected components and contracting to a single connected component.

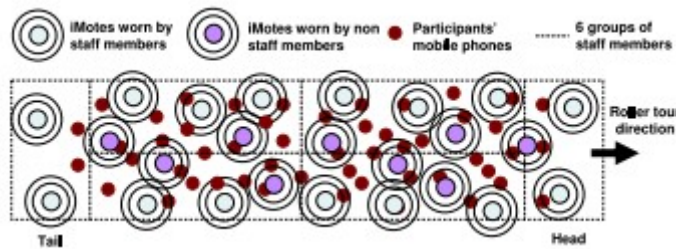


Figure 4: During a tour, staff members are organized into six groups. Over the duration of an outing, these groups have an almost static position relative to each other; there are two groups on each side of the crowd, one group at the front, and another one at the end. In order to distribute coverage uniformly among the crowd; 25 i Motes were distributed among these six groups, 11 i Motes to friends and 26 i Motes to members of roller skating associations.

San Francisco Cab trace is a GPS based mobility traces of San Francisco taxi cabs collected over 30 days in the San Francisco Bay Area. Each cab reports its location every minute and the data is

stored in a database.

There also other many mobility traces and synthetic mobility models that can be used for MANET and DTN routing schemes.

2.4 Performance metrics

In mobile wireless ad hoc networks, there might exist different network metrics to characterize performance of routing schemes. Nevertheless, some common metrics have been applied to evaluate and quantify the network performance of different routing schemes.

- *Delivery ratio* is the ratio of the number of delivered messages to total number of messages sent. This is the first metric to evaluate if a new proposed MANET or DTN routing approach has a throughput gain over other MANET and/or DTN routing schemes.
- *Average delay* is the average of delays experienced in the network by delivered messages. It is an important metric as delivery ratio for performance evaluation. Average delay has to be improved as much as possible for optimal communication. It is crucial for efficient communication in very critical scenarios.
- *Overhead ratio* is the ratio of the sum of control messages and message replicas to the total number of messages consumed in the network. This metric helps to estimate energy consumed and bandwidth wasted for control messages. Routing schemes that provide optimal communication with a small overhead ratio are preferable in bandwidth critical scenarios.
- *Bandwidth utility* is the ratio of data messages delivered to the total messages consumed. This metric helps to estimate the percentage of the total bandwidth actually consumed by delivered messages. Some MANET and DTN routing schemes have applied bandwidth utility as one of their metrics to determine their performance compared to other MANET and /DTN routing schemes.

In addition to the metrics explained above performance metrics such as maximum/average buffer size, number of transmissions per message, average hop count can also be used to evaluate performance of some MANET and DTN routing schemes.

Chapter 3

State-of the-art of hybrid MANET–DTN routing schemes

Part of this thesis has been studying researches carried out on hybrid MANET-DTN routing schemes. This chapter will present a review of previous and continuing researches that are related to the topic of this thesis.

Our focus here is to provide state-of the-art and comparison of routing schemes that have applied a combination (an integration) of MANET and DTN routing schemes for an efficient dissemination of data among disconnected groups of a network.

Concise explanations on how different hybrid routing schemes have implemented grouping of mobile nodes, intra-group and inter-group routing is discussed in Section 3.1. In Section 3.2, comparison of the different hybrid MANET- DTN routing schemes based on performance metrics, group formation and management of mobile nodes is provided. At last, Section 3.3 provides summary.

3.1 Overview of hybrid MANET–DTN routing schemes

In opportunistic environments, it is difficult to maintain communication among mobile nodes. Partition of a network in to different isolated regions can occur due to the random mobility of nodes. Different schemes have been proposed that apply different combination of MANET and DTN routing protocols to provide an optimal communication in opportunistic environments.

Some hybrid routing schemes apply explicit grouping of mobile nodes. In these schemes, mobile nodes communicate via MANET routing within a group and via DTN routing with nodes of adjacent groups. Other schemes that don't apply explicit grouping of mobile nodes, route messages among mobile nodes via MANET routing if there is an end-to-end connection or via DTN routing if routing via MANET routing is not possible or if routing via DTN routing provides better performance metrics such as better delivery ratio, improved average delay compared to MANET routing based on the current local information gathered by route discovery packets.

In the following subsections we provide summaries of papers on hybrid MANET-DTN routing that we found by extensive literature search.

3.1.1 Hybrid DTN-MANET Routing for Dense and Highly Dynamic Wireless Networks

HYMAD [27] protocol applies a combination of MANET and DTN routings for communication within and among different groups in dense and highly dynamic wireless networks. Simple distance vector routing is used for the MANET connection of nodes within a group. Within a group each node u regularly broadcasts a list that includes elements such as the minimal number of hops from itself to other member v , list of messages held by each v , and a bit indicating if v is a border node (i.e. in contact with a node of an adjacent group).

A set of connected mobile nodes exchange beacon messages using a self-stabilizing algorithm, and those nodes that have distance less than or equal to the fixed maximum diameter among each other form a group. Let us explain this algorithm using an example.

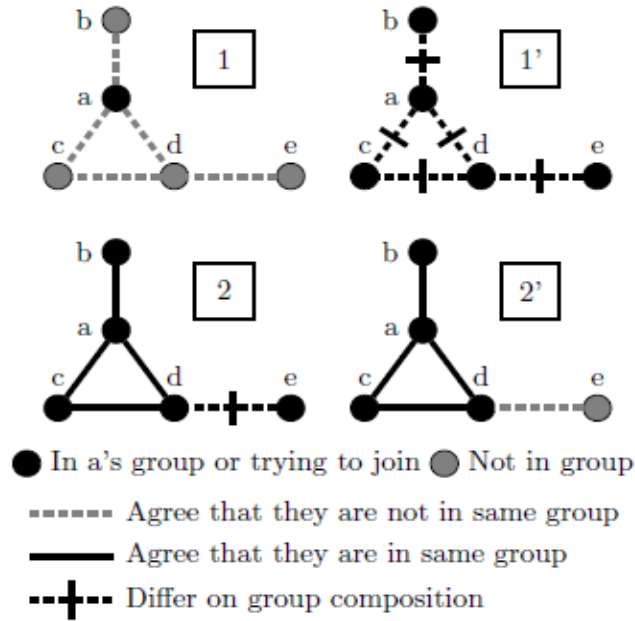


Figure 5: Self-stabilizing group [27, Fig.2]

For instance, let us consider the maximum distance among members of any group is fixed at 2-hops and apply the grouping algorithm for the given topology of nodes in the Figure 5. If we assume node a speaks first, in the first iteration node a broadcasts ($a: 0$) to the 1-hop directly connected nodes. Then after hearing from node a nodes b, c, d decide to join the group and broadcast ($b: 0, a: 1$), ($c: 0, a: 1$), and ($d: 0, a: 1$), respectively. Node e broadcasts ($e: 0, d: 1, a: 2$) (or ($e: 0, d: 1, c: 1, a: 2$) if c spoke before d). In the second iteration, after node a broadcasts ($a: 0, b: 1, c: 1, d: 1$) node d realized that the distance between b and e is greater than 2 hops and it excludes node e from the group. Hence the group stabilized on a, b, c , and d .

Since diameter of a group is constrained by a fixed maximum diameter, any passing by node can join a given group if the diameter of the group stays less than the maximum diameter after including the node. The self-stabilizing algorithm can result in a different group composition for a given topology configuration depending on which node speaks first. Each node has a priority within a group depending on the time when it joins a given group. This helps to create relatively stable groups.

For DTN routing, a group is treated as an individual node. The Binary spray and wait routing protocol is used for inter-group routing and each group will forward its extra copies to neighboring groups until the message arrives at its destination group. Here routing is performed by the border nodes (nodes that are in contact with nodes of adjacent groups).

When a border node learns that its group has acquired copies of a message that a neighboring group does not possess, it requests the message from its custodian (i.e. a node that has a copy of a given message) and passes it to the node of the adjacent group:

- If the adjacent group is a destination group.
- Or if its group has more than one copy, it requests

$\max (1, \lceil \frac{\text{number of copies}}{\text{number of current border nodes} \in \text{the group} + 1} \rceil)$) number of copies from its custodian and pass it on to the adjacent group.

When a border node receives a new message from other group it pass the message via intra-region routing if the destination node is in the group, otherwise it randomly chooses a custodian within the group.

HYMAD was evaluated on Roller net which is a dense and highly dynamic wireless connectivity trace of 62 participants of the regular Sunday afternoon roller blading tour in Paris, France. HYMAD outperforms spray and wait protocol in terms of delay and delivery ratio and it achieves delivery ratio almost as good as epidemic routing in a dense and highly dynamic wireless network.

3.1.2 Routing strategy in disconnected mobile ad hoc networks with group mobility

Like epidemic routing, Group-epidemic routing (G-ER) [29] is used here to disseminate copies of a message into network in hope that one of the copies will be delivered to the destination. But in Group-epidemic routing, a group is treated as a single node for inter-group routing and replicas of messages are exchanged between groups.

Intra-group packets are forwarded within a group by Destination-Sequenced Distance Vector routing (DSDV) protocol see Section 2.1 and nodes keep a list of members of their group. A group is formed by a set of end-to-end connected nodes that have the same mission and same group mobility. Each member follows the logical center (group leader) of the group. The Group leader chooses the destination randomly and each member of the group determines its speed and direction deviation in a random way from the speed and direction of the group leader. If any node wants to leave a group and join an other group, first it randomly generates a probability of leaving (P_l). Then if this probability of leaving (P_l) is greater than the threshold value (T_{gs}), and the number of current members of the group is greater than the minimum value, it can leave its group.

For inter-group routing, groups exchange their Group Summary Vector (GSV) so as to exchange packets that are not received yet and to prevent reception of already received messages. If any node receives new packets from another group, it updates its GSV first and then sends unicast packet to the leader of the group to inform the leader of the newly received packets. The leader of the group will broadcast a GSV update which also contains all 1-hop neighboring members of the group to the members and any member will rebroadcast the GSV update if some of its 1-hop neighboring members IDs are not in the GSV update. Then these IDs are appended to the GSV update.

After exchanging their GSV, those nodes of different groups in contact exchange their messages and if some members of a group have messages that the node in contact with other group doesn't have, they forward their messages to it. In this way groups manage to exchange only one copy of a message per a group when they encounter each other.

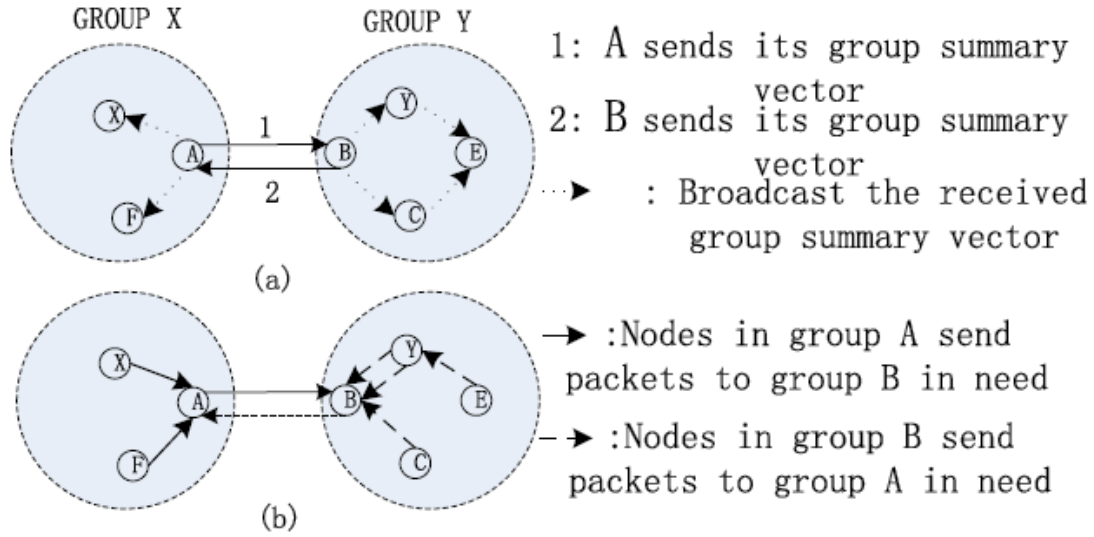


Figure 6: Main procedures in inter-group routing in G-ER. (a) GSV exchange and broadcast; (b) data packet exchange between two groups [29, Fig. 3]

G-ER also does buffer management in two ways. The first way is by providing priority to packets whose destination is within the group to maximize message delivery and the second way is by providing priority to inter-group packets with smaller number of traversed groups to be routed first before those packets with higher number of traversed groups. Moreover, nodes of the same group can do buffer sharing among each other.

G-ER shows better performance in terms of delivery Ratio and delay than Destination-sequenced distance vector routing (DSDV) and epidemic routing protocols.

3.1.3 Leader Based Group Routing with Group Mobility

Leader Based Group Routing [28] implements the same approach as in [29] for group formation and group management. Routing among mobile nodes within a group is done in similar manner via Distance Sequenced Distance Vector (DSDV) routing protocol.

The difference between this scheme and G-ER [29] is in Leader Based Group routing, the inter-group routing is dominated by the group leader. Normal members of a group act as merely requesters and forwarders of inter-group messages to/from the group leaders. Group leader coordinated and controls all activities of a group. The inter-group packets are stored at the group leader's buffer. When two nodes of different groups come close to each other, each node requests Group Summary Vector (GSV) from its respective group leader. After each node receives GSV of its group from its group leader, it forwards it to the other group and sends GSV of the other group to its group leader. Then each group leader decides which messages to send by comparing its GSV with GSV of the adjacent group. Thus the nodes forward received message to their group leaders. So here members of a group only act as requesters and forwarders of inter-group messages. Only the group leader updates the Group Summary Vector (GSV) and inter-group messages are only stored at group leader's buffer.

The main operations and principles of this approach has been studied and compared as part of our study in this thesis. In fact, in our study group mobility is adapted in a way that every member node's position relative to the logical center remains the same during the whole course of movement, and inter-group routing between adjacent groups is performed based on Binary spray and wait [23] protocol. Moreover, in our study mobile nodes build routing entries of their member

nodes based on the minimum hop count metric.

3.1.4 Group Based Routing in Disconnected Ad Hoc Networks

Group Based Routing in Disconnected Ad Hoc Networks [24] proposes proactive Distance Sequenced Distance Vector (DSDV) routing protocol for end-to-end connected nodes of the same group and PROPHET routing protocol for routing between disconnected groups of mobile nodes.

Initially, each node is in its own group and when nodes stayed connected for sufficient time period which is greater than the minimum group merge wait time T_m (this is a pre-set time duration to ensure nodes are not merging accidentally), a node with lowest ID among the nodes is chosen as a group leader. Then the lowest ID will be the group identifier (GID) of the group and the group leader will coordinate the group. When nodes of another group come in contact with nodes of a given group, a group merge operation can be carried out if the two groups stay connected for a time greater than the pre-defined minimum group merge wait time. If two groups agreed to merge, the lowest GID will be the group identifier of the new group and thus the node with the lowest id will be the leader of the new group.

When there is a group split, if the node with the lowest ID leaves the group, a node with lowest ID among the nodes remained in the group is chosen as the group leader and hence the old group identifier (GID) of the group will be replaced by the new group identifier. But if the node with lowest ID doesn't leave its group, the group identifier will remain the same and nodes of the group will only remove the nodes that leave the group from their routing table.

Hence unlike in [29] and [28], here mobile nodes form a group based on their connectivity among each other for a long time not based on their mission or direction. Also unlike HYMAD [27] there is no restriction on the number of members of a group and groups are relatively stable.

For intra-group routing, nodes use their routing table to forward messages to their destinations. But for inter-group routing, Group Based Routing in Disconnected Ad Hoc Networks scheme adapts PROPHET routing [13] at a group level. Groups calculate and update their delivery predictability to each other when they come in contact. Groups exchange their delivery predictabilities for all groups before they exchange messages. A given group with an inter-group message will send a copy to the other group if the other group has higher delivery predictability than its delivery predictability for a given destination group.

When groups merge, delivery predictabilities of the group with lowest group identifier (GID) will be taken as delivery predictabilities of the new formed group.

This approach performs good when the movement of the different groups is deterministic. In opportunistic environment, PROPHET routing [13] mechanism provides poor inter-group routing due to its dependability on the past delivery probabilities of a given group to a given destination group to predict the future delivery predictability of a given group.

3.1.5 Using group structures for efficient routing in delay tolerant networks

This scheme has implemented the same approach as in [24] for group formation and group management. Routing among mobile nodes within a group is done in similar manner via Distance Sequenced Distance Vector (DSDV) routing protocol.

Unlike the replication method in [24], this scheme introduces controlled replication for inter-group messages. This approach limits the number of replica generated by a source node depending on the value of delivery predictability of the source group to the destination group and the expected number of hops from the source group to the destination group. If the delivery predictability value is small or if the expected number of hops is very large, the source node generates a large number of

replicas. So when a node with certain number of copies of a given message comes in contact with a node of an other group with higher delivery predictability, that doesn't have a copy of a given message, the two nodes share the number of copies according to the difference between the two delivery predictability values and the number of expected hops of the two groups to the destination group.

For example, if node u of group A has m number of copies of a message that is destined to node of group C and group B has higher delivery probability than group A to group C , then when node v of group B has comes in contact with node u of group A node v will get n replicas of the message as follows:

$$n = m \times \{1/2 + (DP_{BC} - DP_{AC}) \times \Phi + (1/2 - (EH_{BC}) / (EH_{AC} + EH_{BC}))\} \times \Psi$$

Where, DP_{BC} is the delivery probability of group B to group C , DP_{AC} is the delivery probability of group A to group C , EH_{BC} is the expected number of hops from group B to group C , EH_{AC} is the expected number of hops from group A to group C . And Φ & Ψ are multiplication factors, $0 \leq \Phi, \Psi \leq 0.5$ and $\Psi + \Phi = 0.5$

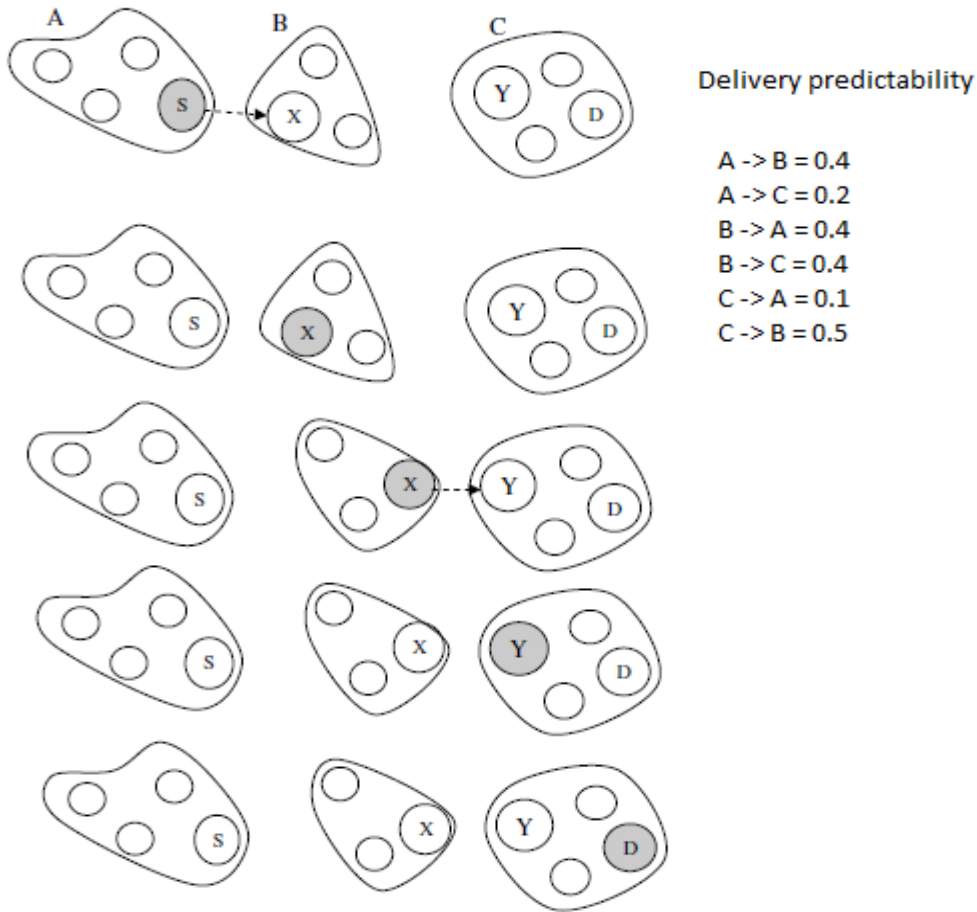


Figure 7: Inter-group packet forwarding from node S of group A to node D of group C [25, Fig. 3].

3.1.6 Island Hopping: Efficient Mobility-Assisted Forwarding in Partitioned Networks

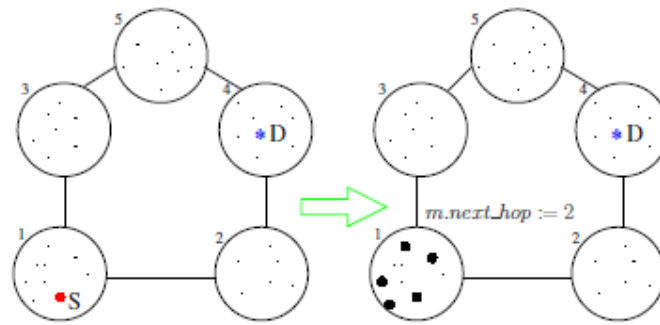
Island hopping [22] proposes an efficient mobility-assisted forwarding scheme for ad-hoc networks that get partitioned in to different stable regions (Concentration points (CPs) where the density of nodes is relatively high).

In each CP, nodes are directly connected with each other and they can communicate via direct connectivity. Flow of nodes occurs frequently between the concentration points and thus a mobility-assisted forwarding algorithm called Island Hopping (IH) is proposed to efficiently route data between the concentration points.

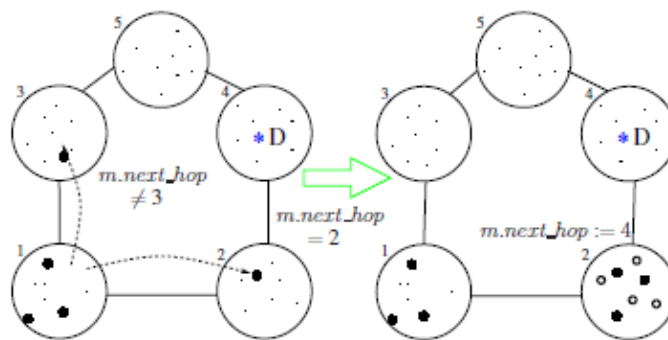
The IH algorithm works as follows:

A source node S at vertex (CP) u generates a message m and makes some copies of it.

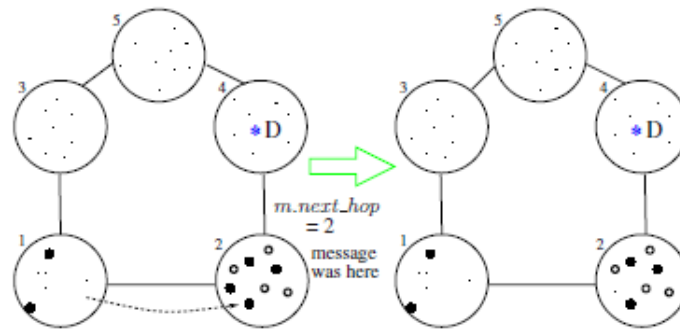
- If the location of the destination node is known, the next hop field is set to the desired next vertex and any node that moves to the desired next-hop vertex carries the message and generates some copies of it at the new vertex. Any node heading from this desired next-hop vertex v to the previous vertex u of the message carries one-hop acknowledgment and broadcasts ACK at the previous vertex u so as to inform the nodes in that vertex to discard the remaining copies. The same process continues until the message is delivered to its destination. But if a node that carries a copy of the message moves to another vertex (i.e. different than the desired next- hop of the message), the message will be discarded at the next vertex.
- But if the location of the destination node is unknown, every node has Last Encounter Table (LET) for other nodes it encounters and thus the source node polls all nodes at its vertex for recent information of the location of the destination node. This estimate is used for determining the next hop of the message.



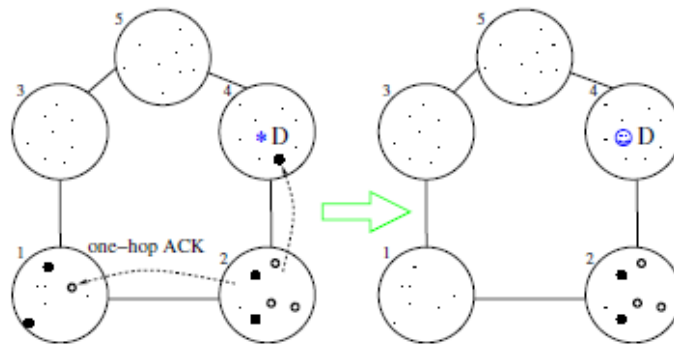
(a) Node S originates a message m to node D .



(b) Node with a copy of m moves to another vertex.



(c) Node with a copy of m moves to a vertex where m has already been observed.



(d) One-hop acknowledgment.

Figure 8: Island Hopping example: small dots - nodes without a copy of m ; large dark dots - nodes with a copy of m ; empty dots at a vertex - nodes without a copy of m , but that know that m was at this vertex. The location of destination node D is known (i.e at vertex 4) [22, Fig. 4]

3.1.7 Efficient Adaptive Routing in Delay Tolerant Networks

Efficient Adaptive Routing (EAR) [14] focuses on dynamic allocation of available bandwidth between multi-hopping (MANET) routing and mobility-assisted routing.

In EAR, each node forms a logical cloud of nodes that have an end-to-end connectivity with it. Nodes are added to logical cloud of a given node based on their hop-count from the node. Any passing by node can be added to the logical cloud of a given node if the number of nodes in the logical cloud is less than the maximum value or if it has small hop-count from the given node compared to some of the nodes in the logical cloud. Nodes with small hop-counts have high priority. Each node routes a message by multi-hop forwarding if its destination is in its logical cloud and sprays a message if the destination is not its logical cloud. Thus by limiting the size of the logical cloud the maximum bandwidth consumed by multi-hop forwarding is limited. For MANET routing within the logical cloud a Distance Sequenced Distance Vector (DSDV) routing protocol is used.

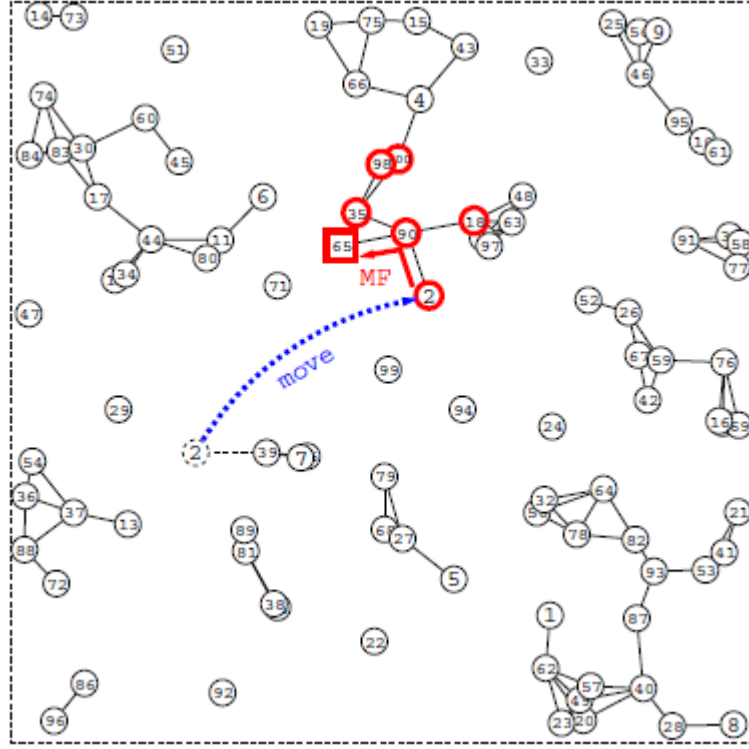


Figure 9: The logical cloud of node 65 with cloud size = 7 originally consists of nodes 18, 35, 65, 90, 98, 100, and 97 [14, Fig. 1]. After node 2 connects to node 90, node 97 is excluded from the logical cloud since node 2 has smaller hop-count compared to node 97 from node 65.

For mobility-assisted routing, a modified spray and wait routing protocol is used. Unlike the original spray and wait routing protocol there is no fixed number of nodes that a message should be forwarded to, the modified spray and wait routing instead use the rest of the bandwidth (Total bandwidth - bandwidth consumed by DSDV) to deliver messages. Each message has a logical ticket and when two nodes exchange the message, the logical ticket value is divided in to two and thus to provide equal chance of spraying, messages with higher logical ticket values get sprayed first. The logical ticket value is used for providing priority to those messages that traveled less distance.

Total Bandwidth of each node is accommodated into bandwidth allocated for spraying (B_s), bandwidth allocated for multi-hopping forwarding (B_f) and into the bandwidth required for route maintenance within the logical cloud (B_p) of each node. EAR aims to maximize the bandwidth utility, which is the ratio of the total messages delivered to the total messages consumed in the network and it is calculated as follows:

$$U = \frac{R_c}{B_s + B_f + B_p}, \text{ where } R_c \text{ represents messages delivered,}$$

B_s bandwidth consumption of spraying,
 B_f bandwidth consumption of forwarding,
 B_p bandwidth consumption of route maintenance.

Maximize bandwidth utility ($U = R_c / B$) is achieved when the average cloud size $C = \sqrt{2N}$ where N is network size. The optimal cloud size C can also be approximated by the estimated values of B_s and R_c as follows:

$$C = 2 B_s / R_c$$

Thus according to the statistically estimated values of B_s , R_c , the value of C can be varied to

maximize bandwidth utility. EAR has achieved better bandwidth utility and delivery ratio than spray and wait protocol.

3.1.8 CAR: Context-aware Adaptive Routing for Delay Tolerant Mobile Networks

CAR [16] is a single copy routing protocol and applies prediction (forecasting) technique to route message to its destination. Next hop to the destination is chosen based on Kalman Filter prediction (“a method of discrete signal processing that provides optimal estimates of the current state of a dynamic system”) and multi-criteria decision of attributes.

Each host calculates its delivery probabilities to different hosts based on different context attributes. CAR mainly focuses on two attributes, change of degree connectivity and the future host co-location. Each attribute has its own utility and Utilities are calculated at a given time t .

Kalman filter predictors take the utility values of the attributes at time t to predict future values at time $t+T$. These future estimate utilities are composed based on the weight importance of the attributes. So composition of the future estimates represents the delivery probability.

Delivery probability = $\sum_{i=1}^n w_i U_i(x_i)$ }, w_i represents the importance of the attribute & U_i represents estimated utility of attribute x_i .

The calculated delivery probabilities are periodically broadcast together with the update routing information to the other hosts in the connected region. Each host keeps an entry with fields (destination, best Host, delivery Probability) in a logical forwarding table for all known destinations. A set of end-to-end connected nodes forms a temporary group. When a node in a group generates a message if a recipient (destination) of the message is in the same group as the source node, the message is forwarded based on Destination-sequenced Distance vector (DSDV) routing protocol. But if the destination node is not in the same connected region, best carrier of the message is determined based on highest delivery probability and thus the message is sent to the best carrier using DSDV protocol. Then the best carrier mobile node forwards the message if it comes in contact with other mobile node with high delivery probability or if it joins a group that includes the destination node.

3.1.9 Adaptive Routing in Mobile Opportunistic Networks

Lakkakorpi et al. [12] has carried out initial simulations on synthetically generated random way point (RWP) models and they have found out that MANET routing is unsuitable for forwarding large message size if the path life time is very short compared to estimated transmitting time, and /or the network density is sparse. However, in dense environment MANET routing performs better than DTN routing in terms of delivery ratio and delay. On the other hand, DTN routing outperforms MANET routing when the network is sparse, nodes move fast, and messages are big.

Thus they have proposed an adaptive routing scheme that enables the application layer of a source node to choose between MANET and DTN routing depending on the current network density, node velocity and message size in opportunistic networks. Message size and node velocity can be determined locally whereas the network density can be estimated based on the number of adjacent nodes. Once the source node chooses one of the routing schemes the intermediate nodes forward the message according to the chosen routing scheme.

Algorithm 1 Send file: *AODV OR DTN*

```
send Probe to DST node
if  $T_{probe\_reply} < T_p$  then
  get  $k \leftarrow hopcount_{DST}$ 
  get  $n \leftarrow AVG(count_{NEIGHBORS})$ 
  get  $T_l \leftarrow AVG(TTL_{link})$ 
   $R = bw/k * n/n_{ref}$ 
  if  $size_{file}/R > T_l$  then
    sendViaDTN
  else
    sendE2E
  end if
else
  sendViaDTN
end if
```

Figure 10: Adaptive routing Algorithm [12]; exponentially averaged link lifetime (T_l) is used as an estimate for the path lifetime. Hop count (k) is obtained from the probe packet reply while the exponentially averaged number of neighbors (n) and the averaged link lifetime are obtained from the DTN agent.

In addition to the synthetically generated random way point (RWP) model, Adaptive routing is evaluated on the following two real-life traces:

- San Francisco Cab trace: it is a GPS based mobility traces of San Francisco taxi cabs collected over 30 days in the San Francisco Bay Area. For the evaluation of adaptive routing scheme, a trace file (area dimensions: 5700 m times 6600 m) with 116 cabs tracked over a period of 3600 seconds is used.
- Helsinki Synthetic trace: it is a more dense mobility trace of 116 nodes that were configured to move between selected points of interest around Helsinki city centre. This trace provides a dense network scenario compared to San Francisco taxi scenario, which is relatively sparse and it is also a period of 3600 seconds.

Results obtained using random way point, San Francisco Cab trace and Helsinki Synthetic trace show that Adaptive routing outperforms pure AODV and pure DTN routing schemes in opportunistic environments other than in dense environment where AODV provides lowest delay.

3.1.10 Integrating DTN and MANET Routing

Integrating DTN and MANET routing [17] scheme enhances the delivery of a message by exploring the possible synchronous communication (end-to-end connection) and asynchronous (DTN) communication options between the source and sink nodes. The application layer of the source node is empowered to choose between the available communication options and hence it can route its message via the optimal option. All nodes are not required to support DTN communication.

AODV's route discovery process has been extended to accommodate DTN-specific information. Like AODV routing, when a node generates a message it broadcasts a RREQ packet to all

neighbors. But here nodes append their DTN routing information to RREQ and RREP packets to indicate their DTN capability and they can update their DTN entries about other DTN capable nodes from these packets as well. Non-DTN capable nodes propagate RREQ and RREP packets along the path by only processing the fields relevant to them.

If the target node is DTN capable, it simply copies the DTN routing information appended along the path to the RREQ packet to the RREP packet generated. But if the target node is not DTN capable it sends back the RREP packet and the DTN capable nodes along the path append their DTN routing info to the RREP packet.

After the originator node receives the RREP packet, it will learn the available DTN capable nodes along the path and the end-to-end connection. The originator then decides whether to transmit the message using the synchronous MANET routing or DTN routing based on the message size and the route stability. If DTN routing is chosen, the originator picks the suitable next-hop DTN nodes to route the message. Multi-hop end-to-end routing can be supported between two DTN capable nodes to enhance communication.

Integrating DTN and MANET routing scheme empowers any one of the DTN capable nodes to take responsibility to generate RREP packet when route discovery fails or the time out to receive RREP packet expires. For each route discovery only one DTN capable node take role of monitoring the route discovery process and the nodes alternatively take the role on each route discovery process.

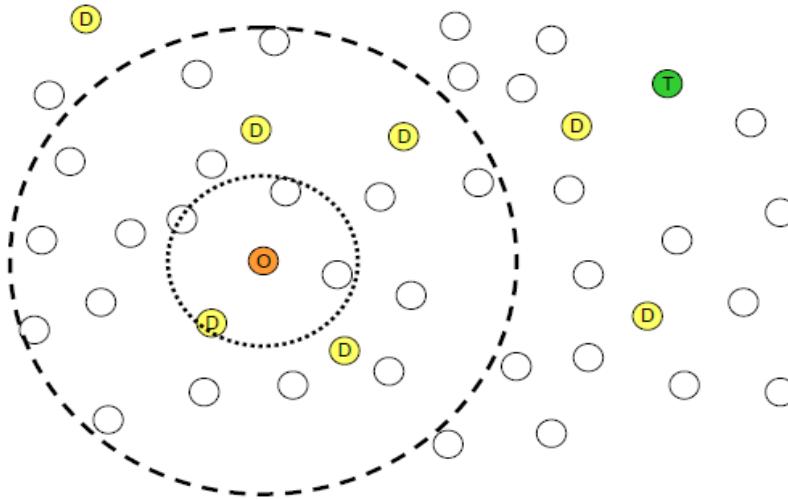


Figure 11: Inner dotted circle marks the immediate neighbors of DTN node O while the outer dashed circle shows the reach if up to three hops are supported by mobile ad-hoc routing. At the same time, including DTN-based routing expands the reach of the originator via multiple DTN hops to the target T which would not be reachable with AODV alone [17].

3.1.11 STAR: Storage Aware Routing Protocol for Generalized Delay Tolerant Networks

STAR [10] is an extended Optimized link State routing protocol (OLSR) for efficient routing at variable mobile and wireless scenarios. STAR learns short term and long term route costs to determine link cost variations due to channel fading and node mobility. Expected packet transmission time (a ratio of packet size to highest transmission rate) is used as a metric to determine the short term and long term link costs. The short term cost is the Expected packet transmission time (EPTT) reported in the most recent message while the long term cost is calculated as the average of the EPTTs reported in consequent “Hello” and “TC” messages.

Every node n_k broadcasts information about its available storage and the best transmission rate can use with each neighbor n_i with its hello message. Moreover, by its Topology Control (TC) messages node n_k broadcasts the most recent Expected packet transmission time for every known destination. Then STAR finds all the shortest (minimum fixed cost)) paths to each destination from the network topology table

If the difference between short term (ste) and long term (lte) Expected packet transmission time along the shortest path is:

- within $\pm \beta \times ste$, it is a candidate forwarding path
- less than $-\beta \times ste$, it is a candidate opportunistic forwarding path
- greater than $\beta \times ste$, the path is slower than usual and data should be stored until the path improves.

Where β represents weightage on long term cost. STAR has been evaluated on Truncated Levy Walk (i.e. a random walk which uses movement lengths and pause times that are drawn from a truncated Pareto distribution) mobility model and has achieved higher throughput but with high end-to-end delay compared to OLSR routing protocol.

3.1.12 A Mobile Ad Hoc and Disruption Tolerant routing protocol for tactical networks

In Tactical military networks, communication between nodes can happen synchronously and /or asynchronously at different parts of the network at the same time. And hence an optimal routing protocol is needed that enhances smooth transition between these two ways of communication. NOMAD [8] extends the proactive OLSR protocol to handle disruptions. In OLSR, every node builds local route table based on local information base (set of actual links for one hop neighbors), neighbor information base (information about one and two hop neighbors), and topology information base. This information is gathered by processing periodic hello messages and Topology control (TC) messages that are generated by multi-point relay (MPR) nodes.

NOMAD protocol adds imaginary routes to handle disruptions, in addition to the real routes constructed from the TC messages. When actual link between two neighbor nodes get broken, these nodes act as DTN selector nodes that generate imaginary TC messages. DTN selector nodes send imaginary TC messages to inform the nodes affected by the disruption that they will act as store-carry- forward routers and hence messages can be forwarded to the DTN selector nodes.

NOMAD supports DTN selector set (a list of DTN selectors and all nodes that are reachable via the DTN selectors) and DTN update sets (a list of nodes removed from the DTN selector nodes) on top of the repositories supported by the OLSR.

NOMAD implements two cache mechanisms; packet based PDU cache mechanism, and Message based PDU cache mechanism to handle short term and long term disruption respectively.

Results show NOMAD protocol outperforms Conventional MANET routing for a tactical mobility model generated by SWarMM tool. SWarMM tool is agent based mobility model generator that aims to produce a more representative mobility model of complex warfare. In this tool, the behavior of an ordinary mobile node is defined as a hierarchy of three layers: Action selection, Steering, and Locomotion. Locomotion is the movement pattern of the mobile node which is guided by a set of steering(guiding) vectors such as seek, pursuit, obstacle avoidance, wander and path following and the action selection controls the mobile node response depending on triggers received from the steering behavior.

3.1.13 Trust Based Algorithm for Candidate Node Selection in Hybrid MANET-DTN

When mobile nodes are end-to-end connected to each other, efficient communication can be

implemented by one of the Conventional MANET routing algorithms. But when end-to-end connection between source and destination nodes doesn't exist due to different reasons, DTN way of communication must be implemented.

Trust Based Algorithm [18] focuses on secured delivery of messages when there is disconnection between nodes and the selection of secure mobile nodes. When there is a stable connection, nodes exchange routing information among each other via DSR routing protocol and each node keep record of the number of RREQ packets, RREP packets, RERR packets and data packets from every node it met in a dynamic structure in memory. Based on the obtained data and routing information, each node locally computes trust values of the nodes. Trust value is computed as follows:

$$T_s = W_{rreq} \left(\frac{R_{req}}{R_{reqc}} \right) + W_{rrep} \left(\frac{R_{rep}}{R_{repc}} \right) + W_{rerr} \left(\frac{R_{rerr}}{R_{rerrc}} \right) + W_{rack} \left(\frac{R_{rack}}{R_{rackc}} \right) \quad (1)$$

$$T_d = W_d \left(\frac{D}{DC} \right) \quad (2)$$

$$T = T_s + T_d$$

Where, R_{req} represents the number of RREQ packets received from a given node,

R_{rep} represents the number of RREP packets received from a given node,

R_{rerr} represents the number of error messages received from a given node,

R_{rack} represents the number of ACK packets received from a given node,

R_{reqc} represents total number of RREQ packets received,

R_{repc} represents total number of RREP packets received,

R_{rerrc} represents total number of error messages received,

R_{rackc} represents total number of ack packets received,

D is the data packets received from each node and DC is total data packets received, and

W_{rreq} , W_{rrep} , W_{rerr} , W_{rack} , W_d are constants, which define a weight of trust value.

According to the computed trust values each node select a node with highest trust value as a secure next-hop mobile node to send data to its corresponding destination when there is no end-to-end connection with the destination (i.e. when there is disconnection/disruption in the network).

3.1.14 Combining on-demand and DTN routing for intermittently connected networks

Space-content-adaptive-time routing (SCaTR) [3] is an extension of on-demand routing to efficiently route messages between source and destination nodes when end-to-end connection doesn't exist (i.e. when source and destination nodes are in different partitions.)

SCaTR requires each node to maintain time-dependent distance to other nodes in the network. Each node's contact value for another node depends on their past connectivity history. When a source node generates a message, it broadcasts proxy request (PREQ) to find a direct route if the source and destination nodes are in the same partitions of the network or to find proxy that is closest (with highest contact value) to the destination among the nodes in the same partition if source and destination nodes are in separate partitions.

When a node receives a PREQ packet if it has higher contact value than the source node, it will send PREP (proxy response) with its contact values and rebroadcast the PREQ in case there are other proxies with higher contact values. But if it has lower contact value than the source node or if it doesn't has contact value, it doesn't send PREP packet to the source node it only broadcasts the PREQ packet to other nodes. But when a node has direct route the destination informs the source node about it and the source node chooses the direct route.

If there is no direct route, the source node chooses at most two proxies for a given destination based on the gathered PREP packets. Then the source node makes one copy of the packet and sends one

packet to each proxy. Each proxy can send PREQ packet to find other node with highest contact value until the message arrives to the destination. But copying of the message is only done once at the source node.

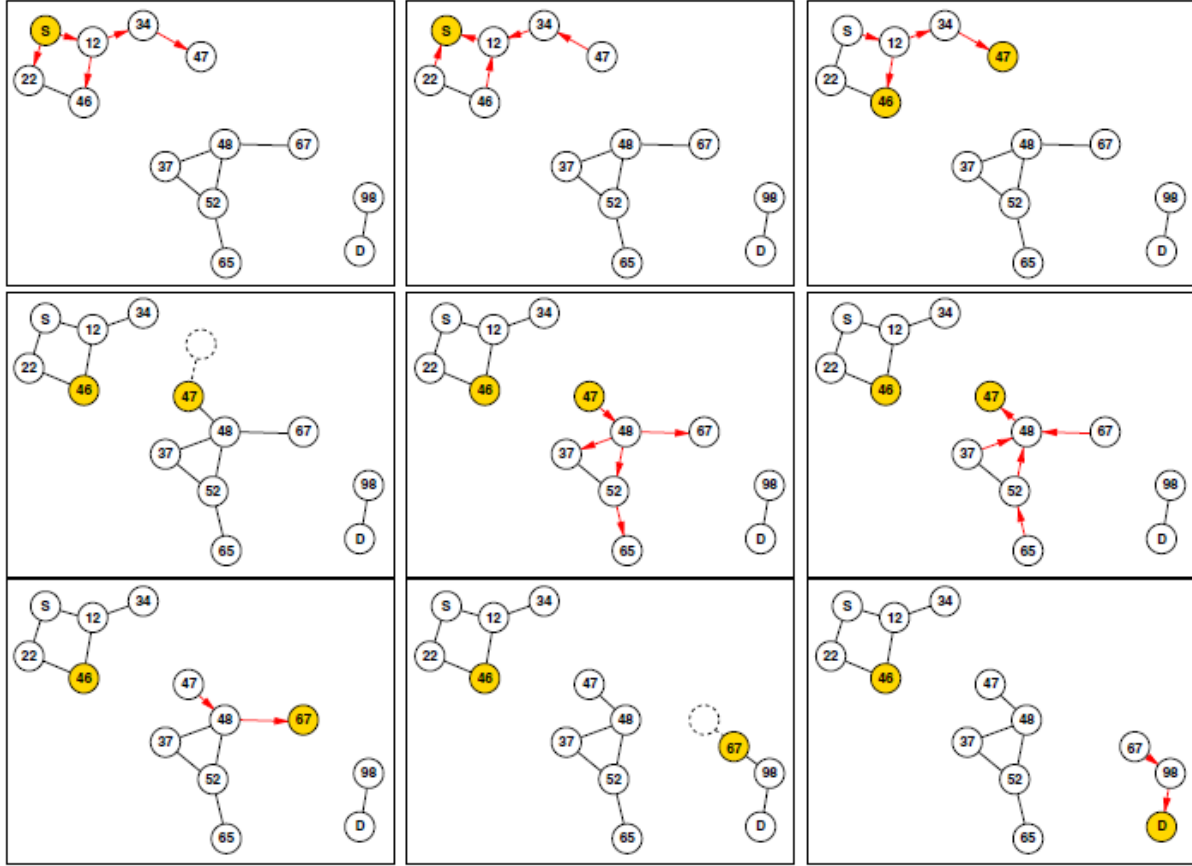


Figure 12 [3, Fig. 1] : Routing from source node S to node D. Numbers inside nodes indicate their contact value to node D. node S first finds two proxy nodes with high contact values and then sends one copy to each proxy. Then a node with 47 contact value finds new proxy with highest contact value when comes in contact with another connected group and forwards the message to it.

3.2 Comparison of hybrid MANET-DTN routing schemes

The hybrid MANET-DTN approaches that have been considered in Section 3 apply different combination of MANET and DTN routing protocols for efficient data dissemination between disconnected nodes. In general, the hybrid MANET-DTN routing schemes aim to provide efficient routing by applying the conventional MANET routing for communication among end-to-end connected nodes and DTN routing when MANET routing is not possible or the situation is such that DTN routing provides better delivery ratio and/or minimum average delay compared to MANET routing.

3.2.1 Performance metrics and mobility models

Hybrid MANET-DTN routing schemes are evaluated using different performance metrics. Delivery ratio and average delay are the common metrics for all hybrid MANET-DTN routing schemes. In addition, some hybrid MANET-DTN routing schemes are evaluated by other metrics such as number of transmissions per message, bandwidth utility, average hop count, overhead, average number of salvage packets, and predictability level of context attribute (accuracy of the prediction

of context information) to determine their performance.

The performance of different hybrid MANET-DTN routing schemes is also evaluated by different mobility models that represent the mobility patterns of real mobile nodes. The mobility models broadly can be categorized in to group mobility models that represent mobile nodes whose movements are dependent on each other and entity mobility models that represent mobile nodes whose movements are independent of each other.

A summary of the mobility models and performance metrics of hybrid MANET-DTN routing schemes used in the papers summarized in Section 3 is presented in Table 1 below.

Table 1: Mobility models and performance metrics of hybrid MANET-DTN routing schemes

Protocols	Mobility models	Performance metrics
HYMAD [27]	Two mobility models: 1) Random Waypoint Mobility model. 2) Rollernet connectivity trace.	1) Delivery ratio 2) Average delay
Routing strategy in disconnected mobile ad hoc networks with group mobility [29]	1) Reference point group movement	1) Delivery ratio 2) Average delay
Leader Based Group Routing in Disconnected Mobile Ad Hoc Networks with Group Mobility [28]	1) Reference point group movement	1) Delivery ratio 2) Average delay
Island hoping [22]	1) Nodes perform random walk from one region to another region (location of a node is either at a region or at route between regions)	1) Delivery ratio 2) Average delay 3) Number of transmissions per message
Using group structures for efficient routing in delay tolerant networks [25]	Three mobility models are used: 1) Random way point model 2) In-Place model - It is a type of RPGM mobility model in which the entire field is divided into several adjacent regions and each region is exclusively occupied by a single group. 3) Community model.	1) Delivery ratio 2) Average delay
Group Based Routing in Disconnected Ad Hoc Networks [24]	Three mobility models are used: 1) Random way point model 2) In-Place model 3) Community model.	1) Delivery ratio 2) Average delay
EAR [14]	1) Random waypoint mobility model.	1) Delivery ratio 2) Bandwidth utility
CAR [16]	1) Community based model	1) Delivery ratio 2) Average delay 3) Predictability level of context attribute.
SCAR [30]	1) Trace generated by Zebranet trace generator	1) Delivery ratio 2) Average delay
Integrating DTN &MANET [17]	Not mentioned	1) Delivery ratio
STAR [10]	1) Truncated Levy Walk mobility model	1) Delivery ratio

NOMAD [8]	1) A tactical mobility model generated by SWarMM tool. Ten Blue Force (BLUFOR) squads were made to clear randomly chosen Patrols.	1) Delivery ratio
Trust Based Algorithm for Candidate Node Selection in Hybrid MANET-DTN [18]	1) Random waypoint model	1) Average number of salvage packets 2) Average delay 3) Average hop count
Combining on-demand and opportunistic routing for intermittently connected networks. [3]	1) Gridded random waypoint 2) Scheduled routes 3) Random waypoint model	1) Delivery ratio 2) Signaling ratio(overhead)
Adaptive Routing [12]	1) Random waypoint model. 2) San Francisco Cab Trace 3) Helsinki Synthetic Trace	1) Delivery ratio 2) Average delay 3) Average hop count

3.2.2 Group-based hybrid MANET-DTN routing schemes

Hybrid MANET-DTN routing schemes that are discussed in Section 3 can be broadly categorized into hybrid MANET-DTN routing schemes that apply explicit grouping of mobile nodes and hybrid MANET-DTN routing schemes that don't apply explicit grouping of mobile nodes. Hybrid MANET-DTN routing schemes that apply explicit grouping of mobile nodes, adapt different ways of group formation and group management. In addition to an end-to-end connectivity between mobile nodes, each explicit group-based hybrid MANET-DTN routing scheme that has been studied in Section 3 considers one of the following criteria for group formation:

- Mission (Task): Mobile nodes that have the same target or task move together as members of the same group.
- Connectivity for sufficient time duration to ensure nodes are not merging accidentally
- Maximum diameter of a group: sizes of groups of mobile nodes are restricted by fixed diameter value.
- Maximum number of nodes to be contained in a group

Explicit group-based hybrid MANET-DTN routing schemes also implement different replication strategies for inter-group routing. Some protocols focus on improving delivery rate by implementing unlimited replication mechanisms and others aim on reducing overheads by limiting the maximum number of copies that can exist in a network.

Group formation and management

Group-based hybrid MANET-DTN routing approaches handle group formation and management in different ways.

In [28] and [29], a group is formed by a set of nodes that have the same mission (task) and same group mobility. A group leader coordinates the group and chooses the next destination randomly, and ordinary members move relative to the group leader. When nodes of different groups come close, a member node of one group can leave its current group and join the other group if the node generates a probability that is higher than threshold value (T_{gs}) and if the number of members of the current group are greater than group minimum (G_{min}). The threshold value is a very high value and hence nodes will have a very small chance to leave their groups. Whereas in [27] and [14] group

formation is based on physical proximity of mobile nodes. HYMAD [27] limits the diameter of a group to be less than a fixed maximum diameter. Any passing by node can join a given group if the diameter of the group stays less than the maximum diameter after including the newcomer node. But EAR [14] limits the number of the nodes that are considered as members of logical cloud(group) of a given node and any passing by node can be included in the logical cloud of a given node by replacing a member node with high hop count if the newcomer node has smaller hop count. Since mobile nodes move independent of each other, group formation and management is very dynamic in HYMAD and EAR. In [24] and [25] mobile nodes are required to have end-to-end connectivity for time duration greater than the minimum group merge wait time (this is a preset time duration to ensure nodes are not merging accidentally) to be considered as members of the same group. Island hopping assumes that a network possesses stationary stable regions where the density of nodes is relatively high and mobile nodes within a stable region are directly connected and they are considered as members of the same group.

Intra- and Inter-group routing

For intra-group routing, majority of the group-based hybrid protocols apply Destination-Sequenced Distance Vector routing (DSDV) protocol. HYMAD and Island Hopping use a simple distance vector algorithm for intra – group messages.

For inter-group routing, these different group-based hybrid MANET-DTN schemes apply different routing mechanisms. In [29] and [28], Epidemic routing is used for inter-group routing. Whereas in [24] and [25] PRoPHET routing protocol is applied with unlimited and limited replication method, respectively. Moreover, HYMAD and EAR implement binary spray and wait protocol and spray and wait protocol respectively for inter-group routing. The Island hopping forwards inter-group messages using mobile nodes that move to other groups.

In the table below group formation, group management, Replication mechanism, and intra-and inter-group routing protocols of each group-based hybrid MANET-DTN routing scheme is discussed.

Table 2: Comparison of group-based hybrid MANET-DTN schemes

Protocol	Group formation	Group management	Replication mechanism	Intra-group routing scheme	Inter-group routing scheme
HYMAD [27]	- An end- to- end connected set of nodes that have a diameter less than a predefined maximum diameter (D_{max}) among each other form a group. - Every member node knows its hop distance from all every other member nodes of its group.	- As long as the diameter of a given group is less than the maximum diameter, any new coming node can join the group. - Group membership is dynamic.	- Multi-copy - If a border node of a given group that has more than one copy of a given message comes in contact with node of adjacent group that doesn't have a copy of the message, it forwards max $(1, \lceil \frac{\text{number of copies}}{\text{number of border nodes}+1} \rceil)$ number of copies to the node of the adjacent group	- Distance vector algorithm.	- Binary spray and wait protocol
Routing strategy in disconnected mobile ad hoc networks with group mobility [29]	- Nodes with the same mission grouped together in a predetermined way (i.e. nodes within a group move with a group mobility and they have end-to-end connection among each other).	- Members of a given group stick together with common purpose (mission). - Mobile nodes have a small chance of leaving their group or joining another group. - Group membership is fixed	- Multi-copy. - If a group has a copy of a message, it forwards one copy for every group it meets.	- Destination-Sequenced Distance vector routing	- Epidemic routing for inter-group routing.
Leader Based Group Routing in Disconnected Mobile Ad Hoc Networks with Group Mobility [28]	- Same as in [29]	- Same as in [29]	- Same as in [29]	- Destination-Sequenced Distance Vector routing	- Epidemic routing protocol - Inter-group messages are stored only in the <i>group leader</i>.

Island hopping [22]	- Island hopping assumes a Network that possesses stationary stable regions where the density of nodes is relatively high. - Nodes within a stable region are directly connected and they are considered as members of the same group.	- Mobile nodes move freely among the regions.	- Multi copy - A source node makes some copies of a given message and any mobile node that carry a copy of a given message makes some copies when it arrives at the desired next-hop region if the region doesn't receive copy of a given message before. Only one copy survives to the Next-hop region. And any node that moves to the previous- hop of a given message carries one-hop acknowledgement from the desired next hop. - This way of forwarding copy of a given message between regions continues until a copy arrives at destination.	- Direct connectivity	- Mobility assisted forwarding is used between different regions. - A mobile node that carries copy of a message from one region to the desired next - hop region makes some copies at the next - hop region. Only one copy survives to the Next-hop region.
Using group structures for efficient routing in delay tolerant networks [25]	- Nodes that remain end-to-end connected for sufficient period of time form a group	- Adjacent groups that remain connected for sufficient period of time can merge to form a new group. - Nodes can leave a group at any moment. - Group leader (i.e. node with the lowest ID) coordinates members of a group. - Group membership is dynamic.	- Multi copy - The maximum number of copies is limited. - Meeting groups share copies of a given message according to their difference of delivery predictability and expected number of hops to the destination group.	- Destination-sequenced distance vector routing	- PProPHET routing with controlled replication
Group Based Routing in Disconnected Ad Hoc Networks [24]	- Nodes that remain end-to-end connected for sufficient period of time form a group	- Same as in [25]	- Multi copy - A given group with copy of a message keeps forwarding one copy every time it encounters a group with higher delivery predictability. - Groups exchange copies based on their delivery predictability for a given message.	- Destination-sequenced distance vector routing	- PProPHET routing.

EAR [14]

- Each node forms a logical cloud of nodes that are end-to-end connected with it. The number of nodes within a logical cloud is fixed.
- A given node adds any new arrival node to its logical cloud if the new arrival node has smaller hop- count compared to some of the nodes' hop-counts from the given node in the logical cloud.
- Hop count is used as a priority metric for including a passing by node to logical cloud.
- Size of a logical cloud is fixed
- Multi Copy
- A given node uses Spray and wait protocol to spray copies of a message if the destination is not in its logical cloud.
- Destination-sequenced distance vector routing is used within logical cloud
- Spray and wait protocol is employed for spraying a message if its destination is not in the logical cloud.

3.2.3 Hybrid routing schemes that don't apply explicit grouping of mobile nodes

Unlike group-based hybrid MANET-DTN routing schemes, these schemes don't apply explicit grouping of mobile nodes. These schemes focus on transmitting a given message to its destination either via only MANET routing or DTN routing or by applying both types of routing at different parts of the network based on the local information of the network.

In [17] and [12], the application layer of a source node decides to use either DTN or MANET routing algorithm for a given message delivery based on the local information gathered by route discovery packets. Other schemes use MANET routing at parts of a network where there is an end-to-end connection among mobile nodes and DTN routing at parts of a network where there are disruptions or link breaks between nodes.

Table 3 below shows replication and routing mechanisms of each hybrid MANET-DTN scheme.

Table 3: Comparison of hybrid MANET-DTN routing schemes that don't apply grouping of mobile nodes

protocol	Replication mechanism	Routing
Integrating DTN &MANET [17]	- Single copy	- Extended AODV route recovery is used to locate DTN capable nodes and non-capable nodes. - AODV routing is used if the source application chooses MANET communication. - If the source node supports bundle protocol, it can choose to transmit by DTN routing mechanism.
STAR [10]	- Single copy	- OLSR routing is used if there is end-to-end connectivity. - Data is stored if unusual link variations (disruptions) occurred along the path.
NOMAD [8]	- Single copy	- OLSR routing is used if there is end-to-end connectivity. - If path is broken between two nodes, these nodes will act as Store-Carry -Forward routers to all affected nodes.
Trust Based Algorithm for Candidate Node Selection in Hybrid MANET-DTN [18]	- Single copy	- AODV routing algorithm is used if there is end- to-end connection. But if connection between source and destination nodes doesn't exist, a given node with a message selects a secured next - hop mobile node based on trust value.
Adaptive Routing [12]	- Multi-copy	- A source node chooses either to use MANET or DTN routing depending on the local information about network density, message size and node velocity. - AODV is used for MANET communication. - Epidemic routing is used for DTN communication. - DTN routing can be preferred to MANET routing if the estimated message life time is greater than path life time or if the network

density is sparse.

CAR [16]

- Single copy
- Best carrier is determined by prediction technique and multi-criteria decision of attributes.

- Destination-Sequenced Distance vector routing is used for MANET communication.
- Mobility-assisted routing is used when there is no end-to-end connection to a destination node. Best carrier node carries a message from one group to another group.

Combining on-demand and opportunistic routing for intermittently connected networks. [3]

- Two-copy; Original message and one backup copy are used.

- AODV is used for MANET communication.
- If there is end-to-end connection to destination node, a source node selects two proxy nodes (based on contact values) that are deemed closest to the destination and transmits each copy to each proxy. And each proxy forwards the message to another node with higher contact value when they get connected to other partition.

3.3 Summary

We have studied different hybrid MANET-DTN routing schemes that are proposed for data dissemination in opportunistic networks of mobile nodes and we have learned that these different routing schemes have implemented different ways of grouping, replication mechanisms, and different ways of integrating MANET and DTN routing protocols.

Hybrid MANET-DTN routing schemes implement MANET routing schemes among end-to-end connected nodes and apply DTN routing when mobile nodes are intermittently connected or the situation is such that DTN routing provides better delivery ratio and/or minimum average delay compared to MANET routing.

In general, hybrid MANET-DTN routing schemes can be broadly categorized into hybrid MANET-DTN routing schemes that apply explicit grouping of mobile nodes and hybrid MANET-DTN routing schemes that don't apply explicit grouping of mobile nodes.

Hybrid MANET-DTN routing schemes which apply explicit grouping of mobile nodes, adapt different ways of group formation and group management. In some protocols, mobile nodes are grouped according to their mission in a pre-determined way similar to groups of soldiers or rescue crews in emergency scenarios. Some others group end-to-end connected mobile nodes based on their physical proximity. However grouping based on the physical proximity of mobile nodes is unstable and very dynamic due to independent movement of mobile nodes. To reduce group instability, some schemes consider connectivity for sufficient time duration as criteria for group

formation and merging groups.

Other schemes do not apply explicit grouping, but forward messages using conventional MANET routing when there is a stable end-to-end connection between nodes or using DTN routing mechanisms when nodes are intermittently connected.

Different hybrid MANET-DTN routing schemes also implement different replication strategies. Some protocols focus on improving delivery rate by implementing multi-copy mechanisms and others aim on reducing overhead by using single-copy mechanisms.

Chapter 4

Group communication approaches

The aim of this chapter is, first to discuss the group mobility (Section 4.1) and MANET (intra-group) routing (Section 4.2) applied in our study. In Section 4.3, we present a detailed explanation of the two distinct group routing approaches proposed in this research.

4.1 Group Mobility

As stated in Section 2.3, mobility in a mobile ad-hoc network can be broadly categorized into group mobility and entity mobility. In entity mobility, individual nodes move independently of each other. Whereas in group mobility, mobile nodes with the same interest or mission are generally grouped and move together. Moreover, in group mobility group dynamics is limited and most of the time mobile nodes are close together and always keep the same group membership.

For our study, we assume mobile nodes are grouped in a predefined way. This criterion of group formation is reasonable in many practical scenarios. For example, in military operations, the formation of soldiers or groups of vehicles is predetermined before the operation starts..

One of the commonly used group mobility models is Reference Point Group Movement (*RPGM*) [11]. In *RPGM*, mobile nodes with the same interest (mission) follow the logical center of the group. The destination of the logical center is chosen randomly and each member of the group determines its speed and direction deviation in random way from the logical center.

In our simulation scenarios, the mobility model is modified in such a way that the movement pattern of the logical center is a Random way point mobility model (*RWMM*) [1] the same as in *RPGM* but the deviation in speed and direction of each member from the speed and direction of the logical center is kept fixed during the whole course of movement. This way, relative position of group members with regard to the logical center stays the same and routing inside a group is fixed within a group. Member nodes are end-to-end connected to each other.

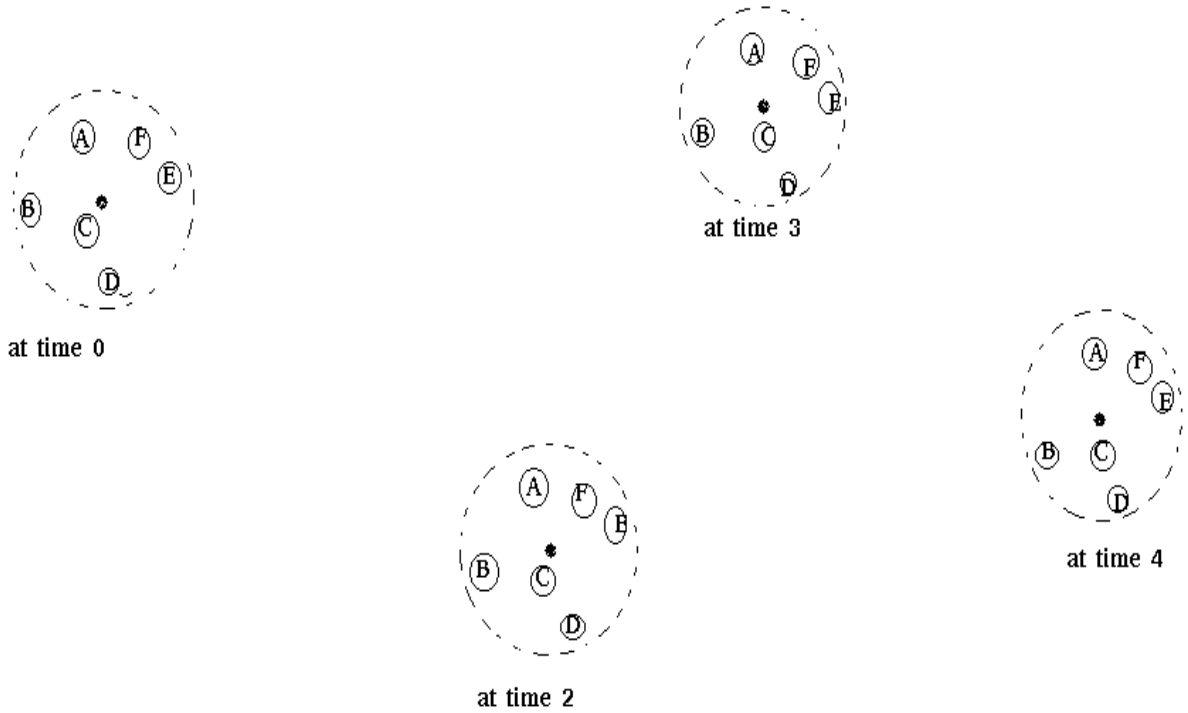


Figure 13: Group mobility where the logical center of the group moves in a random way point fashion and each member node follows the center in a fixed position.

4.2 Intra Group Routing

In group movement, mobile nodes stay close and connected to each other almost all of the time. Each mobile node is connected to other nodes in the group either in the form of direct, or relayed end-to-end connectivity. Thus, intra-group routing can be easily managed via either table driven distance vector or link state routing protocols. Since, in both group routing approaches(i.e. we going to discuss them in next section) group formation and movement of the mobile nodes is implemented in exactly the same way, there is no difference in intra-group routing.

In this modified group mobility model, each mobile node will build its routing table information about the other members of the group at initial stage of the movement based on the hop-count metric. Each mobile node has a fixed positional deviation from the logical central of the group and thus routing tables of mobile nodes remain the same during the overall movement.

4.3 Proposed group communication approaches for inter group routing

The center of the research topic is the inter-group routing mechanisms of the group routing approaches that we are going to discuss in the following sections. In both approaches, adjacent groups communicate via their border nodes. Groups exchange inter-group messages lists that contain a list summary of identifiers of inter-group messages contained in the group and a list summary of identifiers of delivered messages and inter-group messages during their brief contact times. Binary spray and wait protocol is implemented for the DTN communication between the adjacent groups. Each group with copies of a given message keeps forwarding

$\lfloor \text{number of current copies} / 2 \rfloor$ copies when it comes in contact with an adjacent group that doesn't have a copy until it is left with one copy of the given message. Groups with only 1 copy keep their copies until they encounter the destination group of the inter-group message. The detailed implementations and operations of the inter-group routing mechanism in each approach is discussed in the following Sections.

4.3.1 Leader Based Group Routing

In this approach, the group leader decides explicitly which inter-group messages should be forwarded when another group is encountered, by comparing its own inter-group messages list with the list received from the nearby group, which are exchanged when they get in contact with each other. Nodes of the same group are end-to-end connected to each other. Ordinary members forward received inter-group messages to their group leader using their routing table. Inter-group messages are stored at the group leader and ordinary nodes of a group act as requesters /forwarders from/to their group leader. Mobile nodes broadcast hello control messages periodically so as to discover nodes of adjacent groups. In our simulation, hello control messages are broadcast every 2 seconds.

When a group member comes in contact with a node of an adjacent group, first it requests its group inter-group messages list from its group leader (since the group leader is the only node that stores the inter-group messages). Then after it receives the inter-group messages list which contains lists of identifiers of the inter-group messages contain in the group and lists of identifiers of already delivered messages from its group leader, it forwards it to the node in contact from another group. The other node also performs the same task. Then each group leader will know which inter-group messages to send to their respective requesters after comparing its list of inter-group messages with the received list from the adjacent group. It also eliminates messages from its buffer for which identifiers of the messages are in the lists of identifiers of already delivered messages received from the adjacent group. Each group leader will send $\lfloor \text{number of current copies} / 2 \rfloor$ of a given inter-group message that is not contained in the buffer of an adjacent group to its border node using its routing table which is build based on hop count. After it receives message from its group leader, the border node will route the message to the in contact node of adjacent group. This way, each group will keep routing copies of inter-group messages that the other group doesn't have in its buffer until either one of the groups move out of range or the group leaders finish exchanging messages. This process lasts for maximum 2 seconds. Every 2 seconds mobile nodes broadcast hello message and discover adjust nodes.

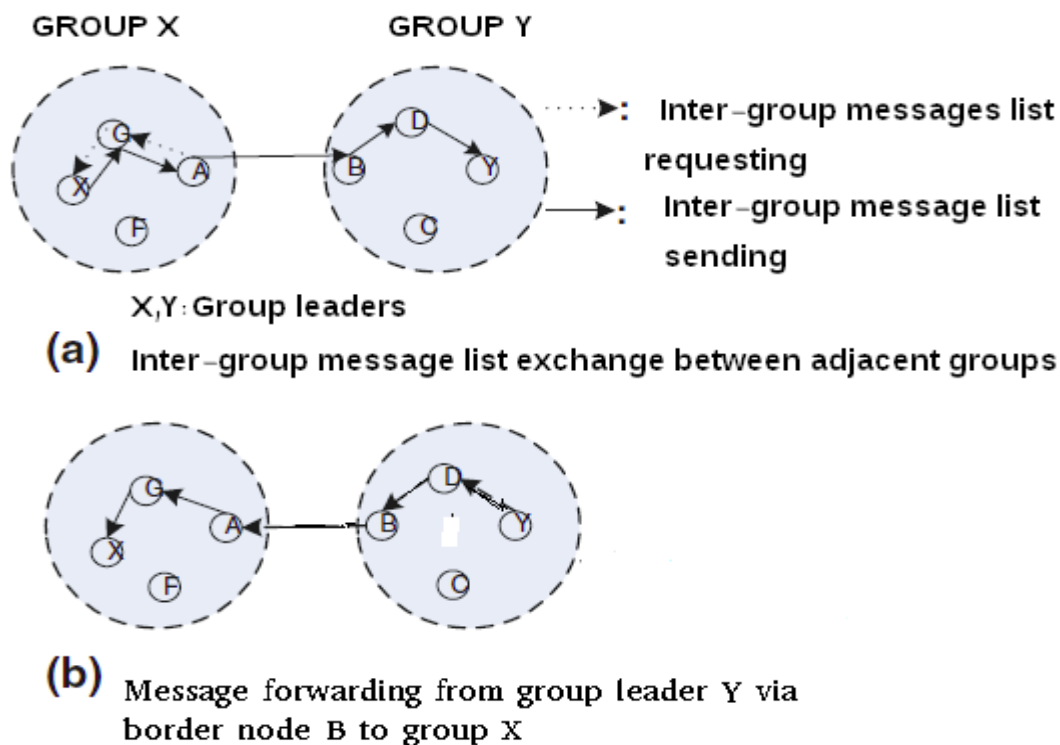
To make it more clear, let us discuss the scenario shown in Figure 14 as an illustration. When node A and node B come in transmission range of each other (when each node receives hello message of the other), node A and B will request inter-group messages list from their leaders X and Y respectively. Then group leaders X and Y will send their inter-group messages list to the border nodes A and B respectively. Then after node A and Node B exchange the inter-group messages lists and forward the received list to the next hops of their leaders using their routing table entries. When group leaders X and Y receive inter-group messages lists of each other, each group leader decides which messages to send to the other group and it also eliminates messages from its buffer which are already delivered to their destination nodes. The group leader that has messages to send to the adjacent group starts sending a given message with $\lfloor \text{number of current copies} / 2 \rfloor$ budget of copies according to Binary Spray and Wait replication mechanism to its border node. Then the border node will forward the message received from its group leader to the border node of adjacent group. Then group leader X and Y keep exchanging messages they have via nodes A and B until one of them moves away or they finish exchanging messages. As explained above, this inter-group

communication lasts for only 2 second and periodically every 2 seconds send hello messages so as to know if adjacent groups move away or if another nodes of adjacent groups come in to transmission range.

Thus, inter-group messages will be exchanged between the group leaders via the communicating (border) nodes, but the central figure in inter-group routing is the group leader. Group members are mainly required to send the inter-group packets received from other groups to their group leader. In addition, each newly generated inter-group packet at each member also needs to be sent to the group leader for storing. The group leader monitors the inter-group messages exchanged with adjacent groups in a synchronized and centralized way so as to decrease the possible duplicate transmission of messages with adjacent groups when more than one border nodes are engaged in transmission of messages with nodes of adjacent groups.

When more than one border nodes come in contact with nodes of adjacent groups, there will be more than one parallel transmission routes between groups similar to the scenario shown in Figure 14. Thus, to reduce the possible reception of a given inter-group message more than once by any given group, group leader has to include the traversed groups in the message header. For example, in Figure 15 when a copy of a given message from group Y is about to be sent to group X via node B, the group identifiers (GIDs) of traversed groups including GID of X will be recorded in the header of the copy that is sent to group X and in the copy remained in the group Y. Thus, the same message will not be sent to group X when a parallel transmission route is created via node C at the same time.

Figure 14: Inter-group routing



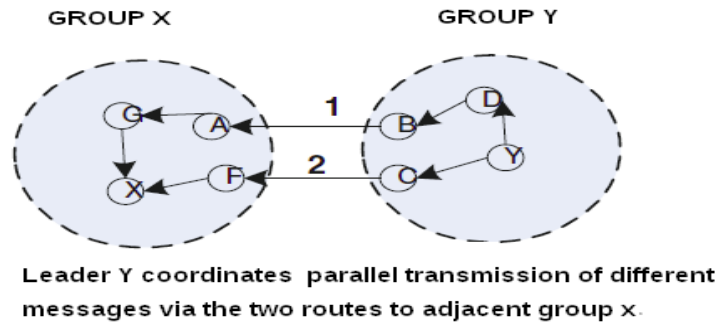
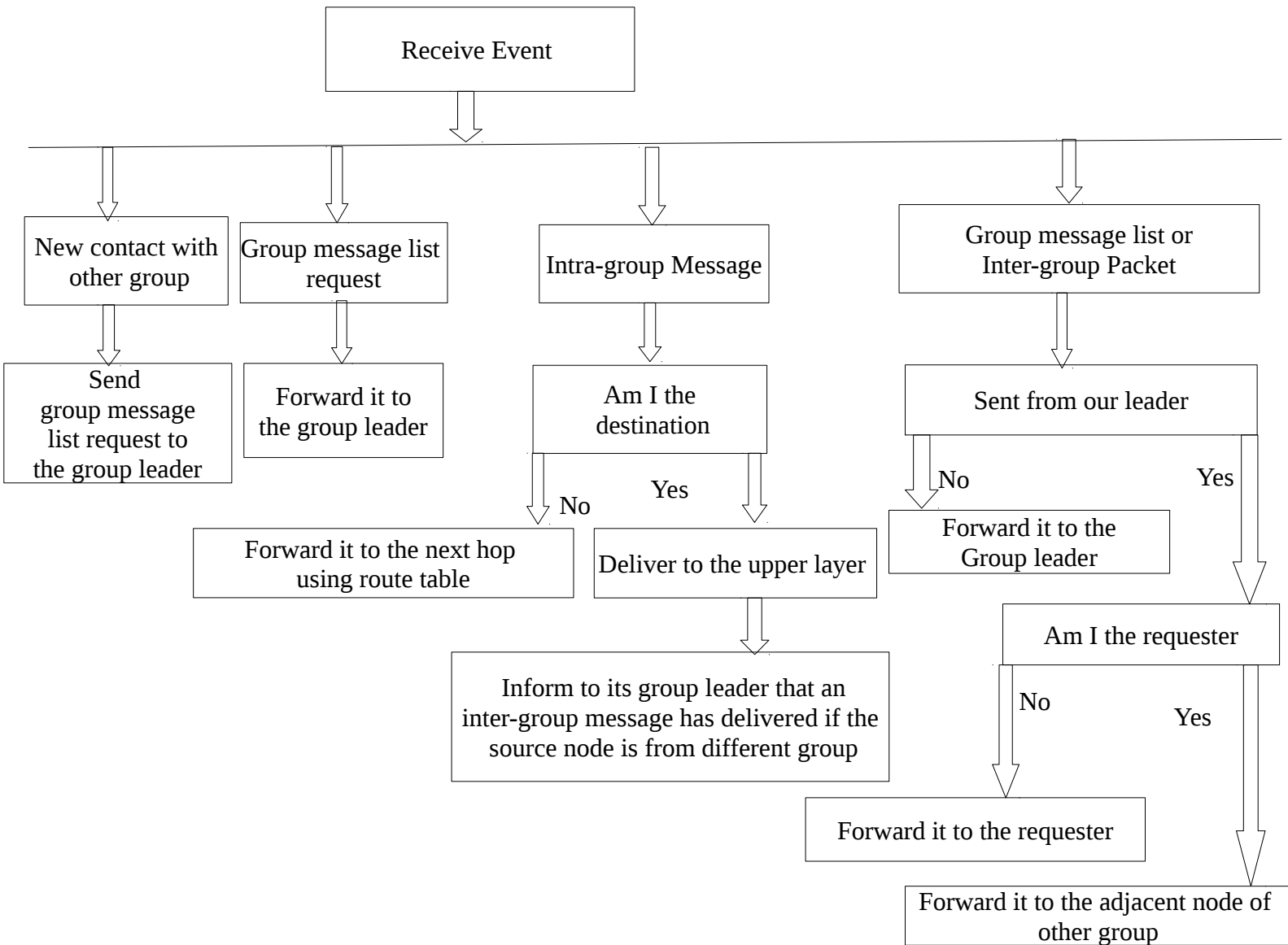


Figure 15: Parallel transmission

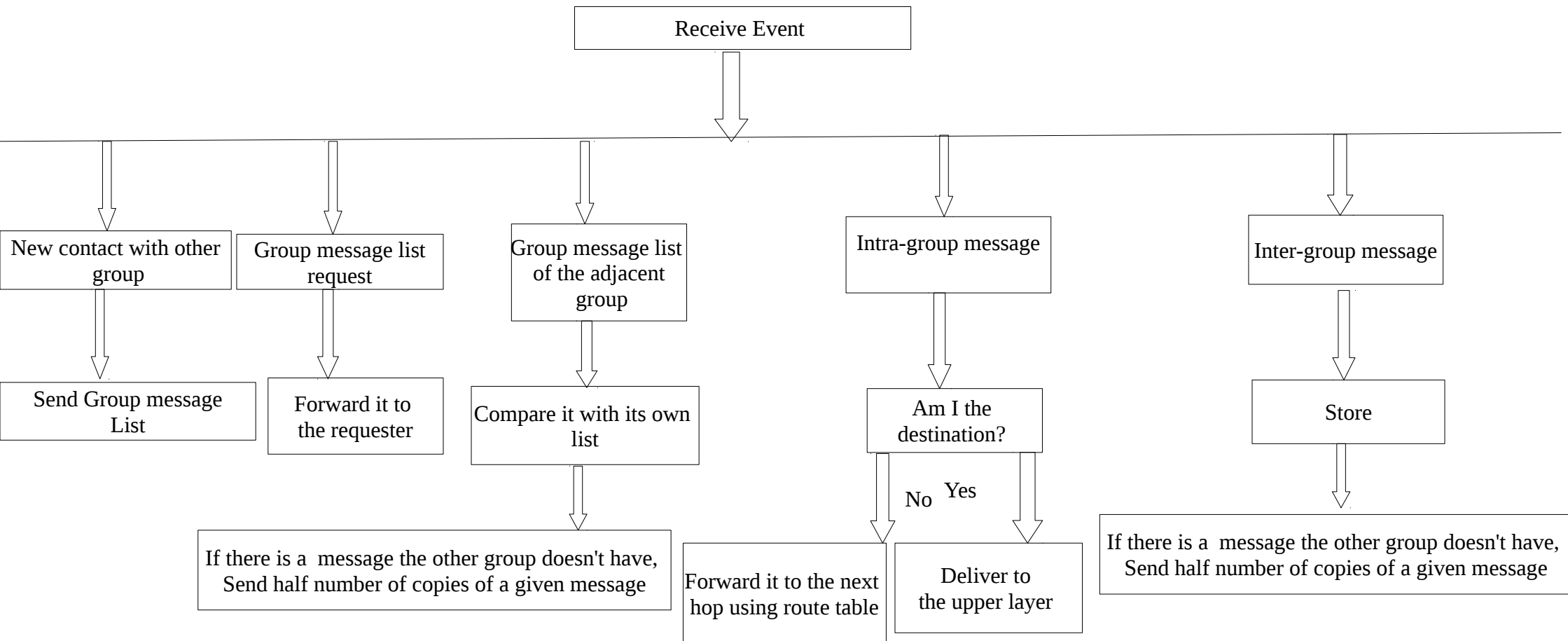
The main operations that are carried out by ordinary members and the group leaders when a new contact with new adjacent group is detected and messages are exchanged are summarized in the flow charts A and B.

A) This flow chart describes how an ordinary group member handles receive events



Flow chart 1: Main procedures of Leader based group routing at ordinary group member

B) This flow chart describes how a group leader handles events received



Flow chart 2: Main procedures of Leader based group routing at group leader

4.3.2 Distributed Group Routing

In this approach, each member of a group has all the inter-group messages that are currently contained by the group in its buffer and it communicates independently with nodes of adjacent groups. Like in leader based group routing approach, mobile nodes broadcast hello control messages periodically every 2 seconds so as to discover nodes of adjacent groups.

When nodes of different groups detect each other, they first exchange their inter-group message list. Inter-group messages list contains lists of identifiers of the inter-group messages contain in the group and lists of identifiers of known delivered messages. Each node eliminates messages from its buffer for which identifiers of the messages are in the lists of identifiers of known delivered messages received from the node of adjacent group. Then if there are new identifiers of delivered messages from the list received, a decrease copy control message which contains the identifiers of these new delivered messages will be broadcast across the group so as to inform the other members about the delivered messages. Then each node starts sending messages that the other node doesn't have, with budget $\lfloor \text{number of current copies}/2 \rfloor$ of their copies.

Here, when inter-group messages are generated or received from another group, they have to be broadcast to all members of a group as soon as possible. Moreover, a decrease copy control message is broadcast across the group when any given inter-group message is forwarded to node of another group or when a message arrives at destination node or when new identifiers of delivered messages received from the adjacent group.

Thus, when any member node forwards an inter-group message to a node of adjacent group, it informs the other members of its group to decrease the copy value of the given message by broadcasting a decrease copy control message. This decrease copy control message contains the group identifier (GID) of the group to which the inter-group message is forwarded to. The main purpose of this control message is to have synchronized way of managing the copy value of a given message in a given group. Hence, the other member nodes will decrease the copy value of the given message and also they will record the GID received via the control message in the inter-group message so as to reduce duplicate transmissions of a given message to adjacent groups when more than one nodes of a given group in contact with nodes of adjacent groups. The other purpose of decrease control message is to inform other member nodes about delivered messages and thus they can delete messages from their buffers if they contain already delivered messages in their buffers.

All member nodes of a given group might not be immediate neighbors to each other. So inter-group messages and control messages have to be disseminated to all member nodes in a way that doesn't impose too much load on the network.

Hence, when a member node generates or receives a given message from another group, first it records the addresses of its immediate neighbors in the header field of the message and broadcasts it to its immediate neighbor members. Once an immediate neighbor member node receives the message, it will rebroadcast it only if it has some 1-hop neighboring members which are not recorded in the header of the message. If the member node decides to rebroadcast the message, it will also append its 1-hop neighboring members which are not already included to the header of inter-group message. Hence, we can see that this 1-hop neighbor information included in the message header is used to avoid the unnecessary rebroadcasting and flooding mechanisms. In similar fashion, decrease copy message is broadcast to all members of a given group.

For example, in Figure 16 when node A of group X and node B of group Y detect each other, they

exchange inter-group message lists of each other. Each node will compare its list of inter-group messages it has with the list it received from the node of the adjacent group, and it eliminates messages from its buffer if identifiers of the messages are in the lists of identifiers of known delivered messages received from the adjacent group. Then informs its group members about the already delivered messages by broadcasting a decrease copy message. Then if it has message to forward to the adjacent group, it will forward the given message with $\lfloor \text{number of current copies} / 2 \rfloor$ budget of copies to the node of adjacent group. Thus, as it is illustrated in Figure 16 (B) node B has message to sent to group X, it forwards the given message with $\lfloor \text{number of current copies} / 2 \rfloor$ budget of copies to node A. Then node B broadcasts a decrease copy message to all members of a group to inform them to decrease the copy of the forwarded message by $\lfloor \text{number of current copies} / 2 \rfloor$ and it also includes group identifier (GID) of group x in the control message. This will help other members to stop duplicate transmission of already forwarded message to group X. Thus, node B includes the IDs of its immediate neighbors in the control message and broadcasts it to its immediate neighbors. Then some of the neighbors that have neighbors which are not included in the header of the received decrease copy message will rebroadcast the message to their neighbors until the message delivered to all members of a group. In similar fashion, Node A broadcasts the received message across its group members.

As shown in Figure 17, when more than one border nodes comes in contact with nodes of adjacent group, the decrease copy messages sent from the border nodes will have significant role in reducing duplicate transmission of messages to the same adjacent group. Node B and node D will learn what messages has already forwarded to group X when they receive control messages from each other.

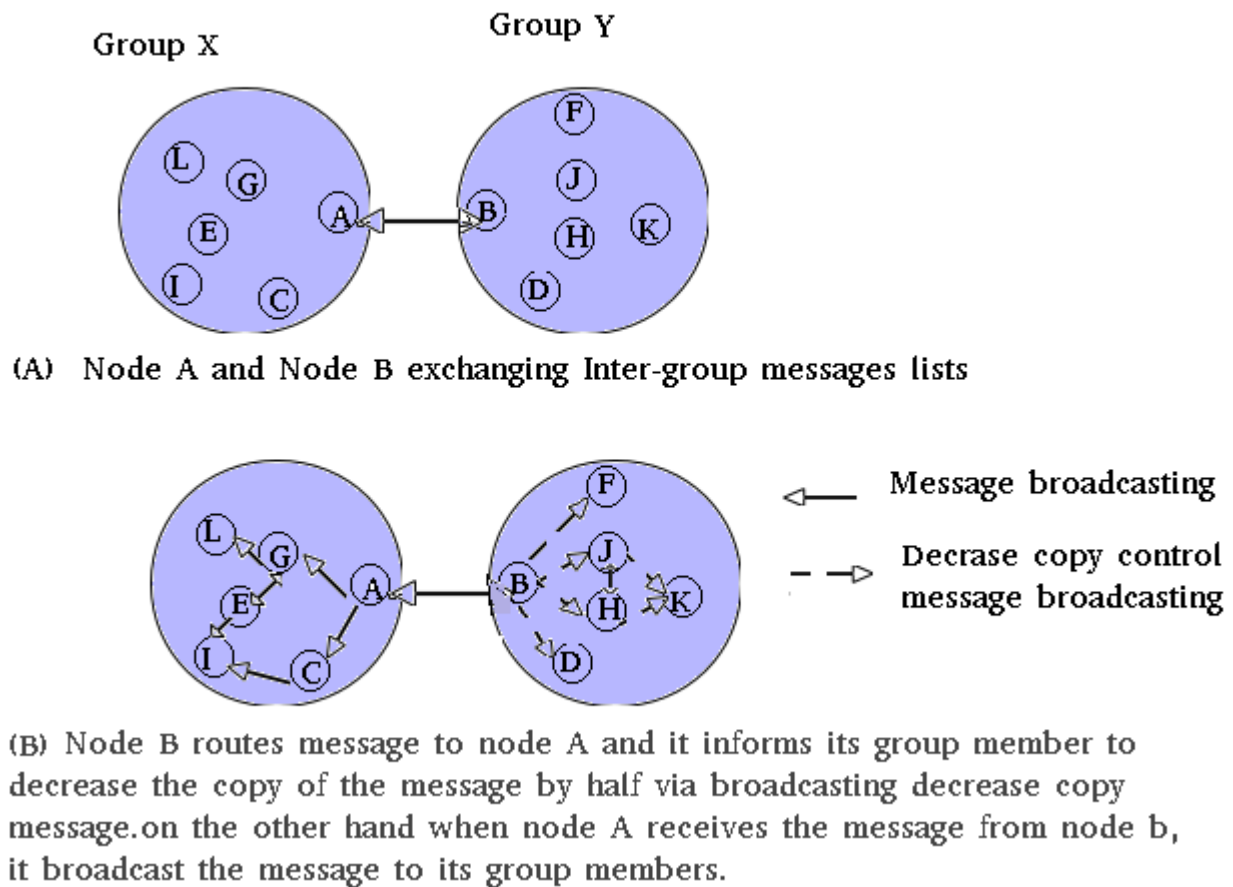


Figure 16: Inter-group routing

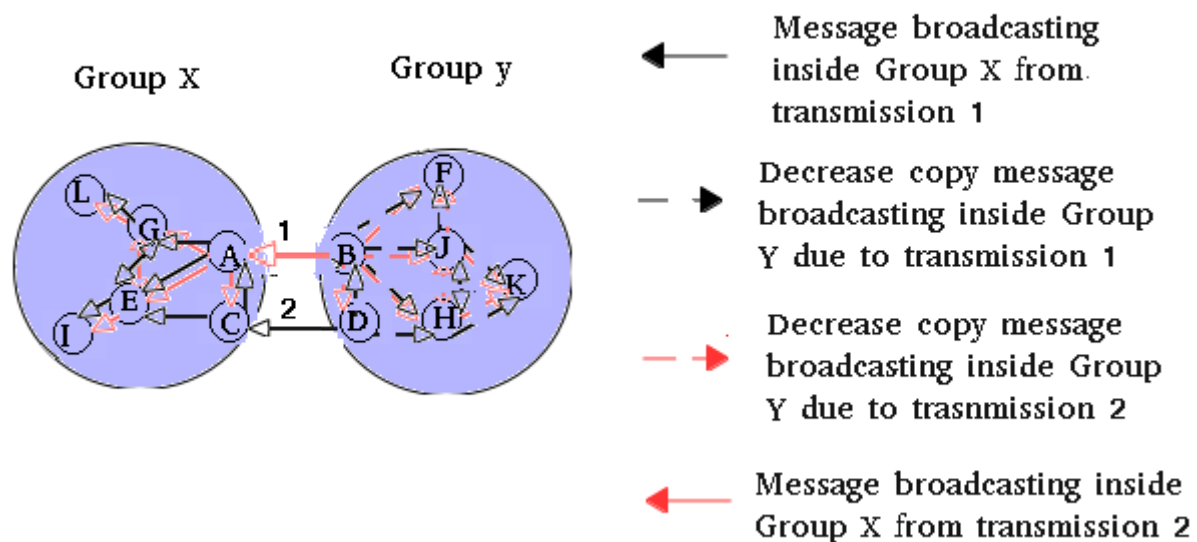
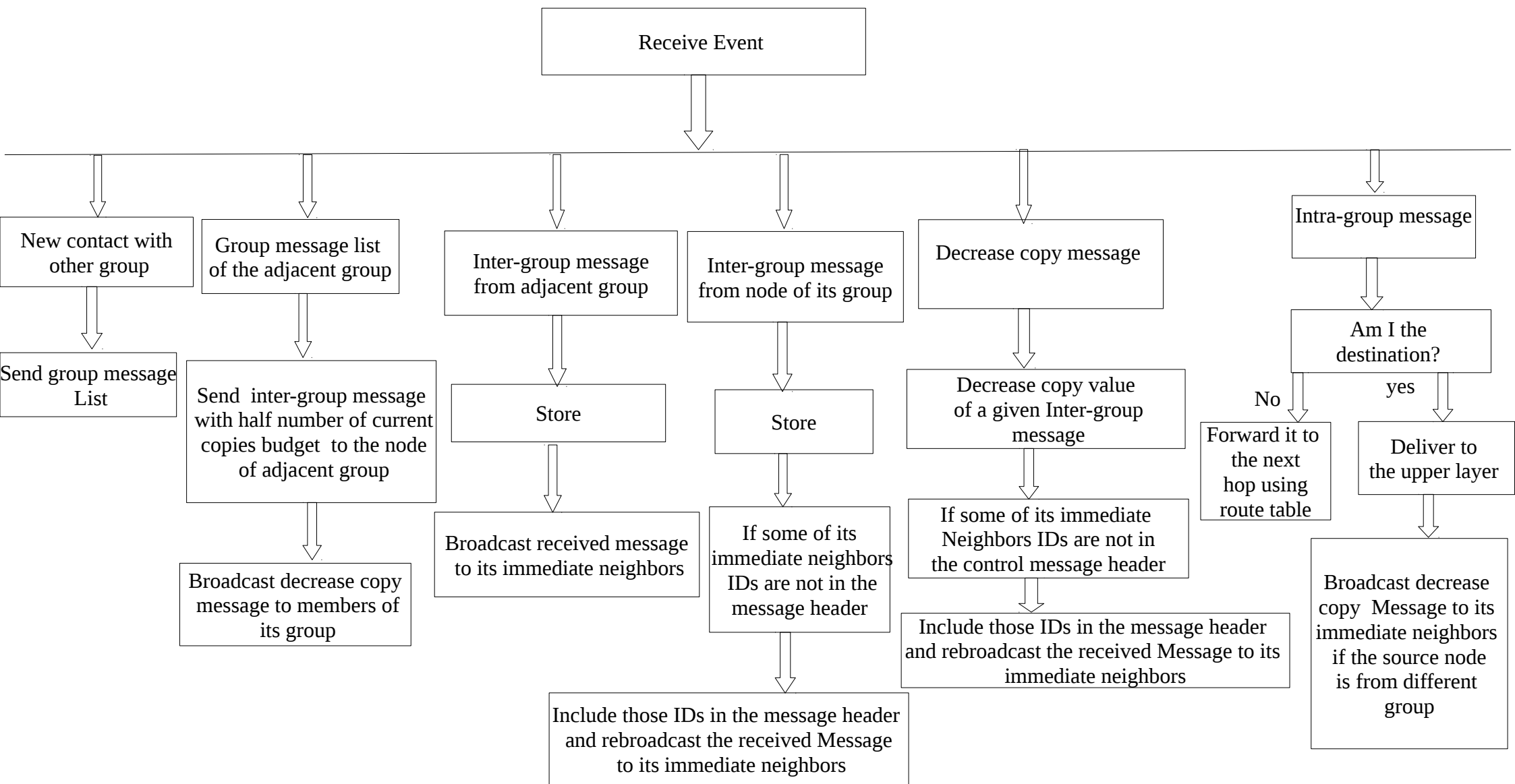


Figure 17: Parallel transmission

The main difference between the two approaches are :

- In Distributed group routing, all member nodes play the same role whereas in leader based group routing the group leader is the only one in charge of the inter-group routing.
- In Distributed group routing, to manage the inter-group messages received or generated, member nodes have to disseminate them across the group whenever inter-group messages are received or generated. In leader based group routing, inter-group message generated or received have to be forwarded to the group leader.

The following flow chart summarizes the major operations performed by the member node in distributed group routing.



Flow chart 3 : Main procedures of distributed group routing at ordinary group member

4.3.3 Buffer Management

In our study, only one message type is considered. All inter-group messages have the same priority status. In leader based group routing, buffer management is needed only in the group leader. The group leader will buffer inter-group messages based on their arrival times in a FIFO buffer. Intra-group messages don't have to be buffered as they will be immediately forwarded to their respective destinations. In the distributed group routing approach every member node has its own FIFO buffer to store all inter-group messages currently contained in the group. In both approaches, buffer management is implemented in a First - In First - Out (FIFO) way.

Chapter 5

Set-up of simulation experiments

This chapter first discusses simulation methodology that is used in our study (Section 5.1). Then in it explains scenarios (Section 5.2) and simulation parameters (Section 5.3) that are applied in this research.

5.1 Simulation Methodology

In our simulation, we have implemented both approaches in NS2-3.5 simulation tool. NS2 is a discrete event driven simulator that aims at network research. NS2 comprises two languages: C++ and Object-oriented Tool Command Language (OTcl). C++ determines the internal mechanism (i.e., back end) of the simulation, while the OTcl assembles and configures objects, and schedules discrete events (i.e., a front end). Input parameters are provided via a Tcl control script. The control script is needed to set up the communications, routing, and application parameters, as well as import generated node mobility and traffic generation files before running the NS2 simulation. Simulation outputs are generated in .tr trace file which is used for tracing and post processing of performance metrics, and in .nam file which is used for visualization of the simulation.

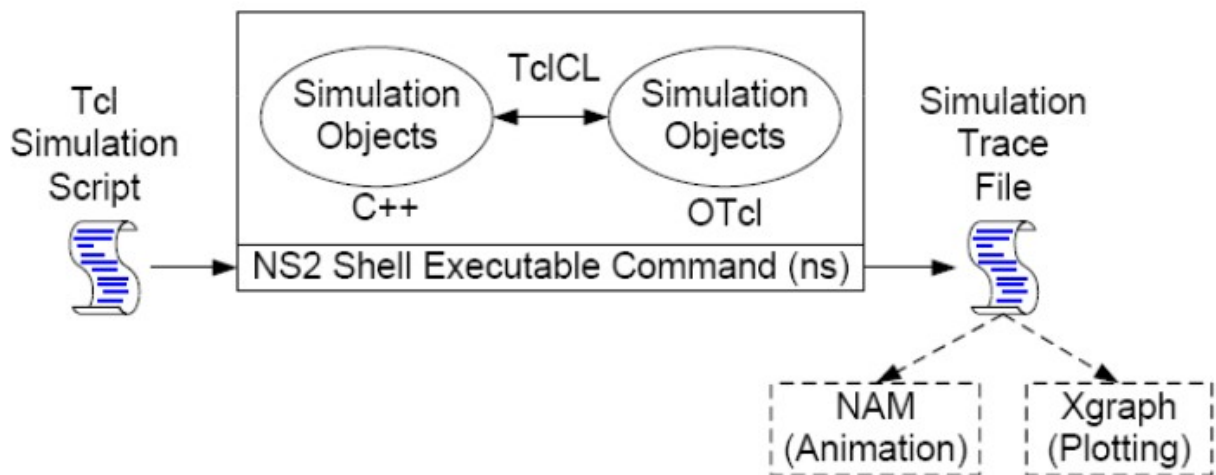


Figure 18: Simplified user's view of NS2

Since NS2 simulation tool is only suitable for MANET simulation, to simulate DTN routing (inter-group routing) of both approaches we extended NS2 to support DTN mechanisms with the existing

MANET routing schemes. Moreover, as it is explained in Section 4.1 we adapted the group mobility used in our study from RPGM[11] in a such a way that the relative positional deviation of each member node from the logical center of the group stays the same during the overall simulation period.

5.1.1 DTN mechanisms

Since the aim of our study is to compare the DTN (inter-group) routing performance of the two approaches during brief random contact times of different groups, we focus on the routing aspect of DTN. Thus we don't consider DTN security mechanism in our simulation scenarios.

In both approaches, we have applied Binary Wait and Spray protocol [23, Def.3.2]. The maximum possible copies of a given inter-group message that can exist in the network is set at 5 copies.

Initially, a source node of a given inter-group message sets the maximum budget of the message to be 5 copies. Then the source group of the given message forwards 2 copies of the message to the first group it encounters, keeping 3 copies to itself. Then each group with copies of a given message keeps forwarding $\lfloor \text{number of current copies} / 2 \rfloor$ of copies when it comes in contact with other group that doesn't have a copy until it is left with one copy of the given message. Groups with only 1 copy keep their copies until they encounter the destination group of the given message.

Group is treated as an individual node for the inter-group routing mechanism. Prior to exchanging copies of inter-group group messages, adjacent groups first exchange lists of identifiers of delivered messages and lists of identifiers of the inter-group messages contained in their groups. Then each group will know which messages to forward to the adjacent group.

In both approaches, to reduce reception of the same inter-group message for more than once by a given group, the group identifier (GID) of every group that is traversed by the given message is included in the header of the message. Moreover, we have set the lifetime of the inter-group messages to be in terms of hop counts and thus there is no dropping of messages during buffering mechanism. The time to live of each inter-group message is set to be 32 hops.

In distributed group routing, when a member node forwards a copy to a neighbor node of adjacent group, it has to inform the other member node to decrease the copy value of the given message and to record the GID of the group to which the message is forwarded to in the message header. Thus, copies of a given message will be easily managed.

5.1.2 MANET routing

Since all members of a group have direct or relayed end-to-end connectivity, communication within a group is done via MANET routing. In the first 5 seconds of simulation time, member nodes build their routing table by building list of member nodes with their minimum hop counts.

Initially, each member node will broadcast its id and then after first iteration, each member node will know its immediate neighbors. Then member nodes keep building and broadcasting their lists of member nodes with their minimum hop-counts until each node gets a complete “knowledge horizon” of member nodes of its group. As the relative position of each node is fixed with respect to the logical center of the group, routing tables of member nodes remain the same during the full simulation time.

5.1.3 Traffic generation

There are four traffic generation types used in NS2.

- A Constant bit traffic (CBR) generator: this generates a fixed size payload burst for every fixed interval.
- An exponential on/off traffic generator: it acts as a CBR traffic generator during an ON interval and there is no any packet generation during an OFF interval. ON and OFF periods are both exponentially distributed.
- A Pareto On/Off traffic generator: it has similar mechanism as an exponential On/Off generator but the ON and OFF periods conform to a Pareto distribution.
- A traffic trace generator: it generates packet bursts according to a given trace file.

In our simulation, a constant bit rate(CBR)traffic generation model is used to generate inter-group messages at different time interval sizes.

5.1.4 Simulation parameters

To compare the performance metrics such as delivery ratio and average delay of both approaches without limit on the size of buffer of the group leader in Leader based group routing and size of buffers of nodes in the Distributed group routing approach, we don't set upper limit size on the buffers in our simulation.

In both approaches, mobile nodes build their routing tables in the first 5 seconds of the simulation time as discussed in Section 4.6.2. Moreover, nodes broadcast periodically Hello control messages for the purpose of neighbor discovery every 2 seconds during the simulation time.

All simulation parameters that are used in our simulation are presented in the table provided below.

Antenna :	OmniAntenna
Mac:	802_11
Network area:	1000 m * 1000 m
Propagation:	TwoRayGround
Radio transmission range :	100 m
Carrier sensing range:	250 m
Packet size:	512 bytes
Transport layer protocol:	User datagram protocol (UDP)
Interface queue:	500 packets
Bandwidth:	2Mbps

Table 4: Simulation parameters

5.2 Scenarios

Extensive simulation experiments have been done under different scenarios in low and high mobility environments. The scenarios are chosen in a way to represent real challenging scenarios that can occur in critical situations. For example, in real life scenarios some groups might remain isolated for long time from other groups, i.e. messages that are originated from these groups or messages that are destined to these groups from other groups might encounter long delays, potential propagation degradation factors and/or bottleneck effect along their way to their destinations. Moreover, there may be occasions when groups communicate with more than one adjacent groups

at the same time. Hence, the scenarios we considered here for our study comprises such asymmetry challenges for data dissemination among mobile nodes.

In both low and high mobility environments, we have preformed simulations for three scenarios.

One scenario is when source and destination node pairs are chosen randomly from different groups. For this scenario, we have applied two different experiments by varying numbers of groups of mobile nodes. In first experiment, we have used 5 groups and each group contain 10 member nodes. Whereas in the second experiment, we doubled the number of groups to 10 but we decreased the number of member node per group in to 5.

The second scenario that we have considered is when there is asymmetric sending (when traffic generation is only from nodes of one group). For this experiment, source nodes are chosen from one group and one destination node from each group except the source group. This literally represents when groups in emergency scenarios or tactical operations have to follow commands from a group that leads critical operations

The third scenario is when there is asymmetric receiving (when the destination nodes are from one group only). In this scenario, one source node is chosen from each other group except the destination group, i.e. data dissemination is aimed to a specific group of mobile nodes. This scenario occurs when rescue teams or emergency respondents need to maintain continuous communication with a team that is highly involved in a critical task or when the teams have to provide continuous update to a team that gathers real time information from the different groups.

The parameters that are used for mobility and traffic generations are provided in the tables below.

Min speed	0.5 m/sec
Max pause	10.0 seconds
Movement area	990 m *990 m
Max speed	36 km/h.

Table 5: Low mobility parameters

Min speed	0.5 m/sec
Max pause	0 seconds
Movement area	990 m *990 m
Max speed	72 km/h

Table 6: High mobility parameters

Traffic generation intervals	1, 2, 5, 10, 100 seconds
Number of source-destination nodes pairs	10
Source - destination pair selection criteria	Randomly from different groups

Table 7: when source-destination pairs are chosen randomly from different groups

Traffic generation intervals	0.5, 1, 5 ,10 seconds
Number of source-destination nodes pairs	4
Source nodes	4 nodes Randomly chosen from the same group
Destination nodes	One node chosen from each group except the source group

Table 8: When only one group generates traffic

Traffic generation intervals	0.5, 1, 5, 10 seconds
Number of source-destination nodes pairs	4
Destination nodes	4 nodes chosen from the same group
Source nodes	One node chosen from each group except the destination group

Table 9: Only one destination group scenario

5.3 Simulation parameters

Source nodes first randomly choose their starting time in uniform distribution way from time interval between 0 and 90 second. Then they keep generating messages at fixed time intervals. Traffic generation stops at 1000 second simulation time but the simulation runs for extra 1000 seconds. Messages that do not arrive at their destinations within 2000 seconds simulation time are considered as lost messages in our study. All messages have the same priority and they will be handled in buffers of nodes in a FIFO way. Sharing copies of a given message is implemented according to the Binary Spray and Wait DTN protocol [23].

For each simulation seed, exactly the same mobility trace of the groups and traffic generation parameters are used in both approaches. Simulations have been done on different set of scenarios, different number of groups and with different mobility parameters.

Basic network parameters which are used in all scenarios are provided in Table 10 below.

Simulation duration:	2000 seconds
Number of nodes:	50 nodes
Maximum number of copy per a given message	5

Table 10: Basic network parameters

Chapter 6

Performance results

This chapter presents and discusses the results of the performance simulations of both group routing approaches, the leader based group routing and the distributed group routing, in terms of delivery ratio, average delay, number of duplicate messages, and average buffer size. The goal of these simulation experiments is to determine the inter-group routing approach that provides better performance in most of the scenarios.

6.1 Low mobility environment

For this experiment, groups move according to the mobility parameters provided in Section 5.2 and the logical center of each group has a random way point mobility model. Member nodes follow the logical center of their group in a fixed relative position during the whole simulation time. To evaluate the performance of each approach at different traffic loads, we varied the time interval at which the messages are generated at source nodes.

6.1.1 Source-destination pairs chosen randomly from different groups (5 groups of 10 nodes)

In this scenario, in each simulation seed we have chosen 10 source-destination node pairs (from different groups). Maximum number of copies per given inter-group message is fixed at 5 copies. The traffic generation intervals we used for study of the performance are 0.5, 1, 2, 5, 10 and 100 seconds time intervals.

The results that we are going to discuss in this chapter are average values obtained from 4 different simulation seeds. Detailed result for each simulation are contained in Appendix A.

Average delay

Average delays are highly affected by the movement patterns of groups. Some of the groups might stay isolated for considerably long time which significantly affect the average delay of messages. In leader based group routing, the number of messages which are forwarded to adjacent groups are determined by the group leader (which can become bottleneck when more than one member nodes in contact with nodes of other group). The bottleneck effect will be magnified by the movement patterns of the groups if messages, which are unable to be forwarded to adjacent groups in a given encounter, have to wait a considerable time until other contact detected with adjacent groups.

Thus, as we can see from Figure 19 given below leader based group routing has higher average delay of messages than the distributed group routing approach. Distributed group routing performs better in terms of average delay in all traffic loads and this is mainly due to the case every node has all currently contained messages of the group in its buffer. There is no dependence on single member node (which is the case in leader based group routing; where every border node depends on the central node). Therefore, there is an obvious difference in the performance of both approaches. Distributed group routing outperforms Leader based group routing in terms of average delay metric.

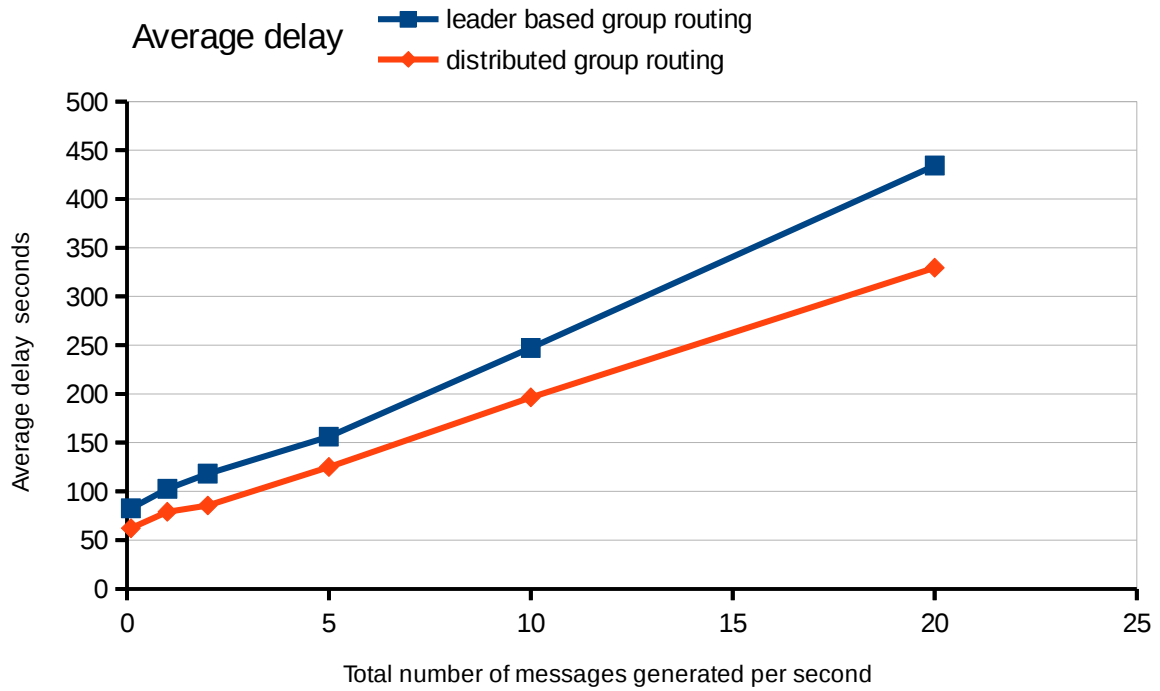


Figure 19: Average delay

Delivery ratio

In our simulation, we don't limit the sizes of buffers of mobile nodes and hence there are no messages lost due to buffer overflow. Moreover, we set the the life time of messages in terms of hops (i.e 32 hops), messages can only get expired if their time to live reach zero values which is highly unlikely. Thus, messages can only be lost due to the hidden terminal problems, collisions, and recipient nodes moving out of transmission range. Exposed terminal problem can also affect messages exchange between groups. Moreover, we have claimed messages that don't arrive within the 2000 second simulation time as lost messages.

As we can see from Figure 20 given below, the delivery ratios of the two approaches are close to 1 when the traffic loads are low. At low traffic loads, we are able to see very small number of messages (1 or 2 messages) lost due to the fact that nodes moving out of range during transmission. These problems happen in both approaches due to the nondeterministic contact times of different groups. Significant difference between the two approaches happens to show up when the traffic load becomes high. At high traffic, group leaders become bottleneck to the number of messages that is transmitted to adjacent groups at the leader based group routing. Hence, leader based group routing shows significant decrement in delivery ratio when the traffic load is high.

Overall, distributed group routing provides better delivery ratio than leader based group routing.

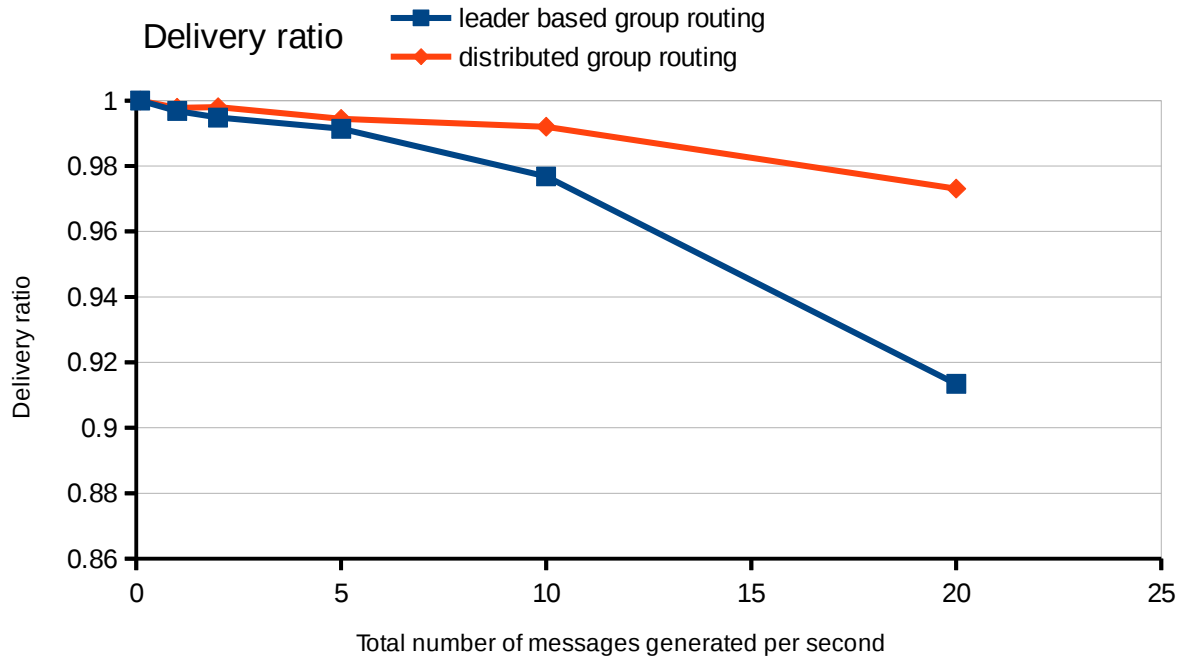


Figure 20: Delivery ratio

Duplicate messages

The other metric that we used in our study is the number of messages that are received more than once at destinations. In leader based group routing, all inter-group routings are controlled by the group leaders. Before a group leader forwards a copy of a given message, it adds the GID of the adjacent group to the list of GIDs of transversed groups recorded in the header of a given message so as to eliminate the possible duplicate transmission of messages via parallel transmissions. However, there exist situations when a given destination group receives duplicate messages when it is in contact with different groups at the same time.

Similarly in distributed group routing approach, mobile nodes include traversed groups in the headers of messages to decrease duplicate transmission of messages. Moreover, any member node that has forwarded copy of a message to adjacent group has to inform the other member nodes of a group to which group is the message forwarded by broadcasting control message. However, there are significant number of duplicate transmissions when multiple nodes of a given group are in contact with nodes of adjacent groups. Moreover, in distributed group routing broadcast control messages take a while before they arrive at every member node. Thus, as is seen in Figure 20, leader based group routing results into much smaller number of duplicate messages than distributed group routing for all given traffic loads.

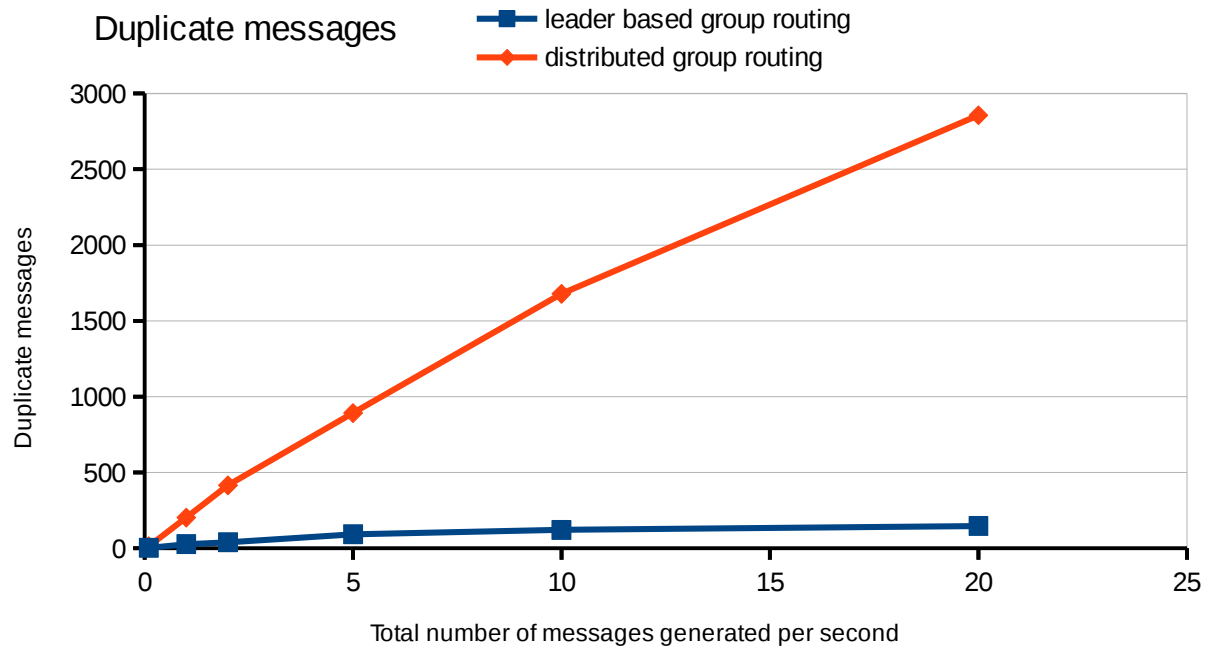


Figure 21: Number of duplicate messages

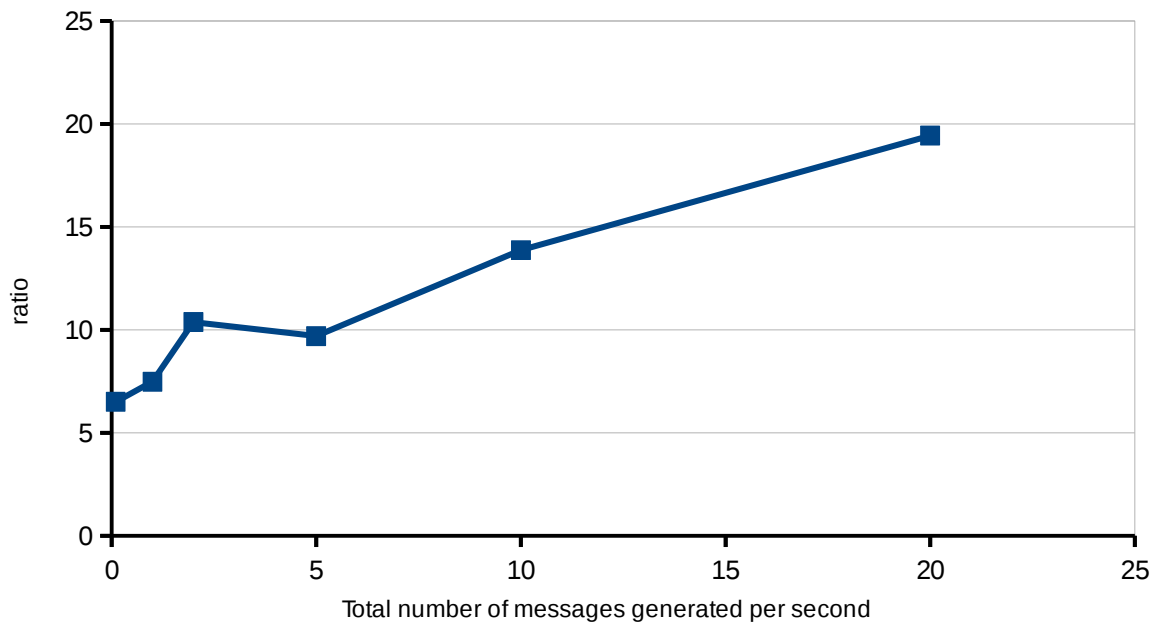


Figure 22: ratio of the number of duplicate in distributed group routing to number of duplicate messages in leader based routing

Average buffer size

Average buffer size shows the average number of messages contained in buffers of nodes. In leader based group routing, messages are only stored in group leader and thus the average buffer size computed is average of sizes of group leaders' buffers. Whereas in distributed group routing,

average buffer size is average of sizes of buffers of all nodes. In distributed group routing as messages that are contained by a group have to be stored in every member node, member nodes of a group have more or less the same buffer sizes.

As can be seen from Figure 23, distributed group routing have higher average buffer sizes than leader based group routing at low traffic loads, but as the traffic load get higher the leader based group routing have higher average buffer size due to the high number of undelivered messages. Basically, average buffer size value can be determined by the average number of messages (copies) exchanged among groups and by the average number of undelivered messages piled up at source or intermediate groups.

As it is described in Section 5.2.1, at low traffic loads (until 10 messages generated per second) both group routing have high delivery ratios (close to 1) and thus higher average buffer size values in distributed group routing implies there is higher distribution of copies of messages among groups in distributed group routing than in leader based group routing. But when the number of messages generated per second increased to 20 messages, there is a substantial decrease in delivery ratio of leader based group routing and this shows there are relatively high number of undelivered messages that are stored in the buffers of intermediate groups in leader based group routing. Hence, we see higher average buffer size at 20 messages per second in leader based group routing.

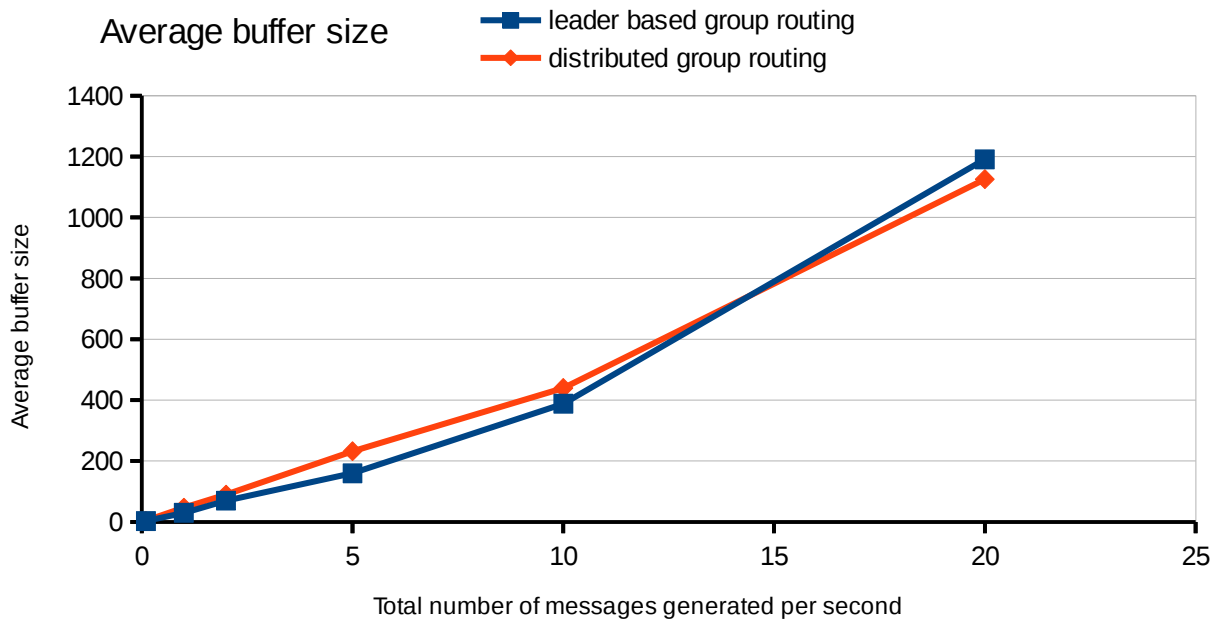


Figure 23: Average buffer size

6.1.2 Source-destination pairs chosen randomly from different groups (10 groups of 5 nodes)

In this scenario, we have used the same source-destination node pairs applied in Section 6.1.1. Here, the number of member nodes is halved, but the number of groups is doubled.

Average delay

As we can see from Figure 24 below, distributed group routing provides lower average delay values than leader based group routing in all considered traffic loads. This is due to two reasons as it is also described in Section 6.1.1. The bottleneck effect of a group leader in leader based group routing when more than one border nodes in contact with nodes of other groups. and the delaying effect of other message transmissions within or around a group to the propagation of messages from group leader to the border node which leads to increase in the overall delay values of messages.

Compared to the average delay values obtained in Section 6.1.1, here the average values for both approaches are relatively higher due to the increased traversed number of groups which adds extra buffer and propagation delays to the end-to-end delays of messages.

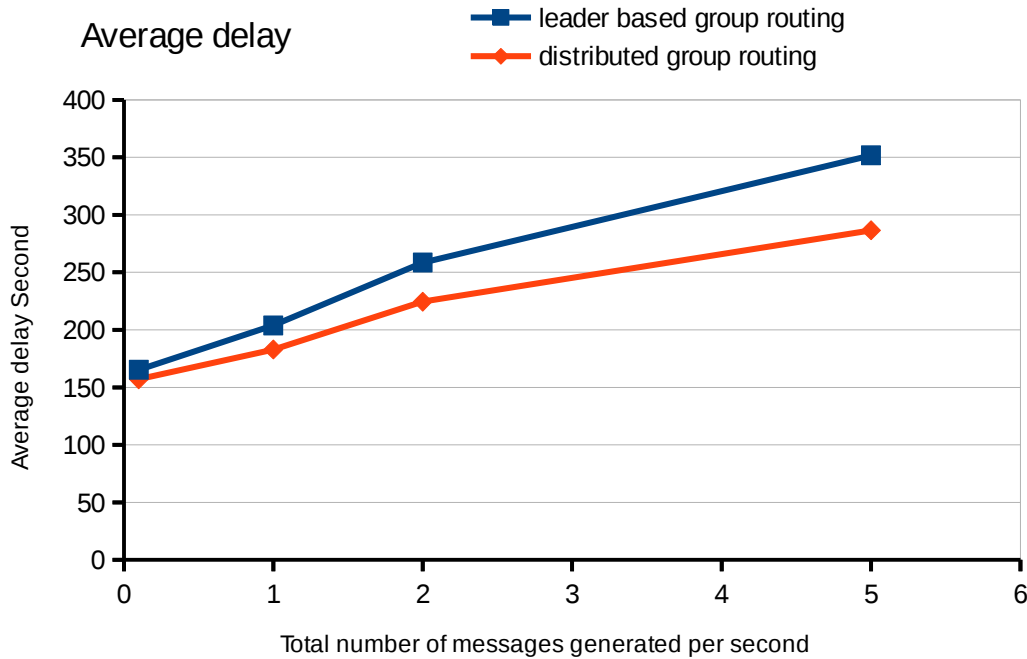


Figure 24: Average buffer

Delivery ratio

The number of groups is doubled, but the maximum number of copies per a given message remains at 5. The maximum number of groups that can be traversed by a given message is 5 groups including the source group before it is delivered to its destination group. Thus, in this scenario there are might be few messages that are unable to arrive at their destination groups if destination groups don't encounter with any of those intermediate groups that have copies. Moreover as described in Section 6.1.1, messages can be lost due to the hidden terminal problem, moving out of range of nodes. And also messages that don't arrive within the 2000 second simulation time are claimed as lost messages.

Distributed group routing has achieved relatively higher delivery ratio values than the leader based group routing for high traffic loads mainly due to the independent communication of member nodes with other nodes of adjust groups unlike to the group leader controlled inter-group routing in leader based group routing.

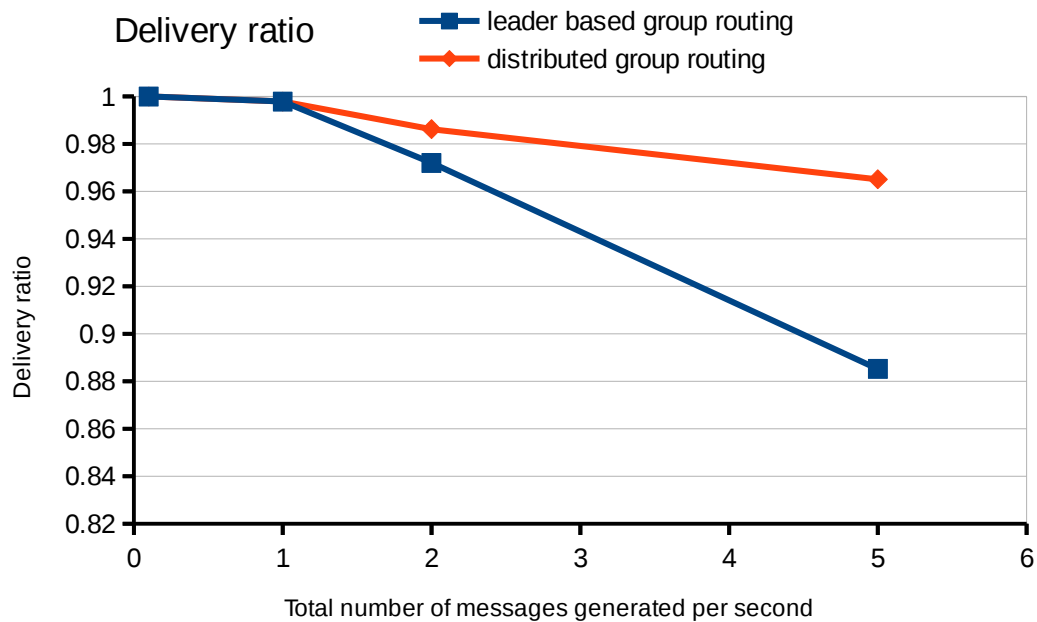


Figure 25: Delivery ratio

Duplicate messages

In Distributed group routing when more than one mobile nodes of a given group come in contact with nodes of one or more adjacent groups, there could be parallel exchange of duplicate messages between adjacent groups. Whereas in leader based group routing duplicate message can only be received when any given group is in contact with two or more adjacent groups at the same time. Thus, as it is shown in Figure 26, leader based group routing performs much better than distributed group routing.

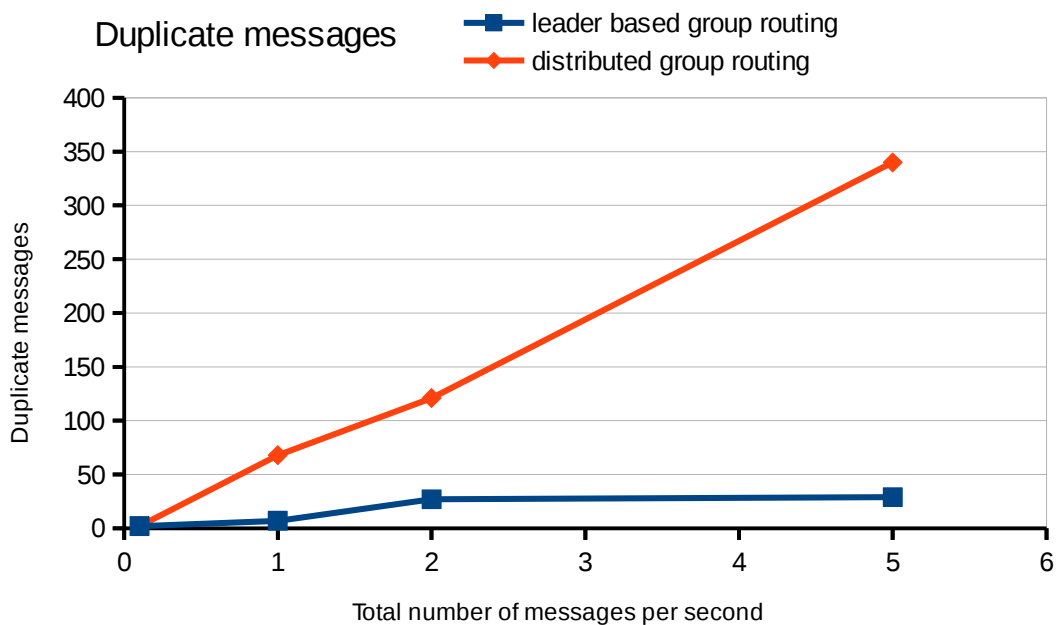


Figure 26: Duplicate messages

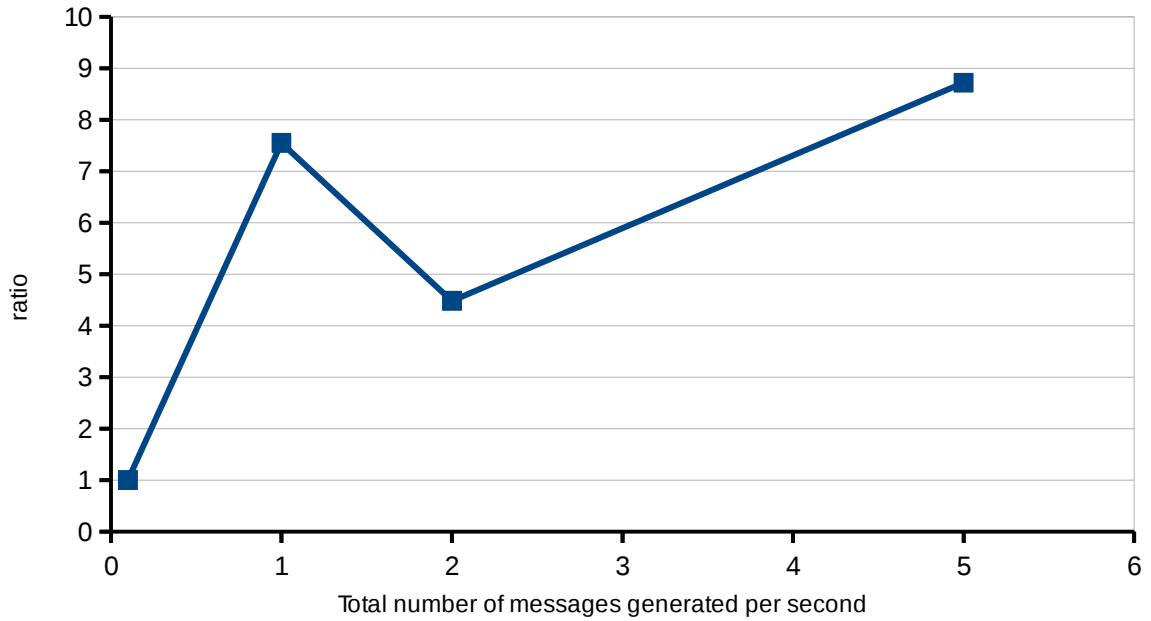


Figure 27: ratio of the number of duplicate in distributed group routing to number of duplicate messages in leader based routing

Average buffer size

In leader based group routing it is an average of the buffer sizes of the group leaders, while in distributed group routing it is an average of the buffer sizes of all nodes. Since here the number of groups is doubled but the maximum number of copies per a given message remains at 5. The maximum number of groups that can have copy of a given message is 5 groups before it is delivered to its destination group. Hence, as can be seen from Figure 28 the difference between average buffer size values of both approaches is relatively smaller than in the case of Section 6.2.1.

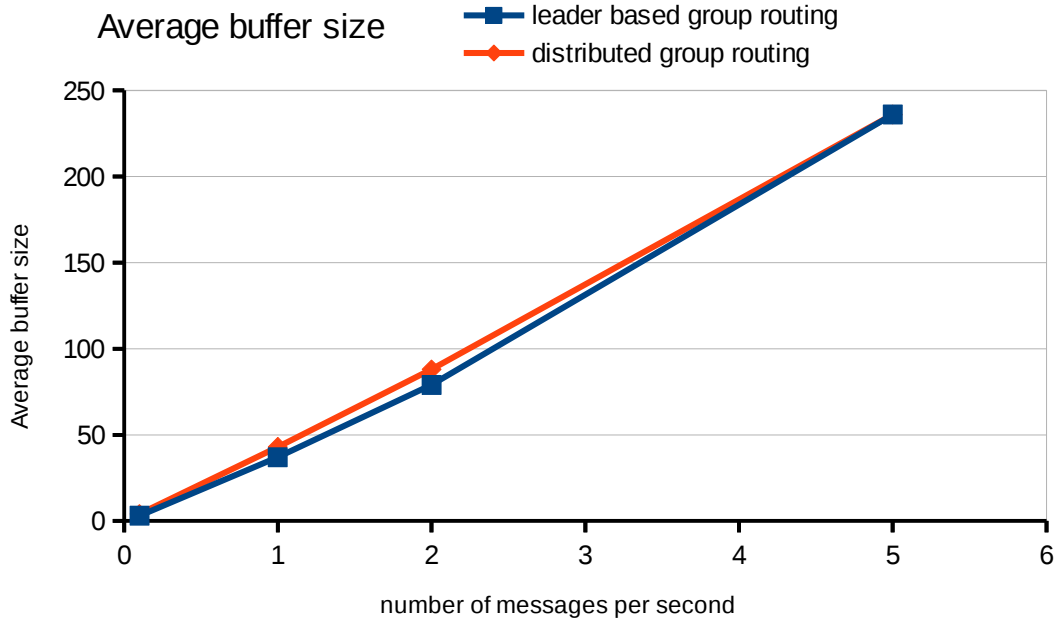


Figure 28: Average buffer size

6.1.3 When only one group generates traffic

In this scenario, we pick four source nodes from one group and one destination node from each group except the source group to evaluate how the two approaches perform in an asymmetric condition. It is obvious the source group is the bottleneck for the dissemination of the traffic across the network. Moreover, the movement pattern of the source group relative to the movement of the other groups plays a predominant role. If the source group doesn't meet the other groups frequently, there will be low delivery ratios and high average delays in both approaches.

For this experiment, we perform 5 different simulations for 5 different source groups for each considered traffic generation interval size [see Table 8 in Section 5.2]. Depending on the movement of these different source groups, we have obtained different results. The results provided are average values of the different simulations at each interval size. Source groups that meet up with different groups quite often have relatively high delivery ratios and low average delay values than others.

Average delay

In both approaches, the movement of the source group is the bottleneck. Messages spend long time at their source group, they pile up in buffer until the source group encounters other groups. Thus, for the same traffic loads, we see difference in average delays of the different simulation seeds (see the Appendix for detail results at each simulation seed).

But for each simulation seed, distributed group routing provides better average delay than leader based group routing in all time interval sizes.

In leader based group routing, when a given group come in contact with more than one different groups or when there are more than one parallel transmissions with adjacent group, the group leader

in leader based group routing becomes the bottleneck to the number of messages that are routed to the adjacent groups. This coupled with the relative movement pattern of the source group with respect to the other group results high end-to-end delays of messages in leader based group routing.

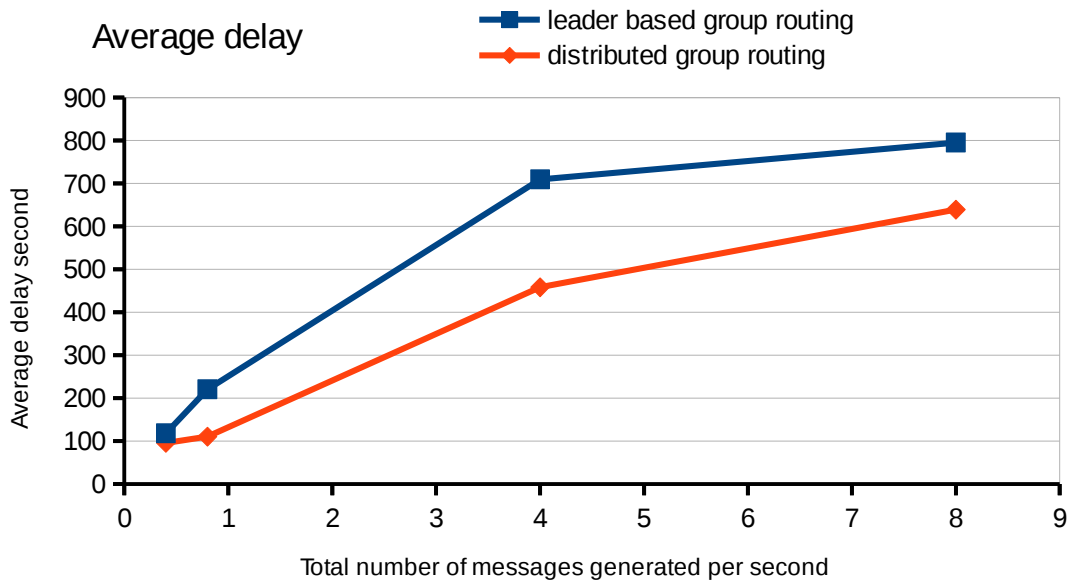


Figure 29: Average delay

Delivery ratio

As it can be seen from Figure 30, at high traffic loads the delivery ratios for both approaches are low. This is due to the movement of the source group. The maximum number of messages that can possibly be delivered in this scenario are limited by the movement of the source group relative to the other groups. The leader based group routing has lower delivery ratio than the distributed group routing approach. This is due to the bottleneck effect of the group leader. The source group has already piled up messages in its buffer when its border nodes come in contact with nodes of adjacent groups. And thus, every message transmission has to be controlled by the group leader which in fact becomes a bottleneck to the number of messages that is transmitted to adjacent groups. Moreover, the fact that border nodes have to wait until a message arrives from the group leader affects the number of packet exchanges during the brief contact times of adjacent groups. This is not the case in distributed group routing where every border node transmits a packet independent of any central control.

A huge difference between the two approaches occurs when more than two groups come in transmission range of each other. Leader based group routing has a slower message exchange rate due to the fact that all inter-group messages are controlled by the group leader which limits the number of packets that are forwarded during a given contact time with an adjacent group. But in distributed group routing, all border nodes communicate with the adjacent nodes of other groups independently. Overall, leader based group routing performs very poorly in the asymmetric sending scenario.

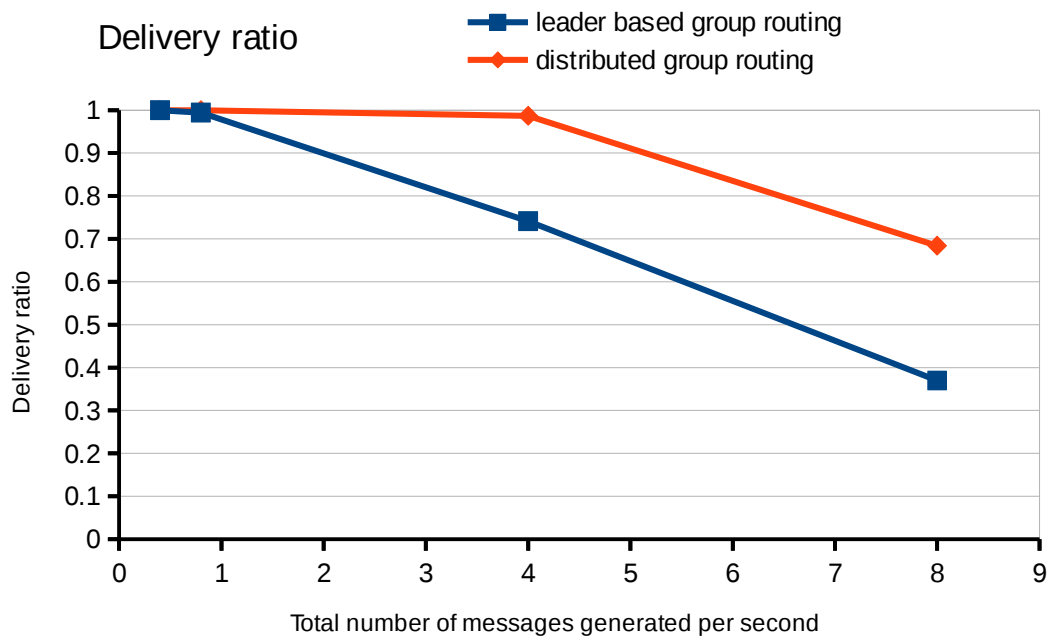


Figure 30: Delivery ratio

Duplicate messages

Similar to the case in symmetric traffic generation, in asymmetric sending scenario, distributed group routing performs poor compared to leader based group routing. When multiple nodes of adjacent groups come in contact with each other, multiple duplicate messages are exchanged in distributed group routing. Even though every border node sends a control message to inform the other member nodes to decrease copy of messages that are transferred to the adjacent group and to record the GID of the adjacent group, this message takes some time to propagate along the group. Meanwhile other member nodes can be engaged in transmission of messages to nodes of the same adjacent group. Whereas in leader based group routing the group leader controls every message transmission from its group, leader based approach provides almost zero number of duplicate messages at all considered traffic generation interval sizes. Distributed group routing is very poor in this performance metric. Duplicate message transmission results in unnecessary consumption of bandwidth and can delay transmissions of other messages. This can be improved to some extent if member nodes forward messages by picking the messages randomly from their buffers than retrieving according to FIFO principle.

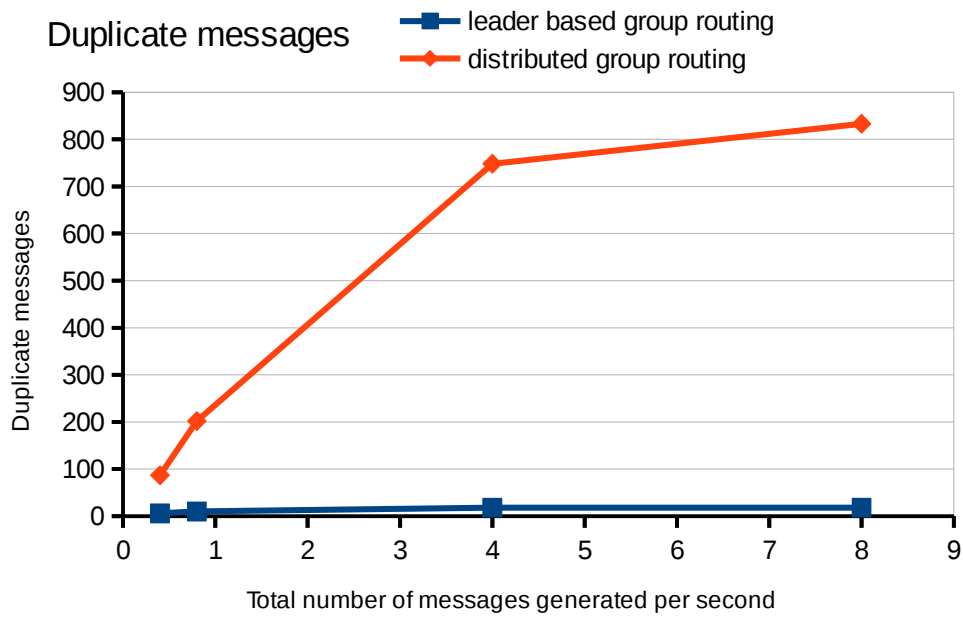


Figure 31: Duplicate messages

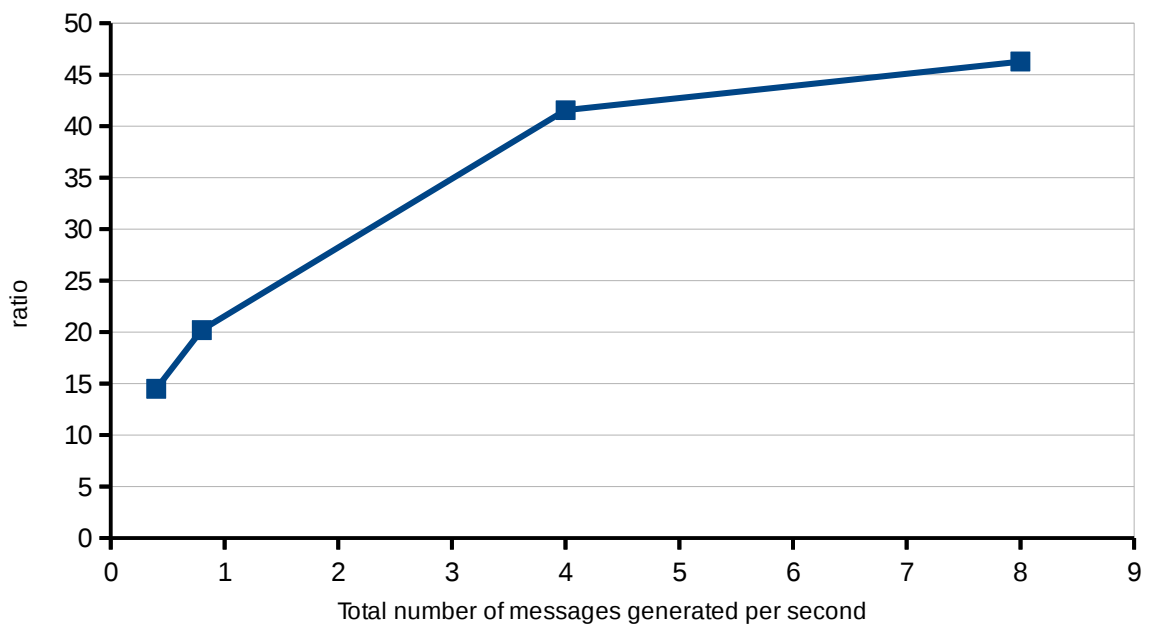


Figure 32: ratio of the number of duplicate in distributed group routing to number of duplicate messages in leader based routing

Average buffer size

In leader based group routing it is an average of the buffer sizes of the group leaders, whereas in distributed group routing it is an average of the buffer sizes of all nodes. In asymmetric sending scenario, the leader based group routing has lower delivery ratio compared to the distributed group leader due to the bottleneck effect of the group leaders as it is clear explained in Section 6.1.1. There is a big difference in the number of delivered messages between the two approaches. This indicates that there are high number of yet to be delivered messages stored up for long time in the source group or in intermediate groups in leader based group routing than in distributed group routing. For this reason, we see in Figure 33 higher average buffer size values for leader based group routing compared to the distributed group routing.

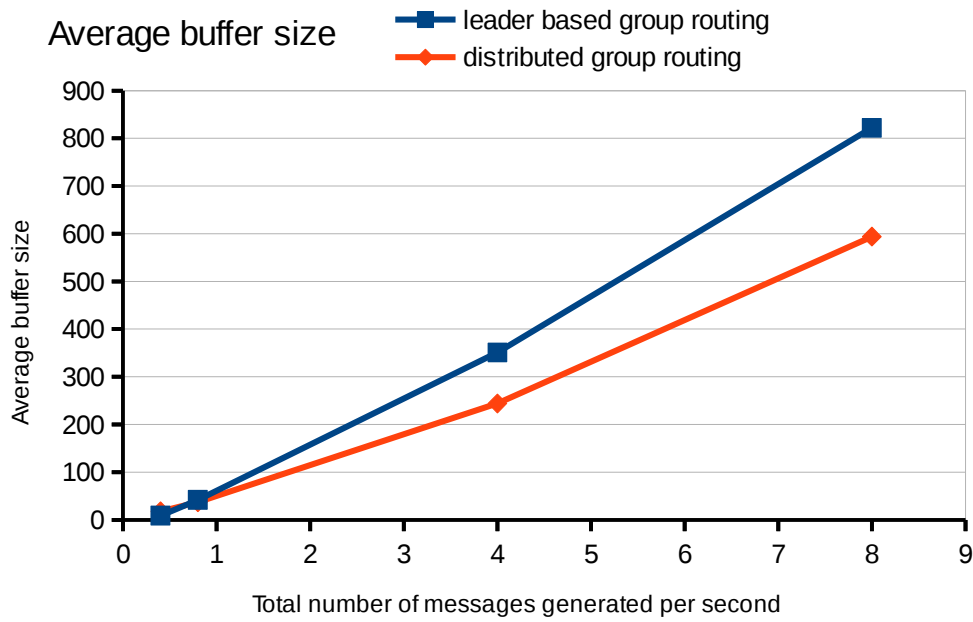


Figure 33: Average buffer size

6.1.4 Only one destination group scenario

Here, we pick all the destination nodes to be from the same group. One source node is chosen from each group except the destination group to evaluate how the two approaches perform in asymmetric conditions. The movement pattern of the destination group relative to the movement of the other groups is the bottle neck for the delivery ratios and average delays in both approaches. In scenarios where the destination group is easily reachable, we obtained relatively high delivery ratios and low average delay values. But when the destination group stay isolated for long time, the performance with respect to delivery ratio and average delay is very poor in both approaches.

In this experiment, we perform 5 different simulations for 5 different destination groups. We have considered 5 groups and each group contains 10 member nodes.

Average delay

In this asymmetric receiving scenario, the movement of the destination group highly affects the end-to-end delay values of messages and arrival of messages to their destination nodes. Thus for both approaches the average delay values are highly determined by the long time spent by the messages in buffers of the intermediate groups. Similar to the asymmetric sending scenario, in leader based group routing group leaders become bottleneck to the number of messages that are routed to the destination group or to other adjacent groups when the random encounter duration is short. The fact that messages are contained in buffers of all member nodes of a group and mobile nodes communicate immediately when they come in contact with nodes of other groups enables distributed group routing to achieve lower average delay. Hence, as it provided in Figure 30, there is visible difference in the average delay values of both approaches for all traffic loads.

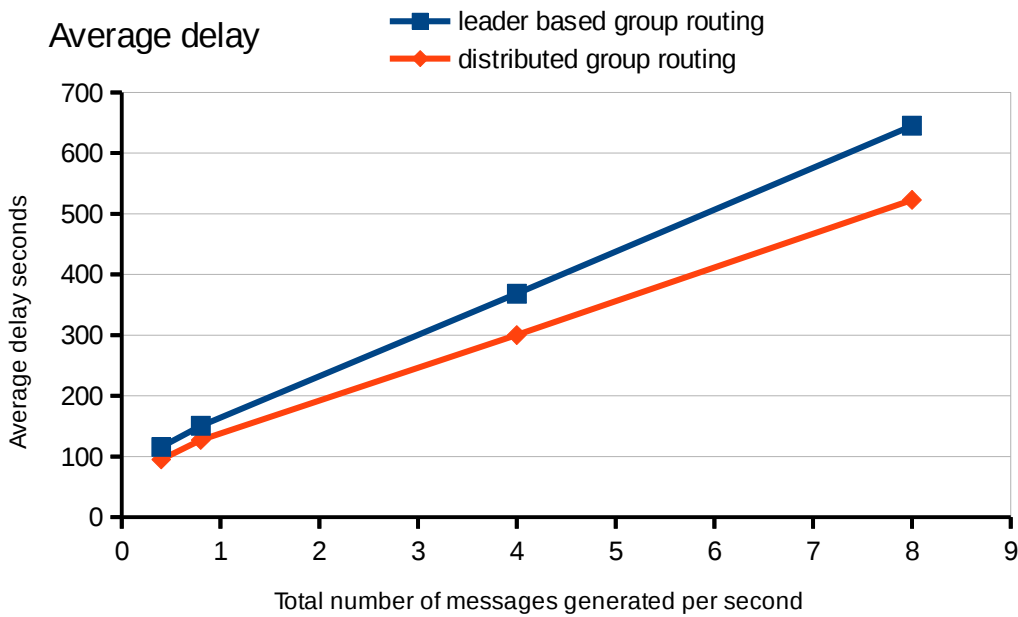


Figure 34: Average delay

Delivery ratio

Similar to the average delay metric, the delivery ratio of messages is also highly affected by the movement patterns of the destination group relative to the movement of the other groups. For instance while the destination group is away or isolated from the other groups, intermediate groups or source groups will have long queue of messages in their buffers when there is high traffic load and when they encounter with the destination group the number of messages forwarded will be determined by the contact duration.

From Figure 35 provided below, we see there is viable difference between the delivery ratio values of the two approaches when the traffic load is high. This is due to the bottleneck effects of the group leaders in leader based group routing. At high traffic loads when two groups meet up, each group might have high number of messages that the other group don't have and thus, in leader based group routing the fact that only the group leader is in charge of sending the messages limit the number of messages forwarded to the adjacent group unlike to the distributed group routing where any member node can forward messages to its adjacent node of other group.

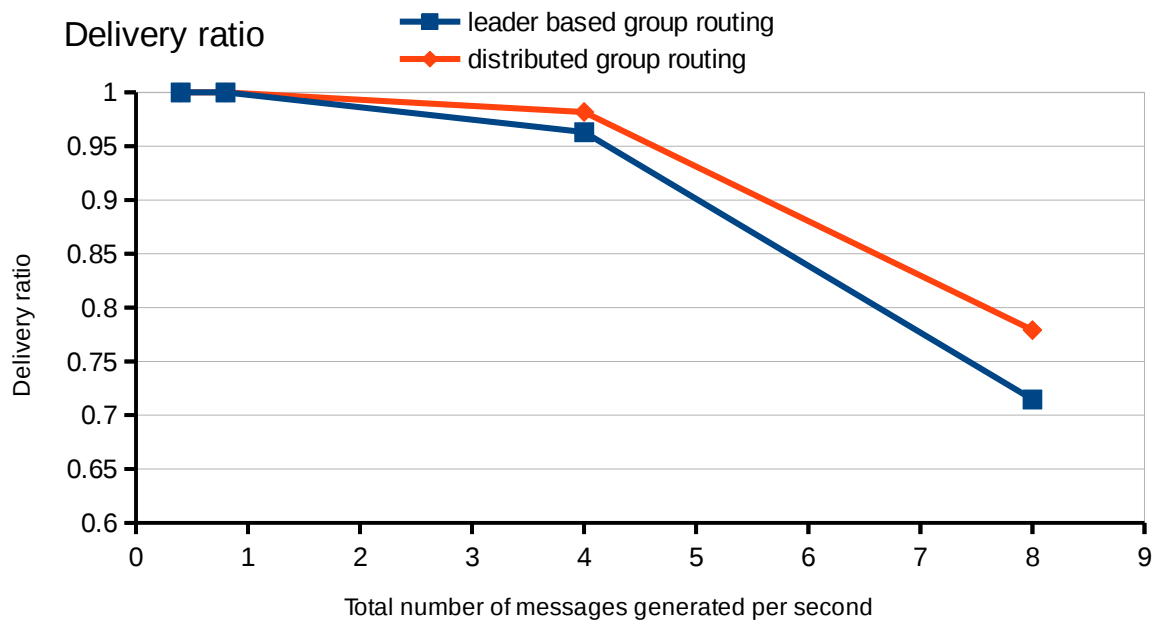


Figure 35: Delivery ratio

Duplicate messages

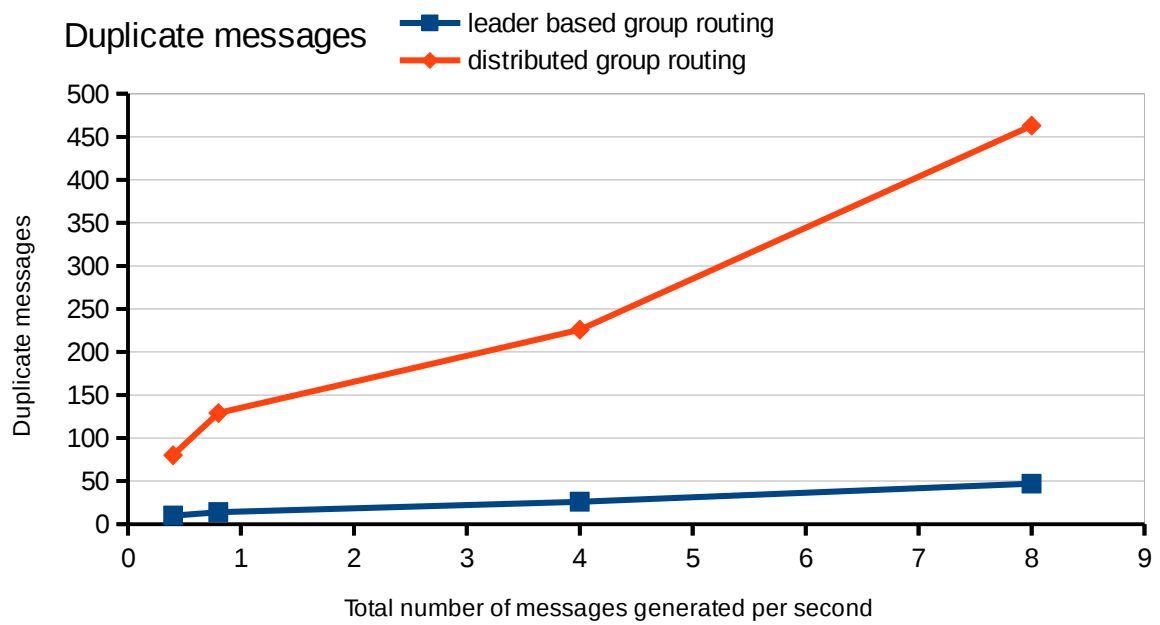


Figure 36: Duplicate messages

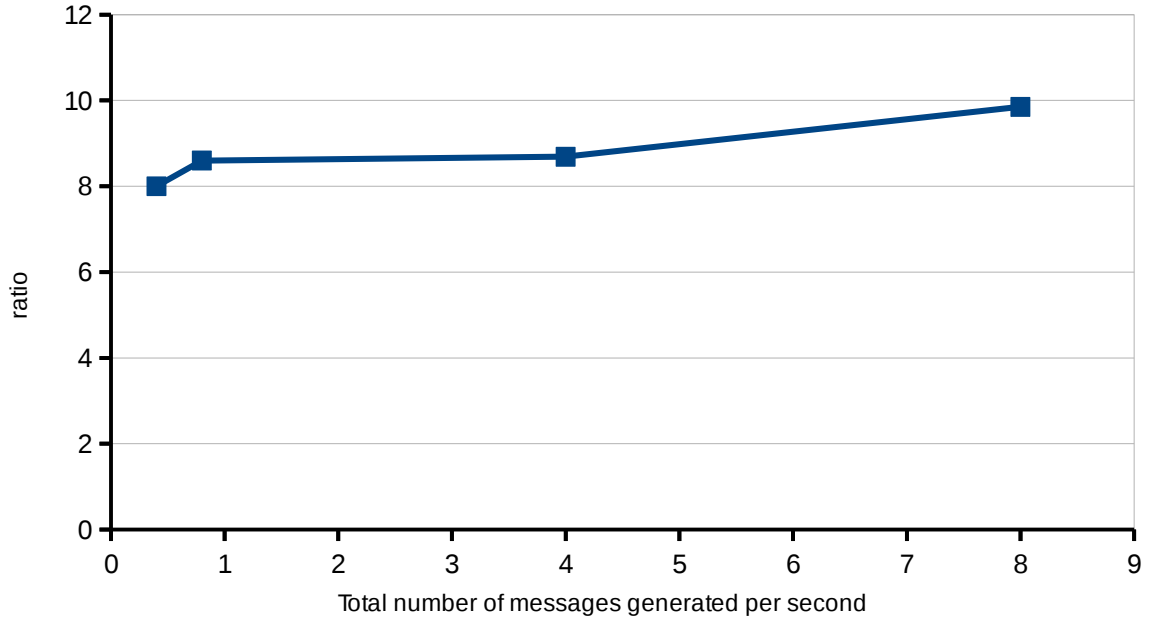


Figure 37: Figure 41: ratio of the number of duplicate in distributed group routing to number of duplicate messages in leader based routing

Similar to the other scenarios, here there are high number of copies of messages received more than once in the destination group in distributed group routing approach due to the same reasons described in Section 6.2.1

Average buffer size

As it is described in Section 6.1.3, average buffer size is an average of the buffer sizes of the group leaders in leader based group routing and it is an average of the buffer sizes of all nodes in distributed group routing. There are high number of messages that are unable to arrive at their destinations within the 2000 seconds simulation time in both group routing approaches. Hence, we see in Figure 34 high average buffer sizes in both approaches. Leader based group routing have higher average buffer size mainly due to the relatively higher number of copies of undelivered messages.

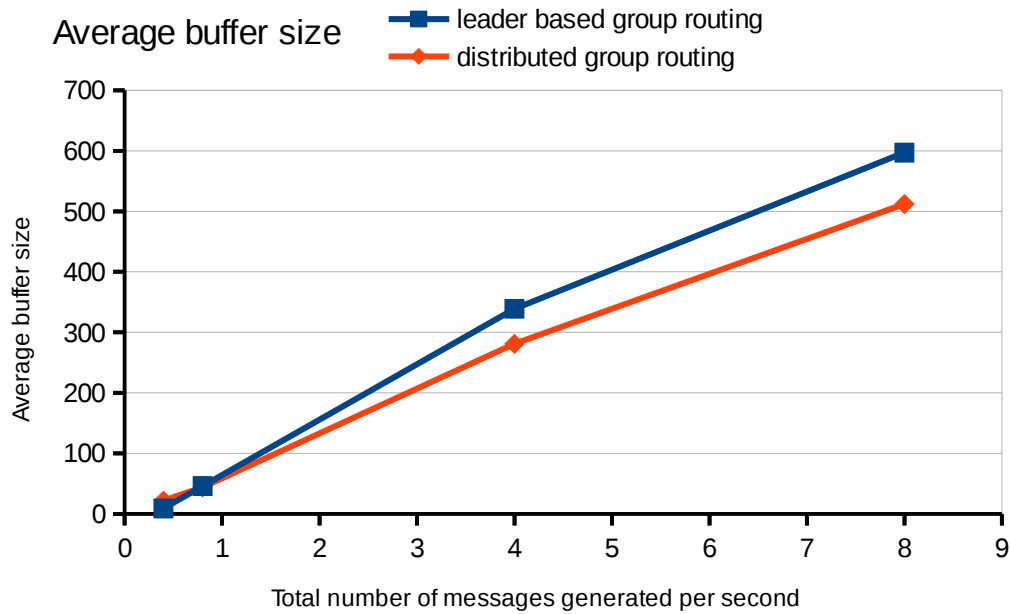


Figure 38: Average buffer size

6.2 High mobility environment

For this experiment, most of the simulation parameters remain the same as in low mobility scenarios except the parameters used for the group mobility model. Here, the maximum speed of the groups is doubled and there is no pause duration. In this high mobility environment, groups will meet up frequently but their contact durations will be shorter than the case in low mobility. We redo the scenarios we studied at low mobility and evaluate the performances of both approaches.

6.2.1 Source-destination pairs chosen randomly from different groups (5 groups of 10 nodes)

In this scenarios, we have applied the same set of parameters used in Section 6.2.1.

Average delay

In high mobility groups have higher chance of meeting up each other. Though the contact durations are shorter than the contact durations in low mobility environment which can limit the number of messages exchange, the fact that groups move fast lowers the end-to-end delays of messages in the network. Thus lower average delay values obtained for the delivered messages in both approaches at high mobility scenarios. In leader based group routing, the propagation of messages between the border nodes and the group leader still plays a significant part in increasing the average delay. In distributed group routing unlike the leader based group routing, there is no propagation time that

can affect the communication of nodes of adjacent groups, mobile nodes transmit messages immediately after comparing their set of messages with the list summary of messages received from the adjacent nodes of different groups. Thus, as we can see from the Figure 39, it is clear that distributed group routing does better than leader based group routing approach in all traffic load scenarios.

Both approaches achieved relatively lower average delay values than their average delay values obtained in low mobility environment.

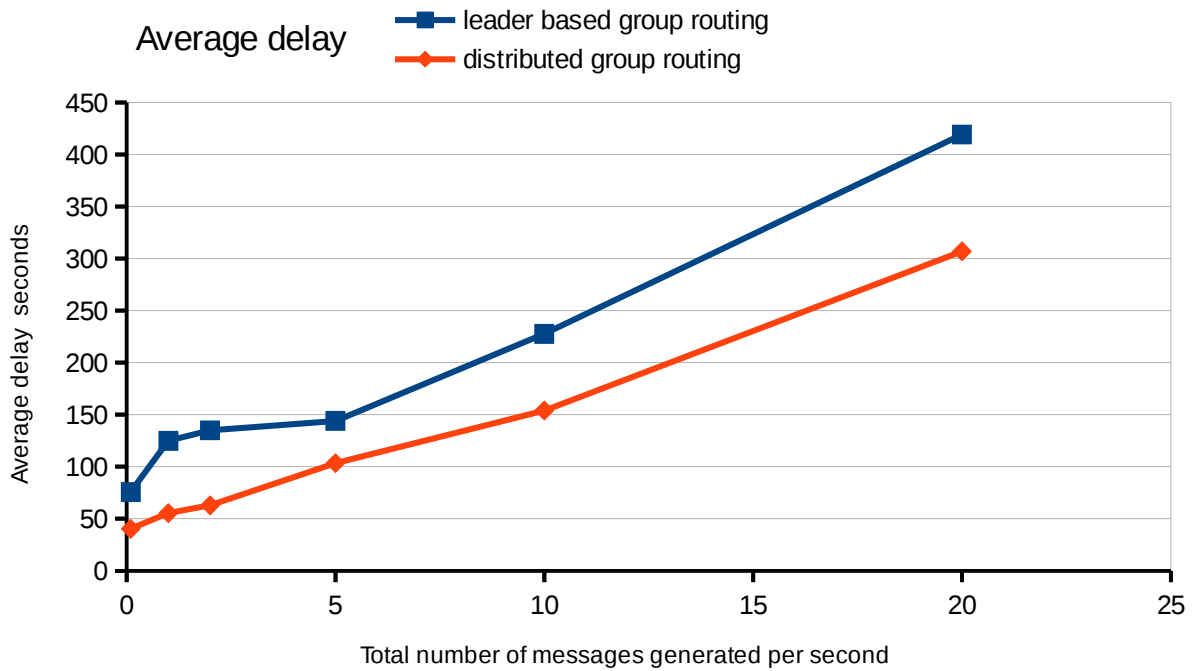


Figure 39: Average delay

Delivery ratio

In high mobility scenario, we do expect a significant difference in the delivery ratio values of both approaches. In high mobility, it is obvious there will be increased number of contacts between groups coupled with many short contact durations which can result in lost messages due to adjacent groups moving out of range during transmission. At high traffic scenario, parallel transmission can also occurs between adjacent groups and in such cases the group leaders becomes bottleneck to the number of messages exchange in a leader based group routing. Thus distributed group routing achieves higher delivery ratio. Moreover, the fact that borders nodes have to wait arrival of messages from their group leader which can take long time due to other transmissions with a group limits the number of messages exchange at brief encounters of groups in a leader based group routing.

As we can learn from the results presented in Figure 40, at light traffics there is no noticeable difference between the two approaches. The delivery ratios are almost 1. At higher traffic, however there is a visible difference between the two approaches. Considerable number of messages can be lost due to groups moving out of range during transmission in both approaches. Altogether, distributed group routing achieves higher delivery ratio than leader based group routing.

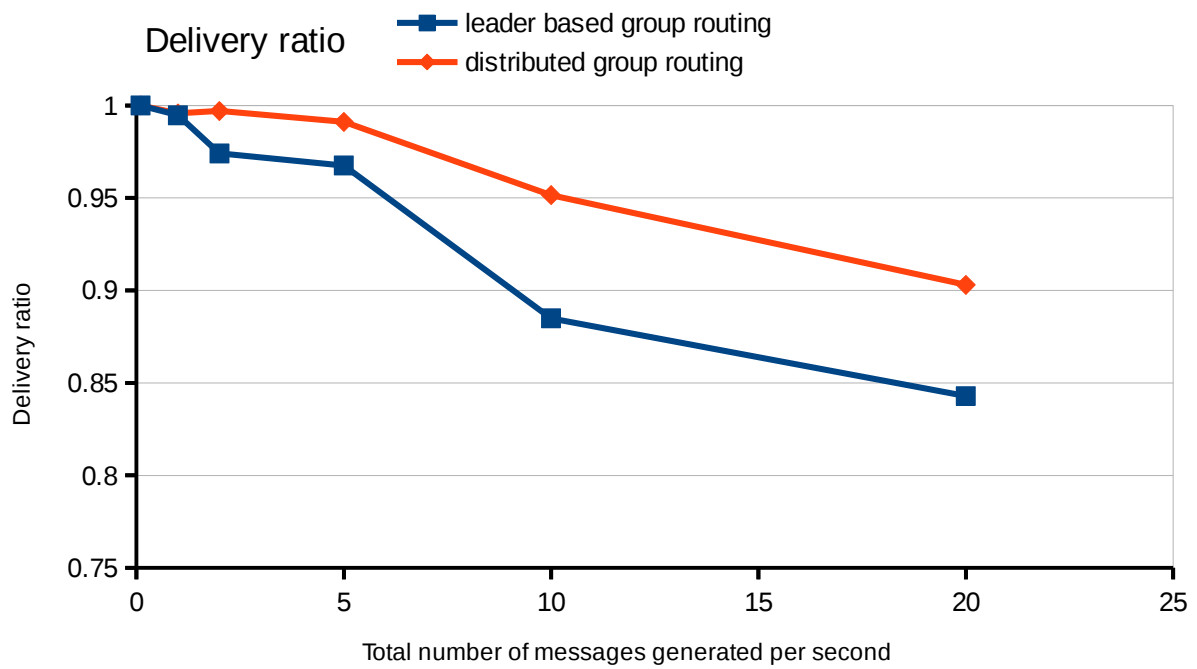


Figure 40: Delivery ratio

Duplicate messages

As we can see the from Figure 41 below, leader based group routing results smaller number of duplicate messages than distributed group routing in all considered traffic loads. This is mainly due to no centralized controlling of the member nodes in distributed group routing. In distributed group routing when there are parallel transmissions between groups, control messages sent by border nodes might not propagate fast enough across the group to eliminate duplicate transmission of messages to adjacent groups.

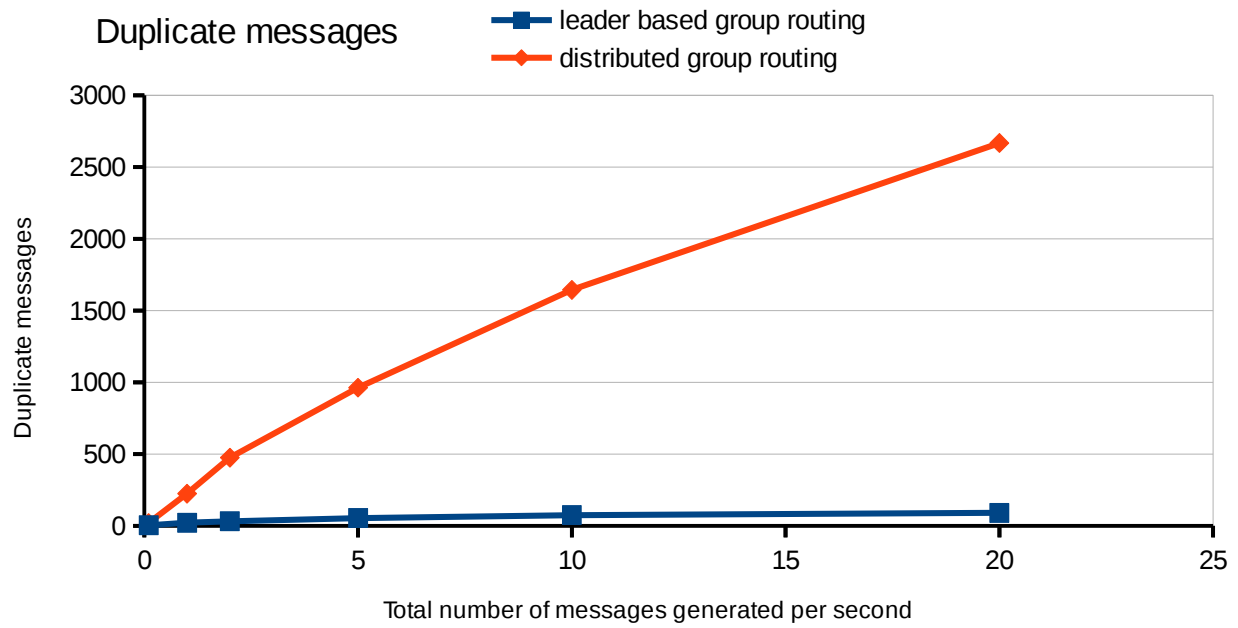


Figure 41: Number of duplicate messages

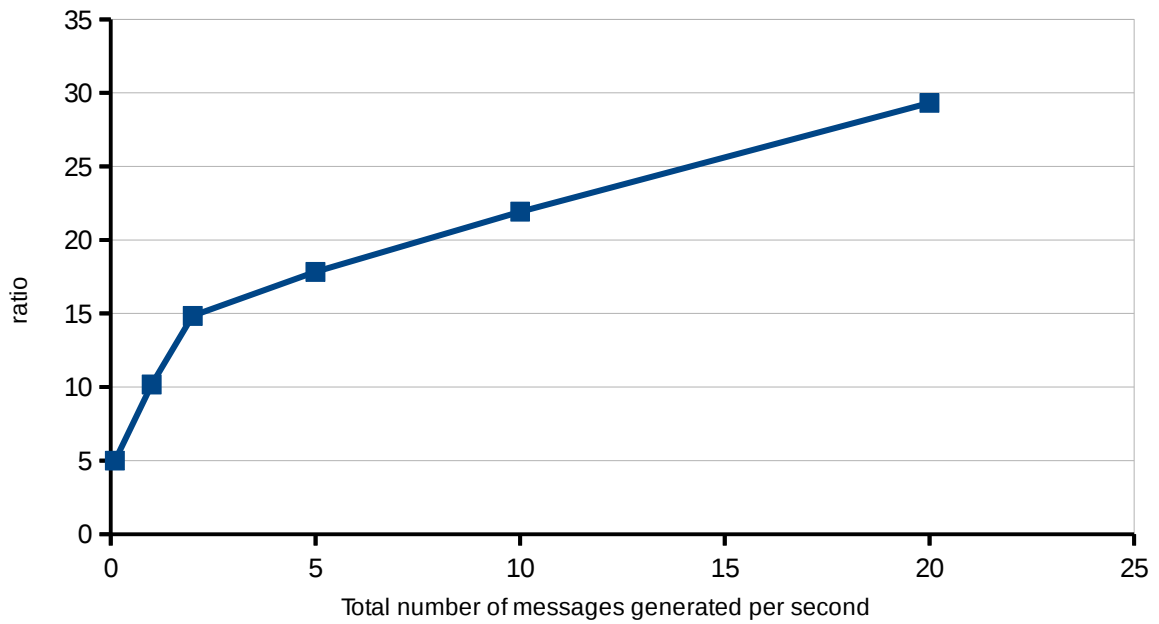


Figure 42: ratio of the number of duplicate in distributed group routing to number of duplicate messages in leader based routing

Average buffer size

In the case of leader based group routing this is an average of the buffer sizes of the group leaders; in distributed group routing it is an average of the buffer sizes of all nodes. In high mobility

scenario, we have higher average buffer values of both approaches compared to the average buffer sizes obtained in low mobility scenario in Section 6.1.1. Here as it is shown in Figure 38 the difference in average buffer size values of both approaches is smaller than the difference obtained in low mobility scenario. As the traffic load gets higher, average buffer size in leader based group routing gets bigger than in distributed group routing due to the relatively high number of undelivered messages in leader based group routing.

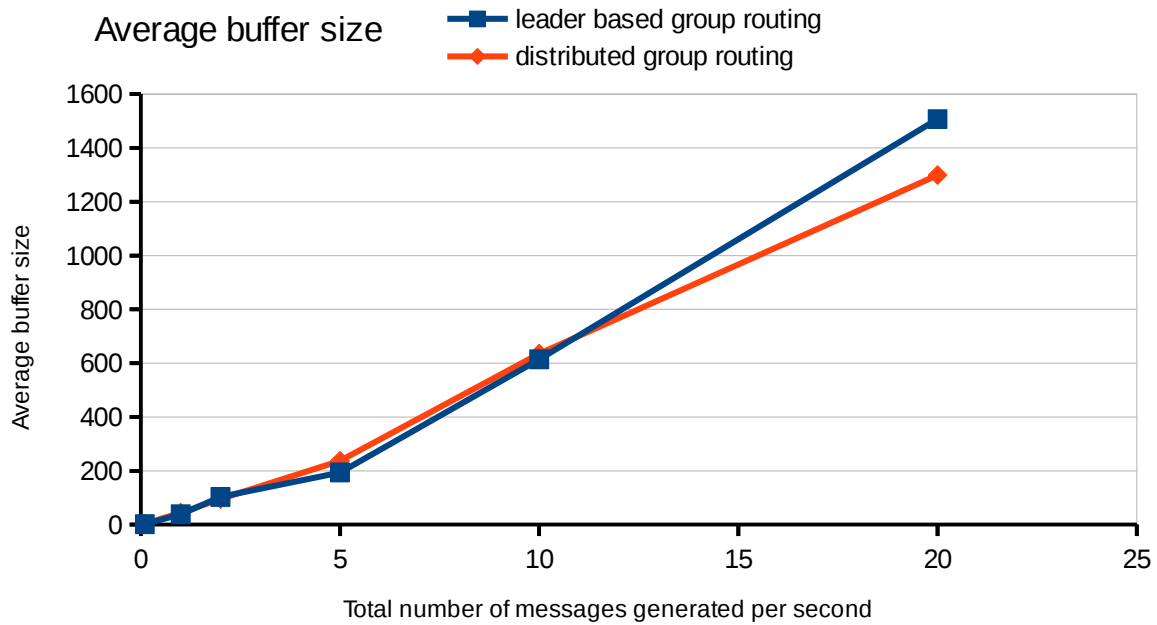


Figure 43: Average buffer size

6.2.2 Source-destination pairs chosen randomly from different groups (10 groups of 5 nodes)

In this scenario, the same traffic generation parameters implemented as Section 6.1.2.

Average delay

Both approaches have achieved lower average values compared to the average values obtained in low mobility. As it is shown in Figure 44, distributed group routing has achieved lower average delay than leader group routing in all considered traffic loads.

The average delay values obtained at each approach are higher values compared to the values obtained for the same approach with 5 groups in section 6.2.1. This is due to the increased traversed number of groups which add extra buffer and propagation delays to the end-to-end delays of messages.

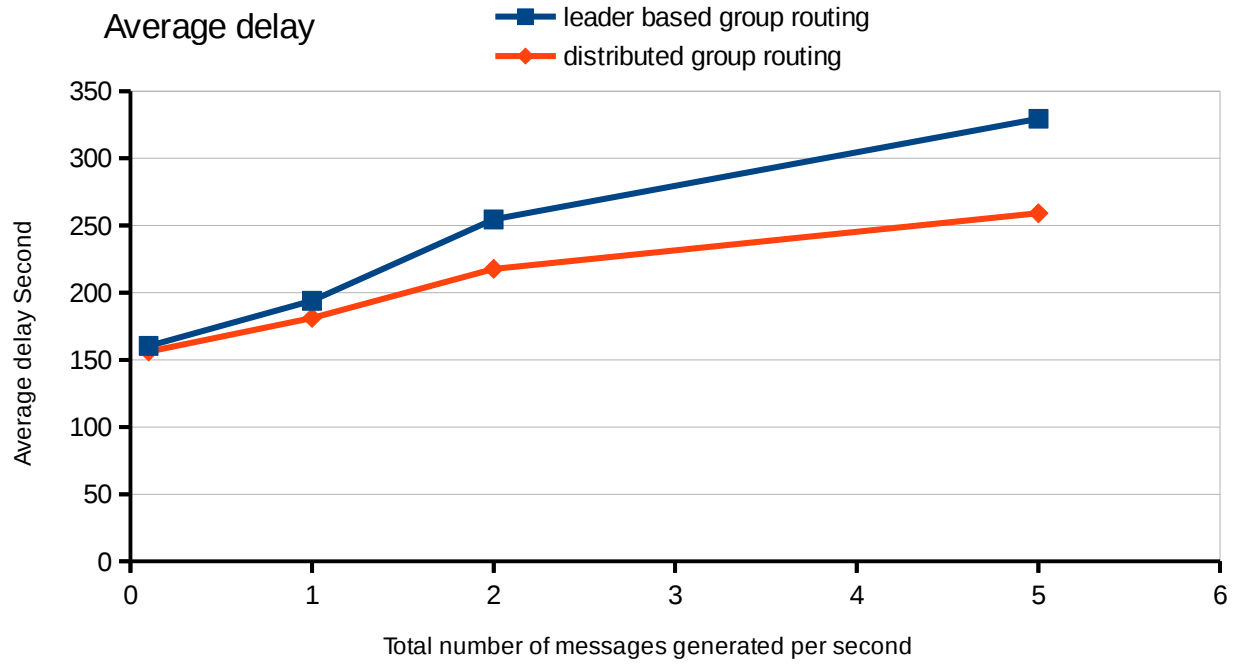


Figure 44: Average delay

Delivery ratio

Here due to the higher mobility of groups, there are shorter contact durations between the groups compared to the contact durations in low mobility and this limits the number of message exchange between groups. Moreover, some messages can be lost due to the moving out of range of nodes. Hence due to the described reasons, we have obtained lower delivery ratio values at high traffic loads compared to the values obtained at lower mobility for both approaches in Section 6.1.2.

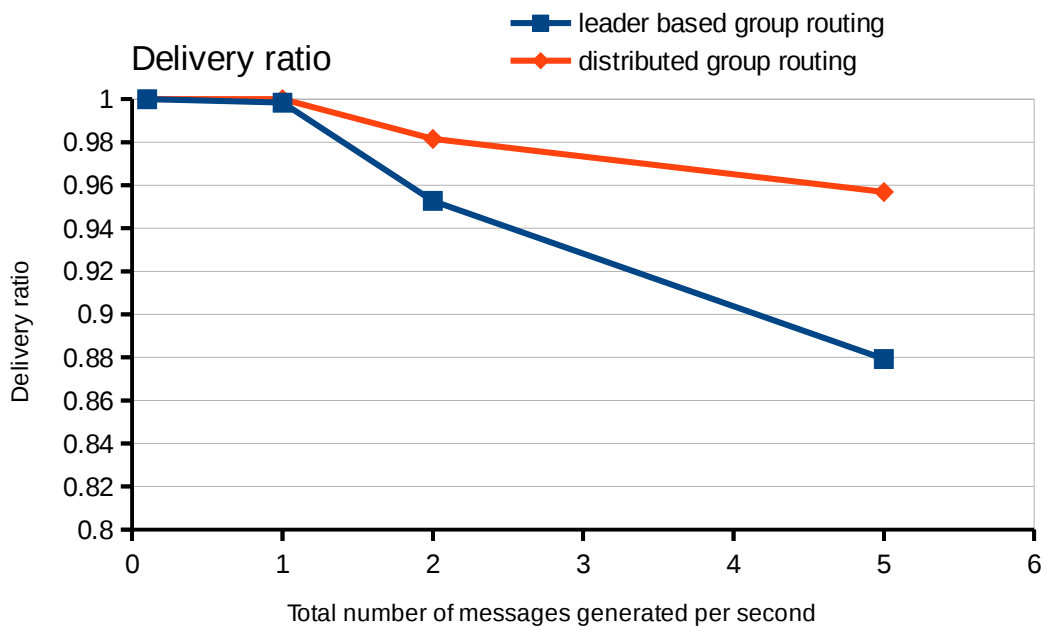


Figure 45: Delivery ratio at high mobility

Duplicate message

As it is shown in Figure 46 the distributed group routing performs poor compared to the leader based group routing. As it is also described in Section 6.2.1, the fact that message exchange is centrally controlled by the group leader enables leader based group routing to achieve very low number of duplicate messages.

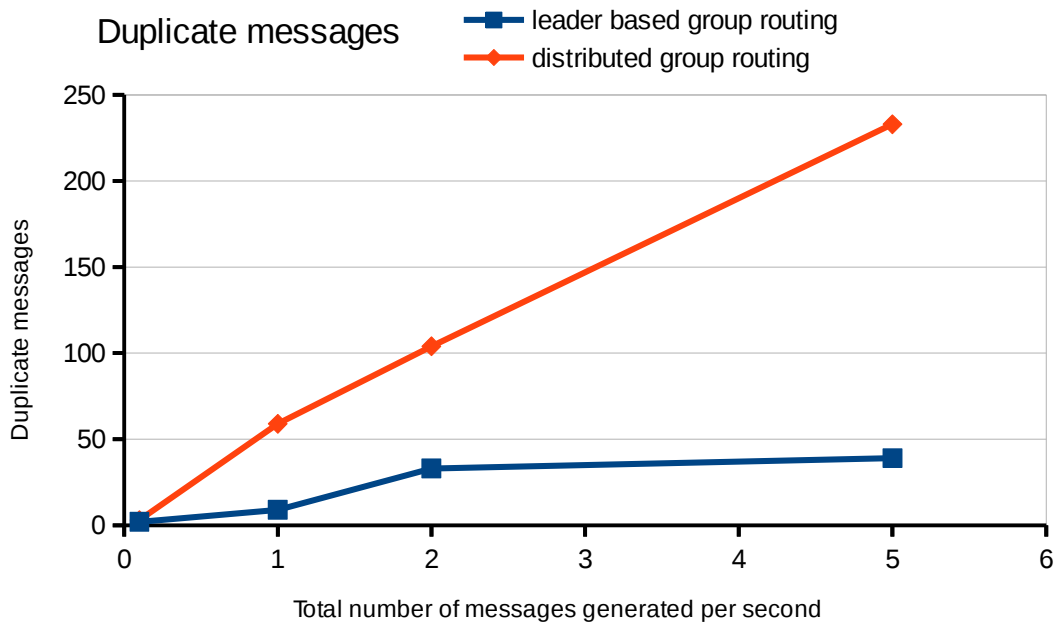


Figure 46: Duplicate messaaes

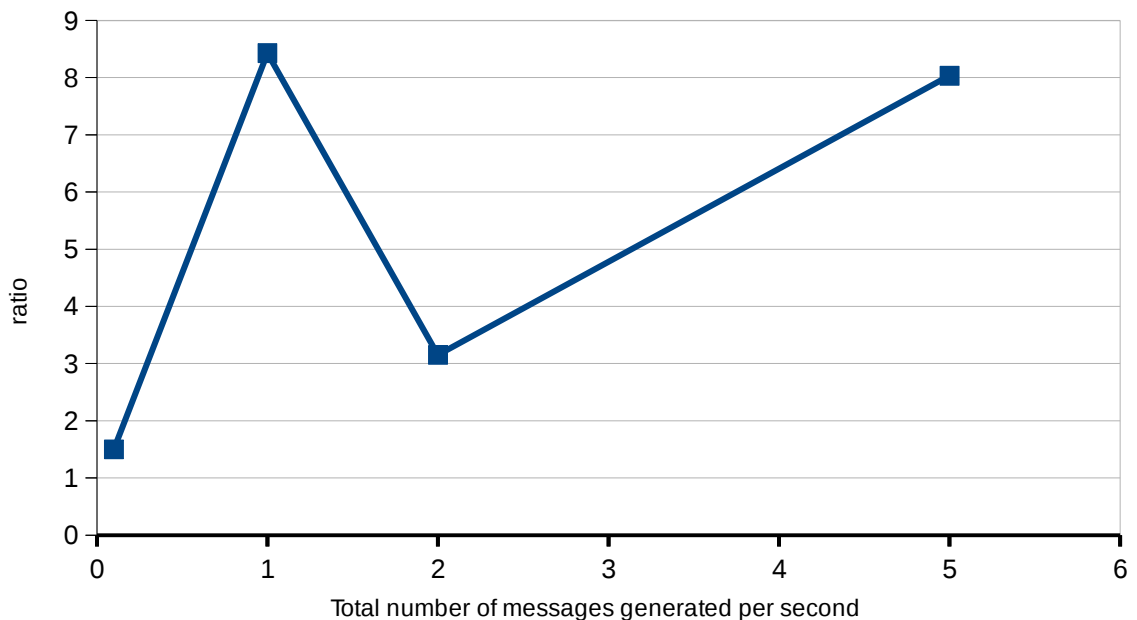


Figure 47: ratio of the number of duplicate in distributed group routing to number of duplicate messages in leader based routing

Average buffer size

It is an average of the buffer sizes of the group leaders in leader based group routing and it is an average of the buffer sizes of all nodes in distributed group routing. As it can be seen from Figure 48, the difference between the average buffer sizes of the two approaches get smaller than the difference values obtained in low mobility. Here, leader based group routing tends to have higher average buffer size as the traffic load increases due to the increase in number of undelivered messages in leader based group routing.

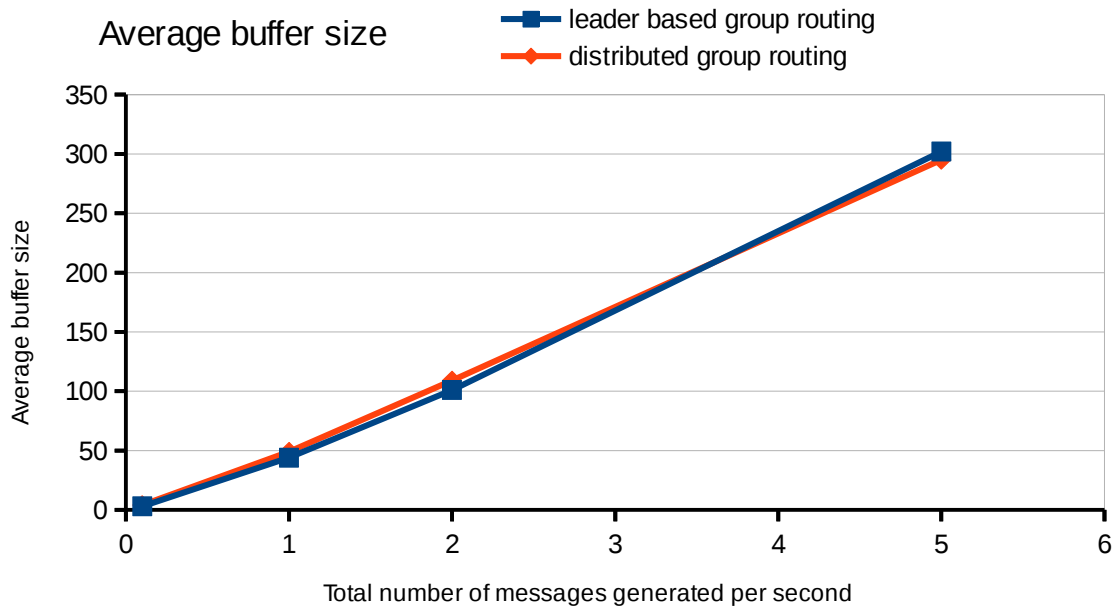


Figure 48: Average buffer size

6.2.3 When only one group generates traffic

For this experiment, we perform 5 different simulations for 5 different source groups at each considered interval size. The whole traffic generation scenario used here is the same as the traffic generation scenario used in Section 6.1.3.

Average delay

In asymmetric sending, the movement of the source group plays a significant role in timely disseminating messages to other groups. Source groups that stay isolated for long time in low mobility scenario have higher chances to meet different groups in high mobility scenarios. Thus high mobility lowers end-to-end delays of messages which results lower average delay values compared to the average delay values obtained in low mobility scenario.

As we can see from the results provided in the Figure 49, distributed group routing has achieved lower average delays than leader based group routing.

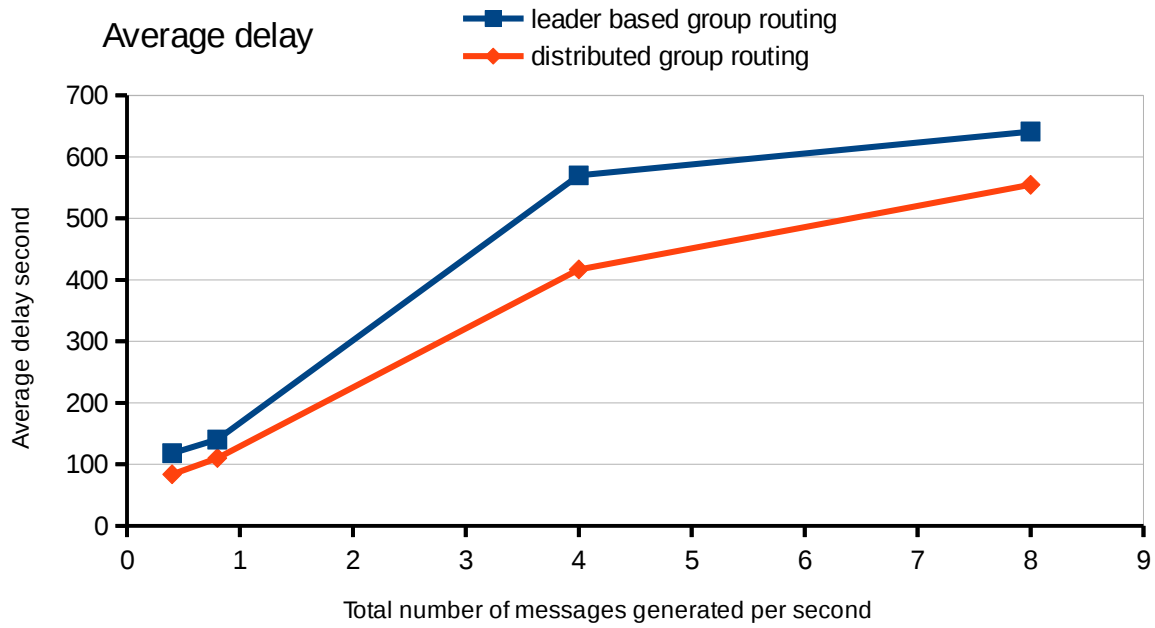


Figure 49: Average delay

Delivery ratio

In leader based group routing, the group leader is the only node in charge of inter-group routing. This will be a bottleneck when more than border nodes come in contact with nodes of other groups. Moreover, in high mobility scenarios, contact durations between the groups are very short which limits messages exchange between the adjacent groups. Thus, there will be low delivery ratio in leader based group routing compared to the distributed group routing approach where there is no central control and bottleneck effect of one central node unlike leader based group routing.

Hence, we see very large difference between the approaches in the result provided in Figure 50. The delivery ratio values obtained for both approaches are lower values compared to the delivery ratio values obtained in Section 6.1.3 at low mobility environment. This is mainly due to the shorter contact durations in high mobility which limit the number of messages exchange between groups.

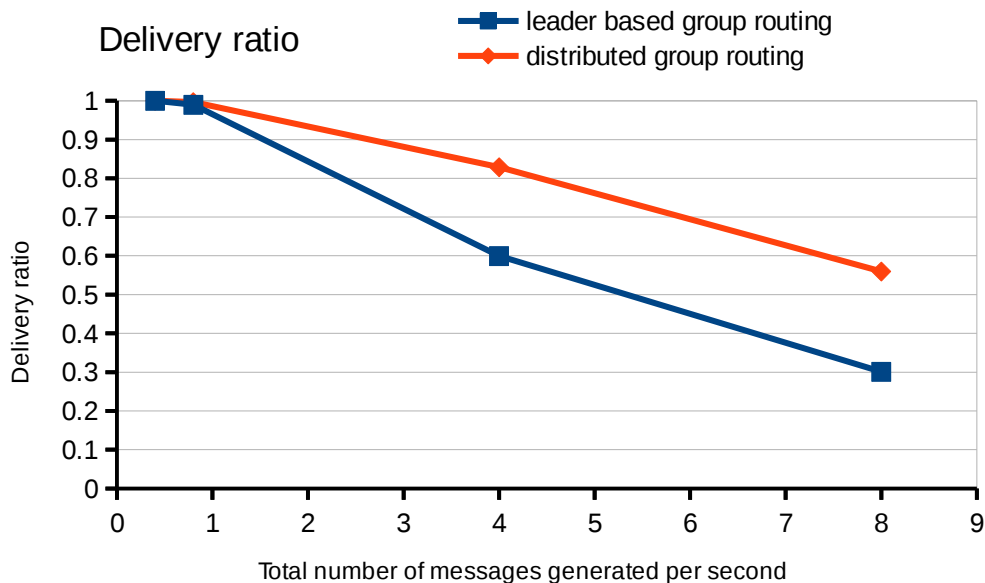


Figure 50: Delivery ratio

Duplicate messages

Similar to Section 6.2.2, leader based approach provides almost zero number of duplicate messages at all considered traffic generation interval sizes, whereas in distributed group routing there are high number of duplicate messages exchange among the groups. For both approaches, we have obtained lower number of duplicate messages than the values obtained at low mobility.

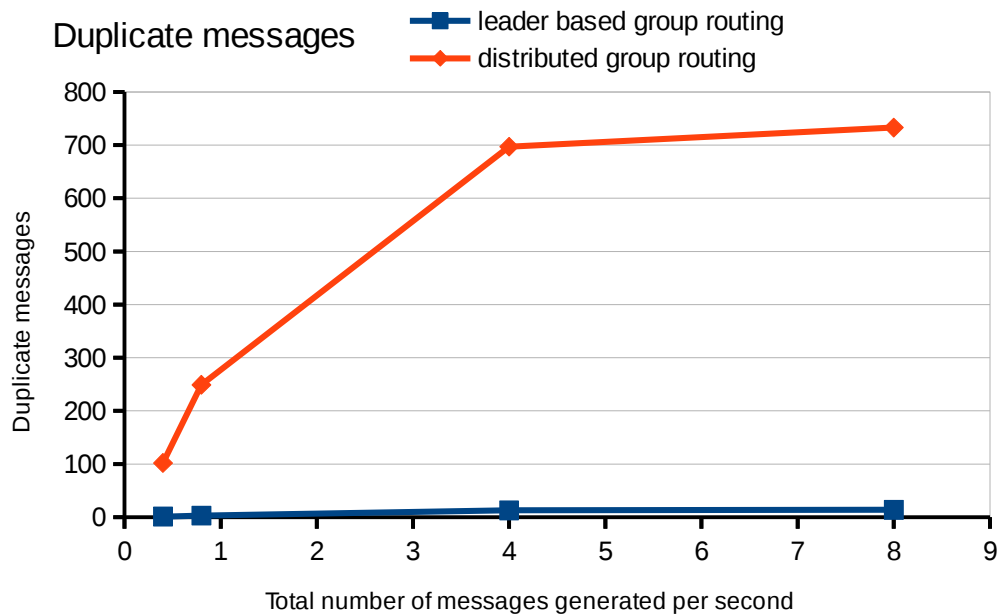


Figure 51: Duplicate messages

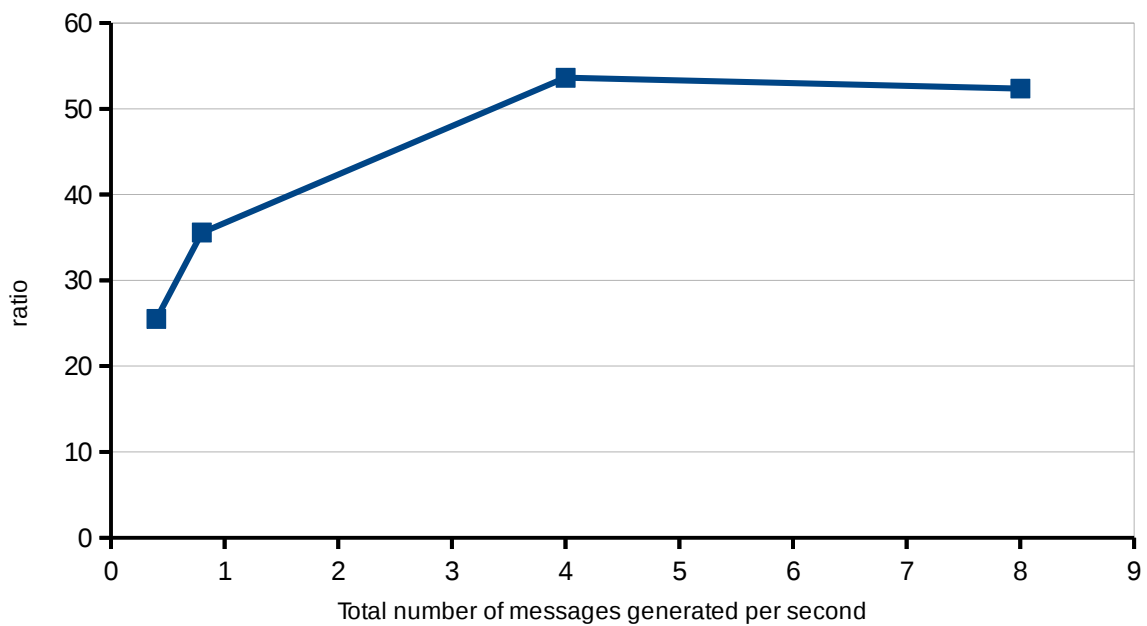


Figure 52: ratio of the number of duplicate in distributed group routing to number of duplicate messages in leader based routing

Average buffer size

In the case of leader based group routing this is an average of the buffer sizes of the group leaders; in distributed group routing it is an average of the buffer sizes of all nodes. The higher number of average buffer size in leader based group routing is mainly due to the higher numbers of undelivered messages that are stored up in buffers of intermediate groups or source group for a long time. In high mobility, there are higher number of undelivered messages for both approaches compared to the number of undelivered messages in low mobility and thus we see in Figure 46, higher average buffer size values for both approaches than the values obtained in Section 6.1.3.

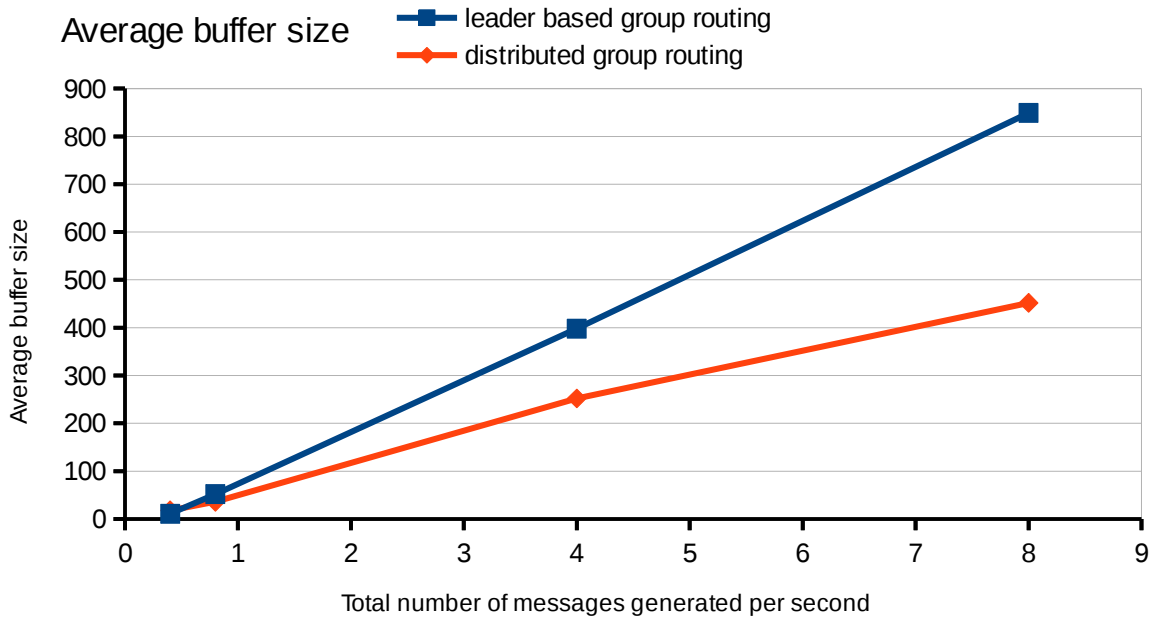


Figure 53: Average buffer size

6.2.4 Only one destination group scenario

Here, we have considered 5 groups and each group contains 10 member nodes. We perform 5 different simulations for 5 different destination groups. The values provided for the performance metrics in the figures are average of the values obtained for different destination groups.

Average delay

In high mobility, each group have higher chances to meet different groups. Despite the fact that shorter contact durations limit the number of messages exchange between groups in high mobility environment, higher mobility of groups lowers end-to-end delays of those messages which manage to arrive at their destinations. Thus lower average delay values are obtained for each approach in high mobility scenarios compared to the values obtained in low mobility scenario.

As we can see from the results provided in the Figure 54, distributed group routing has achieved lower average delays than leader based group routing. This is due to the bottleneck group leaders in leader based group routing.

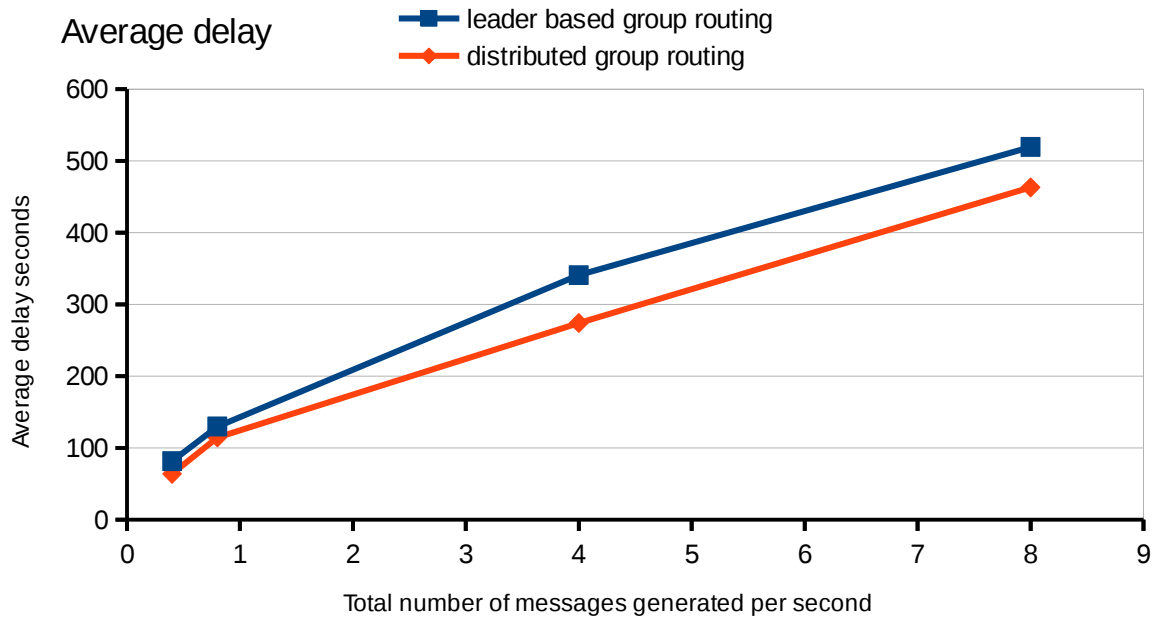


Figure 54: Average delay

Delivery ratio

Groups have higher rate of change of location in time in high mobility than in low mobility scenario. In high mobility, there are many short contact durations which can limit the number of messages exchange between groups. Moreover, messages lost is higher in high mobility due to nodes moving away of transmission range

As shown in Figure 55 below, we obtained lower delivery ratio values for both approaches compared to the values obtained in Section 6.1.4 for low mobility scenario. Here, the difference between the delivery ratios of distributed group routing and leader based group routing get bigger due to the bottleneck group leaders along with the short contacts of adjust groups limit the number of messages between groups in leader based group routing.

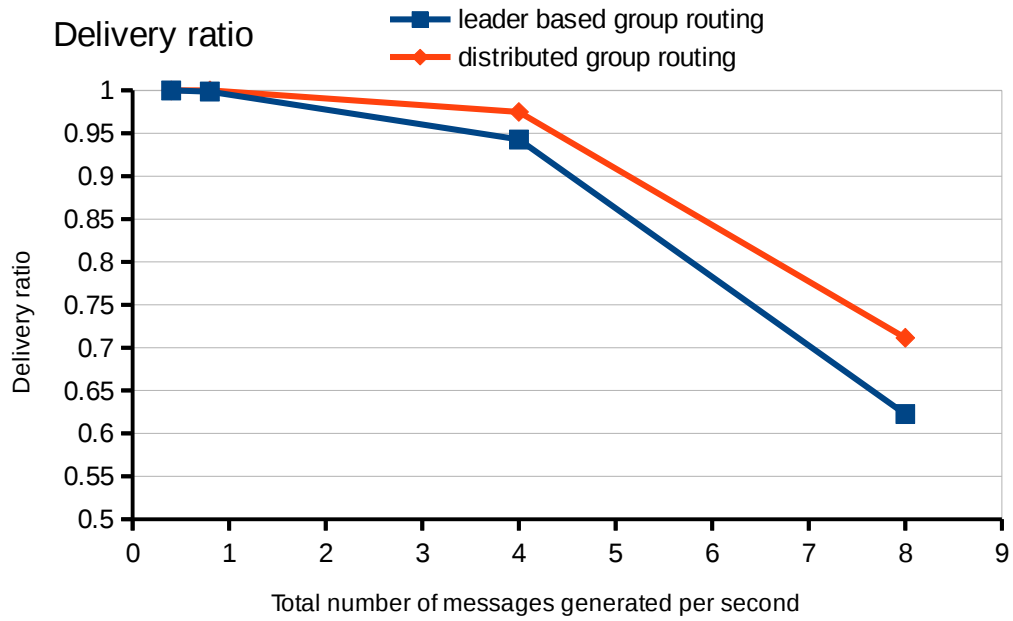


Figure 55: Delivery ratio

Duplicate messages

In this performance metric, similar to the other scenarios, leader based routing approach outperforms distributed group routing as very lower number of duplicate messages obtained in leader based approach.

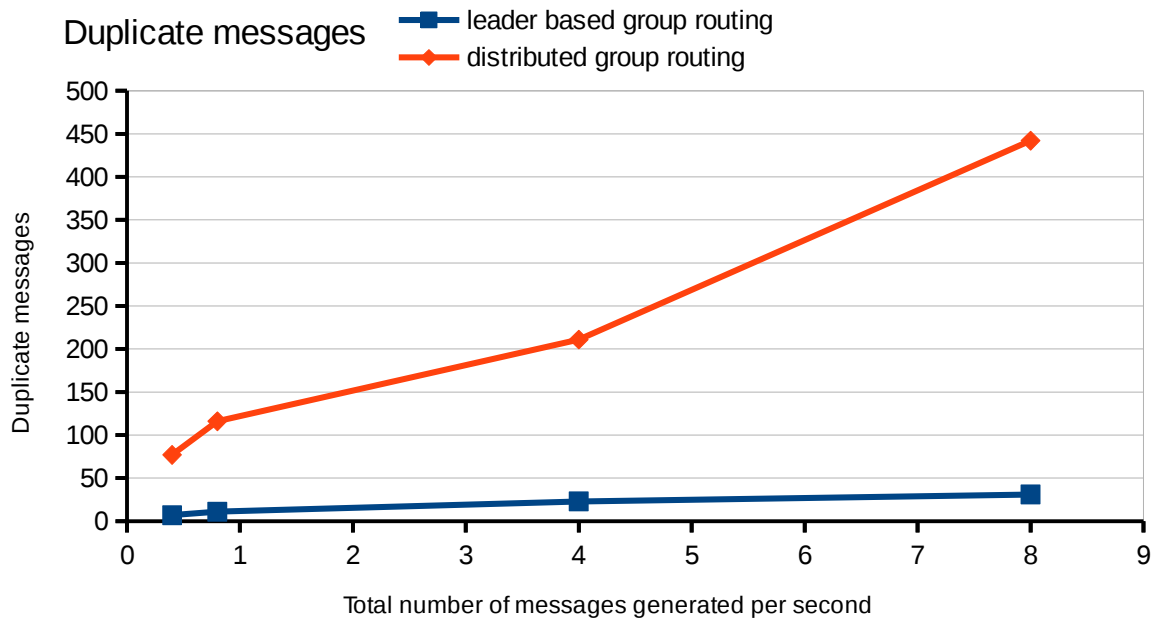


Figure 56: Duplicate messages

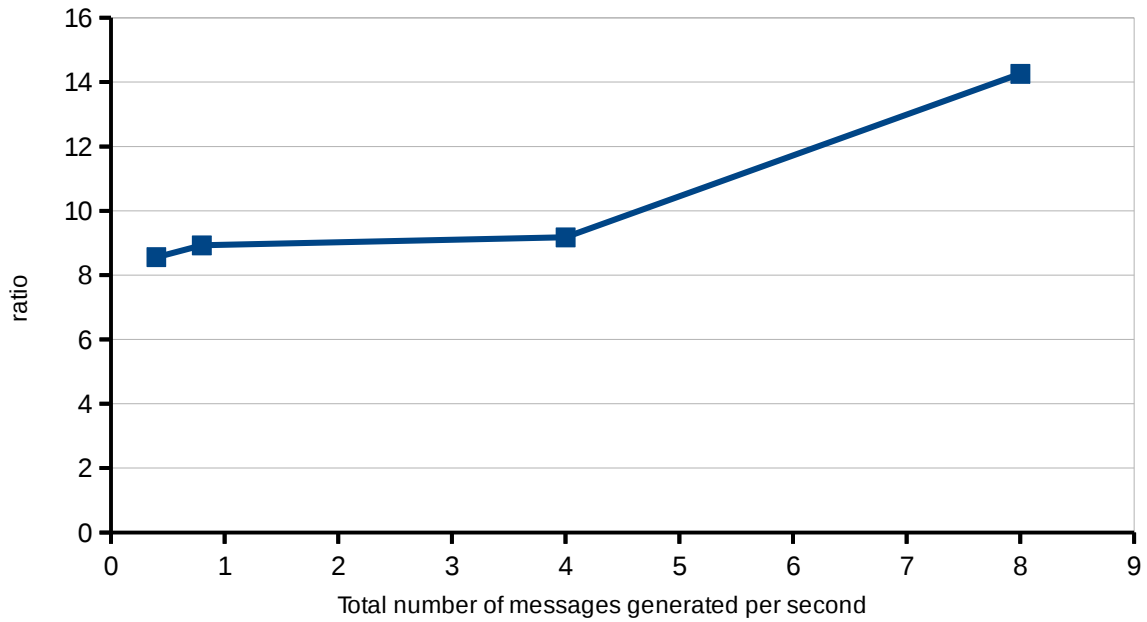


Figure 57: ratio of the number of duplicate in distributed group routing to number of duplicate messages in leader based routing

Average buffer size

This is an average of the buffer sizes of the group leaders in lead based group routing and it is an average of the buffer sizes of all nodes in distributed group routing. In high mobility, there are higher number of undelivered messages for both approaches than in low mobility and these undelivered messages piled up in the buffers of the intermediate groups for long time which leads to higher average sizes.

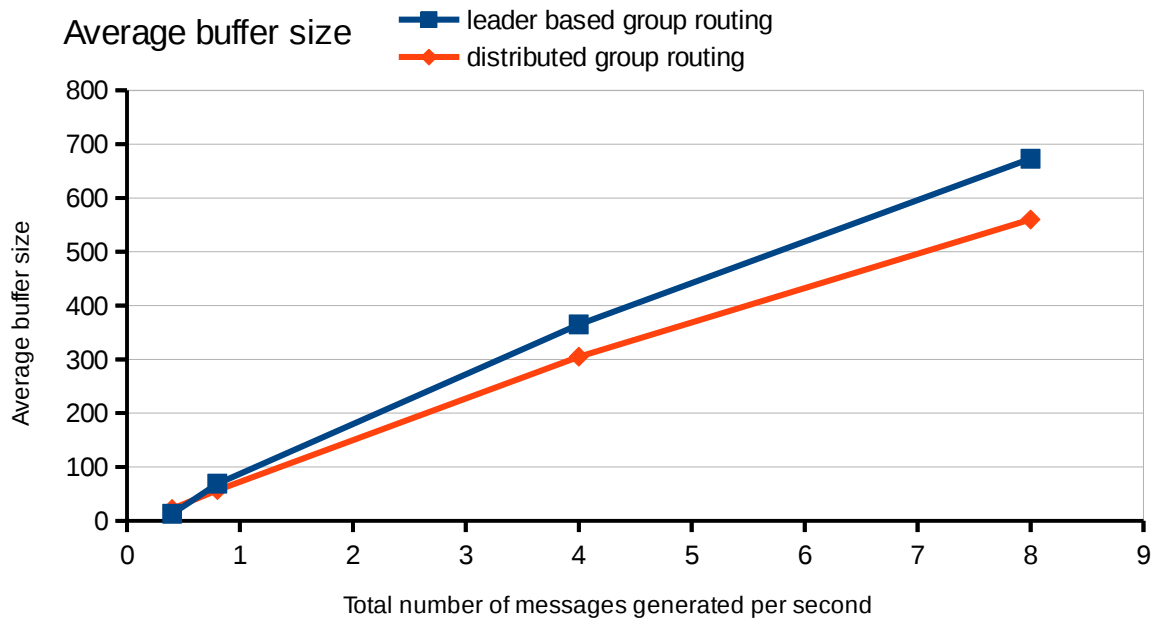


Figure 58: Average buffer size

Chapter 7

7 Conclusions and Future Work

7.1 Summary

In certain critical situations, mobile ad hoc network can get partitioned into smaller disconnected mobile ad hoc networks. For instance, in rescue operations different groups of vehicles or rescue workers may diverge to execute their missions. Members of a group move together and communicate with each other via MANET routing schemes as there is end-to-end connection between any node pairs within a group, but nodes of a group act as a unit when they communicate via DTN routing with randomly encounter adjacent groups. Hence routing strategies have to represent the real communication scenarios and they should integrate DTN routing schemes with conventional MANET routing schemes to provide optimal communication during network disruptions in critical scenarios.

In our study we analyze and compare performance of two group routing approaches for disconnected mobile ad-hoc networks.

The first approach is leader based group routing. In this approach, messages are stored at the group leader. Message exchange with other groups is centrally controlled by the group leader. The other member nodes act as merely forwarders of messages to /from the group leader.

The second group routing approach is a distributed approach, where every member node has all messages that are contained by the group in its buffer. In this approach, inter-group messages generated by the member nodes or received from another group are disseminated across the group as soon as possible. Moreover, copy management of a given message within a group is implemented by broadcasting a " decrease-copy-control-message " across the group.

For our study, in both approaches:

- Mobile nodes perform intra-group routing based on their routing tables. Routing tables are built based on the minimum hop count metric which is discussed at Section 4.2.
- The Binary Spray and Wait protocol [23] for DTNs is used, as explained in detail at Section 4.3.
- There is one type of messages. Buffer management is implemented in a First Input First Output (FIFO) way.

To study the performance of the two approaches we used important common performance metrics, namely average delay, delivery ratio, number of duplicate messages and average buffer size (occupancy).

In some rescue operations, there are some common challenges such as long delays, message

propagation degradation factors, communication bottlenecks, and there are also groups remained isolated for long durations. Hence, the scenarios we considered here for our study presents similar asymmetry challenges for data dissemination among mobile nodes in critical situations.

We have used three scenarios. For both approaches exactly the same traffic generation scenarios are used. The first traffic generation scenario is when source-destination node pairs are chosen randomly from different groups. For this scenario, we have done two experiments. In the First experiment we have used 5 groups and each group has 10 member nodes. Whereas in the second experiment we have applied 10 groups and each group contain 5 member nodes. The second traffic generation scenario is when source nodes are chosen from only one group and one destination node from each group except the source group. This is basically asymmetric sending scenario. In the third traffic generation scenario, destination nodes are chosen from one group and one source node is chosen from each group except the destination group.

To evaluate the two group routing approaches using simulation experiments, we extended NS2 to support DTN mechanisms together with the existing MANET routing schemes.

In our simulation experiments, we adapted our mobility model from Reference Point Group Movement (*RPGM*) [11] in such a way that the movement pattern of the logical center is a Random way point mobility model (*RWMM*) [1]. Unlike *RPGM* in our mobility model every member node follows the logical center such that its position relative to the center remains the same during the whole course of movement. Simulation experiments have been carried out at high and low mobility environments. In each simulation experiment, exactly the same movement trace of groups has been used for both approaches.

To sum up, we have learned that disseminating messages to all member nodes as in distributed group routing results into considerably lower delay and higher delivery ratio values at the cost of requiring buffers at all member nodes and overhead of many same message in network. Moreover, distributed group routing approach allows member nodes to communicate with nodes of adjacent groups freely without relying on any node; leader based group routing, where inter-group communication is entirely determined by the group leader, is much more vulnerable. But the fact that there is no centralized monitoring of inter-group communication in distributed group routing makes it difficult to eliminate reception of duplicate messages by different member nodes and to manage copies of messages when there are more than one parallel transmissions between groups. Broadcasting control messages and data messages across a group may take time until they arrive at all member nodes.

7.2 Revisiting the Research Questions

Based on the results obtained from the previous chapter, the research question formulated in Chapter 1 will be addressed in this section.

The main research question was:

How does a leader based group routing perform compared to a distributed group routing in hybrid MANET-DTN networking ?

This question was split in different subquestions

Answer to each subquestion defined in Section 1.2 is given as follows:

1. What is the state-of-the art of hybrid MANET-DTN routing ?

Different hybrid MANET-DTN routing schemes have been proposed for data dissemination in opportunistic networks of mobile nodes that implemented different ways of grouping, replication mechanisms, and different ways of integrating MANET and DTN routing protocols. Some protocols focus on improving delivery rate by implementing multi-copy mechanisms and others aim on reducing overhead using single-copy mechanisms.

In general, hybrid MANET-DTN routing schemes can be broadly categorized into hybrid MANET-DTN routing schemes that apply explicit grouping of mobile nodes and hybrid MANET-DTN routing schemes that don't apply explicit grouping of mobile nodes.

Hybrid MANET-DTN routing schemes which apply explicit grouping of mobile nodes, adapt different ways of group formation and group management. Some of the protocols group mobile nodes based on their mission/task in a pre-determined way and some others group end-to-end connected mobile nodes based on their physical proximity. However, grouping based on the physical proximity is vulnerable to group instability and thus some schemes consider connectivity for sufficient time duration as an additional criteria for group formation.

Those schemes which don't apply explicit grouping forward messages using conventional MANET routing when there is a stable end-to-end connection between nodes or using DTN routing mechanisms when nodes are intermittently connected.

This sub question has been addressed in detail in Chapter 3.

2. How is inter-group routing among randomly moving groups of mobile nodes coordinated in leader based group routing and distributed group routing?

In both approaches a group is treated as a single node for inter-group routing. Groups exchange copies based on Binary Spray and Wait routing protocol. Groups exchange messages based on the principle of one inter-group message for one group. Any given group forwards a copy of a given message to adjacent group only if the adjacent group doesn't have the given message. Prior to exchanging copies of inter-group group messages, adjacent groups first exchange lists of identifiers of delivered messages and lists of identifiers of the inter-group messages contained in their groups. Then each group will know which messages to forward to the adjacent group.

In leader based group routing, inter-group messages are only stored in the group leaders. Group leaders control the exchange of messages with adjacent groups. Border nodes inform their group leaders when they come in contact with nodes of other groups. Group leaders exchange their lists of identifiers of known delivered messages and lists of identifiers of inter-group messages contained in their buffers via those border nodes. Then each group leader will decide which messages to send to the other group and start sending messages via the border nodes.

In distributed group routing all member node play the same role. All messages contained in a group are stored at all member nodes. Member nodes broadcast generated or received messages from other group across the group. Moreover, any member node that forwards copy of a given message to adjacent group informs the other members of its group to decrease the current copies of the message by broadcast control message.

Detail answer for this sub question is given in Chapter 4 in Section 4.3.

3. What are the pros and cons of using each approach?

The main advantage of using leader based group routing is the fact that buffer is only needed at the group leader. This can be helpful in resource constrained environment. Other advantage of using

leader based group routing is, there is less waste of bandwidth and energy as there is small number of duplicate messages. On the other hand, the main weakness of this approach is that the throughput is limited by the group leaders. This is clearly shown from the results found in Chapter 6. Leader based approach provides higher average delay values and lower delivery ratios compared to the distributed group routing which implies lower throughput. In addition to the bottleneck effect of group leaders, there is also a reliability issue in leader based group routing. If the group leader fails, there will not be communication with other groups.

In distributed group routing, owing to the decentralized control of communication, there is high performance with respect to the delivery ratio and average delay. Hence high throughput is obtained using distributed group routing. Moreover, as every node can independently communicate with nodes of other groups, there is better reliability in this approach.

The main drawback of this approach is the cost of buffers in all mobile nodes. This can be a great deal in resource constrained environment. Other disadvantage of distributed group routing is inefficient use of network resources by duplicate messages during parallel transmission.

4. How do the two approaches perform under different scenario?

For study of the performance of the two approaches, we have considered three different traffic scenarios in low and high mobility environments. The performance of the two approaches is evaluated based on performance metrics ; average delay, delivery ratio, average buffer size and number of duplicate messages. Thus the performance of both approaches with respect to each metric is given as follows.

- *Average delay:* Distributed group routing provides lower average delay values in all considered scenarios. Higher average delay values are obtained in leader based group routing because group leaders become bottleneck. This occurs when nodes of a group come in contact with nodes of one or more adjacent groups and each border node has to wait its time to receive message from its leader. Messages that are not forwarded to the adjacent groups in a given contact duration have to wait for other encounters which can happen after considerable time passed by. Thus the movement of the groups plays a significant role in magnifying the bottleneck effect. Obviously, these effects become particularly prominent for higher network load and increased mobility.
- *Delivery ratio:* Higher delivery ratio values are obtained in distributed group routing in all scenarios. The bottleneck effect of the group leaders and the propagation delays of messages from the group leader to the border nodes lower the delivery ratio in leader based group routing. Big difference between the delivery ratios of the two approaches when there is high traffic load, when there are short contact durations due to high mobility of groups, and when there are large number of messages piled up or stored up in buffers of source or intermediate groups in the asymmetric scenarios. In addition to the bottleneck effect of the group leaders, propagation delays of messages from the group leader to the border nodes (member nodes in contact with nodes of adjacent groups) can limit the number of messages exchanged in leader based group routing when the contact durations are very short.
- *Number of duplicate messages:* Leader based group routing provides almost zero number of duplicate messages in all considered scenarios. In distributed group routing, unlike the leader based group routing there is no centralized way of controlling messages. Mobile nodes try to control duplicate message transmission by broadcasting a control message across a group to inform other member nodes to which group a given message is forwarded. However, this control message can take a while before it is received by all member nodes

and thus there might occur parallel reception of duplicate messages by different nodes when more than one nodes of adjacent groups come in contact. Due to this reason, high number of duplicate messages are obtained in a distributed group routing approach.

- *Average buffer size:* In the case of leader based group routing this is an average of the buffer sizes of the group leaders; in distributed group routing it is an average of the buffer sizes of all member nodes. In scenarios where the two approaches have delivery ratio values that are close to 1, we have obtained higher average buffer size values in distributed group routing than in leader based group routing. This indicates there are high number of messages exchange between groups in distributed group routing. But in the asymmetric scenarios where there are big differences in delivery ratios of both approaches, we have obtained higher average buffer size values in leader based group routing compared to the values in distributed group routing due to the high number of messages that are piled up in the buffers of source groups or intermediate groups and they are not able to arrive at their destinations due to the bottleneck group leaders in leader based group routing.

Finally, back to the main question :

How does a leader based group routing perform compared to a distributed group routing in hybrid MANET-DTN networking ?

From the results found in Chapter 6, we have learned that distributed group routing results into lower delay and higher delivery ratio values at the cost of requiring buffers at all member nodes. Particularly in scenarios where the bottleneck effect of group leaders is visible, distributed group routing has large performance gain over leader based group routing in both delivery ratio and average delay metrics. On the other hand, in leader based group routing substantial buffering is needed only at the group leader.

To choose one from the two approaches we have to take into account the cost of requiring buffers in all member nodes and broadcast messages in distributed group routing which can be expensive in resource constrained environment, and the bottleneck effect of group leaders and reliability issue of leader based group routing that can highly degrade communications in critical scenarios.

Though we expect similar results as we obtained in this study, we recommend further investigation at other different scenarios and mobility traces to find out.

7.3 Future work

While we carried out our simulation experiments under three different scenarios, we feel there are still other more scenarios under which further experiments on the performance of the two approaches can be executed. For instance, in some rescue operations some members of a group may be detached temporary or permanently from their group, or some new mobile nodes might join a given group. Thus such situations should be literally represented by group mobility models that provide group dynamics. In existing group mobility models including the mobility model implemented in our study, group dynamics is limited. Moreover, as has been noted in this research we have used only one type of messages with unlimited buffer size, but in real-life critical scenarios there can be different messages (commands) which need different QoS and accordingly different buffer management needed. Dropping of less important messages due to buffer overflow and dropping of messages due to their time expirations should also be considered. Henceforth, it is worth to explore the performance of the two approaches in such scenarios. These scenarios might provide better perspective on the performance of both approaches.

Furthermore, the performance of the two group approaches should also further be examined using mobility traces that are collected from real-life scenarios.

When we were doing our study, there were not open source simulators that support DTN routing. Developing new simulator that supports both DTN and MANET network was not feasible time wise for this study, it would take a long time. So we had to implement the necessary DTN mechanisms on existing Ad hoc network simulators. Hence we have implemented DTN routing along side the MANET routing in NS2 simulation tool. NS2 includes all Internet protocol packages from application layer to the physical layer when any simulation is carried out As our extended NS2 simulator works at different time scales,mac layer at milliseconds/microseconds and DTN connection in seconds/minutes depending on the moment patterns of the groups,there are a lot of packages/events execute internally which can be less important but make the simulations very slow at high traffic loads. For this reason, it has been difficult to run longer simulation experiments with heavy traffic loads. At heavy traffic load one single simulation takes more than 3 days. This problem can be mitigated by developing a customized simulator with simple but adequate features for hybrid DTN-MANET networks. Some of the layers can be easily represented by simpler designs. Thus we recommend further investigation of performance of the two approaches at heavy traffic loads using other fast customized simulators.

Appendix A

1. Low mobility

I. 10 Source- Destination node pairs (5 groups)

A) Traffic generation per Interval =0.5 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	18880	17338	0.9183	393.2403	83	1115
2	18880	17606	0.9325	416.5471	72	1123
3	18880	16495	0.8736	519.6415	264	1341
4	18880	17547	0.9293	407.4123	171	1187
Average	18880	17246	0.9134	434.2103	147	1191

Table 11: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	18880	18463	0.9779	240.0760	2823	966
2	18880	18424	0.9758	309.8451	3142	1087
3	18880	18122	0.9598	453.1246	2546	1257
4	18880	18480	0.9788	314.8743	2914	1195
Average	18880	18372	0.9731	329.48	2856	1126

Table 12: results of distributed group routing

B) Traffic generation per Interval =1 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average Buffer size
1	9442	9246	0.9792	192.838	72	430
2	9442	9336	0.9888	220.56	65	453
3	9442	9010	0.9542	389.15	201	737
4	9442	9303	0.9853	198.85	149	321
Average	9442	8822	0.9768	247.187	121	388

Table 13: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average Buffer size
1	9442	9377	0.9931	120.939	1672	394
2	9442	9359	0.9912	159.65	1881	453
3	9442	9346	0.9898	343.519	1481	949
4	9442	9387	0.9942	161.43	1678	405
Average	9442	9367	0.9920	196.3845	1678	440

Table 14: results of distributed group routing

C) Traffic generation per Interval =2 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	4724	4704	0.9958	136.2194	66	144
2	4724	4665	0.9875	137.8145	130	147
3	4724	4680	0.9907	208.6189	104	219
4	4724	4686	0.9920	141.9461	69	130
Average	4724	4683	0.9914	156.1497	92	160

Table 15: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	4724	4704	0.9958	99.5786	799	203
2	4724	4678	0.9903	114.6291	750	228
3	4724	4705	0.9960	178.3769	850	310
4	4724	4704	0.9958	107.4632	1170	188
Average	4724	4697	0.9944	125.01195	892	232

Table 16: results of distributed group routing

D) Traffic generation per Interval = 5 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	1894	1886	0.9958	105.6286	42	62
2	1894	1883	0.9942	114.2484	43	61
3	1894	1883	0.9942	129.6797	53	99
4	1894	1885	0.9952	123.22	25	58
Average	1894	1884	0.9948	118.1941	40	70

Table 17: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	1894	1892	0.9989	75.5021	337	90
2	1894	1889	0.9974	82.0472	317	87
3	1894	1890	0.9979	98.37	434	98
4	1894	1890	0.9979	86.1705	572	87
Average	1894	1890	0.9980	85.5224	415	90

Table 18: results of distributed group routing

E) Traffic generation per Interval = 10 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	950	945	0.9947	99.9871	29	28
2	950	946	0.9958	107.5474	23	29
3	950	948	0.9979	104.2230	39	38
4	950	948	0.9979	98.5866	16	25
Average	950	947	0.9968	102.5860	27	30

Table 19: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	950	949	0.9989	75.7276	167	44
2	950	948	0.9979	76.95	142	44
3	950	950	1	85.28	256	57
4	950	948	0.9989	78.3115	246	46
Average	950	949	0.9978	79.0672	202	47

Table 20: results of distributed group routing

F) Traffic generation per Interval = 100 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	99	99	1	82.7323	3	3
2	99	99	1	87.8198	1	3
3	99	99	1	80.9678	1	3
4	99	99	1	78.8723	6	2
Average	99	99	1	82.5980	2	3

Table 21: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	99	99	1	59.3883	14	3
2	99	99	1	62.3380	14	4
3	99	99	1	70.2849	13	4
4	99	99	1	56.7354	22	4
Average	99	99	1	62.1866	13	4

Table 22: results of distributed group routing

II. Only one group generates traffic scenario

A) Traffic generation per Interval =0.5 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	7650	2509	0.3279	926.29	24	864
2	7650	3193	0.4173	757.12	21	790
3	7650	2664	0.3482	765.33	24	831
4	7650	3118	0.4075	834.98	7	816
5	7650	2663	0.3481	693.1	15	812
Average	7650	2829	0.3698	795.364	18	822

Table 23: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	7650	4362	0.5701	743.617	491	678
2	7650	6409	0.8377	512.22	1106	474
3	7650	5323	0.6958	627.58	778	586
4	7650	5446	0.7118	691.11	1129	611
5	7650	5230	0.6836	608.45	664	622
Average	7650	5234	0.6841	639.352	833	594

Table 24: results of distributed group routing

B) Traffic generation per Interval =1sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	3826	2520	0.6586	858.74	24	372
2	3826	3191	0.8340	650.79	22	316
3	3826	2785	0.7279	564.19	22	357
4	3826	3114	0.8139	723.41	7	343
5	3826	2670	0.6978	630.7	15	368
Average	3826	2836	0.7412	709.68	18	351

Table 25: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	3826	3715	0.9709	590.55	480	284
2	3826	3801	0.9934	288.26	853	178
3	3826	3785	0.9892	409.98	747	215
4	3826	3791	0.9908	535.46	1036	279
5	3826	3787	0.9898	464.9	628	264
Average	3826	3775	0.9868	458.23	748	244

Table 26: results of distributed group routing

C) Traffic generation per Interval =5 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	767	761	0.9921	332.31	5	55
2	767	766	0.9987	125.21	13	28
3	767	762	0.9935	244.11	21	45
4	767	766	0.9987	162.78	7	37
5	767	758	0.9882	239.6	4	49
Average	767	762	0.9942	220.802	10	42

Table 27: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	767	765	0.9973	127.95	178	40
2	767	767	1.00	88.87	244	35
3	767	767	1.00	95.669	203	44
4	767	767	1.00	93.72	223	38
5	767	767	1.00	145.08	165	32
Average	767	767	1	110.2578	202	37

Table 28: results of distributed group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	383	383	1	181.2785	4	12
2	383	383	1	74.2411	8	9
3	383	383	1	103.2275	9	10
4	383	383	1	138.8168	5	10
5	383	383	1	92.3460	4	8
Average	383	383	1	117.9819	6	9

Table 29: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	383	383	1	118.7281	65	20
2	383	383	1	70.1843	101	18
3	383	383	1	71.9891	75	17
4	383	383	1	137.5892	124	19
5	383	383	1	79.7790	73	17
Average	383	383	1	95.6539	87	18

Table 30: results of distributed group routing

III. Only one destination group scenario

A) Traffic generation per Interval =0.5 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	7650	5105	0.6673	710.4621	44	710
2	7650	5748	0.7513	476.6629	52	546
3	7650	5332	0.6969	653.254	46	590
4	7650	5914	0.7730	669.1523	49	534
5	7650	5241	0.6850	576.1749	45	605
Average	7650	5468	0.7147	644.95	47	597

Table 31: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	7650	5540	0.7241	623.621	425	612
2	7650	6480	0.8470	403.7149	471	465
3	7650	5853	0.7650	542.1082	474	496
4	7650	6312	0.8250	551.9874	485	471
5	7650	5617	0.7342	491.4774	462	520
Average	7650	5960	0.7791	522.9114	463	512

Table 32: results of distributed based group routing

B) Traffic generation per Interval =1sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	3826	3634	0.9498	422.5243	22	351
2	3826	3712	0.9702	315.241	27	314
3	3826	3695	0.9657	373.6214	24	355
4	3826	3706	0.9686	384.123	31	320
5	3826	3678	0.9613	346.321	29	354
Average	3826	3685	0.9631	368.3661	26	339

Table 33: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	3826	3703	0.9678	361.2345	205	314
2	3826	3807	0.9950	232.7291	216	255
3	3826	3720	0.9879	301.0580	256	305
4	3826	3812	0.9963	308..4567	242	240
5	3826	3741	0.9777	297.1465	211	294
Average	3826	3756	0.9818	300.1249	226	281

Table 34: results of distributed based group routing

C) Traffic generation per Interval =5sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	767	767	1	159.7841	10	56
2	767	767	1	144.1847	15	44
3	767	767	1	149.6733	14	43
4	767	767	1	152.478	16	42
5	767	767	1	146.264	14	48
Average	767	767	1	150.4768	15	46

Table 35: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	767	767	1	148.1847	115	56
2	767	767	1	122.4408	134	38
3	767	767	1	102.5482	145	40
4	767	767	1	136.0838	126	42
5	767	767	1	126.9354	129	46
Average	767	767	1	127.2385	129	44

Table 36: results of distributed based group routing

D) Traffic generation per Interval =10sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	383	383	1	126.7813	7	10
2	383	383	1	103.4516	14	10
3	383	383	1	93.1997	12	8
4	383	383	1	137.3242	13	12
5	383	383	1	117.7676	7	7
Average	383	383	1	115.7048	10	9

Table 37: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	383	383	1	110.1008	65	27
2	383	383	1	90.6116	81	16
3	383	383	1	71.8075	97	14
4	383	383	1	105.1896	71	28
5	383	383	1	98.0907	90	13
Average	383	383	1	95.16004	80	19

Table 38: results of distributed based group routing

2. High mobility

I. 10 Source- Destination node pairs (5 groups)

A) Traffic generation per Interval =0.5 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	18880	16297	0.8632	396.5903	91	1465
2	18880	15859	0.8451	391.478	57	1497
3	18880	15338	0.8124	487.467	104	1593
4	18880	16168	0.8563	401.147	112	1474
Average	18880	15915	0.8429	419.1705	91	1507

Table 39: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	18880	17692	0.9370	252.2515	2724	1092
2	18880	17766	0.9420	274.5417	2976	1184
3	18880	15989	0.8468	415.241	2187	1508
4	18880	16748	0.8871	285.6479	2786	1414
Average	18880	17048	0.9030	306.9205	2668	1299

Table 40: results of distributed group routing

B) Traffic generation per Interval =1 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	9442	9175	0.9717	159.07	78	464
2	9442	8701	0.9215	199.76	41	491
3	9442	7046	0.7462	353.00	58	927
4	9442	8499	0.9001	198.85	126	574
Average	9442	8355	0.8849	227.67	75	614

Table 41: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	9442	9316	0.9867	107.75	1625	451
2	9442	9355	0.9908	106.98	1778	449
3	9442	8393	0.8889	295.42	1530	985
4	9442	8872	0.9396	105.56	1644	658
Average	9442	8984	0.9515	153.9275	1644	635

Table 42: results of distributed group routing

C) Traffic generation per Interval =2 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	4724	4681	0.9909	129.5543	34	198
2	4724	4667	0.9879	136.0838	41	178
3	4724	4370	0.9251	198.0514	55	399
4	4724	4564	0.9661	112.0430	86	197
Average	4724	4570	0.9675	143.9331	54	194

Table 43: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	4724	4692	0.9932	87.2014	919	219
2	4724	4705	0.9960	75.3958	931	237
3	4724	4706	0.9962	171.0738	922	268
4	4724	4626	0.9793	79.8911	1083	225
Average	4724	4682	0.9911	103.3905	963	237

Table 44: results of distributed group routing

D) Traffic generation per Interval = 5 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	average buffer size
1	1894	1876	0.9905	123.12	35	85
2	1894	1889	0.9974	88.78	27	70
3	1894	1806	0.9535	210.459	30	165
4	1894	1810	0.9556	117.26	37	94
Average	1894	1845	0.9741	134.90	32	103

Table 45: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	average buffer size
1	1894	1886	0.9958	63.9622	428	90
2	1894	1890	0.9979	56.4439	443	103
3	1894	1886	0.9958	74.7826	508	99
4	1894	1892	0.9989	56.2487	522	91
Average	1894	1888	0.9970	62.8593	475	95

Table 46: results of distributed group routing

E) Traffic generation per Interval =10 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	average buffer size
1	950	942	0.9916	96.65	19	38
2	950	948	0.9979	91.62	19	34
3	950	946	0.9958	144.82	19	49
4	950	946	0.9958	166.60	32	33
Average	950	945	0.9947	124.92	22	38

Table 47: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	average buffer size
1	950	945	0.9947	58.4444	184	43
2	950	949	0.9989	49.61	210	53
3	950	942	0.9916	60.3610	239	43
4	950	948	0.9979	53.2085	265	40
Average	950	946	0.9957	55.4059	224	44

Table 48: results of distributed group routing

F) Traffic generation per Interval =10 0sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	average buffer size
1	99	99	1	84.09	4	3
2	99	99	1	69.63	4	2
3	99	99	1	79.06	2	2
4	99	99	1	69.93	7	2
Average	99	99	1	75.67	4	2

Table 49: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	average buffer size
1	99	99	1	48.5109	16	3
2	99	99	1	39.34	18	4
3	99	99	1	35.35	22	4
4	99	99	1	37.90	24	3
Average	99	99	1	40.275	20	3

Table 50: results of distributed group routing

II. Only one group generates traffic scenario

A) Traffic generation per Interval =0.5 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	7650	2680	0.3503	588.29	12	807
2	7650	2077	0.2715	418.91	13	858
3	7650	2568	0.3356	791.9	15	831
4	7650	2170	0.2836	744.87	20	870
5	7650	2015	0.2633	640.4	13	882
Average	7650	2302	0.3009	641.2116	14	849

Table 51: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	7650	5530	0.7228	482.48	1293	452
2	7650	3488	0.4559	324.08	487	644
3	7650	5001	0.6537	645.45	876	536
4	7650	3982	0.5205	660.57	571	684
5	7650	3416	0.4465	662.70	442	744
Average	7650	4281	0.5596	554.72	733	612

Table 52: results of distributed group routing

B) Traffic generation per Interval =1sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	3826	2669	0.6975	497.19	10	383
2	3826	2075	0.5423	355.59	13	407
3	3826	2551	0.6667	724.1	15	383
4	3826	2174	0.5682	657.61	17	396
5	3826	2004	0.5237	620.3	11	423
Average	3826	2294	0.5995	570	13	398

Table 53: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	3826	3649	0.9537	290.70	1108	140
2	3826	2982	0.7794	236.259	498	248
3	3826	3281	0.8576	445.52	881	214
4	3826	3160	0.8259	500.83	573	334
5	3826	2785	0.7279	592.42	426	328
Average	3826	3171	0.8288	416.94	697	252

Table 54: results of distributed group routing

C) Traffic generation per Interval =5sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	767	756	0.9857	130.645	8	32
2	767	765	0.9973	129.11	8	55
3	767	761	0.9921	149.49	8	33
4	767	760	0.9908	154.4	6	64
5	767	757	0.9869	137.95	8	76
Average	767	759	0.9895	140.319	7	52

Table 55: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	767	766	0.9987	70.66	301	35
2	767	767	1.00	53.528	258	31
3	767	767	1.00	59.746	220	36
4	767	762	0.9935	97.95	223	40
5	767	761	0.9921	137.239	244	40
Average	767	765	0.9968	83.7646	249	36

Table 56: results of distributed group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	383	383	1	86.2053	4	11
2	383	383	1	87.6733	4	11
3	383	383	1	80.8728	4	10
4	383	383	1	117.3137	3	12
5	383	383	1	88.9983	4	14
Average	383	383	1	92.2126	4	11

Table 57: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	383	383	1	61.5905	138	21
2	383	383	1	55.2266	112	17
3	383	383	1	65.1745	88	19
4	383	383	1	77.1515	92	20
5	383	383	1	64.1456	84	16
Average	383	383	1	64.6577	102	18

Table 58: results of distributed based group routing

III. Only one destination group scenario

A) Traffic generation per Interval =0.5 sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	7650	4594	0.6005	512.7451	25	721
2	7650	4958	0.6482	411.4685	29	638
3	7650	4684	0.6124	577.1970	34	686
4	7650	4910	0.6418	582.1425	36	640
5	7650	4668	0.6101	514.2153	27	680
Average	7650	4762	0.6225	519.5536	31	673

Table 59: results of leader group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	7650	5144	0.6724	436..5512	414	615
2	7650	5746	0.7512	350.1878	446	545
3	7650	5282	0.6905	491.9263	462	535
4	7650	5801	0.7583	492.4126	468	541
5	7650	5245	0.6856	435.7745	420	562
Average	7650	5443	0.7115	463.1702	442	560

Table 60: results of distributed based group routing

B) Traffic generation per Interval =1sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	3826	3551	0.9281	351.4786	19	374
2	3826	3627	0.9479	294.5412	22	361
3	3826	3602	0.9414	362.1475	26	368
4	3826	3660	0.9566	364.1247	25	355
5	3826	3596	0.9398	332.1786	24	366
Average	3826	3607	0.9428	340.8941	23	365

Table 61: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	3826	3674	0.9602	285.4152	194	336
2	3826	3785	0.9892	224.4512	207	286
3	3826	3685	0.9631	286.5920	229	324
4	3826	3794	0.9916	294.1478	231	270
5	3826	3713	0.9704	280.1465	197	312
Average	3826	3730	0.9749	274.1505	211	305

Table 62: results of distributed based group routing

C) Traffic generation per Interval =5sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	767	767	1	147.456	10	74
2	767	767	1	121.1089	13	69
3	767	764	0.9960	127.412	17	76
4	767	765	0.9973	129.478	14	61
5	767	767	1	123.8954	11	67
Average	767	766	0.9986	129.8700	13	69

Table 63: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	767	767	1	134.5476	104	63
2	767	767	1	111.1089	121	54
3	767	767	1	93.6383	129	56
4	767	767	1	124.4789	118	55
5	767	767	1	108.457	107	57
Average	767	767	1	114.4461	116	57

Table 64: results of distributed based group routing

D) Traffic generation per Interval =10sec, simulation time=2000 seconds

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	383	383	1	83.3825	10	4
2	383	383	1	91.9723	11	8
3	383	383	1	69.9463	9	19
4	383	383	1	78.4321	10	6
5	383	383	1	83.5582	9	30
Average	383	383	1	81.4582	9	13

Table 65: results of leader based group routing

Simulation	Packet sent	Packet received	Delivery ratio	Average delay	Duplicate messages	Average buffer size
1	383	383	1	63.2644	86	19
2	383	383	1	79.0015	83	19
3	383	383	1	53.1928	68	24
4	383	383	1	60.6381	78	18
5	383	383	1	62.6240	72	32
Average	383	383	1	63.7416	77	22

Table 66: results of distributed based group routing

References

- [1] Bai, F., & Helmy, A. (2004). A Survey of Mobility Models in Wireless Adhoc Networks. *Journal of Wireless Ad Hoc and Sensor Networks*, pp. 1–30.
- [2] Balasubramanian, A., Levine, B., & Venkataramani, A. (2007). DTN routing as a resource allocation problem. *Proceedings of conference on Applications, Technologies, Architectures, and Protocols for Computer Communications-SIGCOMM '07*, vol. 37, pp. 373-384.
- [3] Boice, J., Garcia-Luna-Aceves, J. J., & Obraczka, K. (2009). Combining on-demand and opportunistic routing for intermittently connected networks. *Journal of Ad Hoc Networks*, vol. 7, pp. 201–218.
- [4] Burgess, J., Gallagher, B., Jensen, D., & Levine, B.N. (2006). MaxProp: Routing for Vehicle-Based Disruption-Tolerant Networks. *Proceedings of the 25th IEEE International Conference on Computer Communications- INFOCOM '06*, pp.1 - 11.
- [5] D. Johnson, D. M. (1996). Dynamic source routing in ad hoc wireless networks. *The Kluwer International Series in Engineering and Computer Science -Mobile Computing*, vol. 353, pp. 153–181.
- [6] Haas, Z. J., Member, S., & Pearlman, M. R. (2001). Zone Routing Protocol. *Journal of Research in Engineering & Applied Sciences*, vol. 9, pp. 427–438
- [7] He, G. (2002). Destination-sequenced distance vector (DSDV) protocol. *Networking Laboratory, Helsinki University of Technology*
- [8] Holliday, P. (2009). NOMAD A Mobile Ad Hoc and Disruption Tolerant Routing Protocol for Tactical Military Networks. *Proceedings of the 29th IEEE International Conference on Distributed Computing Systems Workshops-ICDCS Workshops '09*, pp. 488 – 492.
- [9] Jacquet, P., Muhlethaler, P., Clausen, T., Laouiti, a, Qayyum, a, & Viennot, L. (2001). Optimized link state routing protocol for ad hoc networks. *Proceedings of IEEE International Multi Topic Conference -IEEE Inmic 2001*, pp. 62–68.
- [10] Jain, S., Gopinath, S., & Raychaudhuri, D. (2011). STAR: Storage aware routing protocol for generalized delay tolerant networks. *Digital Proceedings of IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks- WoWMoM 2011*, pp. 1 - 4.
- [11] Jayakumar, G., & Ganapathi, G. (2008). Reference Point Group Mobility and Random Waypoint Models in Performance Evaluation of MANET Routing Protocols. *Journal of Computer Systems, Networks, and Communications*, pp. 1–10.
- [12] Lakkakorpi, J., Pitkänen, M., & Ott, J. (2010). Adaptive routing in mobile opportunistic networks. *Proceedings of the 13th ACM International Conference on Modeling, Analysis, and Simulation of Wireless and Mobile Systems - MSWIM '10*, vol. 101.

- [13] Lindgren, A., Doria, A., & Schelén, O. (2003). Probabilistic routing in intermittently connected networks. *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 7, pp. 19.
- [14] Liu, C. L. C., & Wu, J. W. J. (2009). Efficient Adaptive Routing in Delay Tolerant Networks. *Proceedings of IEEE International Conference on Communications-ICC '09*, pp. 1-5.
- [15] Musolesi, M., & Mascolo, C. (2006). A community based mobility model for ad hoc network research. *Proceedings of the Second International Workshop on Multi-Hop Ad Hoc Networks: From Theory to Reality-REALMAN '06*, pp. 31–38.
- [16] Musolesi, M., & Mascolo, C. (2009). CAR: Context-aware adaptive routing for delay-tolerant mobile networks. *IEEE Transactions on Mobile Computing*, vol. 8, pp. 246–260.
- [17] Ott, J., Kutscher, D., & Dwertmann, C. (2006). Integrating DTN and MANET routing. *Proceedings of the 2006 SIGCOMM Workshop on Challenged Networks - CHANTS '06*, pp. 221- 228.
- [18] Papaj, J., & Dobos, L. (2014). Trust Based Algorithm for Candidate Node Selection in Hybrid MANET-DTN Proposed Trust Algorithm for Hybrid MANET-DTN. *Proceedings of Advances In Electrical Engineering ELECTRONIC ENGINEERING -AEEE '14*, vol. 12, pp. 271–278.
- [19] Perkins, C. E., Park, M., & Royer, E. M. (1999). Ad-hoc On-Demand Distance Vector Routing. *Proceedings of Second IEEE Workshop on Mobile Computing Systems and Applications -WMCSA '99*, pp. 90–100.
- [20] Roy, R. R. (2011). Drift Group Mobility - Handbook of Mobile Ad Hoc Networks for Mobility Models, pp. 721–732.
- [21] Sandulescu, G., & Nadjm-Tehrani, S. (2008). Opportunistic DTN routing with window-aware adaptive replication. *Proceedings of the 4th Asian Conference on Internet Engineering - AINTEC '08*, pp. 103–112.
- [22] Sarafijanovic-Djukic, N., Piórkowski, M., & Grossglauser, M. (2007). Island hopping: Efficient mobility-assisted forwarding in partitioned networks. *Proceedings of 3rd Annual IEEE Communications Society on Sensor and Adhoc Communications and Networks- SECON '06*, vol. 1, pp. 226–235.
- [23] Spyropoulos, T., Psounis, K., & Raghavendra, C. S. (2005). An Efficient Routing Scheme for Intermittently Connected Mobile Networks. *Proceedings of the ACM SIGCOMM workshop on Delay-tolerant networking -SIGCOMM '05*, pp. 252–259.
- [24] Thomas, M., Gupta, A., & Keshav, S. (2006). Group Based Routing in Disconnected Ad Hoc Networks. *Proceedings of 13th International Conference on High Performance Computing-HiPC '06*, vol. 4297, pp. 399–410.
- [25] Thomas, M., Phand, S., & Gupta, A. (2009). Using group structures for efficient routing

in delay tolerant networks. *Journal of Ad Hoc Networks*, Vol. 7, pp. 344–362.

- [26] Vahdat, A., & Becker, D. (2000). Epidemic routing for partially connected ad hoc networks. *Technical Report Number CS-200006, Duke University*, pp. 1–14.
- [27] Whitbeck, J., & Conan, V. (2010). HYMAD: Hybrid DTN-MANET routing for dense and highly dynamic wireless networks. *Journal of Computer Communications*, vol. 33, pp. 1483–1492.
- [28] Xie, L. F., Chong, P. H. J., & Guan, Y. L. (2012). Leader Based Group Routing in Disconnected Mobile Ad Hoc Networks with Group Mobility. *Journal of Wireless Personal Communications*, vol. 71, pp. 2003–2021.
- [29] Xie, L. F., Chong, P. H. J., & Guan, Y. L. (2013). Routing strategy in disconnected mobile ad hoc networks with group mobility. *EURASIP Journal of Wireless Communications and Networking*, vol. 105.
- [30] Xie, L. F., Chong, P. H. J., Guan, Y. L., Whitbeck, J., Conan, V., Thomas, M., Anzaldi, D. (2010). Opportunistic Mobile Sensor Data Collection with SCAR. *Journal of Ad Hoc Networks*, vol. 101.