碩士學位論文

ASSOCIATIVITY-BASED DYNAMIC SOURCE ROUTING (ADSR) IN MOBILE AD HOC NETWORKS (MANETs)

濟州大學校大學院

컴퓨터工學科

샤프카트-우르-레만

2008 年 06 月

Associativity-based Dynamic Source Routing in Mobile Ad hoc Networks
(MANETs)

指導教授 安 基 中

샤프카트-우르-레만

이 論文을 工學碩士學位論文으로 提出함

2008 年 06 月

샤프카트의 工學碩士學位論文을 認准함

審查委員長 ___邊翔庸___ 印

委　　員 ___安基中___ 印

委　　員 ___金度縣___ 印

濟州大學校大學院

2008 年 06 月

Associativity-based Dynamic Source Routing (ADSR) in Mobile Ad hoc Networks (MANETs)

Shafqat-ur-Rehman

(Supervised by Professor Khi-Jung Ahn)

A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science

2008.06
The thesis has been examined and approved.

Thesis Committee Chair
Sang-Yong Byun, Professor, Cheju National University

Khi-Jung Ahn, Professor, Cheju National University

Do-Hyun Kim, Associate Professor, Cheju National Uniersity

Department of Telecommunication and Computer Engineering
GRADUATE SCHOOL
CHEJU NATIONAL UNIVERSITY

Dedicated to

My Parents and Teachers

ACKNOWLEDGEMENTS

Foremost, I would like to present my humble gratitude to God Almighty who bestowed me with the courage and ability to come this far and make accomplishments in the noble cause of learning and serving. It is a great pleasure to extend my heartiest thanks to all those who have provided guidance and extended a helping hand to me and have contributed directly or indirectly in this work.

I feel greatly indebted to my advisor Prof. Wang Cheol Song for his continuous guidance and support throughout my masters studies at Cheju National University. This work would not have been possible without his encouragement, helpful discussions and keen interest. My advisor in the final year of MS, Professor Ahn Khi Jung, has been abundantly helpful. I would like to grab this opportunity to extend my heartfelt gratitude for his kindness, generous help, precious advices and always putting up a cheerful disposition. Hats off to him! I will always respect and honor Prof. Junghoon Lee, Department of Computer Science and Statistics. Due to his hard-work, knowledge and research efforts; he has been a continuous source of inspiration for me.

A lot of thanks go to Prof. Do-Hyun Kim, Prof, Sang-Yong Byun for their helpful discussions during my studies and very helpful comments and suggestions during my thesis evaluation. I also wish to extend my gratitude to other professors of my department Prof. Young-Cheol Byun, Prof. Ho-Young Kwak, Prof. Sang-Joon Lee and Prof. Jang-Hyung Kim for their guidance during my studies at Cheju National University. I greatly commend my Korean language teacher, Madam Kim Mee Jin. Her devotion, teaching and hardwork are exemplary.

I am indebted to my many ex/current student colleagues/friends for providing a stimulating and fun environment in which to learn and grow. I am especially grateful to Dr. Umer Zeeshan Ijaz(Cambridge University), Dr. Farrukh Aslam Khan (FAST-NU, Pakistan), Dr. Abu Affan (Korea Ocean Research & Development Institute), Sung-Soo Kim, Mano Sameul, Li Ying, Abhijit Saha, Jasim Uddin, Mohammad Rakib, Nauman Malik, Ahmer Rashid and the three Rahmans(Khalid Rahman, Asif Rahmani and Ahsan Rahman) for their enormous help and co-operation. I especially want to admire the last four guys for putting up with me for the last six months and preparing delicious savory foods which helped me keep energetic and cozy in the wintry but heavenly aura of Jeju Island. Folks, thanks for all the fish! I am also thankful to Santhosh Kumar, Anil Kumar, Anji Reddi, Shrikant, Yasanta, Mahanama, Chamlani and Min Ahn for affording me a wonderful company.

There are lots of friends and mentors who have helped me in countless ways to climb the ladder of higher studies. I would like to express deep respect, gratitude and love for my high school teacher, Mr. Shabir Ahmed. His guidance and encouragement was pivotal in my academic success and future direction. I greatly acknowledge the role of Dr. Wasim Ikram as a teacher and project supervisor during my undergraduate studies. Sir, you are a role model for us all. I am greatly indebted to Prof. Dr. Aftab Ahmed Maroof for his fatherly love and support during my undergraduate studies. I acknowledge and sincerely express my gratitude to Safee Ullah Chaudhary for all his help and guidance.

I greatly honor the generous assistance provided by the Korean Government under the IT Scholarship Program (ITSP) through the Institute of Information Technology Assessment (IITA), South Korea. I am truly indebted to Prof. Gyung-Leen Park for his encouragement and generous support for my research through ITRC. Thanks to our department secretaries, Eun-Gyung Jung and Jung-ha Lee for their valuable assistance in academic matters throughout my studies.

Finally, it is a great pleasure to pay homage to my beloved parents who have taken great care of me through thick and thin of my academic life and have been a great source of inspiration for me. They have inculcated in me a sense of self-respect, diligence, patience and firm faith. Their prayers and admiring attitude have provided impetus to my drive for higher studies and research.

ABBREVIATIONS

MANET	Mobile Ad hoc Network
RREQ	Route Request
RREP	Route Reply
RERR	Route Error
NS2	Network Simulator 2
ADSR	Associativity-based Dynamic Source Routing
AODV	Ad hoc On-demand Distance Vector
DSDV	Destination Sequenced Distance Vector
AOMDV	Ad hoc On-demand Multipath Distance Vector
TCP	Transport Control Protocol
CBR	Constant Bit Rate
DREAM	Distance Routing Effect Algorithm for Mobility
DSR	Dynamic Source Routing
OLSR	Optimized Link State Routing
GPRS	Greedy Perimeter Stateless Routing
NA	Neighbor Acquisition: NA and Hello messages are used interchangeably

TERMINOLOGY

Network Diameter	Minimum number of hops required for a packet to travel from any node located at one edge of the network to any node located at the opposite edge of the network.
Transmission Range	Area in which signal of a node can be received
Route	Path made up of a number of nodes which connect the source to the destination.
Hop	The hop count of a route is one less than the number of its constituent nodes
Data Packet	Unit of data. Data is broken down into packets in order to transmit it over to the destination across the network.
Nodal Health	Factors like residual battery power, buffer occupancy rate, signal stability, storage capacity, processing power etc. are collectively treated as nodal health.
Multipath routing	Routing mechanism wherein multiple routes are constructed and maintained between a communicating pair of nodes.
Unipath routing	Routing mechanism wherein only a single route is constructed and maintained between the source and the destination.
Nodal Associativity	Nodes exhibiting relatively longer direct inter-connectivity are said to be associative.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

요약문

본 논문에서는 송신자와 수신자 사이의 안정된 경로를 세울 수 있도록 애드 혹 네트워크를 위해 Associativity 에 기반하여 새로운 on-demand 다중 경로 라우팅 프로토콜을 제안한다. 이를 위해노드들의 시간적 및 공간적 안정성 측정은 물론 그 노드들 사이의 경로 측정하기 위한 새로운 개념을 제안한다. 논문의 주요 초점은 경로상의 노드가 겹치지 않는 비인접 다중 경로 라우팅에 두고 있지만, 단일 경로 라우팅은 물론 제안된 라우팅 프로토콜을 널리 쓰이고 있는 on-demand 소스 라우팅 프로토콜들과 비교하여 그 효율성에 대해서도 고찰하였다. 관련 연구에 의하면 다중 경로 라우팅은, 노드들이 그룹 형태로 이동하는 경우와 네트워크 밀도가 높은 환경에서는 단일 경로 라우팅에 비해 큰 성능 차이를 보이고 있지 않다.

애드 혹 네트워크는, 개인 및 공공, 비즈니스 영역에서의 일상생활에서 점점 더 광범위하게 적용되고 있어서, 일정정도의 QoS 프로비저닝을 보장하는 분산 솔루션에 대한 요구가 매우 중요해졌다. 따라서, 본 연구는 QoS 프로비저닝에 더 적합하게 하고, 사용자의 QoS 요건에 맞추는 것이 용이하게끔, 안정된 경로를 발견하는 주제를 논의한다. 제안된 프로토콜은 처리율(Throughput), 정규화된 라우팅 오버헤드(Normalized routing overhead) 그리고 패킷 전송률(Packet Delivery ratio) 등에서 기존의 라우팅 프로토콜 중에서 두 개의 단일 경로 프로토콜(DSDV, AODV), 그리고 한 개의 다중 경로 프로토콜 (AOMDV)과 비교하였다. 일반적으로, on-demand 프로토콜은 모바일 환경에서 proactive 접근법에 비해 낮은 트래픽 오버헤드를 가지면서 좋은 성능을 보이지만, 경로 탐색과 유지보수 때문에 지점(End-to-End)간 더 큰 지연을 발생시키는 경향이 있다. 그러나 본 논문에서 제안한 프로토콜은 안정되고 유지보수가 용이한 경로 확립(설정)으로 인해 지점(End-to-End)간 발생되던 지연을 최소화 하게 되었으며, 결과적으로, 더 나은 데이터 통신 성능과 QoS 프로비저닝을 보장하게 되었다.

ABSTRACT

This thesis is primarily concerned with multi-path routing in Mobile Ad hoc Networks (MANETs). We propose a novel associativity-based on-demand source routing protocol for ad hoc networks which attempts to establish relatively stable path(s) between the source and the destination. We introduce a new notion for gauging the temporal and spatial stability of nodes and hence the paths interconnecting them. Our focus is on node-disjoint multi-path routing, but we also touch on unipath routing and study the affectiveness of our method with respect to widely used on-demand source routing protocols. According to the literature, multi-path routing edges out unipath routing in densely populated network environments and in environments where nodes move in the form of groups. Ad hoc networks are becoming more and more pervasive in our personal, public and business day-to-day lives and hence the need for distributed solutions which guarantee certain level of QoS provisioning is of paramount importance. This thesis addresses the issue of discovery of stable route(s) which are more suitable for QoS provisioning and can be tailored easily according to the users' QoS requirements. The proposed protocol is compared with other unipath (DSDV and AODV) and multi-path (currently AOMDV) routing protocols. We investigate the performance in terms throughput, normalized routing overhead, packet delivery ratio etc. All on-demand protocols show good performance in mobile environments with less traffic overhead compared to proactive approaches but they are prone to longer end-to-end delays due to route discovery and maintenance. Our protocol tries to minimize the end-to-end delays by establishing paths which are stable and easier to maintain. This results in better QoS provisioning and data communication performance.

Chapter 1

1 INTRODUCTION

1.1 Background

Wireless Ad hoc Networks were introduced in 1970s in the form of Packet Radio Networks (PRNETs) which were sponsored by DARPA (WikiAd). Ad hoc networks started gaining popularity in early 1990s and have seen a steady growth worldwide due to the miniaturization of personal computing devices, proliferation in their number and advances in wireless communication technologies. Wireless ad hoc networks have provided an excellent stage for *Everywhere* computing because of their "3 Anys"– Any person, Anywhere and Any time (Zou and Ramamurthy, 2002). Ad hoc wireless networks utilize multi-hop radio relaying and are capable of operating without the support of any fixed infrastructure (hence they are also called infrastructureless networks) (Murthy and Manoj, 2004). The decentralized nature of wireless ad hoc networks makes them suitable for a variety of applications where central nodes cannot be relied on, and may improve the scalability of wireless ad hoc networks compared to wireless managed (or infrastructured) networks, though theoretical (Gupta and Kumar, 2000) and practical (Li et al., 2001) limits to the overall capacity of such networks have been identified (WikiAd).

Wireless ad hoc networks can be generally divided into two categories: quasi-static and mobile. In a quasi-static ad hoc network, nodes are static or portable. However, the resulting network topology may be dynamic due to power controls and link failures. A typical sensor network is an example of a quasi-static ad hoc network. In mobile ad hoc networks, the entire network may be mobile and nodes may move quickly relative to each other. A major technical challenge in a wireless ad hoc network is the design of the efficient routing protocols to cope with the rapid topology changes. Figure 1.1 illustrates a typical ad hoc network made up of a number of portable computing devices.

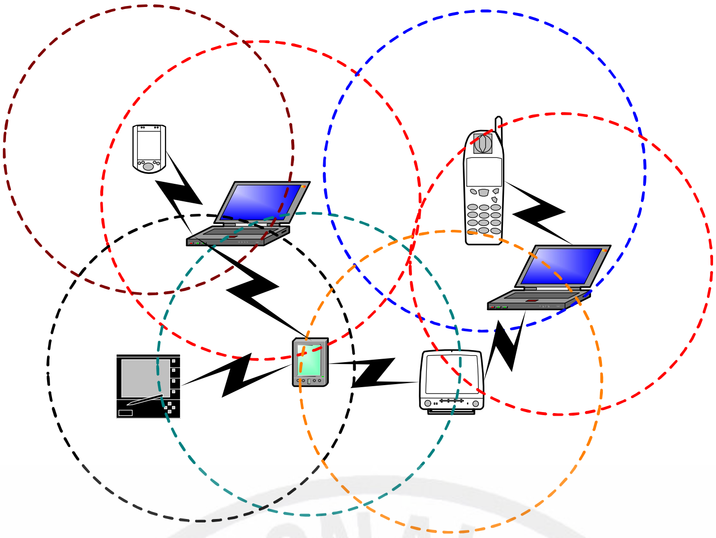

Figure 1.1. A typical Ad Network.

1.2 Wireless Ad hoc network characteristics and major issues

The cornerstone of wireless ad hoc networks is the wireless medium. Since the characteristics of wireless medium are completely different from those of wired medium, wireless ad hoc networks exhibit behavior and characteristics that are intrinsically specific to these networks. Some of these characteristics are described as follows (Murthy and Manoj, 2004):

- Infrastructure-less
- Multi-hop wireless links
- Shared radio channel (more suitable for best-effort data traffic)
- Distributed routing
- Packet-switched (evolving toward emulation of circuit switching)
- Frequent path breaks due to mobility
- Quick and cost-effective deployment

- Dynamic frequency reuse based on carrier sense mechanism
- Time synchronization is difficult and consumes bandwidth
- Bandwidth reservation requires complex medium access control protocols
- Application domains include battlefields, emergency search and rescue operations, and collaborative computing
- Self-organization and maintenance properties are built into the network
- Mobile hosts require more intelligence (should have a transceiver as well as routing/switching capability)
- Main aim of routing is to find paths with minimum overhead and also quick reconfiguration of broken paths
- Several issues are to be addressed for successful commercial deployment even though widespread use exists in defense.

These characteristics make the task of designing an optimal ad hoc network system quite challenging. The major issues that affect the design, deployment, and performance of an ad hoc wireless system are as follows (Murthy and Manoj, 2004):-

- Medium access scheme
- Routing
- Multicasting
- Transport layer protocol
- Pricing scheme
- Quality of service provisioning

- Self-organization, security
- Energy management
- Addressing and service discovery
- Scalability

In this dissertation, we focus on a class of wireless ad hoc networks wherein nodes are capable of moving autonomously. Such networks are generally referred to as Mobile Ad hoc Networks (MANETs) in the literature. MANETs are self-organizing and self-configuring multi-hop networks wherein nodes act co-operatively to establish the network "on-the-fly". Communication between any two nodes might require the packets to traverse multiple hops and the constituent nodes act both as host and router. MANETs bear great application potential where wired infrastructure is not viable and temporary wireless network for instant communication is desirable such as disaster and emergency situations, battlefield communications, mobile conferencing, lectures, meetings, law enforcement operations, crowd control and so on (Perkins, 2001).

MANETS employ the traditional layered structure of TCP/IP to achieve end-to-end communication between mobile nodes (hosts). Due to wireless nature of the links, mobility and resource constraints, all layers of the TCP/IP architecture need redefinitions and modifications in order to function properly in MANETs. A key research area in MANETs is routing. Routing in MANETs has received a tremendous interest from the networking research community (Abolhasan, 2004). A typical multi-hop routing scenario is shown in Figure 1.2. Source S and destination D are not within the direct reach range of each other. Communication between the two nodes can be enabled if intermediate nodes are capable of routing and forwarding data on behalf of the communication pair. Given the topology in Figure 1.3, a logical route between the source and destination is illustrated in Figure 1.3.

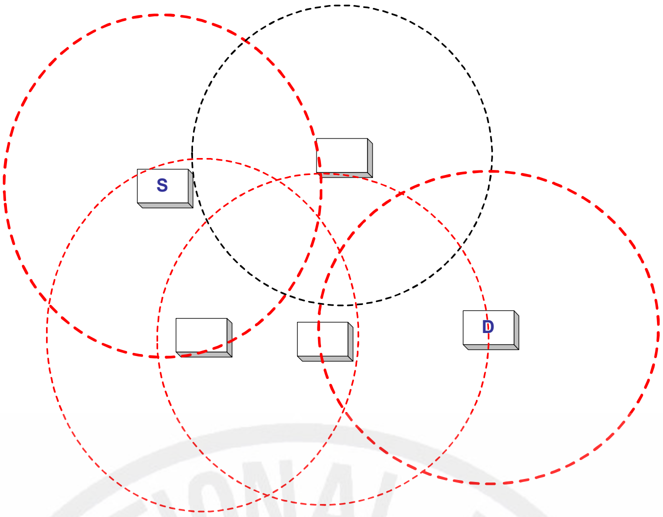

Figure 1.2. . Source S and Destination D are not within the direct radio range of each other, but they are reachable through multiple hops.

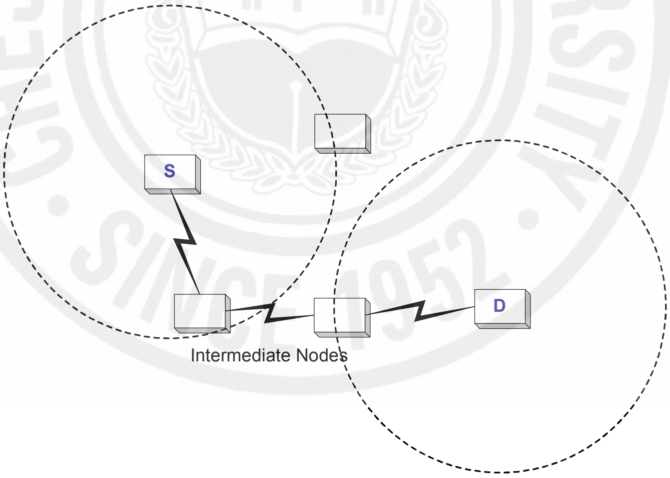

Figure 1.3. A typical multi-hop routing scenario. Node S can send data to node D through at least three hops.

1.3 Challenges in Routing

Due to the various limitations in MANETs, designing an efficient and reliable routing protocol is a challenging task. Major challenges faced by a MANET routing protocol are mobility, limited resource, error prone channel states and hidden terminal problems (Murthy and Manoj, 2004). An ongoing session may suffer frequent path breaks due the self-organization of mobile nodes. Disruptions may take place due the movement of intermediate nodes in the path or due to the movement of end hosts. Routing protocols are, therefore, responsible for not only constructing durable paths but also for maintaining and reconstructing the failed paths in an efficient and timely manner. An intelligent routing strategy is required which is adaptive to the changing network conditions such as topology, network density, partitioning etc and can accomplish the above tasks without incurring excessive control traffic overhead. Unnecessary control messages can choke the network, increase the processing load and cause the nodes to drain their energy quickly because wireless nodes can offer only limited bandwidth. Reduction in control traffic improves network efficiency and nodal energy consumption.

Link capacity and link error probability are time varying characteristics of wireless links. Employment of cross-layer feedback to get better quality links and avoid congested links can contribute towards the overall throughput and durability of routes (Murthy and Manoj).

1.4 Accomplishments and Contributions

Our accomplishments and contributions which are elaborated throughout this dissertation are summarized as follows:-

- We have given a new dimension to the concept of associativity in MANETs. Stability and associativity depends on network conditions. Nodes periodically monitor their stability and associativity. The aggregate effect of the two measures is termed as nodal weight.

- An on-demand source routing protocol for MANETs is proposed which capitalizes on the aforementioned concept of nodal weight.

- The mechanism is put to use in the discovery and maintenance of multiple optimal routes between the source and the destination. The mechanism is generic and is applicable to unipath routing but the focus in this thesis is on multipath routing.

- DSR is modified to implement ADSR. Extensive simulation are performed and comparative analysis is performed with well-known unipath and multipath routing protocols.

- The dissertation sets the tone and stage for interesting future research work and extensions.

1.5 Organization of the dissertation

The rest of the dissertation is as follows:

Chapter 2 provides an overview of the related and previous literature on source routing, multipath routing and associativity-based routing.

Chapter 3 proposes an associativity-based on-demand multipath source routing protocol for mobile ad hoc networks (MANETs).

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

Chapter 5 presents the summary of the dissertation, draws conclusion to the research and sheds light on possible enhancements and the future work.

Chapter 2

2 RELATED WORK

This chapter summarizes the related work already done in the field of wireless ad hoc networks. The main focus is on on-demand routing, multipath routing and associativity-based routing. We discuss the working of various protocols, their salient features, strengths, weaknesses and prepare a stage whereon some of the deficiencies of the existing routing protocols can be overcome or reduced.

2.1 Ad hoc Routing Protocols

Unlike traditional wired and cellular networks, wireless ad hoc networks don't employ any infrastructure and the constituent nodes are autonomous and self-configuring. Bandwidth and power constraints are the main concerns in current wireless networks because multihop MANETs rely on each node in the network to act both as host and a router. This places bandwidth, power and processing demands on mobile hosts which must be taken into account when designing a routing protocol. Moreover, due to frequent topological changes, finding an optimal route has been a challenging task for networking researchers since the inception of ad hoc networks. A routing protocol should be able to efficiently utilize the limited nodal resources and adapt to the frequently changing network conditions.

2.1.1 Classification of Routing Protocols

Routing protocols for MANETs can be classified into several types based on different criteria. For the sake of simplicity and relevance to our work in this thesis, we look into their classification based on only *routing information update mechanism*(Murthy and Manou, 2004). They are, therefore, fall into following three major categories:-

1. Proactive or table-driven routing protocols

2. Reactive or on-demand routing protocols

3. Hybrid routing protocols

Furthermore, routing protocols in each of the above categories can be either hierarchical or flat. Irrespective of whether a routing protocol is one-tier or multi-tier, it can be further classified into unipath and multipath. If we delve into finer details, more classification is possible. Figure 2.1 illustrates an abstract level classification.

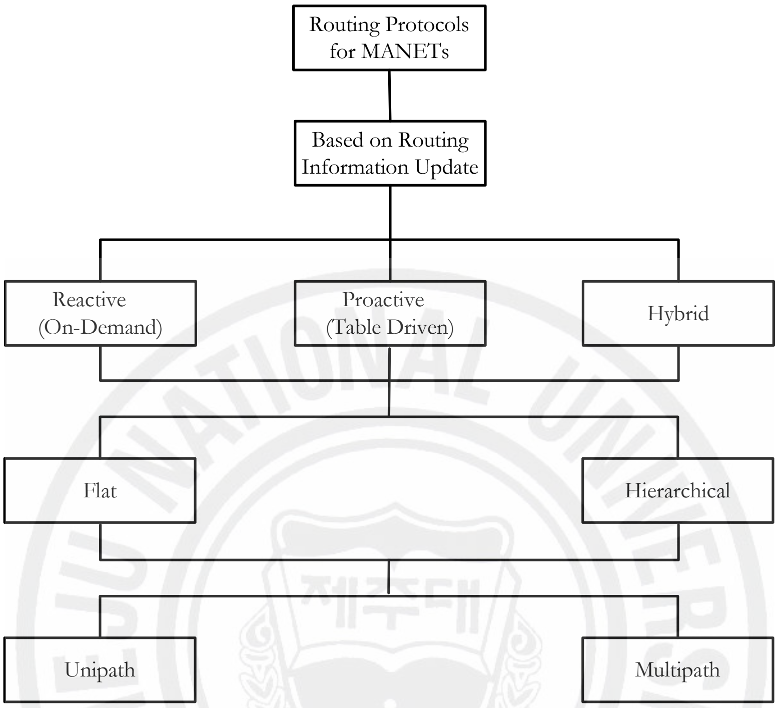

Figure 2.1. Classification of routing protocols based on *routing information update mechanism*

Table 2.1 lists some well-known routing protocols categorized as per Figure 2.1. Proactive routing algorithms make routing decisions based on the pre-accumulated topological information at each node, e.g., DSDV, OLSR, DREAM, STAR etc. Reactive approaches construct routes on demand e.g., DSR, MSR, AODV, AOMDV, CBRP, LAR, GPSR etc. Hybrid schemes capitalize on the combined best features of both reactive and proactive approaches. Some example hybrid routing protocols are ZRP, DDR etc.

All of the aforementioned protocols also fall under the category of either unipath or multipath routing. DSDV, OLSR, DREAM, STAR, DSR, AODV, CBRP, LAR, GPSR, ZRP, DDR are unipath whereas MSR and AOMDV are multipath.

Table 2.1. Some ad hoc routing protocols

Protocol	Proactive/ Reactive/Hybrid	Flat/ Hierarchical	Unipath/ Multipath
DSR	Reactive	Flat	Unipath
MSR	Reactive	Flat	Multipath
AODV	Reactive	Flat	Unipath
AOMDV	Reactive	Flat	Multipath
DSDV	Proactive	Flat	Unipath
ZRP	Hybrid	Flat	Unipath
TBRPF	Proactive	Flat	Unipath
OLSR	Proactive	Flat	Unipath
CBRP	Reactive	Hierarchical	Unipath
DREAM	Proactive	Flat	Unipath
LAR	Reactive	Flat	Unipath
GPSR	Reactive	Flat	Unipath
STAR	Proactive	Hierarchical	Unipath
DDR	Hybrid	Hierarchical	Unipath

2.2 Routing Protocols Review

2.2.1 Dynamic Source Routing (DSR)

Dynamic Source Routing (DSR) (Johnson and Maltz, 1999) is an on-demand source routing protocol. Each data packet carries along the path to the destination. The main benefit of source routing is that intermediate nodes need not keep topological information although intermediate nodes of a valid source path are required to temporarily store routing information in the form route caches. DSR does not depend on any kind of periodic messages to be sent and supports uni-directional and asymmetric links. The protocol consists of two major phases: route discovery and route maintenance, which are explained in the following sections.

2.2.1.1 Route Discovery

When a source has a data packet to send to some destination but does not have any route in its cache to that destination, it initiates route discovery. The source broadcasts a Route Request (RREQ) message. RREQ packet carries along address of the destination, source node's address, a unique request ID and the path it has traversed. When this RREQ message reaches the destination or a node that has route information to the destination, it sends a Route Reply (RREP) message with path information contained therein back to the source. Each node records routes the node has learned and overheard over time in its *route cache* to reduce overhead generated by the route discovery process.

When a node receives a RREQ packet, it forwards the packet only if following conditions are met: (a) the node is not the target (destination) of the RREQ packet, (b) the node is not present in the source route, (c) the packet is not a duplicate and (d) no route information to the target node is available in its route cache. If all are satisfied, the node appends its ID to the source route and broadcasts the packet to its 1-hop neighbors. If either of the conditions (b) and (c) is not met, it simply discards the packet. If a node is the target of the packet or has route information to the destination, it constructs and sends a Route Reply (RREP) to the source.

2.2.1.2 Route Maintenance

DSR monitors the validity of existing routes and detects route failures based on the passive acknowledgments of data packets transmitted to neighboring nodes. When a node fails to receive an acknowledgment, a Route Error (RERR) packet is sent to the original sender to invoke a new route discovery phase. Nodes that receive RERR message delete any route entry (from their route cache) which uses the broken link. Note that RERR message is propagated only when a node has a problem sending packets through that link. Although this selective propagation reduces control overhead, it yields a long delay when a packet needs to go through a new link.

2.2.1.3 Strengths and Drawbacks

There are no table update messages due to the reactive approach employed by DSR. Routes are discovered only when there is demand of data transmission from the source. Hence there is no need to find routes to all other nodes in the network as is required by proactive routing approaches. The control overhead is further reduced by the use of route caches. However, DSR suffers from higher connection delays, possible inconsistent routes during reconstruction phase due to stale information in route caches and performance degradation in high mobility scenarios.

.

2.2.2 Ad Hoc On-Demand Distance Vector Routing

Ad Hoc On-Demand Distance Vector (AODV) routing (Perkins et al., 2003) is a reactive protocol, even though it still uses characteristics of a proactive protocol. AODV takes the interesting parts of DSR and DSDV, in the sense that it uses the concept of route discovery and route maintenance of DSR and the concept of sequence numbers and periodic hello beacons from DSDV.

Routes in AODV are discovered and established and maintained only when and as long as needed. To ensure loop freedom sequence numbers, which are created and updated by each node itself, are used. These allow also the nodes to select the most recent route to a given destination node. AODV takes advantage of route tables. In these it stores routing information as destination and next hop addresses as well as the sequence number of a destination. Next to that a node also keeps a list of the precursor nodes, which route through it, to make route maintenance easier after link breakage. To prevent storing information and maintenance of routes that are not used anymore each route table entry has a lifetime. If during this the time the route has not been used, the entry is discarded.

2.2.2.1 Route Discovery

When a source node wants to send a message to some destination node and does not already have a valid route to that destination, it initiates a route discovery process to locate the other node. It broadcast a route request (RREQ) packet to its neighbors, which then forward the request to their neighbors, and so on, until either the destination or an intermediate node with an active route to the destination is located. AODV utilizes the destination sequence numbers to ensure all routes are loop-free and contain the most recent route information. Each node maintains its own sequence number, as well as a broadcast ID. The broadcast ID is incremented for every RREQ the node initiates, and together with the node's IP address, uniquely identifies an RREQ. Along with its own sequence number and the broadcast ID, the source node includes in the RREQ the most recent sequence number it has for the destination. Intermediate nodes can reply to the RREQ only if they have a route to the destination whose corresponding destination sequence number is greater than or equal to that contained in the RREQ.

During the process of forwarding route request, intermediate nodes record in their route tables the address of the neighbor from which the first copy of the broadcast packet is received, thereby establishing a reverse path. If additional copies of the same RREQ are later received, these packets are discarded. Once the RREQ reaches the destination or an intermediate node with an active route, the destination/intermediate node responds by unicasting a route reply (RREP) packet back to the neighbor from which it first received the RREQ. As the RREP is routed back along the reverse path, nodes along this path set up forward route entries in their route tables which point to the node from which the RREP came. These forward route entries indicate the active forward route. Associated with each route entry is a route timer which will cause the deletion of the entry if it is not used within the specified life time. Because the RREP is forwarded along the path establishing by the RREQ, AODV only supports the use of symmetric links.

2.2.2.2 Route Maintenance

When a route has been established, it is being maintained by the source node as long as the route is needed. Movements of nodes effect only the routes passing through this specific node and thus do not have global effects. If the source node moves while having an active session and loses connectivity with the next hop of the route, it can rebroadcast an RREQ. If though an intermediate station loses connectivity with its next hop it initiates an Route Error (RERR) message and broadcasts it to its precursor nodes and marks the entry of the destination in the route table as invalid, by setting the distance to infinity. The entry will only be discarded after a certain amount of time, since routing information may still be used. When the RERR message is received by a neighbor it also marks its route table entry for the destination as invalid and sends again RERR messages to its precursors.

2.2.2.3 Strengths and Drawbacks

The main advantage of AODV is that routes are established on-demand and destination sequence numbers are used to find the latest route to the destination. The connection setup delay is less. One drawback of this protocol is that intermediate nodes can lead to inconsistent paths if the source sequence numbers is very old and intermediate nodes don't have the latest destination sequence number. Also periodic beaconing leads to unnecessary bandwidth consumption.

2.2.3 Split Multipath Routing with Maximally Disjoint Paths

Split Multipath Routing (SMR) proposed in (Lee and Gerla, 2001) is an on-demand multipath source routing protocol that builds multipath using a route request/reply cycle.

SMR can find an alternative route that is maximally disjoint from the source to the destination. When the source nodes needs a route to the destination but no route is known, it floods the route request (RREQ) message to the entire network in order to find maximally disjoint paths, so the approach has a disadvantage of transmitting more RREQ packets. Because of this flooding, several duplicate RREQ packets through different routes reach the destination. The destination node selects multiple maximally disjoint routes and sends route reply (RREP) packets back to the source via the chosen routes. In order to choose proper maximally disjoint route paths, the destination must know the entire path of all available routes. Therefore, SMR uses the source routing approach where the information of the nodes that compromise the route is included in the RREQ packet.

SMR is similar to DSR, and is used to construct maximally disjoint paths. Unlike DSR, intermediate nodes do not keep a route cache, and therefore, do not reply to RREQs. This is to allow the destination to receive all the routes so that it can select the maximally disjoint paths. Maximally disjoint paths have as few links/nodes in common as possible. Duplicate RREQs are not necessarily discarded. Instead, intermediate nodes forward RREQs that are received through a different incoming link, and whose hop count is not larger than the previously received RREQs. In the algorithm, the destination sends a RREP immediately for the first RREQ it receives, which represents the shortest delay path. The destination then waits to receive more RREQs. From the received RREQs, the path that is maximally disjoint with the shortest delay path is selected. If more than one maximally disjoint path exists, the shortest hop path is selected. If more than one shortest hop path exists, the path whose RREQ was received first is selected. The destination then sends an RREP for the selected RREQ.

2.2.4 Ad Hoc On-Demand Multipath Distance Vector

Ad Hoc On-Demand Multipath Distance Vector (AOMDV) (Marina and Das, 2001) is an extension to the AODV protocol for finding multiple loop-free and link disjoint paths. The protocol computes multiple loop-free and link-disjoint paths. Loop-freedom is guaranteed by using a notion of “advertised hopcount”. Link disjointness of multiple paths is achieved by using a particular property of flooding.

To keep track of multiple routes, the routing entries for each destination contain a list of the next-hops together with the corresponding hop counts. All the next hops have the same sequence number. For each destination, a node maintains the advertised hop count, which is defined as the maximum hop count for all the paths. This is the hop count used for sending route advertisements of the destination. Each duplicate route advertisement received by a node defines an alternative path to the destination. To ensure loop-freedom, a node only accepts an alternative path to the destination if it has a lower hop count than the advertised hop count for that destination. Because the maximum hop count is used, the advertised hop count therefore does not change for the same sequence number. When a node advertisement is received for a destination with a greater sequence number, the next-hop list and advertised hop count are reinitialized.

AOMDV can be used to find link-disjoint routes. To find disjoint routes, each node does not immediately reject duplicate RREQs. Each RREQ carries an additional field called first hop to indicate the first hop (neighbor of the source) taken by it. Also, each node maintains a first hop list for each RREQ to keep track of the list of neighbors of the source through which a copy of the RREQ has been received. In an attempt to get multiple link-disjoint routes, the destination replies to duplicate RREQs regardless of their first hop. To ensure link-disjointness in the first hop of the RREP, the destination only replies to RREQs arriving via unique neighbors. The trajectories of each RREP may intersect at an intermediate node, but each takes a different reverse path to the source to ensure link-disjointedness.

3 ASSOCIATIVITY-BASED DYNAMIC SOURCE ROUTING (ADSR) IN MOBILE AD HOC NETWORKS (MANETS)

In this chapter, we propose a distributed on-demand multi-path routing protocol called Associativity-based Dynamic Source Routing (ADSR) for Mobile Ad hoc Networks (MANETs). ADSR uses temporal information of nodes to calculate the fitness of the candidate paths. Routes are selected based on relative stability of the intermediate nodes. A node is classified as stable based on its temporal associativity and health. Associativity is determined by time-averaged nodal connectivity and nodal mobility; and health is the combination of a number of factors like residual battery life, signal stability, buffer occupancy rate, storage capacity, processing power etc. In this dissertation, however, we consider only residual battery power for the calculation of nodal health. The link corresponding to a stable neighbor is considered to be a stable link while a link to an unstable neighbor is called an unstable link. A path having comparatively more stable nodes is considered to be optimal in terms of stability.

On-demand routing protocols are well suited for large, random and dynamic multihop ad hoc networks because they only maintain the active routes. Dynamic Source Routing (DSR) and Ad hoc On-demand Distance Vector (AODV) are two of the most popular on-demand routing protocols for ad hoc networks. However, both are designed to discover and maintain only a single path between a pair of end nodes at any given time. Thus, in the face of route failures, the latency of route repair can disrupt communication for an extended period of time [liu et al., 2007].

Multipath routing can broadly be classified into two categories: node-disjoint and link-disjoint. Both approaches to multipath routing provide improved fault-tolerance, load balancing, throughput and QoS provisioning. Contemporary research shows that using multipath routing in high-density ad hoc networks results in better throughput than using unipath routing (Pham and Perreau, 2004). Node-disjoint multipath routing provides additional benefits in terms of enhanced fault-tolerance and congestion control, and enhanced capability for load balancing (Liu et al., 2007). In this thesis, we focus on node-disjoint paths, which are particularly beneficial in ad hoc networks for public safety and emergency applications.

The pioneering work on associativity-based routing in MANETs was done by C.K. Toh by the proposition of Associativity-based Routing Protocol (ABR). ABR is beacon-based on-demand source routing protocol. Each node broadcasts periodic Hello messages to signify its presence to its neighbors. These beacons are used to update the associativity table of each node. With the temporal stability and the associativity table, nodes are able to classify each neighbor link as stable or unstable (Toh, C.K. 1996-1997). By selecting nodes with high associativity counts/ticks, the route is expected to be long-lived. This may not result in the shortest path but due to relative stable paths, route failures are lesser and hence route maintenance overhead is lower. The protocol offers better performance as compared to DSR in terms of throughput, end-to-end delays but DSR beats ABR in terms of storage overhead by a small fraction and in terms of simplicity (lee S.J., 2000).

We propose an on-demand multipath source routing algorithm that guarantees discovery of node-disjoint paths in wireless multihop ad hoc networks (liu et al., 2007). The constituent nodes are decided on the basis of their relative temporal stability. Please node that the concept of associativity employed in our protocol is distinct from the one employed in ABR.

3.1 Introduction

With the miniaturization of personal computing devices, proliferation in their number and advances in the wireless communication technologies, mobile ad hoc networks (MANETs) have gained popularity worldwide. Today, wireless networks are becoming popular because of their “3 Anys”–Any person, anywhere and anytime. MANETs are self organizing and self configuring multi-hop networks wherein nodes act co-operatively to establish the network “on-the-fly”. Communication between any two nodes might require the packets to traverse multiple hops and the constituent nodes act as both host and router. MANETs bear great application potential where wired infrastructure is not viable and temporary wireless network for instant communication is desirable such as disaster and emergency situations, battlefield communications, mobile conferencing, law enforcement operations and so on (Perkins, 2001).

There are currently two approaches for enabling data communication in mobile wireless networks. The first is *infrastructured network* also known as *cellular network*. The data is routed to the destination in centralized manner through the backbone wired network and hence simplifies greatly the task of routing and resource management. The second approach to mobile wireless networking is *infrastrucureless mobile network* also know as *ad hoc network*. Hosts in ad hoc network are equipped with short range (150 – 250 meters) packet radios. When communicating pair is not within the radio range of each other, the route between them is multihop. Ad hoc networks have no fixed routers; all nodes are capable of movement and each node can act both as router and host (Abolhasan et al., 2004). Ad hoc networks usually consist of battery-powered autonomous nodes with limited bandwidth, dynamic topology, error-prone shared channel, limited processing power and limited buffer capacity. Due to these issues in ad hoc networks, routing protocols designed and optimized for infrastructured networks are not suitable for mobile ad hoc networks. Routing plays a key role in providing connectivity and enabling data communication. A routing protocol is required to find an optimal path from the source to the destination taking into consideration following parameters: route acquisition delay, quick route reconfiguration, loop avoidance, minimum control traffic overhead, scalability, QoS provisioning, support for soft real-time traffic and security.

Two widely used routing approaches are reactive routing and proactive routing. Proactive routing protocols try to maintain consistent, up-to-date routing information about the whole network at each node. These protocols require each node to maintain one or more routing tables at each node. Reactive or on-demand routing approach is the most popular in ad hoc networks. Instead of periodically exchanging route messages to maintain routing tables at every node, the route is discovered only when a node wants to send data to the destination. Once a route is established it is maintained by a route maintenance process. Hybrid routing approach combines the advantages of proactive and of reactive routing.

Based on the number to routes between source and the destination, routing protocols can be classified as either unipath or multipath. Intuitively, multipath routing can utilize the network resources better and offer performance improvements over unipath routing. Multipath routing is also more promising for QoS provisioning in ad networks. The reason is multipath routing can provide load-balancing, fault-tolerance and higher throughput.

We present a multipath routing protocol which builds multiple nod-disjoint paths between the source and the destination. The path discovery process is initiated by the source. The protocol derives its motivation from on-demand source routing, multipath routing and associativity-based routing. We modify DSR to incorporate periodic beacons for associativity measurements, incorporate associativity metrics in the path discovery process and morph its route maintenance according to our mechanism.

3.2 Associativity-based Dynamic Source Routing

Associativity-based routing protocol proposed here decides the path(s) between the source and the destination based on spatial and temporal stability of the nodes. The temporal and special stability calculated is not based on usual tic-count approach. Instead the stability of a node is based on temporal connectivity of a node, mobility in its 1-hop neighborhood and its health. This approach finds optimal paths and helps reduce route maintenance cost.

3.2.1 Assumptions

We make following assumptions in the design and implementation of ADSR:-

- We assume that all nodes of the ad hoc network are capable of participating in networking protocols and are willing to forward data destined for other nodes.

- Maximum network diameter of up to 16 hops is considered.

- Nodes are capable of detecting and handling packets corrupted during the course of transmission. Some standard mechanism such as CRC (Cyclic Redundancy Check) can be employed.

- Speed with which nodes move is moderate with respect to packet transmission delay and transmission range of the nodes.

3.2.2 Architecture Diagram

ADSR comprises four major modules. They are neighbor acquisition, transmission, route discovery and route maintenance as illustrated by Figure 3.1. Neighbor acquisition involves 1-hop Hello beacons, associativity calculation and health monitoring of a node. Health is a measure of nodal residual battery life and signal stability. Associativity is a measure of its affinity to its 1-hop neighbor nodes.

Transmission module is responsible for dissemination of data and control traffic. Control traffic involves Hello beacons, RERR, RREQ and RREP packets. RERR, RREP and data packets carry along the source route so their forwarding is straight forward. RREQ packets are meant to discover node-disjoint routes to the destination so they are treated as broadcast messages.

Route discovery is achieved by RREQ and RREP messages. Destination node gets to know about the possible routes through RREQ messages and selects the optimal route using the fitness function. Any conflicts are resolved using the conflict resolution algorithm.

Route maintenance is the process of maintaining the discovered routes. Failed routes are detected by various mechanisms as mentioned in section 3.2.12.1. Source node is notified about the route failure via RERR message. Source node then launches the route recovery process.

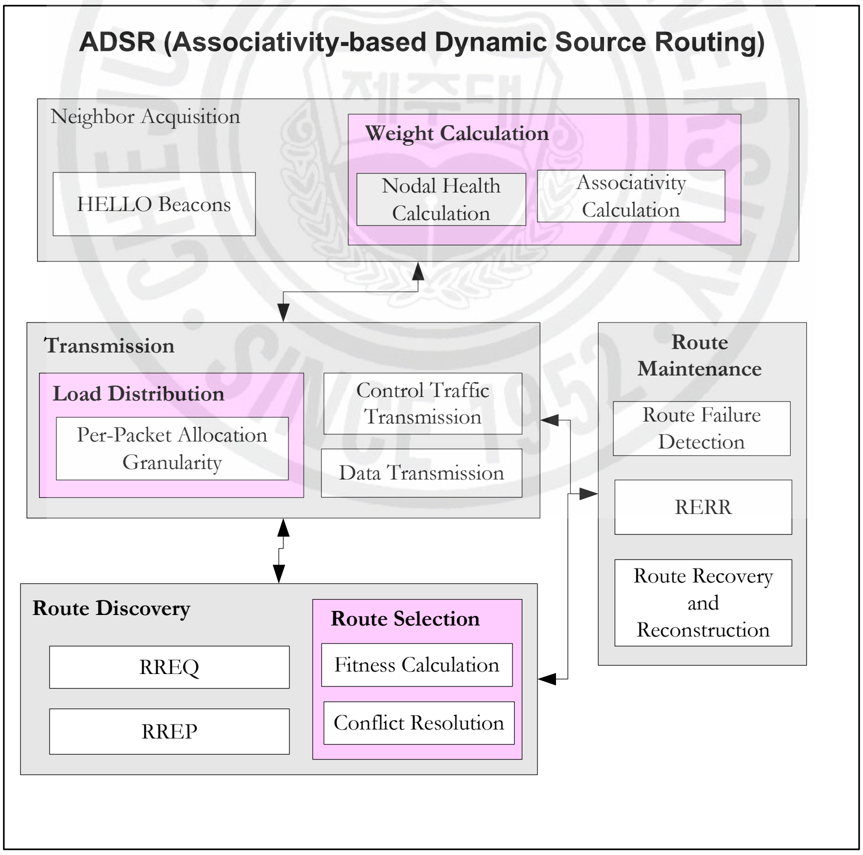

Figure 3.1. Detailed Architecture Diagram

3.2.3 Control Flow

Due to absence of infrastructure and autonomous nature of mobile nodes, distributed solutions are most suitable for MANET environments. Each node is desired to have the capability of making routing decisions and, therefore, is pre-configured with the routing software. Figure 3.2 demonstrates the flow of control through ADSR when a packet is received at the network layer at each node.

When the routing layer of a mobile node receives a packet, it checks the type of the message. Figure 3.2 is a high level control flow diagram which depicts an abstract overview of the working of ADSR. Neighbor acquisition or Hello messages are 1-hop broadcast messages. Sender node just broadcasts the message and all the nodes which are able to listen to this broadcast, record the corresponding neighbor's identity. This is handled by the HandleReceipt() function. A callback function gets called after a pre-configured number of hello intervals to update the associativity and health metrics of a node.

If an RREQ packet is received by the ADSR agent, control is transferred to HandleRREQ() which appends nodal weight to the path. If the packed is destined for this very node, it is handed over to HandleReceipt() function which handles the fitness calculation and route selection. Data, RREP and RERR packets are treated almost in a similar way. An intermediate node simply forwards these packets by examining the source route contained therein. An end node handles the receipt. In case of RERR packet, receiver is the source node and it can launch the route recovery process. In case of RREP packet too, receiver is the source node and it caches the route and transmits the data according to the allocation granularity onto the cached routes.

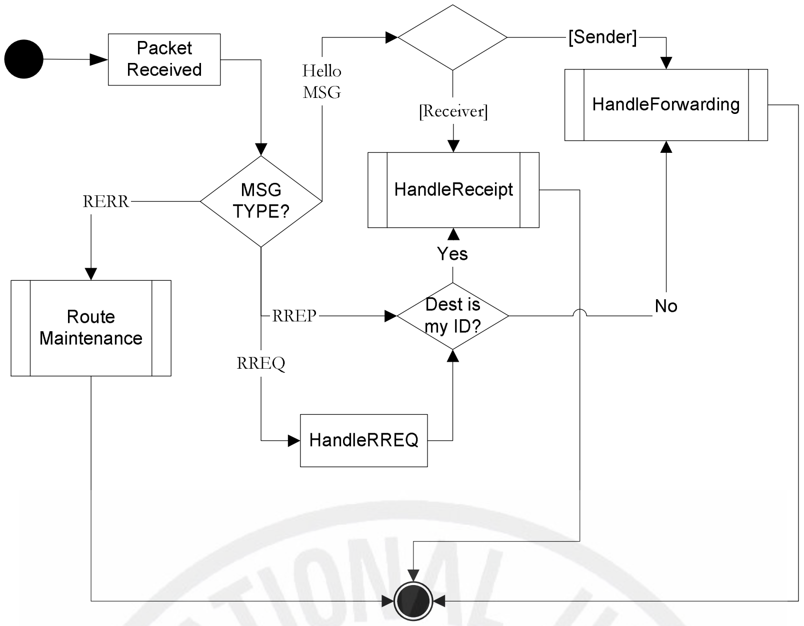

Figure 3.2. Flow of the ADSR algorithm at each MANET node

3.2.4 Basic Operation

Source node embeds the route in the packet header and transmits the packet to the next hop through the node's network interface. If a node hearing the packet is not the final destination, it simply re-transmits the packet to the next hop as specified in the source route in the packet header. When the packet reaches the final destination, the network layer passes it on the upper layer for delivery to the target application.

As the nodes are mobile and battery powered, the route may be invalidated due to node movements and node failures. While submitting packets, intermediate constituent nodes continuously monitor the validity of path. In case a failure occurs, the route is repaired or a new route is discovered. This falls into the domain of route maintenance.

3.2.5 Neighbor Discovery

Each node periodically relays Hello messages to its 1-hop neighbors in order to make its presence known to them. Each node maintains a neighbor history table which is used to keep track of the neighbor nodes discovered through Hello messages. Interval for periodic Hello broadcasts is configured during network setup. The node keeps the record of neighbor nodes discovered only during the last *h* periodic intervals. This set of records is used to calculate the temporal connectivity and the degree of movement in the 1-hop neighborhood of a node. This measurement is referred to as *nodal associativity*. *Nodal associativity* together with *nodal health* decides the overall stability of a node. This stability is termed as the *nodal weight* whose calculation is elaborated in the next section.

3.2.6 Nodal Weight Calculation

Each node, after h NA broadcasts, calculates its weight based on associativity index and residual power capacity.

$$W_v = \left| P_b \times \rho + I_v \times (1-\rho) \right| \text{ where } \rho \in \mathbb{R} : 0 \le \rho \le 1 \tag{3.1}$$

Here ρ represents the level of weightage assigned to P_b or I_v. P_b is the residual battery life and I_v is the associativity index of the node. I_v is calculated as

$$I_v = N_c - N_{topo} \tag{3.2}$$

In (3.2), N_c is average nodal connectivity of a node and N_{topo} is the estimation of relative mobility of nodes in the 1-hop neighbor of a node. Both of these measurements are explained in the next section.

3.2.7 Calculation of Associativity Index

Our calculation of I_v is based on both connectivity and relative mobility of the nodes. Connectivity of a node is measured by periodic exchange of NA messages. Each node maintains a topology cache of size h. h is a pre-defined constant. After h broadcast of NA messages, average nodal connectivity is calculated as follows:-

$$N_c = \frac{\sum_{i=0}^{h-1} c_i \left| X_i \right|}{h} \tag{3.3}$$

X_i is the set of neighbors figured out by i^{th} NA broadcast. c_i is the weightage assigned to i^{th} neighbor set and is decided such that $c_0 + c_1 + ::: + c_{h-1} = 1$ and $c_0 < c_1 < ::: < c_{h-1}$. Using arithmetic series [Wolfrom], c_0 is calculated as $h/_2(2c_0 + (h-1)d_c) = 1$. We assume that common difference $d_c < \frac{1}{2h}$. Successive weight terms are found by the arithmetic sequence $c_i = c_0 + (i)d_c$. By summing over the cardinalities of h X_i's and dividing by h, we get the average connectivity of the node. Also we measure the change in the 1-hop neighbors of a node which gives a pretty good estimation of the relative mobility of neighboring nodes. Again we utilize the h-sized local cache of neighbor sets.

$$N_{topo} = \frac{\sum_{i=1}^{h-1} w_i \left|(X_i \cup X_{i-1}) - (X_i \cap X_{i-1})\right|}{h-1} \tag{3.4}$$

Here $w_1 + w_2 + \ldots + w_{h-1} = 1$ such that $w_1 < w_2 < \ldots < w_{h-1} = 1$. w_1 is calculated as $\frac{(h-1)}{2}(2w_1 + (h-2)d_t)$ (Wolfrom). It is recommended that common difference $dt < \frac{1}{2(h-1)}$.

Using arithmetic series successive weight terms are found by $w_i = w_1 + (i-1)d_t$.

We combine (3.3) and (3.4) to get the final associativity index for a node. Therefore, from (3.2), we have

$$I_v = \frac{-\left(\sum_{i=1}^{h-1} w_i \left|\left(X_i \cup X_{i-1}\right) - \left(X_i \cap X_{i-1}\right)\right|\right)}{h-1} + \frac{\sum_{i=0}^{h-1} c_i \left|X_i\right|}{h} \tag{3.5}$$

Suppose 1-hop neighbor sets of a node discovered against 3 NA broadcasts are X_i = {1, 2, 4, 5, 6}, X_{ii} ={1, 2, 4, 10} and X_{iii} = {4, 6, 7, 10, 11, 12, 14} as shown in Figure 3.3.

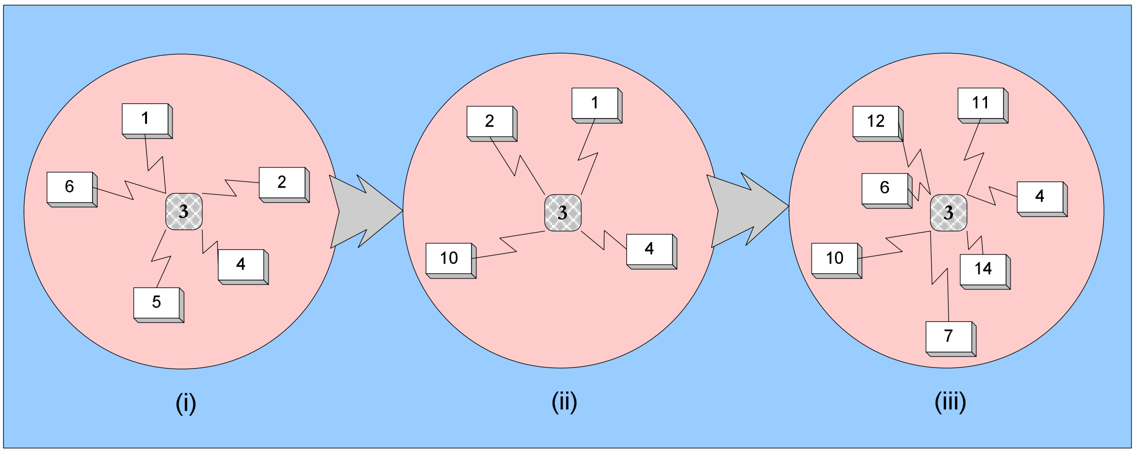

Figure 3.3 Gradual change in 1-hop neighbors of node 3

Let

$$d_c = 0.16 < \frac{1}{2h}$$

$\Rightarrow c_0 = 0.17$, $c_1 = 0.33$ and $c_2 = 0.49$.

Therefore,

$$N_c = \frac{c_i \left|X_i\right| + c_{ii} \left|X_{ii}\right| + c_{iii} \left|X_{iii}\right|}{3}.$$

$$\Rightarrow N_c = \frac{0.17(5) + 0.33(4) + 0.49(7)}{3}$$

$$\Rightarrow N_c = 1.87$$

For N_{topo}, assume

$$d_t = 0.25 < \frac{1}{2(h-1)}$$

Then $w_i = 0.375$ and $w_{ii} = 0.625$.

From (3.4), we get

$$N_{topo} = \frac{w_i \left|\left((X_{ii} \cup X_i) - (X_{ii} \cap X_i)\right)\right| + w_{ii} \left|\left((X_{iii} \cup X_{ii}) - (X_{iii} \cap X_{ii})\right)\right|}{2}$$

Therefore,

$$N_{topo} = \frac{0.4\left|\left(\{1,2,4,5,6,10\} - \{1,2,4\}\right)\right| + 0.6\left|\left(\{1,2,4,6,7,10,11,12,14\} - \{4,10\}\right)\right|}{2}$$

$$\Rightarrow N_{topo} = \frac{0.375(3) + 0.625(7)}{2}.$$

$$\Rightarrow N_{topo} = 2.75$$

Hence

$$I_v = \left|1.87 - 2.75\right| = 0.88$$

3.2.8 Route Discovery

ADSR is an on-demand source routing protocol wherein routes are built through RREQ/RREP cycles. The source node broadcasts a Route Request (RREQ) if it does not already have a route to the destination. The destination node receives multiple RREQ packets through multiple routes. It, then, decides the most suitable node-disjoint paths based on fitness function and sends Route Reply (RREP) to the destination through the specified routes.

3.2.9 Route Request (RREQ) Propagation

When source node does not know the route to the destination, it floods Route Request (RREQ) throughout the network. RREQ carries along two metrics. First metric is the source path in which accumulated is a record of the sequence of hops visited by the RREQ packet as it is propagated through the network. Each subsequent node appends its address to the source path as RREQ travels on towards the destination. Path is also pre-appended with hop count which is the number of legs that the RREQ packet has traversed between the source and the current node. Second metric is the weight of a node which represents its relative stability. Each intermediate node adds its weight to the path weight. When a RREQ packet arrives at the destination it contains summation of all the nodal weights along the traversed path. We modify the DSR Route Request (RREQ) packet in order to incorporate nodal weight.

The aim of the algorithm is to construct on-demand multiple node-disjoint paths. In order to achieve this purpose, destination node must know all the alternating paths so that it can choose the optimal paths. As we are using source routing, the route is included in the RREQ packets. Additionally, Route Replies (RREPs) from the intermediate nodes are disabled. This facilitates the centralized decision making about the selection of optimal routes at the destination. RREQ packet also contains source ID (set by the source), destination or target host ID and sequence number which uniquely identifies it. When a node receives a duplicate packet, it calculates the fitness of the partial path traversed by the packet so far.

Hop count and nodal weight are the two parameters used by the fitness function. If path fitness is greater than the previous partial paths via this node, then the duplicate packet is allowed to be forwarded.

Destination node receives multiple packets through multiple paths during a pre-defined time window. The destination node calculates the fitness of each path and selects at least two optimal routes which are most fit according to the fitness function.

Figure 3.4 explains a typical propagation of route request (RREQ) through an example network. The request broadcasted by source node S is received by three nodes identified as 1, 2 and 3. The request packets traveling through different paths are identified as $RREQ_1$, $RREQ_2$, $RREQ_3$,… $RREQ_N$. Propagation of duplicate packets is allowed under certain conditions. Node 3 broadcasts the request to its neighbor nodes 2 and 6. For node 6, it is a new packet so it updates the hop count, source path and weight fields of the packet and simply transmits. For node 2, it is a duplicate packet. Node 2 has to decide whether this duplicate packet is fit enough to be allowed to propagate further. It compares the fitness of the route [S, 3, 2] with that of route [S, 2]. The request packet is discarded because its fitness is not greater than the previous routes (in this case [S, 2]) through node 2. Similar is the case with the route request packet broadcasted by node 9. Node 7 allows the packet to be broadcasted further but node 8 discards for not being sufficiently fit. Now consider another case, where a duplicate packet is allowed to be transmitted by a node. Node 7 receives a duplicate RREQ packet from node 5. Node 7 lets it be forwarded because it fitness comes out to be greater than that of the previous routes through it. As is obvious from the figure only four RREQ packets are able to make it to the destination. They are identified as $RREQ_1$, $RREQ_2$, $RREQ_3$ and $RREQ_4$. We are interested in two most optimal node-disjoint routes. The algorithm can easily be generalized for selecting only one best route or more than two optimal routes. This means that the algorithm is can easily be adapted to unipath and multipath scenarios.

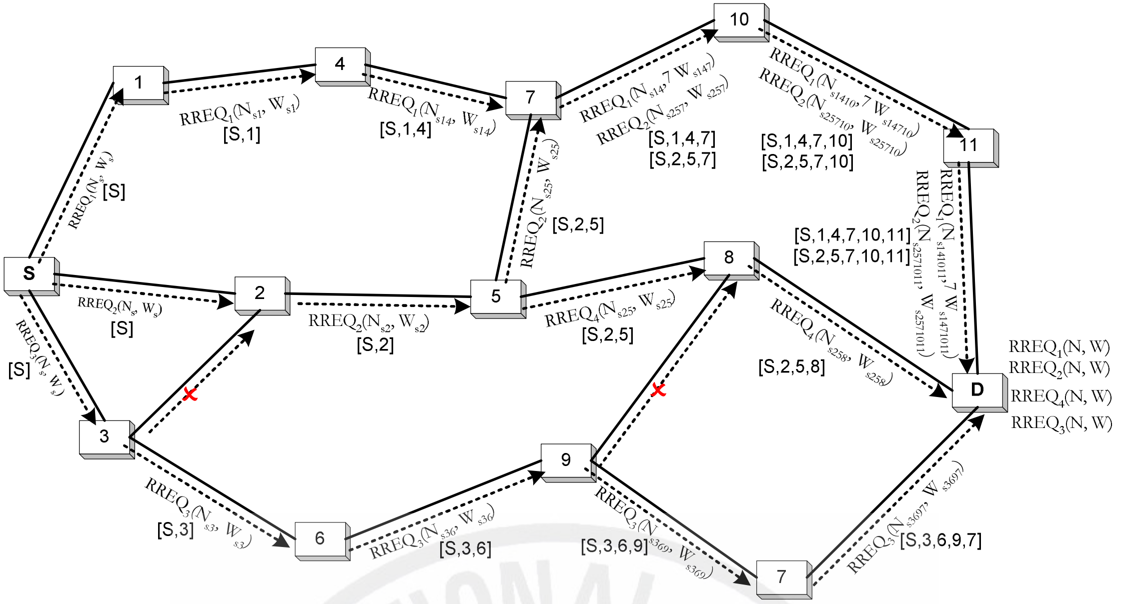

Figure 3.4: Route Request (RREQ) propagation

3.2.10 Route Selection

In our algorithm, the destination selects two optimal node-disjoint routes. Which routes are the best, is decided by evaluating the fitness function.

$$W_p \times \rho + N_p \times (1-\rho) = P_p \text{ where } \rho \in \mathbb{R} : 0 \le \rho \le 1 \tag{3.6}$$

Fitness function takes hop count and route weight as parameters. The effect of both these parameters on path fitness can be controlled by ρ . ρ simply provides a way to assign priority to the the two parameters. The solution to the function is a measure of the route fitness. Two routes which have higher fitness value than the rest are selected and transmitted back to the source on their respective reverse paths. In order to reduce the route acquisition latency, a variation of the above route selection mechanism is also proposed. We can choose the route corresponding to the RREQ packet which arrived first at the destination as the first route. This route is the shortest delay route. Destination immediately sends the route to the source using Route Reply (RREP) packet without waiting for the time window to expire. Fitness function is used to measure the fitness of the remaining routes received during the time window. Route which has the highest fitness value and is node disjoint with the shortest delay route is selected and transmitted to the source using RREP. Both of the above mentioned options are elaborated int the upcoming sections.

In Figure 3.4, destination node D receives four route request packets during the time window. P_1 = {S, 1, 4, 7, 10, 11, D}, P_2 = [S, 2, 5, 7, 10, 11, D], P_3 = {S, 3, 6, 9, 7, D} and P_4 = {S, 2, 5, 8, D} are the candidate paths that destination has to decide between and select the top two. Given below are the sample fitness values for the above mentioned paths:-

S, 2, 5, 8, D	P_4	0.8
S, 3, 6, 9, 7, D	P_3	0.7
S, 2, 5, 7, 10, 11, D	P_2	0.6
S, 1, 4, 7, 10, 11, D	P_1	0.5

We consider following two cases:-

3.2.10.1 Case 1

The destination node delays the route selection until the time window expires. Routes received, then, are evaluated using the fitness function. Two routes which are most optimal among the candidate routes according to their fitness values are selected as the final source routes. These routes are transmitted back to the source using the reverse of them. According to the fitness values calculated above for the candidate paths in the example network, P3 and P4 are the best. In this case source node can't start the transmission of data packets until it receives both the routes approved by the destination. Source can either delay the transmission in which case buffer capacity is of greater importance. Normally, nodes in an ad hoc network have limited memory capacity. Hence increased memory consumption resulting from the route acquisition delay may not be feasible. We, therefore, propose a little modification to the route selection process which is explained in Case 2.

3.2.10.2 Case 2

The first route selected is the shortest delay route. This is the route taken by the RREQ packet that arrives at the destination first. The route is sent back to the source using the Route Reply (RREP) packet via reverse route. This minimizes the route acquisition delay. Destination node waits for certain period of time also referred to as time window, in order to learn all the remaining possible candidate paths. It then selects the route that has the highest fitness value according to the fitness function and is node-disjoint with the shortest delay route.

In Figure 3.4, $P_4 = \{S, 2, 5, 8, D\}$ comes out to be the shortest delay route so it is sent back without waiting for the time window to expire and the selection process to begin. The second route then is selected after the expiry of time window and is selected such that it meets two conditions of being both fittest and node-disjoint with the first selected route. In Figure 3.4, P_3 has the best fitness value among the remaining candidate paths and it is node-disjoint as well. P_3 is, therefore, selected as the second route and is sent to the source using RREP packet on the reverse path.

3.2.10.3 Conflict Resolution

If there are more than one route that are equally fit, then the one with the highest weight is chosen. If routes happen to have the same weight, then hop-count is considered. If still they can't be selected on the basis of these two conditions then their respective arrival times at the destination are taken in to account and the one with earliest arrival time assumes priority.

3.2.11 Route Reply (RREQ)

When destination selects a path and needs to send it to the source it prepares a RREP packet. Node IDs of the entire path are recorded in the packet. Intermediate nodes use this information to forward the packet towards the source. Back-propagation of RREP is demonstrated in Figure 3.5. When source node receives a RREP packet, it retrieves the embedded route therein and stores it locally. Source node now has sufficient information about the destination to start the transmission of data packets.

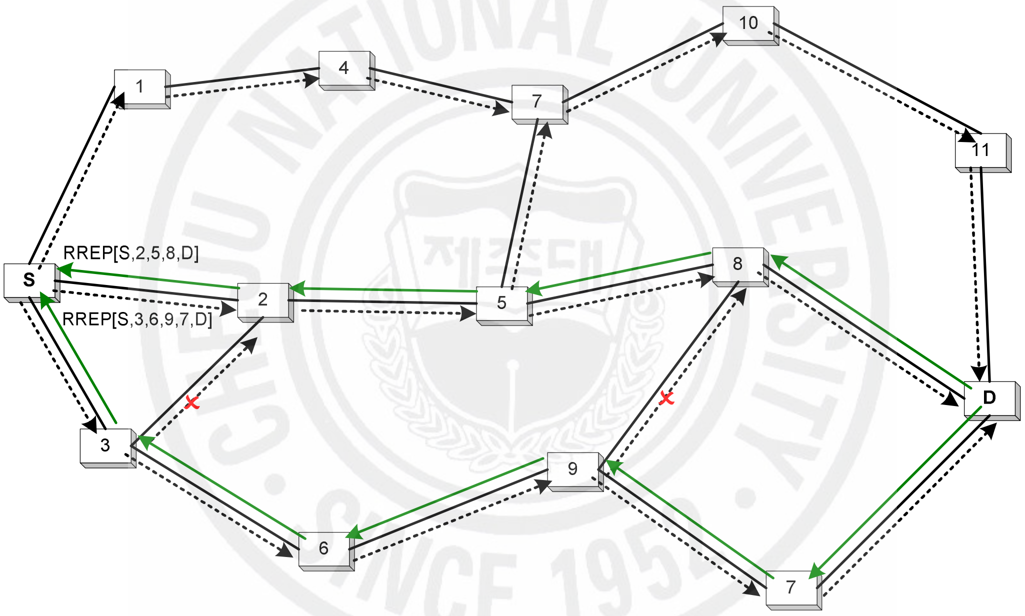

Figure 3.5: Route Reply (RREP) propagation

Our protocol employs source routing wherein entire route is stored in data packets resulting in an increase in the packet size. Because route replies from intermediate nodes are not allowed, only source node keeps track of the routing information to the destination. This puts less demand on memory requirements at the intermediate node.

3.2.12 Route Maintenance

Wireless links are more error prone. They can get broken due to mobility, congestion and packet collisions at any time. This renders the route unfit for carrying the data to the destination. For effective and reliable routing, it is imperative to recover or rediscover the broken route. When a node fails to deliver the data to the next hop of the route, the route is considered to be broken and the node sends Route Error (RERR) packet to its immediate upstream node which forwards it towards the source.

3.2.12.1 Route Failure Detection

Following mechanisms are used to identify link failure on an active route:-

3.2.12.1.1 Hello Messages

We employ periodic Hello messages for neighbor acquisition as explained in section 3.2.5. Periodic Hello messages can also server the purpose of link failure detection. Each node maintains a neighbor table keeping track of it immediate neighbors. If an intermediate node on an active route does not receive Hello message from its downstream node during h time intervals (as explained in section 3.2.7), it assumes the link with the upstream node to be broken and sends the route failure notification to the source node in the form of RERR packet. Two approaches are suggested to convey RERR message to the source.

- When forwarding a data packet a node checks the status of next hop in the neighbor table. If next hop is present in the neighbor table this means that the link connection between the two nodes is intact otherwise link has failed and source needs to be informed about the link failure.

- The intermediate node just logs the link failure and when receives a destination-bound message, sends the route error (RERR) message using the embedded route info in the data packet.

3.2.12.1.2 Passive Acknowledgements

Previous node overhears the radio transmission of a data packet by an intermediate node and uses it as acknowledgement. The previous node then sends RERR message to the source using the reverse of the route embedded in the data packet that was overheard.

3.2.12.1.3 Link Layer Feedback from IEEE 802.11

IEEE 802.11 DCF employs a contention avoidance mechanism wherein a node sends an RTS (Ready To Send) messages and forwards the data frame only if it receives CTS (Clear To Send) from the next hop. After seven failed RTS retransmissions, the link is considered to be failed. MAC layer conveys the feedback to the routing layer where it is taken as route failure and route maintenance procedure is invoked.

3.2.12.2 Route Recovery and Reconstruction

The Route Error (RERR) message contains the source route and upstream and downstream nodes of the broken link. Upon receiving the RERR message, the source invalidates the route containing the broken link. If the remaining route is still valid, the data can immediately be rerouted on to this route without incurring any route rediscovery latency. If the failed route is not in use by an active session, there is no need to rediscover the route. In case the route is servicing an active session, it is intuitive to reconstruct the failed route. For the time during which new route is being discovered, whole traffic is handled by the existing valid route. If source still has data to transmit but both the routes have been invalidated, the source either drops or buffers the packets while route acquisition is in process. In a nutshell, we allow the reconstruction of route(s) only when data session is active i.e., if no demand for data transmission, no route reconstruction is warranted.

3.2.13 Bandwidth Allocation Granularity

Source node immediately starts transmitting the data packets when it receives the first RREP. When it receives the second RREP, it has now two routes available. Efficient utilization of both the route is desirable. There are two well known bandwidth allocation schemes namely per-connection allocation and per-packet allocation. With per-connection allocation it is difficult to ensure even distribution of traffic over multiple paths. Per-packet allocation scheme has proved to be more graceful in the face of route failures though it results in out of order packet delivery and destination is burdened with the task of re-sequencing. However, there are efficient schemes available for re-sequencing. We employ a simple per-packet allocation scheme wherein packets are alternating routed on to the two paths. In case a route gets disconnected, the allocation scheme is disables and the all the packets use the still valid path. Whenever multiple paths are available to the source node, the per-packet allocation scheme kicks in and the load is almost evenly distributed across the two paths.

Chapter 4

4 RESULTS AND INTERPRETATIONS

4.1 Simulation Environment

In order to demonstrate the effectiveness of ADSR, we evaluate the proposed protocol and compare its performance with those of well-known reactive, proactive and multipath routing protocols. At the moment we have performed comparative analysis with AODV, DSDV and a reactive multipath routing protocol AOMDV (Marina and Das, 2001). We have considered throughput, normalized routing overhead and packet delivery ratio as performance metrics. Measurements on the basis of some other metrics, e.g., jitter, end-to-end delay etc are also under consideration.

We have implemented ADSR using the ns-2.33 simulator (USC ISI). The topoloby used for the simulation is shown in Figure 4.1. It was generated using ***setdest*** (USC ISI) utility of NS2. Three mobility scenarios were considered. The measurements for all the protocols were taken against three mobility levels, i.e., 5m/s, 10m/s and 20 m/s. We employed both TCP and CBR traffic sources. CBRGEN.TCL (USC ISI) was used to create 10 random connections for both CBR and TCP traffic models. In case of CBR, 7 traffic sources remain active throughout he run of the simulation. In case of TCP, 6 traffic sources generate TCP traffic according to the default TCP settings in NS2. Mobile nodes are employed in an area of 670m* 670m. Each node is reachable from every other node in the network throughout the simulation run.

As elaborated in Chapter 3, Hello messages are employed to discover the temporal associativity of mobile nodes. All the nodes are pre-configured with this parameter. In our simulations we use a Hello interval of 1000 ms. Network administrators can choose a value for it according to the network conditions and their past experience. For priority attribute ρ in the path fitness function, we use a value of 0.5 which means both hop count and path weight assume equal priority during the simulation analysis.

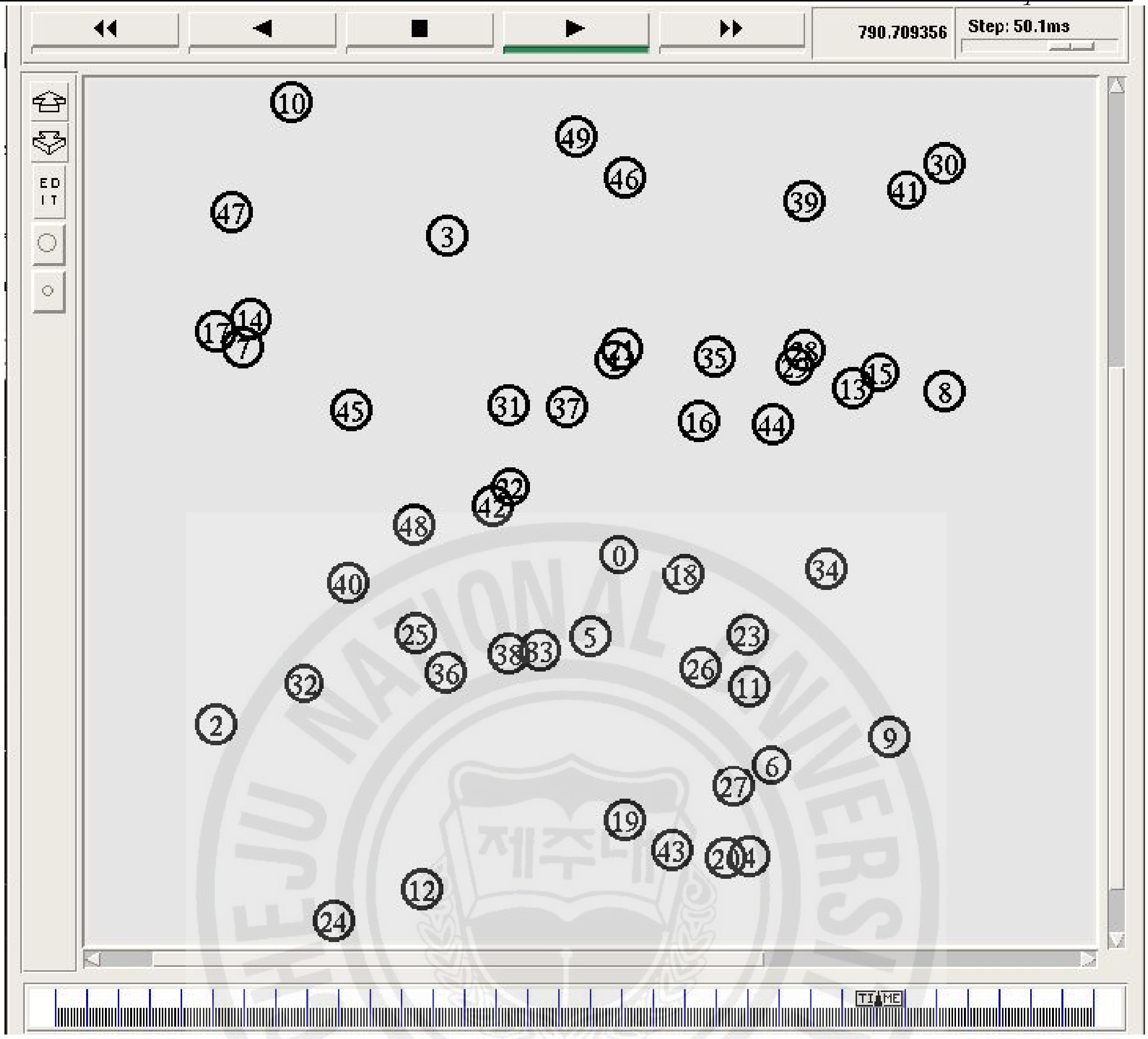

Figure 4.1. MANET topology for ns2 simulation analysis

The environment settings are explained in table below.

Table 4.1. NS2 environment settings

Antenna type	Omnidirectional
Propagation model	TwoRayGround
Transmission range	250m
MAC protocol	802.11 with RTS/CTS
MAC bandwidth	1 Mbit
Interface queue type	CMUPriQueue for ADSR Drop-tail priority queue for the rest
Max. IFQ length	50
Propagation delay	1 ms
Node count	50
Network size	670m × 670m

Simulation time	1000s

4.2 Packet Delivery Ratio

Packet delivery ratio is achieved by dividing the total number of packets sent by the total number of packets received. This provides a good measure of the reliability and robustness a routing protocol. Figure 4.2 and Figure 4.3 compare the packet delivery ratios of ADSR, AOMDV, AODV and DSDV under three different mobility scenarios. Figure 4.3 demonstrates the case wherein all traffic sources are CBR and Figure 4.2 shows the case wherein traffic sources are TCP. ADSR is more fault-tolerant and stable as it achieves greater packet delivery ratios.

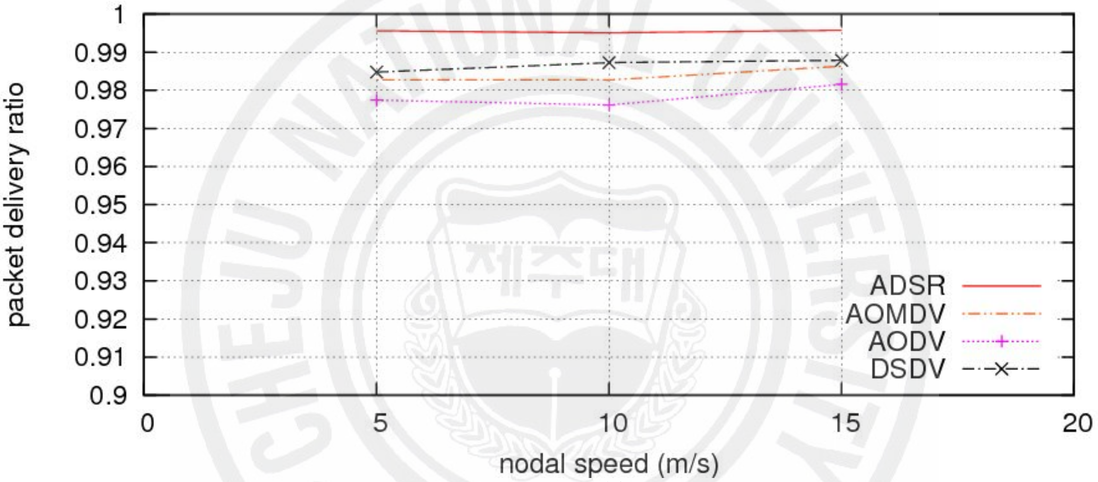

Figure 4.2. Packet delivery ratio for TCP traffic against three mobility levels namely 5m/s, 10m/s and 15m/s

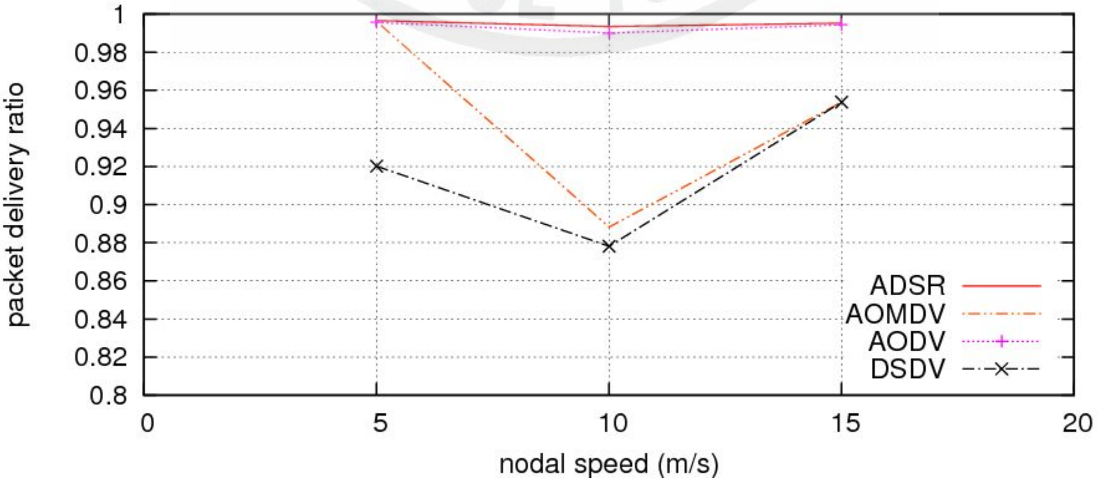

Figure 4.3. Packet delivery ratio for CBR traffic against three mobility levels namely 5m/s, 10m/s and 15m/s.

4.3 Throughput

Throughput is the amount of data transferred from one place to another in a specified amount of time. We measure throughput of the protocol under consideration for time granularity of 2000 ms. Three different mobility scenarios namely 5m/s, 10m/s and 15m/s are taken into consideration and each scenario is analyzed under several TCP and CBR traffic sources.

4.3.1 Throughput for CBR Traffic

In subsections 4.3.1.1 - 4.3.1.3, we compare the throughput of ADSR with those of AODV, DSDV and AOMDV under CBR traffic. Overall, ADSR is shown to have achieved better throughput under the said conditions.

4.3.1.1 Throughput measured at maximum speed of 5m/s

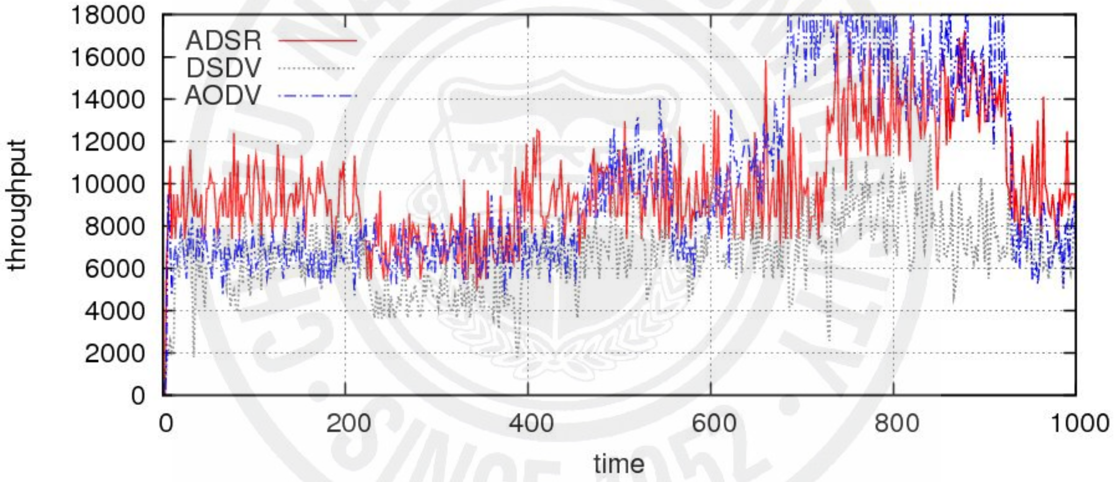

Figure 4.4. ADSR vs DSDV and AODV. Throughput measured under CBR traffic against maximum nodal speed of 5m/s..

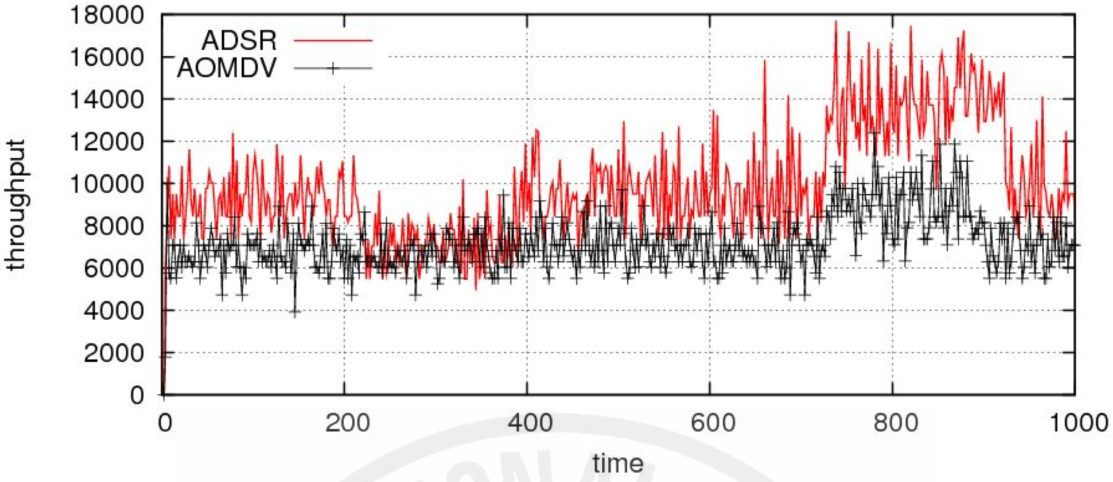

Figure 4.5. ADSR vs AOMDV. Throughput measured under CBR traffic against maximum nodal speed of 5m/s.

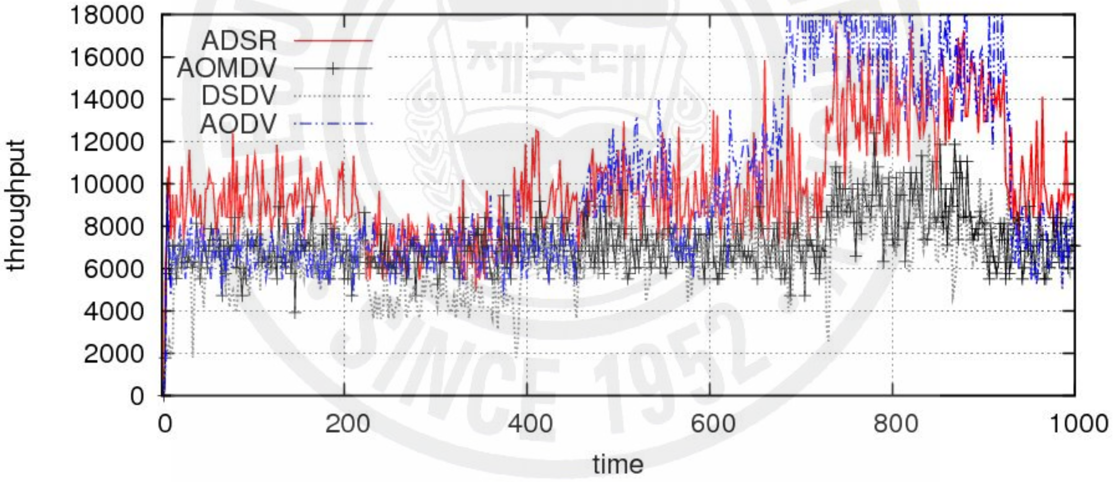

Figure 4.6. ADSR vs AOMDV, DSDV and AODV. Throughput measured under CBR traffic against maximum nodal speed of 5m/s.

4.3.1.2 Throughput measured at maximum speed of 10m/s

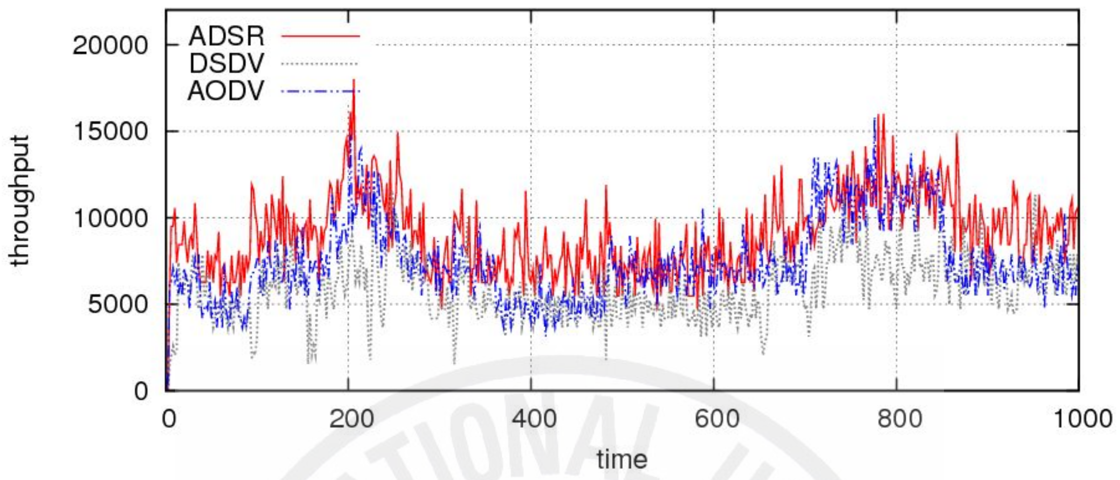

Figure 4.7. ADSR vs DSDV and AODV. Throughput measured under CBR traffic against maximum nodal speed of 10m/s.

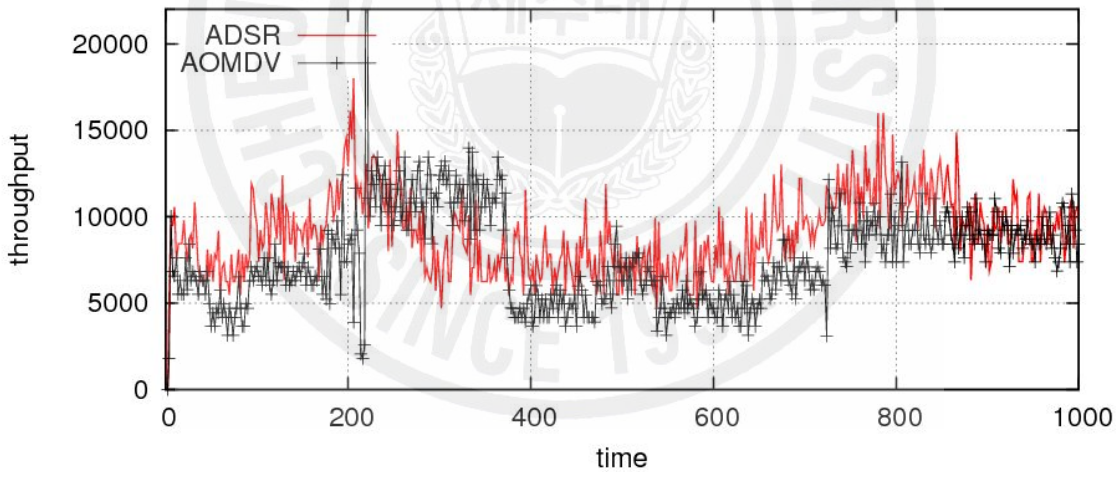

Figure 4.8. ADSR vs AOMDV. Throughput measured under CBR traffic against maximum nodal speed of 10m/s.

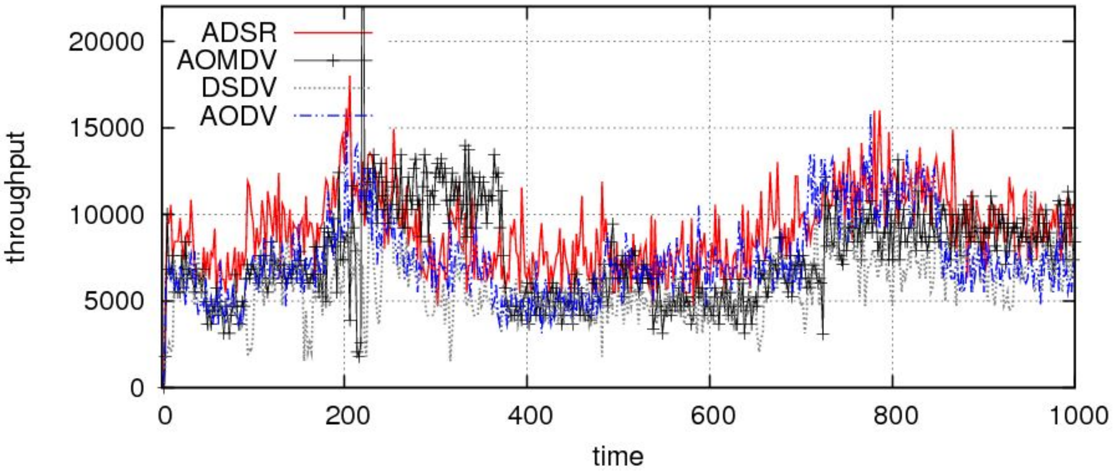

Figure 4.9. ADSR vs AOMDV, DSDV and AODV. Throughput measured under CBR traffic against maximum nodal speed of 10m/s.

4.3.1.3 *Throughput measured at maximum speed of 15m/s*

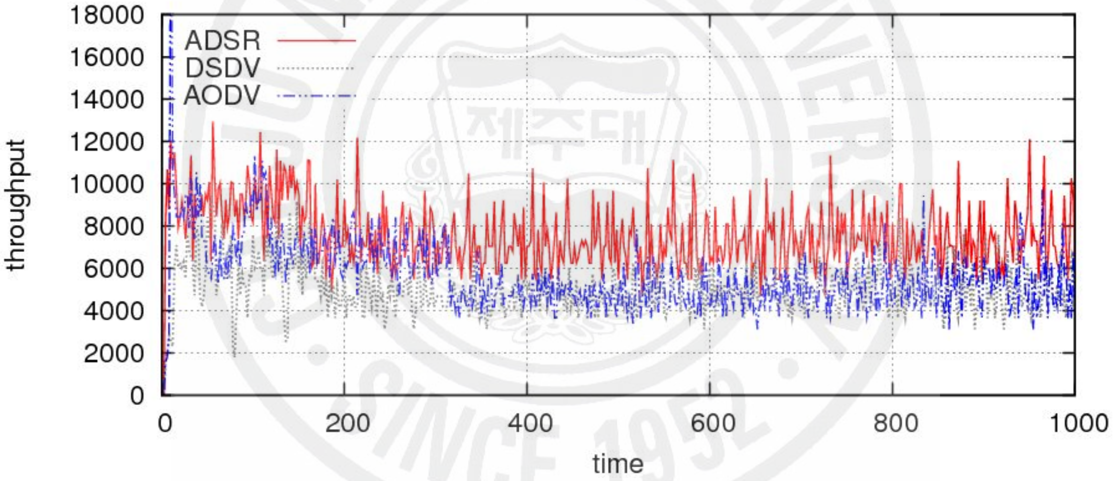

Figure 4.10. ADSR vs DSDV and AODV. Throughput measured under CBR traffic against maximum nodal speed of 15m/s.

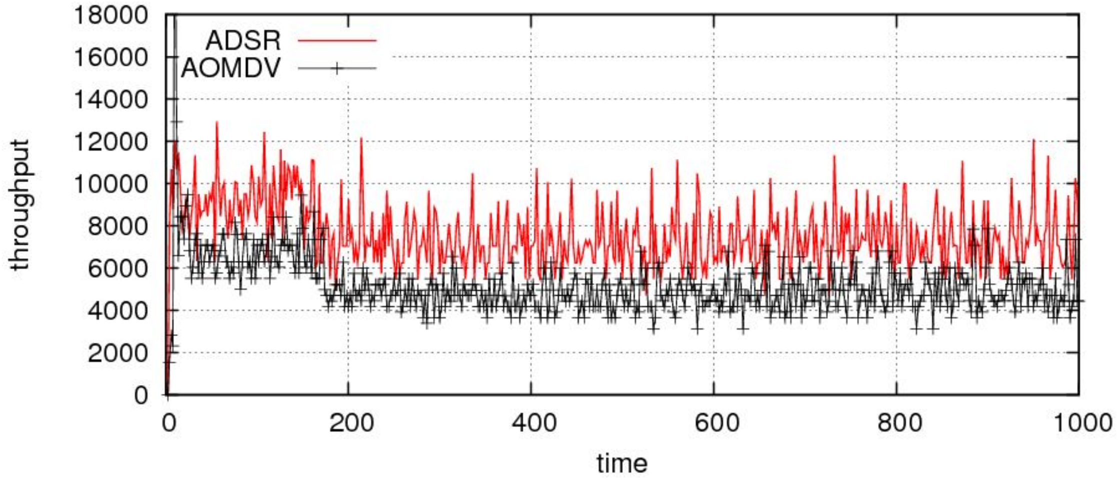

Figure 4.11. ADSR vs AOMDV. Throughput measured under CBR traffic against maximum nodal speed of 15m/s.

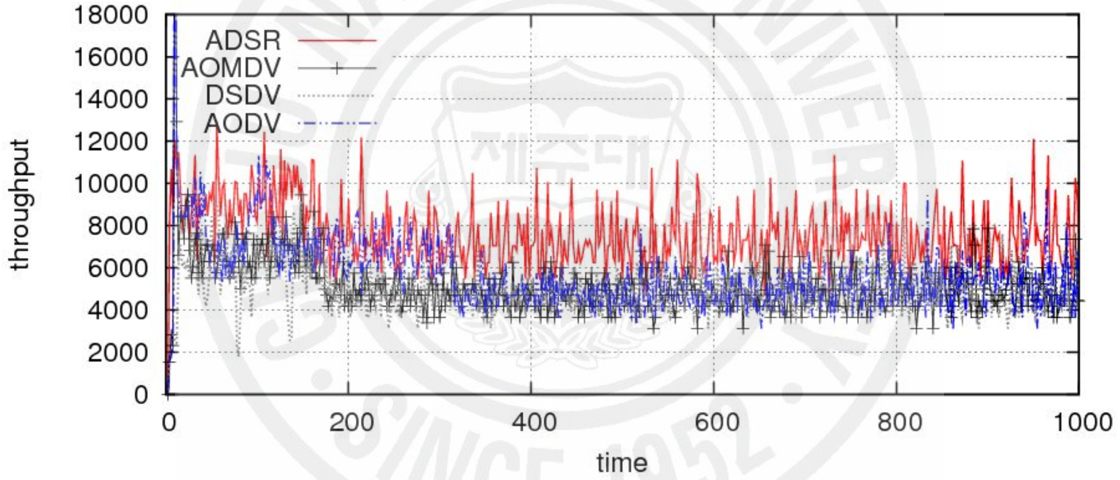

Figure 4.12. ADSR vs AOMDV, DSDV and AODV. Throughput measured under CBR traffic against maximum nodal speed of 15m/s.

4.3.2 Throughput for TCP Traffic

Subsections 4.3.2.1-4.3.2.3 illustrate the throughput performance of ADSR with respect to AOMDV, ADOV and DSDV under TCP traffic. ADSR clearly offers better throughput under the given network conditions.

4.3.2.1 Throughput measured at maximum speed of 5m/s

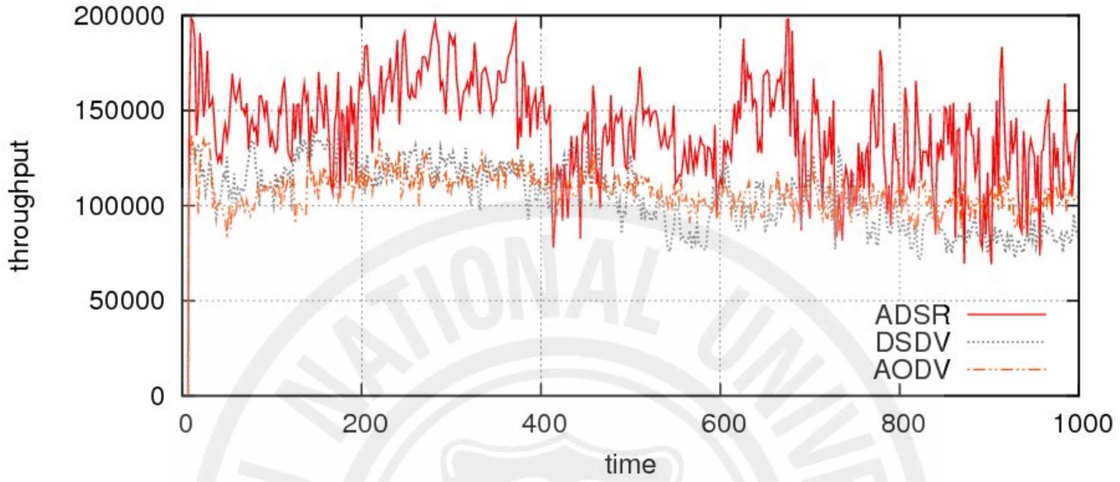

Figure 4.13. ADSR vs DSDV and AODV. Throughput measured under TCP traffic against maximum nodal speed of 5m/s.

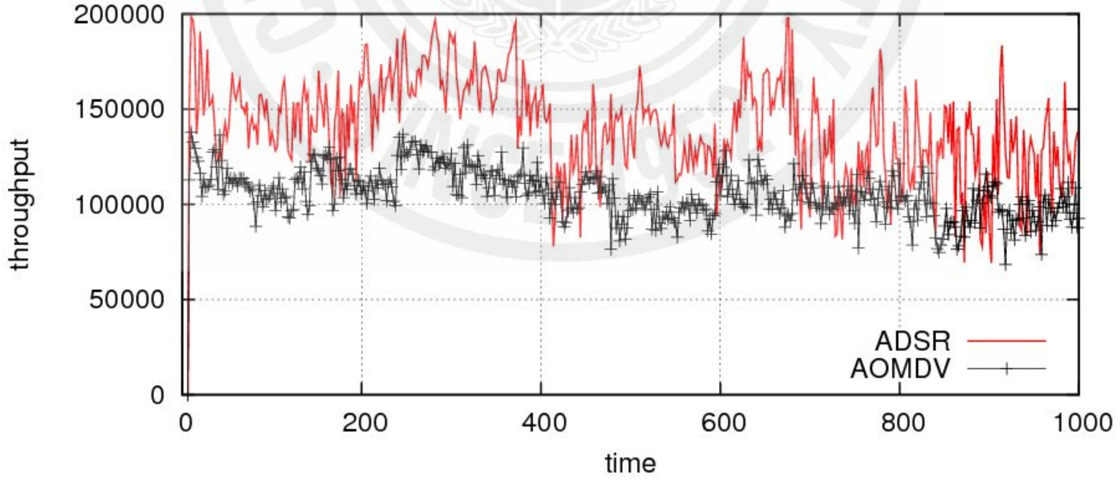

Figure 4.14. ADSR vs AOMDV. Throughput measured under TCP traffic against maximum nodal speed of 5m/s.

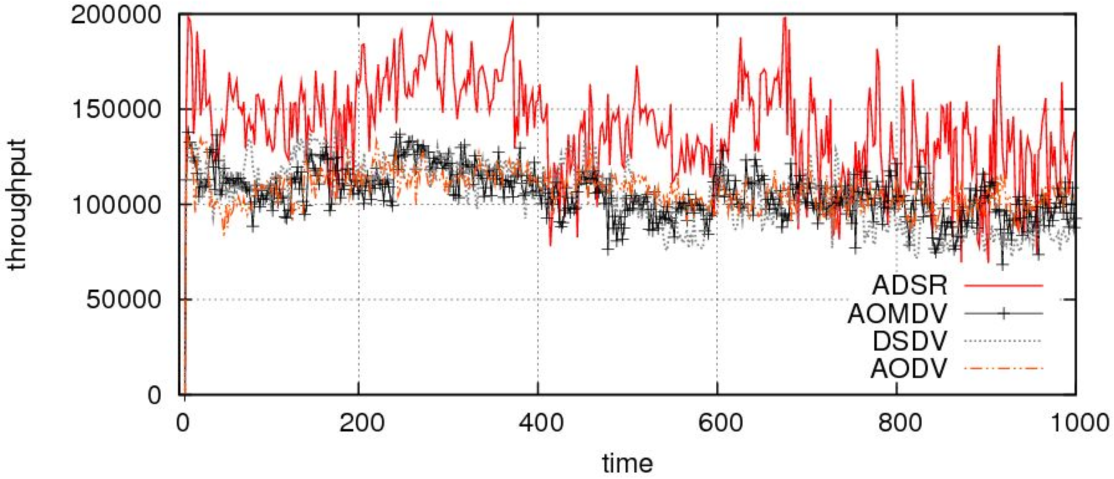

Figure 4.15. ADSR vs AOMDV, DSDV and AODV. Throughput measured under TCP traffic against maximum nodal speed of 5m/s.

4.3.2.2 Throughput measured at maximum speed of 10m/s

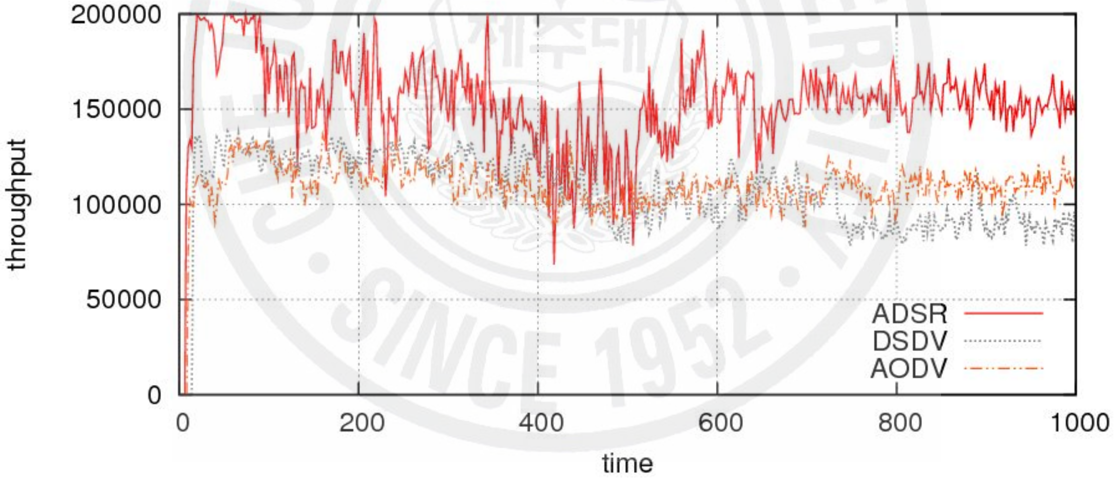

Figure 4.16. ADSR vs DSDV and AODV. Throughput measured under TCP traffic against maximum nodal speed of 10m/s.

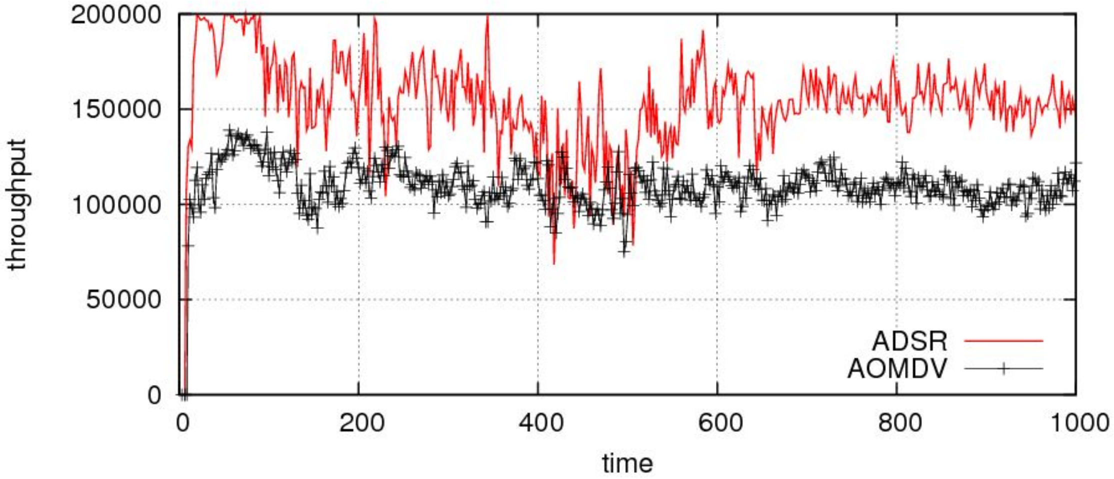

Figure 4.17. ADSR vs AOMDV. Throughput measured under TCP traffic against maximum nodal speed of 10m/s.

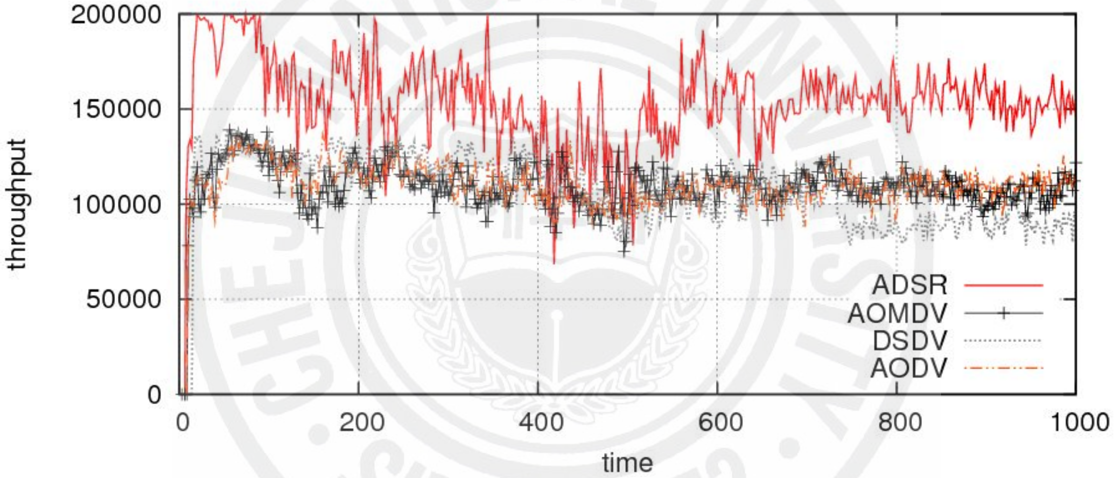

Figure 4.18. ADSR vs AOMDV, DSDV and AODV. Throughput measured under TCP traffic against maximum nodal speed of 10m/s.

4.3.2.3 Throughput measured at maximum speed of 15m/s

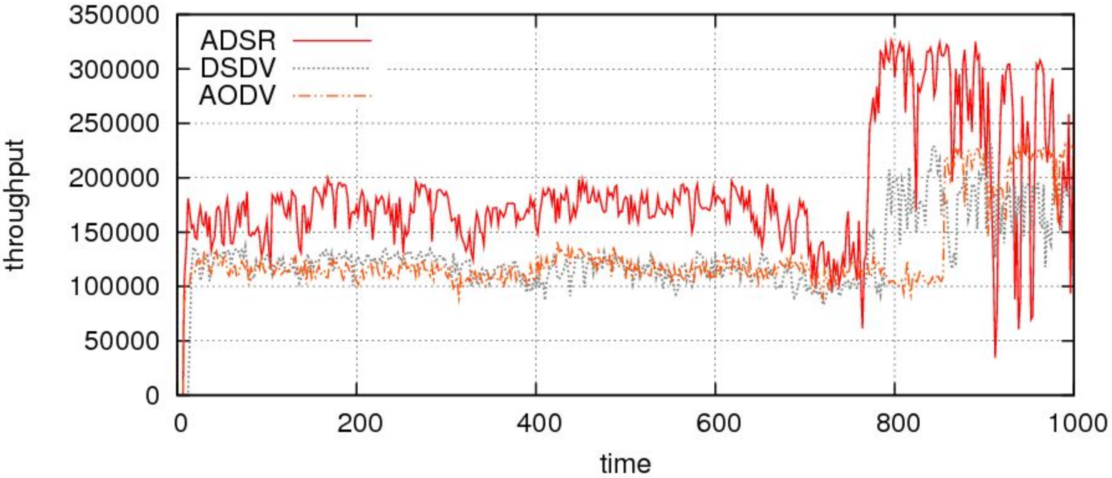

Figure 4.19. ADSR vs DSDV and AODV. Throughput measured under TCP traffic against maximum nodal speed of 15m/s.

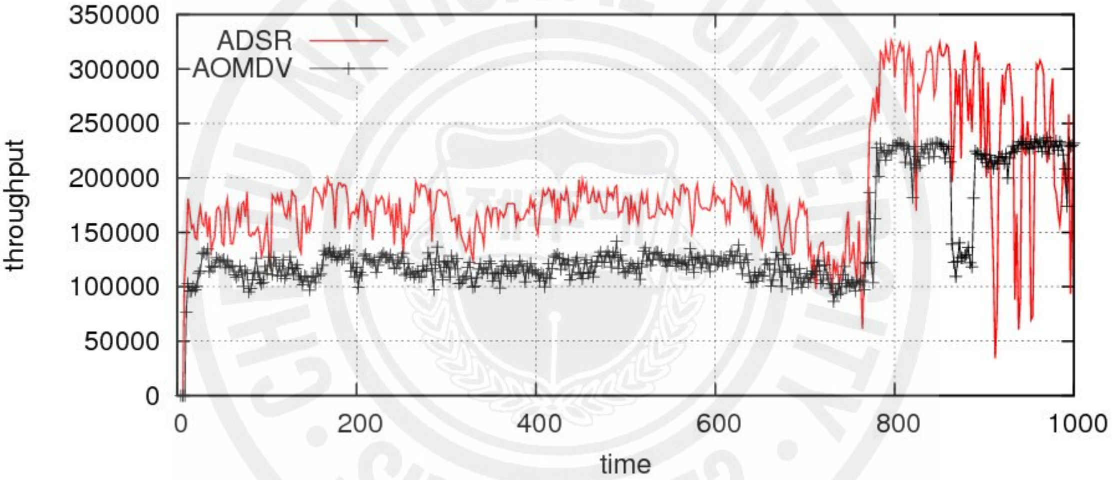

Figure 4.20. ADSR vs AOMDV. Throughput measured under TCP traffic against maximum nodal speed of 15m/s.

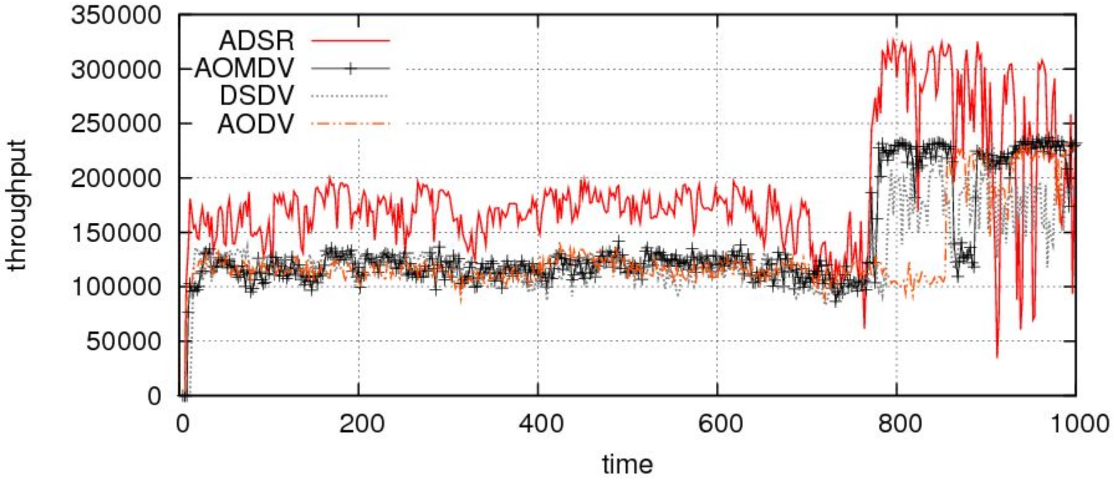

Figure 4.21. ADSR vs AOMDV, DSDV and AODV. Throughput measured under TCP traffic against maximum nodal speed of 15m/s.

4.4 Normalized Routing Overhead

Normalized routing overhead is the number of routing packets transmitted per data packet sent to the destination. This measurement is closely associated with the number of route changes in the network. Figure 13 is shows the comparative normalized routing overhead of ADSR, AOMDV, DSDV and AODV when traffic source is FTP application. ADSR performs better in situations where mobility is higher. Same measurement is performed in Figure 14 but the traffic source is CBR. ADSR shows much better performance than AOMDV, AODV and DSDV.

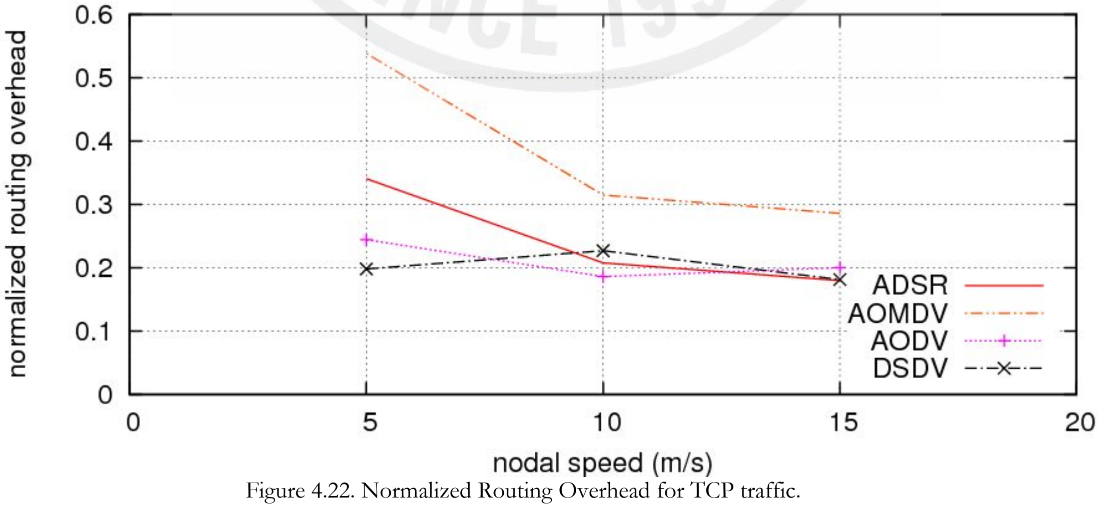

Figure 4.22. Normalized Routing Overhead for TCP traffic.

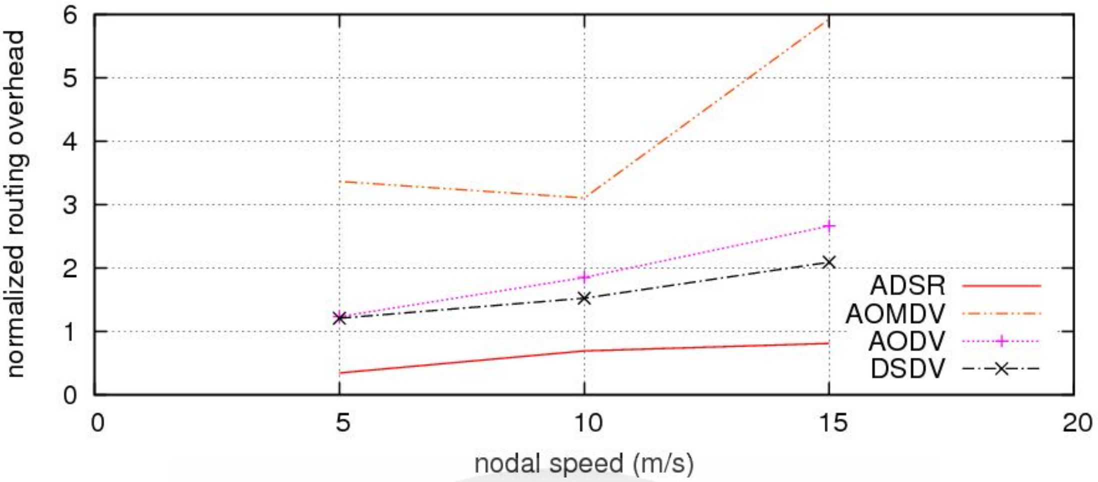

Figure 4.23. Normalized routing overhead for CBR traffic.

Chapter 5

5 SUMMARY AND CONCLUSION

5.1 Summary

MANET is a collection of autonomous mobile nodes. Nodes that are not within the direct radio range of each other communicate with each other via multiple hops. Each node in such a network acts as both host and router. Ad hoc networks are gradually assuming importance in civilian and military applications. Routing is a core function of any network which enables communication among reachable nodes within the network. Design and development of efficient and robust routing protocols for ad hoc networks is a challenging task due to mobility and resource constraints. This thesis is aimed at conducting research and analysis on multipath dynamic source routing in MANETs.

We have proposed a novel Associativity-based Dynamic Source Routing (ADSR) protocol for mobile ad hoc networks. The protocol constructs two optimal node-disjoint routes. We elaborate route construction, route maintenance and packet allocation granularity. We implement the protocol in the simulation environment of ns2.33.

5.2 Conclusion

We have proposed and analyzed through extensive NS2 simulations a dynamic source routing protocol ADSR. The protocol was put to test under diverse traffic and mobility scenarios. ADSR is compared with two unipath routing protocols namely AODV and DSDV and one multipath routing protocol AOMDV. Simulation results demonstrate that ADSR is more efficient and robust because it can offer better packet delivery ratio, reduce normalized routing traffic overhead and improve throughput significantly. ADSR discovers stable node-disjoint multiple routes. These results in less route discoveries, improved fault-tolerance and hence decrease normalized routing overhead. The availability of multiple paths improves reliability by routing traffic over to valid route(s) in the face of a route failure.

5.3 Future Work

We have proposed a novel distributed dynamic source routing protocol for mobile ad hoc networks. We have elaborated and illustrated through simulations only the multipath version although it can be easily configured for both unipath and multipath routing. We believe that the protocol will perform well in unipath routing as well for most scenarios. Given below are possible future improvements, extensions and applications:-

- Performance Evaluation in unipath routing
- Implementation and evaluation of link-disjoint version. Current version of ADSR described in this thesis constructs only node-disjoint routes.
- Measurement of end-to-end delay
- Measurement of total routing overhead
- One important metric that could help construct more long-lived routes is buffer occupancy rate.
- We have employed per-packet allocation granularity for distributing load over multiple paths. A more sophisticated scheme could improve the throughput further.
- Multipath ADSR is suitable for QoS provisioning. This aspect needs to be explored.

BIBLIOGRAPHY

Toh, C. K. 1996. A Novel Distributed Routing Protocol to Support Ad Hoc Mobile Computing, In *Proceedings of the IEEE International Phoenix Conference on Computers and Communications (IPCCC)*, Scottsdale, AZ, pages 480-486.

Liu, C., Yarvis, M., Connera, W. S. and Guo, X. 2007. "Guaranteed on-demand discovery of node-disjoint paths in ad hoc networks", *Computer Communications*, 30(14-15), 2917-2930

Johnson, D. B. and Maltz, D. A. 1996. Dynamic Source Routing in Ad Hoc Wireless Networks, *Mobile Computing*, edited by Tomasz Imielinski and Hank Korth, Chapter 5, Kluwer Academic Publishers, pages 153-181.

Toh, C. K. 1997. Associativity-Based Routing for Ad-Hoc Mobile Networks, *Wireless Personal Communications Journal*, special issue on Mobile Networking and Computing Systems, Kluwer Academic Publishers, 4(2):103-139.

Pham, P. P., Perreau, S. 2004. Increasing the network performance using multi-path routing mechanism with load balance. *Ad Hoc Networks (ADHOC)*, 2(4):433-459

Lee, S. J. and Gerla, M. 2001. Split Multipath Routing with Maximally Disjoint Paths in Ad Hoc Networks," In *Proceedings of IEEE Int'l Conference on Communications,* pages 3201-3205.

Perkins, C. E. 2001. Ad Hoc Networking, Addison-Wesley

Lee, S. J. 2000. Routing and Multicasting Strategies in Wireless Mobile Ad hoc Networks, *PhD thesis*, University of California

WikiAd. "Wireless ad hoc network". Wikipeida. http://en.wikipedia.org/wiki/Wireless_ad-hoc_network. (April 2003)

Zou, X., Ramamurthy, B. 2004. Routing Techniques in Wireless Ad Hoc Networks - Classification and Comparison, In *Proceedings of the Sixth World Multiconference on Systemics, Cybernetics, and Informatics*

Murthy, C. S. R., Manoj, B. S. 2004. Ad hoc Wireless Networks – Architectures and Protocols, Prentice Hall

Gupta, P. and Kumar, P. R. 2000. Capacity of wireless networks, *IEEE Transactions on Information Theory*, 46(2)

Li, J., Charles Blake, C., Douglas, S. J., Lee, H. I., Morris, R. 2001. Capacity of Ad Hoc Wireless Networks, In *Proceedings of the 7th ACM International Conference on Mobile Computing and Networking*, Rome, Italy

Abolhasan, M., Wysocki, T., Dutkiewicz, E. 2004. A review of routing protocols for mobile ad hoc networks, *Ad Hoc Networks*, 2(1):1-22

Lee, S. J., Gerla, M. 2001, SMR: Split Multipath Routing with Maximally Disjoint Paths in Ad Hoc Networks, In Proceedings of IEEE ICC, vol. 10, pages 3201-3205

Perkins, C.E., Belding-Royer, E.M. and Das, S. 2003. Ad Hoc On-Demand Distance Vector (AODV) Routing, IETF RFC 3561

Bellur, B., Ogier, R.G., Templin, F.L. 2003. Topology Broadcast based on Reverse-Path Forwarding (TBRPF) routing protocol, In: *Internet Draft, draft-ietf-manet-tbrpf-06.txt*

Basagni, S., Chlamtac, I., Syrotiuk, , V.R. and Wookward, B.A. 1998. A Distance Routing Effect Algorithm for Mobility (DREAM), In *Proceedings of the 4th annual ACM/IEEE international conference on Mobile Computing and networking (MobiCom '98)*, New York, NY, USA, pages 76-84

Wolfram. "Arithmetic Series". Wolfrom MathWorld. http://mathworld.wolfram.com/ArithmeticSeries.html (April 2008)

USC ISI. "Network Simulator 2". http://www.isi.edu/nsnam/ns/ (April 2008)

Pham, P. P. and Perreau, S. 2003. Performance Analysis of Reactive Shortest Path and Multi-path Routing Mechanism With Load Balance, INFOCOM, San Francisco, USA, pages 251- 259

Haas, Z. J. and Tabrizi, S. 1998. On Some Challenges, and Design Choices in Ad hoc Communications, In *Proceedings of IEEE, Military Communications Conference (MILCOM)*, Bedford, MA, 187-192.

Lin, Y. D., and Hsu, Y. C. 2000. Multi-Hop Cellular: A New Architecture for Wireless Communications, In *Proceedings of IEEE INFOCOM 2000*, 1273-1282.

Zadeh, A. N., Jabbari, B., Pickholtz, R. and Vojcic, B. June 2002 "Self-Organizing Packet Radio Ad Hoc Networks with Overlay," *IEEE Communication Magazine*, 40(6):140-157.

Perkins, C. E. and Bhagwat, P. 1994. Highly Dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for Mobile Computers, *Computer Communications Review*, 234-244

Abolhasan, M., Wysocki, T., Dutkiewicz, E., January 2004. A review of routing protocols for mobile ad hoc networks, Ad Hoc Networks, 2 (1):1-22

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

Wang, L., Shu, Y., Zhao, Z., Zhang, L., and Yang, O. 2002. Load Balancing of Multipath Source Routing in Ad Hoc Networks, In *Proceedings of IEEE ICCC'02*, 3197-3201

Marina, M. K. and Das, S. R. 2001. On-Demand Multipath Distance Vector Routing in Ad Hoc Networks, In *Proceedings of IEEE International Conference on Network Protocols (ICNP)*, pages 14-23

Nasipuri, Castaneda, R. and Das, S. R. 2001. Performance of Multipath Routing for On-demand protocols in Mobile Ad Hoc Networks, *ACM/Baltzer Mobile Networks and Applications J. (MONET), 6,* 339-349.