ROUTING PROTOCOLS ENHANCEMENT FOR DELAY TOLERANT NETWORKS

by

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Abstract

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Routing in Delay/Disruption Tolerant Networks (DTN) is active area of research and acquires the attention of researchers as being the most adequate solution for the problem of intermittently connection in Mobile Ad hoc Networks (MANET). The challenge is to find a routing algorithm that can deal with dynamic environment causing networks to split and merge, considering nodes mobility.

In this dissertation we enhance the performance of DTN routing protocols in Delay Tolerant Mobile Ad Hoc Networks by accomplishing the following goals to address the routing challenges:

- Design a new probabilistic routing protocol based on history of encountered nodes.
- Determination of strength and weakness of DTN routing protocols by comparison.
- Enhancing DTN routing protocols by inclusion of study of the impact of link availability on performance of the DTN-based protocols
- A Cross Layer Design (CLD) to enhance service quality of some common MANET-based routing protocols.

We have designed a DTN-based probabilistic routing algorithm using the concept of History of Encounters, HEPRA. Our routing protocol relies on the knowledge of the mobility of nodes and uses the history of encountered nodes to predict its future suitability to deliver messages to next node toward destination. The probabilistic routing approach is built on a store-carry-forward network to deliver messages to final destination in MANET environment. We evaluate the performance of HEPRA in various network environment behaviors.

We present an evaluation and analysis of performances of some common DTN routing protocols including HEPRA in terms of different parameters in MANET environment. We illustrate the behaviors of the DTN routing protocols in terms of various parameters and variables. This evaluation presents the strengths and weakness of selected protocols.

We study the impact of link availability as a parameter of the physical layer environment on the performance of DTN routing protocols. This study is the first research analysis of the impact of physical layer parameters on the performance of DTN routing protocols. We demonstrate through the simulation how those protocols act against changes in network environment.

We propose a CLD to attain a reliable data transmission in MANET. We present a model that allows the network layer to adjust its routing protocol dynamically based on Signal Noise Ratio (SNR) and Received Power (RP) along the end-to-end routing path for each transmission link to improve the end-to-end routing performance in MANET environment.

In this dissertation, we present the design basis for those contributions, illustrate and evaluate our design efforts, and discuss the advantages of our models.

For my parents, loving wife Entisar, Nadean and Zidan

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I owe my loving thanks to my wife, my daughter and my son. Without their encouragement and understanding it would have been impossible for me to finish this work.

Contents

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Acronyms

AN	Airborne Network
AODV	Ad-hoc On Demand Distance Vector
BER	bit error rate
BP	Bundle Protocol
CLD	Cross Layer Design
DARPA	Defense Advanced Research Projects Agency
DSR	Dynamic Source Routing
DTN	Delay/Disruption Tolerant Network
DTNRG	DTN Research Group
DYMO	Dynamic MANET On-demand
ICN	intermittently connected networks
IN	Interference Node
IPN	Interplanetary Internet
HEPRA	History of Encounters Probabilistic Routing Algorithm
MANET	Mobile Ad-Hoc Networks
MAR	Mobility Assisted Routing
MPR	multipoint relay
NASA	National Aeronautics and Space Administration
OLSR	Optimized Link State Routing Protocol
ONE	Opportunistic Network Environment
PROPHET	Probabilistic Routing Protocol using History of Encounters and Transitivity
QoS	Quality of Service
RERR	Route Error
RP	Received Power

RREP	route reply
RREQ	route request
SNR	signal to noise ratio
SNW	Spray and Wait
TC	Topology control
TS	Time-Slot
TS-HEPRA	Time-Slot HEPRA
TTL	Time-to-Live

Chapter 1

Introduction

1.1 MANET Environment

A Mobile Ad hoc Network (MANET) is a dynamic wireless network with or without fixed infrastructure. Nodes may move freely and arrange themselves randomly. The contacts between nodes in the network do not occur very frequently. As a result, the network graph is rarely, if ever, connected and message delivery must be delay-tolerant.

Traditional MANET routing protocols such as Dynamic Source Routing (DSR), Ad-hoc On Demand Distance Vector (AODV) and Optimized Link State Routing Protocol (OLSR) require that the network graph is fully connected and fail to route messages if there is not a complete route from source to destination at the time of sending. For this reason, traditional ad hoc routing protocols cannot be used in environments with intermittent connectivity. [1].

To defeat this issue, node mobility is exploited to physically carry messages between disconnected parts of the network. Schemes like these are occasionally referred to as Mobility Assisted Routing (MAR) that employs the store-carry-and-forward model.

Mobility-assisted routing comprises each node separately making forwarding decisions that occur when two nodes meet. A message gets forwarded to encountered nodes until it reaches its destination. Messages may have to be buffered for a long time by intermediate nodes, and the mobility of those nodes must be utilized to bring messages closer to their destination by exchanging messages between nodes as they encounter.[2].

Figure 1.1 shows how the mobility of nodes in such circumstances can be employed to ultimately deliver a message to its destination. In this figure, node A has a message (indicated by the node being sky blue) to be delivered to node F, but a path does not exist between nodes A and F. As shown in figures (a-d), the mobility of the nodes let the message be transferred to node B (fig b), then to node E (fig c), and finally, when node E moves within range of node F to node F which is its final destination [3], [12].

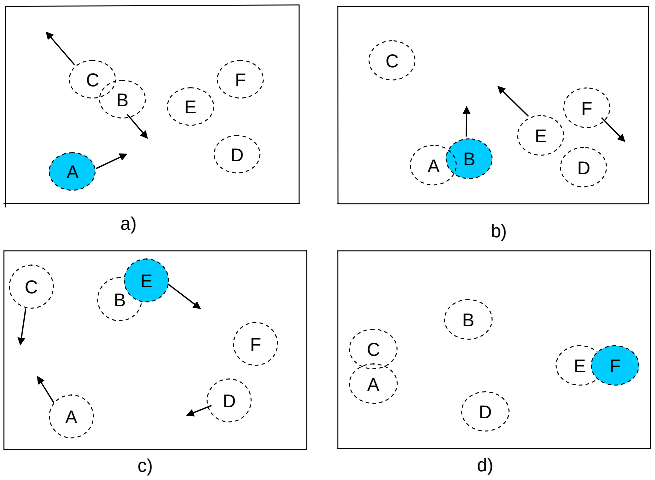


Figure 1.1 A message (shown in the figure by the node carrying the message being sky blue) is moved from node A to F via nodes B and E utilizing mobility of nodes [18]

1.2 Delay/Disruption Tolerant Networks

Delay/Disruption Tolerant Networking (DTN) is an end-to-end network architecture designed to provide communication in and/or through highly stressed networking environments. Stressed networking environments include those with intermittent connectivity, large and/or variable delays, and high bit error rates. [1], [7].

Recently, the term disruption-tolerant networking is frequently used instead of Delay-tolerant due to the support from Defense Advanced Research Projects Agency (DARPA).[4]

Disruption may occur because of nodes sparsity, radio transmission range, energy resources, attack, and noise. DTN architecture looks for addressing the technical issues in heterogeneous networks that may have a continuing lack of network connectivity. [5], [6].

The DTN Research Group (DTNRG) leads the field in DTN research. Members of the DTNRG created the Bundle Protocol (BP) to implement the DTN architecture. The key capabilities of the bundle protocols include custody-based reliability, ability to cope with intermittent connectivity, ability to take advantage of scheduled and opportunistic connectivity, and late binding of names to addresses [7].

As an effort to standardize communications for the Interplanetary Internet (IPN), the Delay Tolerant Networking architecture and protocols were proposed. DTN architecture and protocols were proposed as an effort to standardize communications for the IPN. As work progressed, researchers observed that military networks running tactical protocols, and remote networks where network resources are scarce and data mules might be used to transport data. These networks all had similarities in that they experienced several of these features: asymmetric communication, noisy links, long delays, and intermittent connectivity. As a result, the network community is developing a body of research for which funding has been established by both National Aeronautics and Space Administration (NASA) [9] and DARPA. [4]

The network architecture and protocol design process involves analysis and implementation of the protocols, validation of their behaviors and performance evaluation [10], [11].

1.3 Routing Challenges in DTN

Routing in mobile ad hoc networks (MANET) is difficult because the network graph is episodically connected. The topology is changing rapidly because of weather, terrain, highly variable delay links, error rate links, and jamming. A key challenge is to create a technique that can present good delivery performance and low end-to-end delay in an intermittent network graph and opportunistic or scheduled intermittent links where nodes may move freely. DTN is a message-based store, carry and forward overlay network architecture. Delay/Disruption Tolerant Networking (DTN) architecture is designed to provide communication in intermittently connected networks (ICN) by moving messages towards destination via store-carry-and-forward networking model that supports multi-routing algorithms to acquire best path towards destination. [8].

DTN architecture supports multi-routing algorithms to acquire best path from source towards destination.

1.4 Our Contributions

The aim of this dissertation is to design a routing protocol that can deal with the dynamic nature of MANET where network splits and merges, considering nodes mobility. The new approach shall overcome the intermittent connection in MANET environment and achieve high quality performance in terms of increasing delivery rate, minimal overhead, and reducing delay.

In this dissertation, we present the following contributions:

- *History of Encounters Probabilistic Routing Algorithm in Delay Tolerant Mobile Ad Hoc Network.*

  We designed a probabilistic routing protocol using a novel History of Encounters Probabilistic Routing Algorithm (HEPRA). The new routing depends on the knowledge of nodes mobility in order to utilize the history of encountered nodes to predict future suitable nodes to deliver messages to destination. The probabilistic routing approach is built on a store-carry-forward model to deliver messages to final destination in MANET. We demonstrate through simulation the ability of HEPRA to accomplish good quality performance than the other common existing Protocols.

- *Performance Analysis of HEPRA in Delay Tolerant Mobile Ad Hoc Networks and comparison with other DTN routing protocols.*

We present the progress and development of the performance of HEPRA. We analyze the performance of HEPRA routing protocol in terms of different network environment parameters. We select some of the well-known DTN routing protocols in our evaluation to demonstrate how HEPRA acts comparing to those protocols. We continue developing our algorithm and present TS-HEPRA to provide a detailed analytical as well as simulation-based study. Using simulation we considered in our analysis various parameters. Also, we provide analysis and evaluation of the other DTN routing protocols.

- *Study of the Impact of link Availability on the Performance of DTN Routing Protocols to highlight the affect of physical layer parameter on routing protocols.*

  DTN research filed lacks of study of influence of environment physical layer parameters on DTN-based routing protocols. In this work we study the impact of link availability as a parameter of the physical layer environment on the performance of DTN routing protocols. We demonstrate through the simulation how those protocols act against changes in network environment.

- *SNR/RP Routing Model: Cross-Layer Design for MANET environment*

  We propose a cross-layer design to attain a reliable data transmission in MANET. We present a model that allows the network layer to adjust its routing protocol dynamically based on Signal Noise Ratio (SNR) and Received Power

(RP) along the end-to-end routing path for each transmission link to improve the end-to-end routing performance in MANET. We evaluate our model using well known MANET- routing protocols such as AODV, DSR, OLSR to illustrate that our CLD improved their performances with respect to service quality. We analyze their performance in terms of: packet delivery rate, average End-to-End delay and overhead.

1.5 Organization of the Dissertation

The reminder of this dissertation is organized as follows: Chapter 2 presents our DTN-based routing protocol design and evaluation. Chapter 3 provides a detailed study and evaluation of well known DTN routing protocols including our approach, HEPRA. Chapter 4 provides a study of the impact of link availability on DTN routing protocols. Chapter 5 discusses our Cross-Layer Design model for MANET environment. Chapter 6 discusses our future research work and concludes the dissertation.

Chapter 2

HEPRA: History of Encounters Probabilistic Routing Algorithm in Delay-Tolerant Network

2.1 Motivation

Routing in mobile ad hoc networks (MANET) is complex and complicated because the network graph is intermittently connected. Nodes moves freely and network topology is changing rapidly. In this chapter, we propose a probabilistic routing DTN-based protocol to improve message delivery, reduce overhead and delay in MANET. The new algorithm is designed based on the concept of Social-stratification that used in social network. We evaluate the performance of the new approach, History of Encounters Probabilistic Routing Algorithm (HEPRA) in terms of different network environment parameters. We demonstrate the ability of HEPRA to accomplish good quality performance in MANET environment.

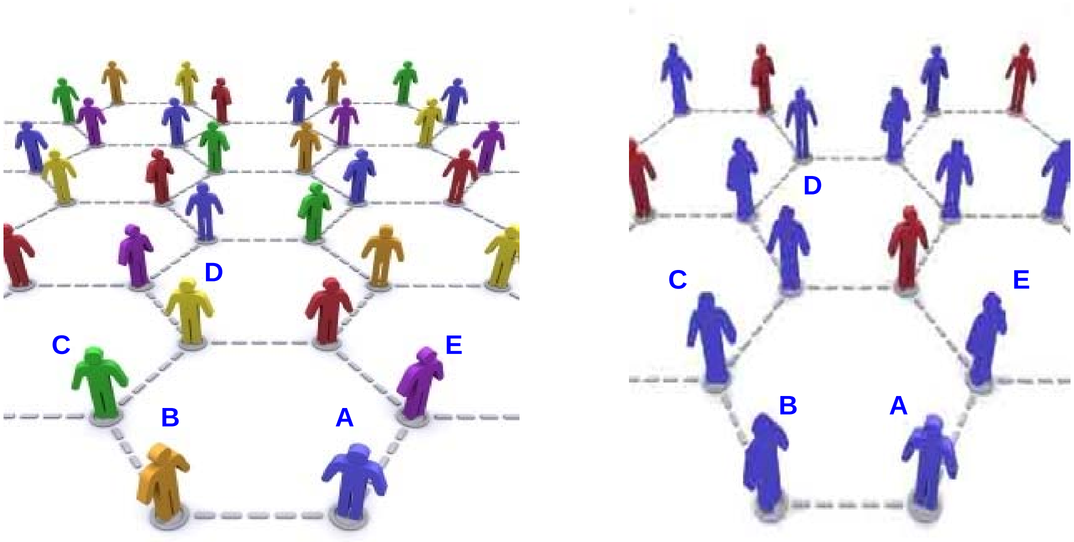
2.2 Social-stratification in Social network

A social network is a social structure formed of nodes that are connected by one or more specific types of interdependency. The nodes in the social network are the people and groups while the links show relationships or flows between the nodes. The notion of social structure in the society is grouped into structurally related groups or sets of roles, with different functions, meanings or purposes. [12].

Social stratification in the social structure refers to the idea that society is separated into different levels according to social characteristics such as a race, class, language, gender and religion. Social network analysis presents both a visual and mathematical analysis of human relationship. One example of social structure is the online social network which refers to social network websites such as Facebook [13], hi5 [14] and Twitter [15]. When you sign up with any of those social network websites, you will be able to meet new friends, reconnect with people you already know, build up relationships over time, learn from others and share what you know. Furthermore, you can find friends in your hometown or other parts of the world even though there is no prior knowledge of their locations.

Figure 2.1 (a, b) demonstrates the mechanism of how is the online social network works and the mechanism of adding new friends.

In figure 2.1.a, person A joined a social network and its list of friends is empty. Person A checks the group and sends an invitation to B to become a friend and B accepts the invitation. At this moment, A becomes a member of B’s group that contains friends C,D, and E. Now, A is able to contact C, D and E independently as shown in figure 2.b in purple. This process gets repeated until A builds up its group that contains B, C, D and E and their subgroups. Figure 2.1.b shows A and its subgroup (new friends) in purple color.



a)

b)

Figure 2.1 shows the process of joining a new person A to the online social network and becomes a member of B's group and how to add new friends

In online social networks, when you add a highly-social person to your list, it will make the process quick to add and find friends in your hometown or other parts of the world without prior knowledge of their locations. So, we could classify people in online social networks based on their social connectivity. This social connectivity called social-stratification of each person.

Figure 2.2 demonstrates the process of reaching a destination through high socially connected persons. If A wants to send a message to a person to whom no connection is available, the probability to go through D is higher than E since D knows 4 persons whereas E knows only 2 persons.

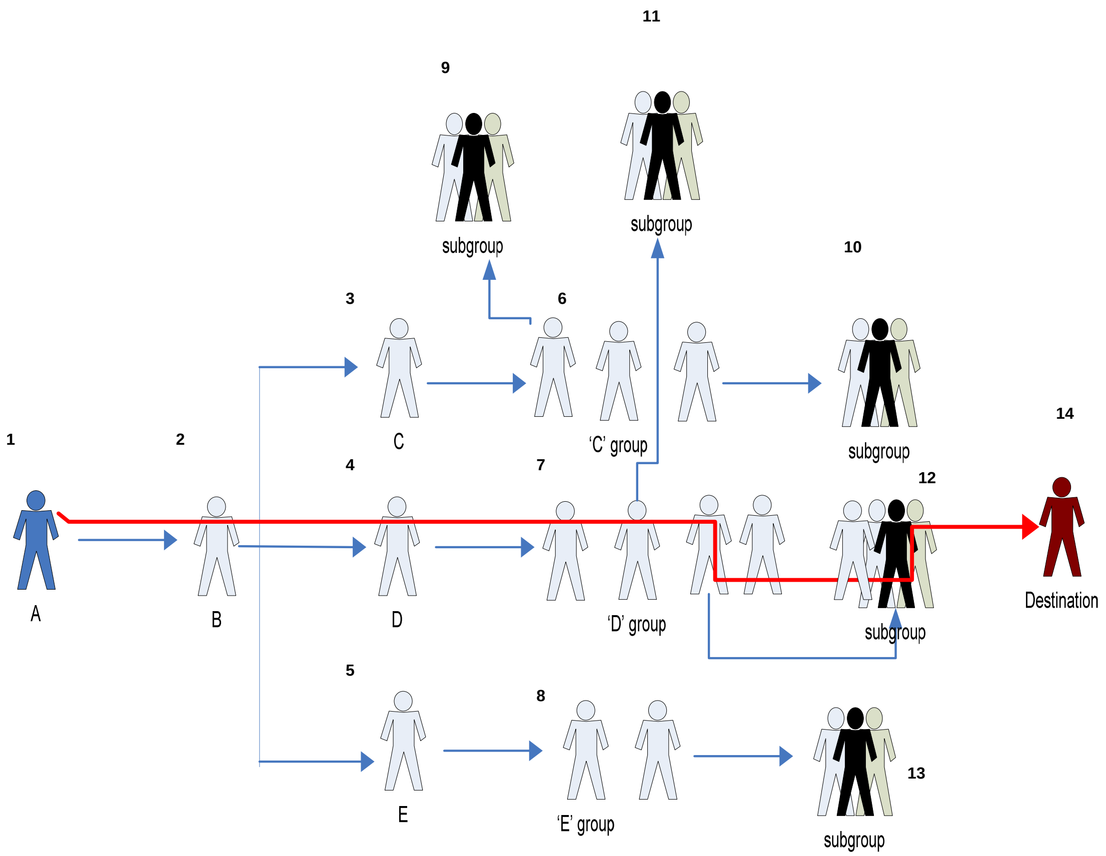


Figure 2.2 demonstrates the process of reaching a destination through high socially connected persons

Table 1 shows our mathematical calculation of figure 2.2 to compute the probabilities to reach destination from A through three different paths. It demonstrates that the path through D has a message delivery probability higher than C or E.

Table 1 shows calculation of figure 2.2 to compute the probabilities to reach destination from A.

```
n = 14;    The number of subgroup
The number of possible ways to arrive at the destination is 30

 Path  1 ===>  1,  2,  3,  6, 10, 14, ===> through C (3 contacts)
 Path  2 ===>  1,  2,  4,  7, 12, 14, ===> through D (4 contacts)
 Path  3 ===>  1,  2,  5,  8, 13, 14, ===> through E (2 contacts)

 Path  1 ===>   Probability = 0.2381
 Path  2 ===>   Probability = 0.3214
 Path  3 ===>   Probability = 0.2143
```

We utilize the concept of social-stratification in social network in our design. Our routing protocol uses the social-stratification concept in forwarding procedures. The node will forward messages to encountered nodes only if those nodes classified as highly-connected in the network.

2.3 HEPRA: History of Encounters Probabilistic Routing Algorithm

Delay tolerant networks have been proposed to address data intermittent communication challenges in networks where an instantaneous end-to-end path between a source and destination may not exist, and the links between nodes may be opportunistic, predictably connectable, or periodically-(dis)connected [11].

In this chapter, we focus on the Delay-Tolerant Mobile Ad Hoc Network to design a probabilistic routing protocol applicable to work in this intermittently connected environment to improve the end-to-end message delivery ratio in a multihop scenario where link availability can be low. We have designed our algorithm to 1) maximize message delivery rate, 2) minimize the total resources consumed in message delivery, 3) minimize the number of hops used in routing and 4) minimize message latency.

In the environment of periodically disconnected, nodes get only episodically connected because of terrain, weather, highly variable delay links, error rate links, and jamming that change topology rapidly.

Our routing algorithm will overcome the problem of periodically-disconnected network by applying the factor of history on encountered of each node for forwarding strategy. We employed the concept of history of encountered which is similar to the concept of social stratification in social network to forward messages to encountered nodes. Messages will be transferred towards destination via store-carry-and-forward technique that is used in DTN based routing protocols. Our new approach is called History of Encounters Probabilistic Routing Algorithm (HEPRA).

The operation of HEPRA relies on the knowledge of the mobility of nodes to forward messages based on encountered nodes in the past. We determine the History of encounters probabilistic factor of any node based on how many nodes did this node encounter until the moment of meeting a new node. If node a meets node b and the History of encounters probabilistic factor of node a is greater than node b, so it means that node a encountered more nodes than node b until the encountering time. In this case, node a will not forward any messages to node b but will do. HEPRA uses the history of encountered nodes to predict its future suitability to deliver messages to next node toward destination. An index of encountered nodes called a summary vector is kept by each node. Each Node maintains the summary vector that lists all encountered nodes during its mobility. The buffer size of each node controls the size of the summary vector.

When two nodes meet, they update the summary vector. Then, they exchange summary vectors which in this case also contains the list of encountered nodes stored at the nodes. This information in the summary vector is used to decide which messages to request from the other node based on the History of encounters factor used in the forwarding strategy.

Our forwarding strategy depends on the History of encounters of nodes in the network. We create a metric called History of encounters at every node. This indicates how highly-encountered the node is, which the number of nodes encountered till that moment is. The calculation of messages delivery depends on the History of encounters metric. When two nodes meet, the first thing to do is to update the metric (increase the metric by one), then they swap the number of encountered nodes till moment of meeting so that nodes that are often encountered more nodes have a high delivery Probability. Encountered nodes exchange only the number of earlier contacts without any details of those nodes. If they met the same number of nodes in the past they exchange new messages and if one of them encountered more nodes than the other in the past, only the node with low number of earlier contacts will deliver the new messages to the node with high earlier contacts. When a message arrives at a node, there might not be a path to the destination available so the node has to buffer the message. Upon each encounter with another node, a decision must be made on whether or not to transfer that particular message.

Our Mathematical model is based on the probability of an event equals the ratio of its favorable outcomes to the total number of outcomes provided that all outcomes are equally likely. According to the classical definition, the probability P(A) of an event A is determined a priori without actual experimentation: It is given by the ratio $P(A) = \frac{N_A}{N}$ where N is the number of possible outcomes and N_A is the number of outcomes that are favorable to the event A. In HEPRA, when node a ,encountered 8 nodes carries messages to deliver to final destinations, meets node b ,encountered 5 nodes, node a will not forward any messages to node b since $P(a)\left(= \frac{N_a}{N} \right) > P(b)\left(= \frac{N_b}{N} \right)$. We will forward messages from a node to another only if the probability of the encountered node is greater than the node that carried messages.

The flow chart in figure 2.3 demonstrates the how mechanism of HEPRA is working to deliver messages towards final destination. When node i meets node j they update the summary vector. Then, they exchange the summary vector. Each node will check the History of Encounters metric of each other. If the history of encounters metric of node i is less than node j, node i will transfer any unseen messages to j but not vice versa. Node i will deliver messages to destinations if path to destination available, otherwise, it will store the messages in the buffer and continue mobility till encountering new node. Employing the concept of history of encounters factor increases the probability of delivering messages to intermediate nodes and destinations since the probability of delivering messages by highly encountered -connected nodes is higher than lower encountered connected nodes.

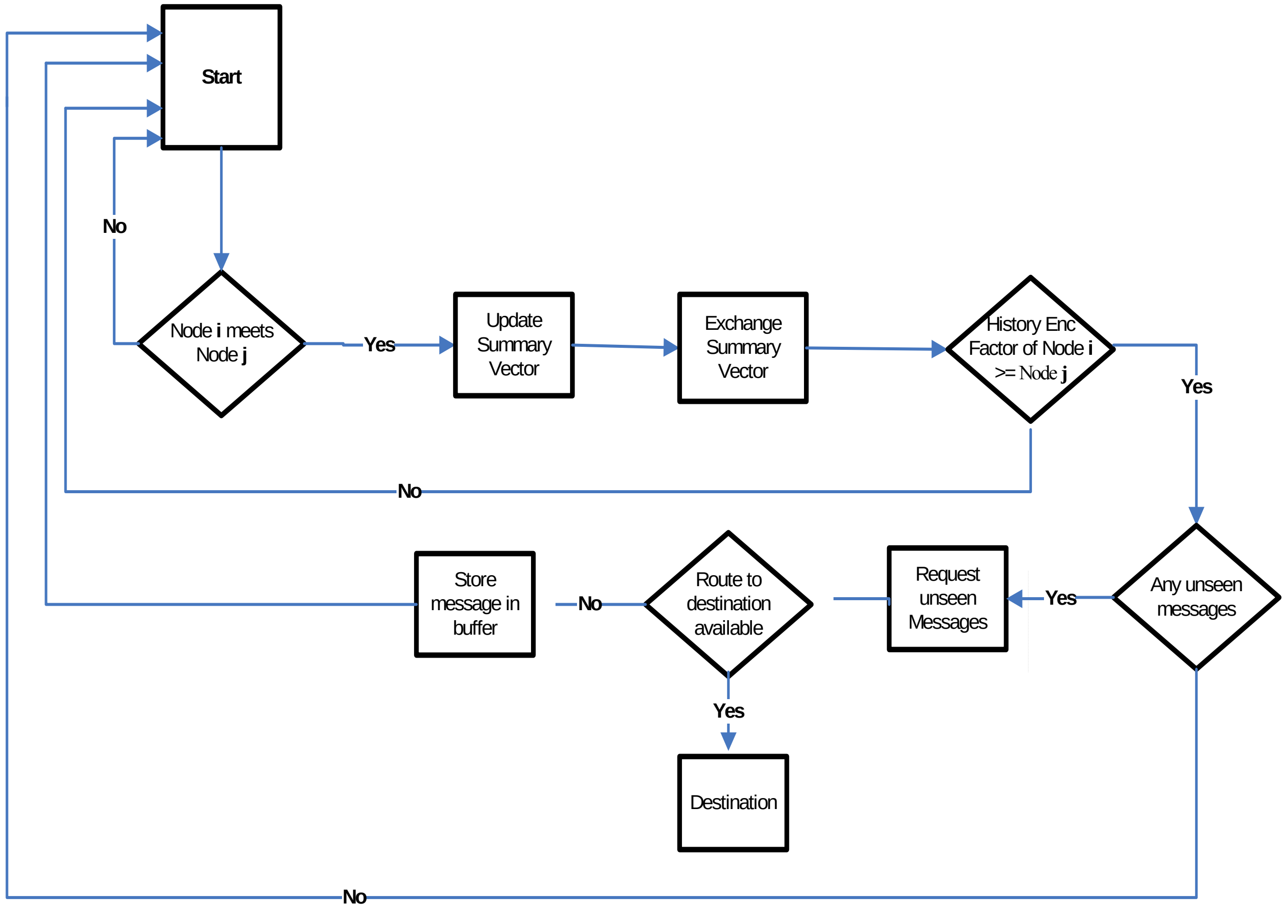


Figure 2.3 shows how the mechanism of message delivery is working in HEPRA algorithm

HEPRA utilizes information about the earlier contacts to predict how good nominee a node is to deliver the message to the recipient. In HEPRA, messages carried by the node with a higher probability, based on the history of encounters condition, only are transferred. Figure 2.4 defines the necessary variables while Figure 2.5 contains the pseudo-code for HEPRA routing protocol.

Variables:

1. *Seconds in time unit:* The unit in seconds for the hourly representation of the *sim clock*
2. *Duration*: The unit in seconds for the latest sociality information for the latest simulation time
3. *KnownHostsMap*: The Map having the current *sim clock* as key and the *other host* as the value.
4. *noofHosts:* The counter that counts the number of hosts.

Figure 2.4 Pseudo-code definitions of HEPRA

```
1 .Getknownhosts:  The method that returns the knownHostsmap for a particular host.
2. ChangedConnection:
{       The connection given as input
        if (connection is up for a node)
        then
        otherHost = the host of the other node
        in  knownHostsMap put  (SimClock, otherHost)
}
3. update:
{       checks for the transferring condition
        if noof messages ==0 or connections size ==0
        then comes out of the loop
        if (there are deliverable messages?)
        [get messages for connected ()]
        Try messages for the connected {start transfer}
        If there is connection, return the connection
        Call tryothermessages()
}
4. Knowledge calculator:
{     Integer S = knownhostsmap key() i.e simclock
    Initialize noofHosts = 0;
    Iterator i
    while(i.hasNext())
    if (i.next() >= (SimClock()- duration))
    then
    increment noofhosts
    return noofHosts;
  }
5. Tryothermessages
    {
    Otherhost =  get the other host
    Otherrouter =  get the router from other host
    If this router noofhosts < other router noofhosts
    Then continue
    For all the messages
    Check for unseen messages
    Add.messages
}
```

Figure 2.5 Pseudo-code of HEPRA routing protocol

2.4 Time-Slots in HEPRA

We develop HEPRA by employing a metric called SimClock to determine the time and number of encountered nodes at anytime in the simulation. In section 2.3, HEPRA counts encountered nodes during the mobility of the nodes throughout the simulation time. We used in our simulation the Opportunistic Network Environment simulator (ONE). [16].

The time simulation set to 12 hours so HEPRA count number of encountered nodes in this time of simulation. In this section, we evaluate the performance of HEPRA by dividing the simulation time to 12 time-slots. Each time-slot equals to 1 hour. We monitor performance of HEPRA in terms of delivery rate, overhead, latency, buffer size, number of hops.

Figure 2.6 defines the parameters used in the evaluation and analysis. The performance of HEPRA was consistent with increasing the time-slot. The results were expected since the additional nodes encountered will increase the delivery probability, minimize latency and increase overhead.

Created messages: number of messages created during simulation
Started messages: number of messages whose transmission was initiated between network nodes
Relayed messages: number of messages successfully transmitted between network nodes
dropped: number of messages dropped from nodes buffers because of full buffer
Removed: number of messages removed from nodes buffers because it was delivered to final destination.

Delivered messages: number of messages successfully delivered during simulation

$$\text{Delivered messages} = \frac{\text{Delivered messages}}{\text{Started messages}} = \text{overall message delivery \%}$$

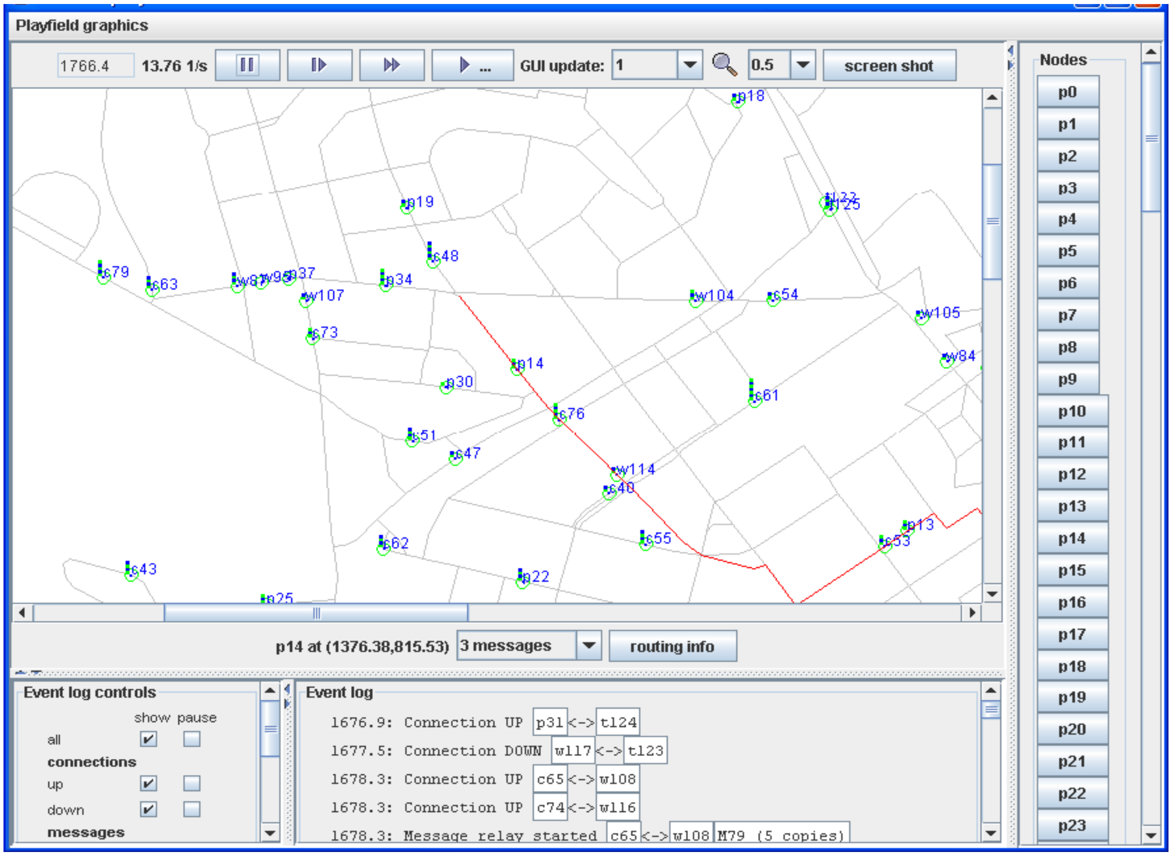
$$\text{Overhead} = \frac{\text{Relayed messages} - \text{Delivered messages}}{\text{Delivered messages}}$$

Latency: overall message average delay (average time between messages creation and delivery)
hopcount: average number of hop counts between the source node and the destination node
buffertime: how long messages stay in the message buffer from receiving/creating them until they're dropped or removed

Figure 2.6 Parameters used in evaluation in the simulation.[16].

2.5 Simulation Tool

Ari Keranen and Jorg Ott [16] presented the Opportunistic Network Environment simulator (ONE-V1.4) which provides a powerful tool for generating mobility traces, running DTN messaging simulations with different routing protocols, and visualizing simulations interactively in real-time and results after their completion. We used ONE-V1.4 in our simulation. Figure 2.7 shows a screenshot of ONE simulator.



1766.4 13.76 1/s

GUI update: 1

0.5

p14 at (1376.38,815.53) 3 messages

Event log controls

	show	pause
all	☑	☐
connections		
up	☑	☐
down	☑	☐
messages		

Event log

```
1676.9: Connection UP p31<->t124
1677.5: Connection DOWN w117<->t123
1678.3: Connection UP c65<->w108
1678.3: Connection UP c74<->w116
1678.3: Message relay started c65<->w108 M79 (5 copies)
```

Figure 2.7 Simulator ONE Screenshot

2.6 Evaluation of HEPRA Performance

We used the simulation setup that used in table 2. It shows the parameters used in our simulation. We ran our simulation with changing numbers of nodes in area of 4500 x 3400 m. We use several different types of speeds of 1.5 m/s (Pedestrians), 15 m/s (cars), 10 m/s (trams). We assume buffer size of 10 Mbyte for each node.

Table 2 Simulation parameters for ST-HEPRA

ENVIRONMENT PARAMETERS	**VALUE**
Simulation Area (W x H) meter	4500 x 3400
Simulation duration (hr)	12
Number of nodes	50
Movement Model	Shortest Path Map Based Movement
Message TTL (minutes)	60
Host speed (m/s)	1.5 -15
Buffer size (Mbyte)	10

It is immediately evident from the results given in Figure 2.8.1 that our algorithm, HEPRA, increases message delivery with increasing number of nodes. This is because HEPRA forward messages to highly connected nodes that meet nodes continually that guaranteed the message delivery.

Figures 2.8.2 shows that overhead decreases when increases number of nodes.

In figure 2.8.3 when number of nodes increases, HEPRA reach low latency with high number of nodes.

Figure 2.8.4 shows that number of hopcount increases when nodes increases since size of network get large so messages travel many hops to reach destination. Figure 2.8.5 shows messages buffertime increase since HEPRA needs time to buffer messages in order to forward messages to only certain nodes that are highly socially connected and sorting required time for this process.

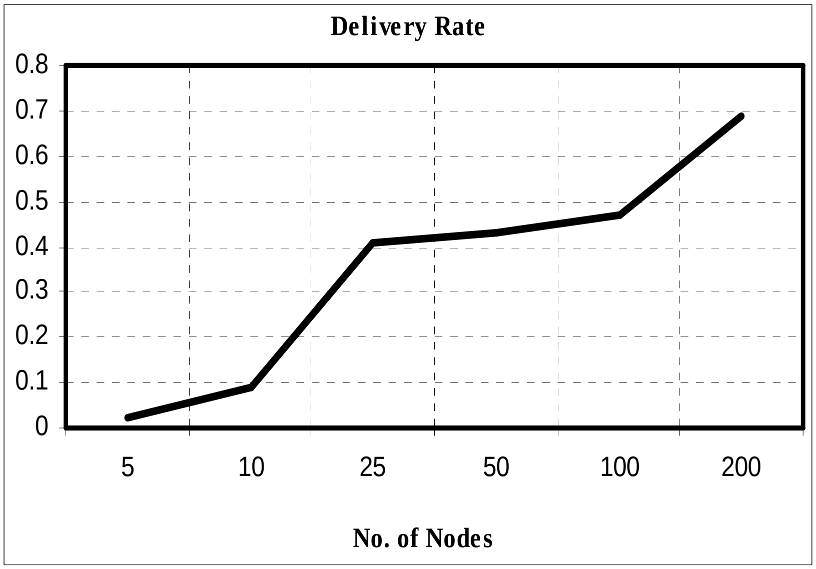


Figure 2.8.1 Delivery Rate increases when no. of nodes increases

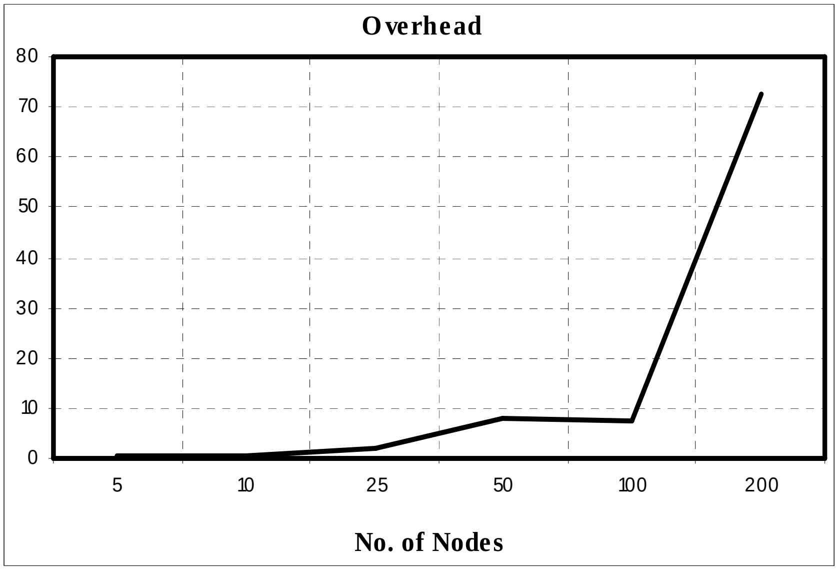


Figure 2.8.2 Overhead increases when no. of nodes increases

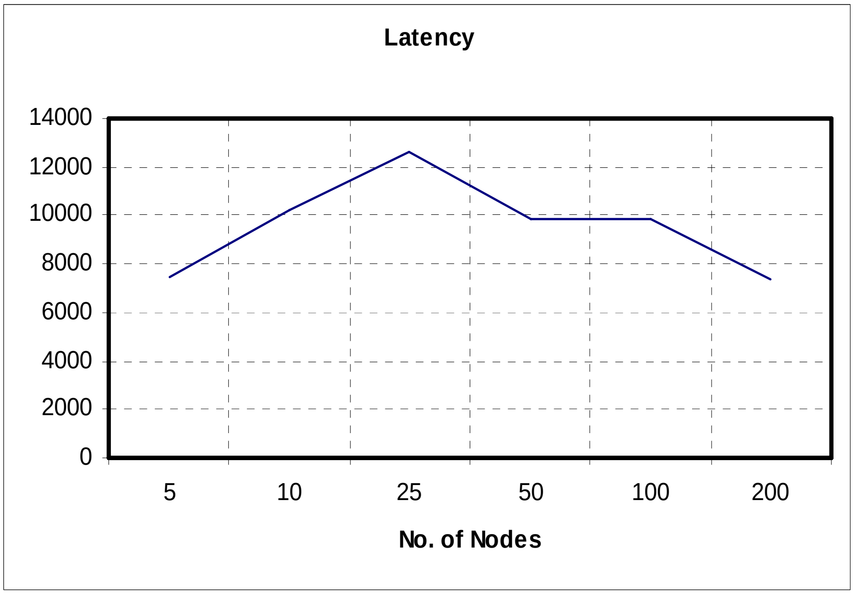


Figure 2.8.3 Latency reaches low delay when no. of nodes equals to 200.

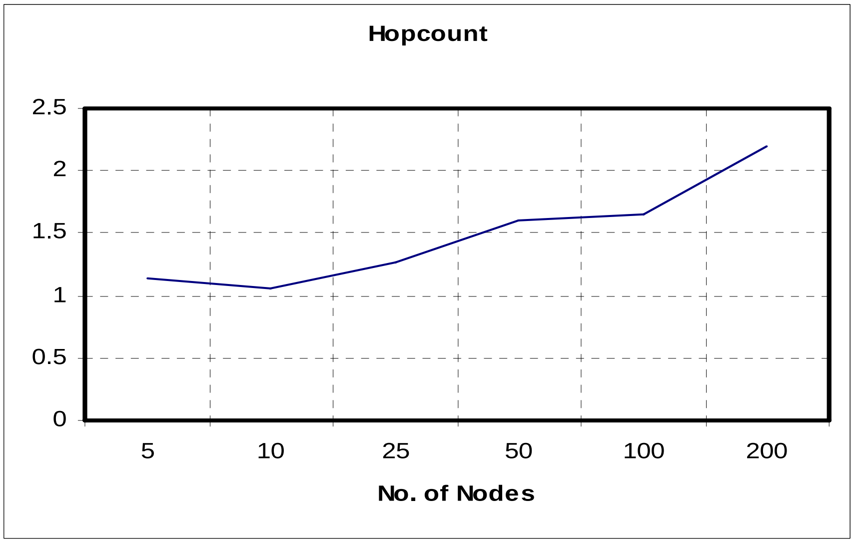


Figure 2.8.4 Hopcount increases when No. of nodes increases

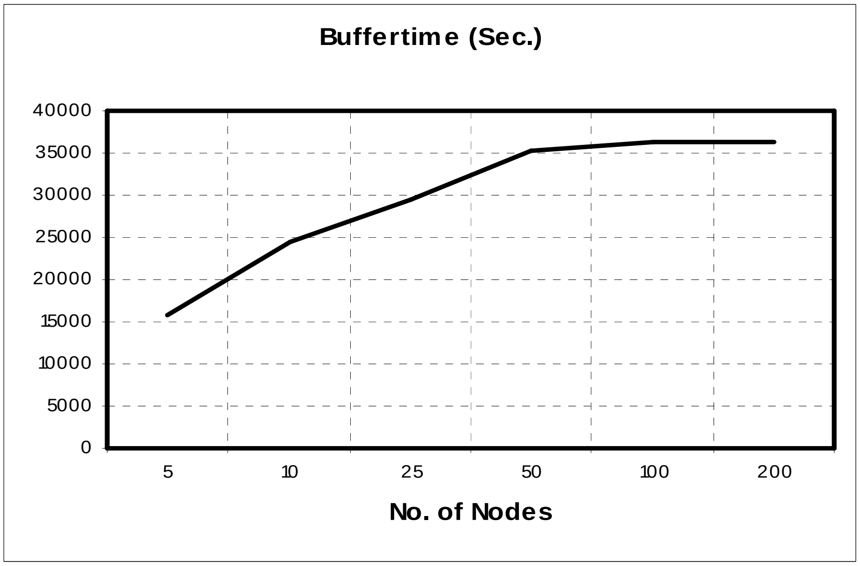


Figure 2.8.5 Buffertime increases when No. of nodes increases

2.7 TS-HEPRA Evaluation

We evaluate the performance of HEPRA by changing the mechanism of the routing and use Time-Slot technique instead of the whole time of simulation. Now, when two nodes meet they update the summary vector and then they exchange the summary vector. Each node will check the History of Encounters metric of each other. We monitor the history of encounters metric of each node in the last time-slot. The 12 hours simulation time was divided into 12 time-slots.

Results in figures 2.9.1- 2.9.5 illustrate how the Time-Slot (TS) feature works in HEPRA. We evaluate the performance in term of delivery rate, overhead, latency, hopcount, buffertime. Figure 2.9.1 illustrates that TS-HEPRA deliver more messages when TS increases since number of encountered nodes will be increases by time. Figure 2.9.2 shows that overhead (defined in figure 2.6) increases since number of relayed and delivered increase. The latency in figure 2.9.3 decrease when TS increase since that the number of encountered nodes increases. Figure 2.9.4 illustrate that hopcount reduces when TS increase since the amount of encountered nodes increase so nodes exchange more messages. In figure 2.9.5 buffertime increases because nodes buffer more messages.

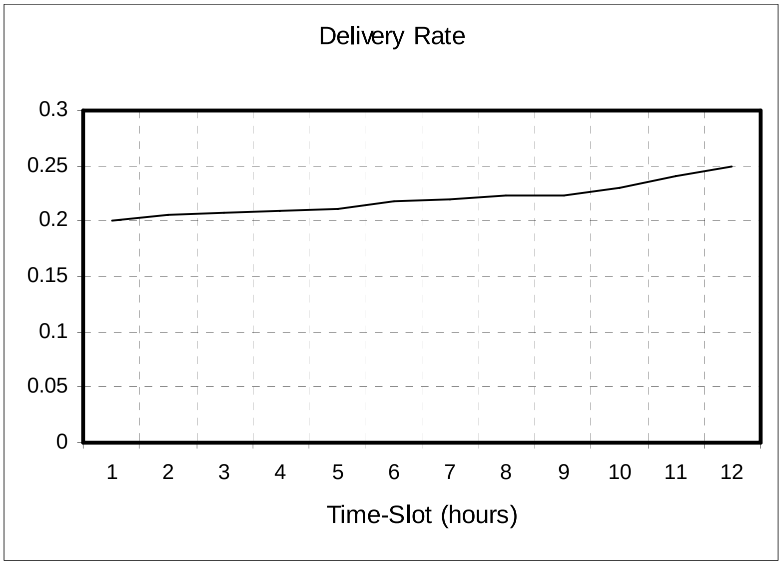


Figure 2.9.1 Delivery Rate increases when Time-Slot (TS) increases

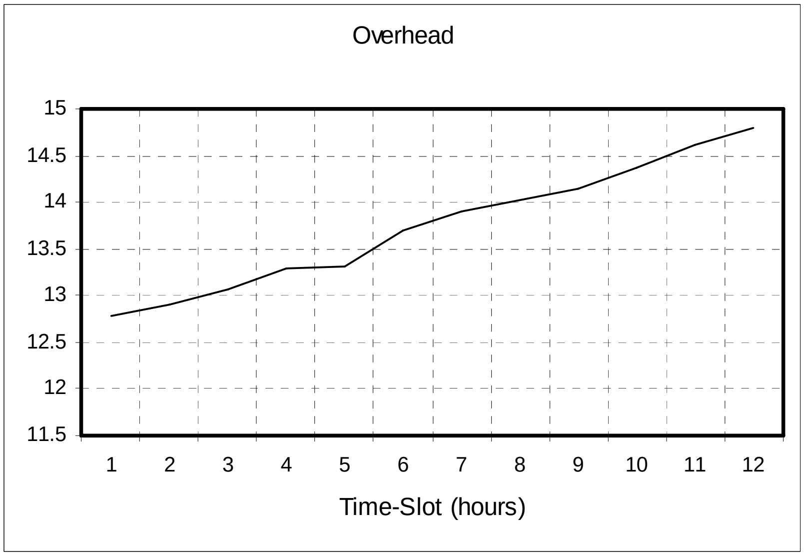


Figure 2.9.2 Overhead increase when TS increases

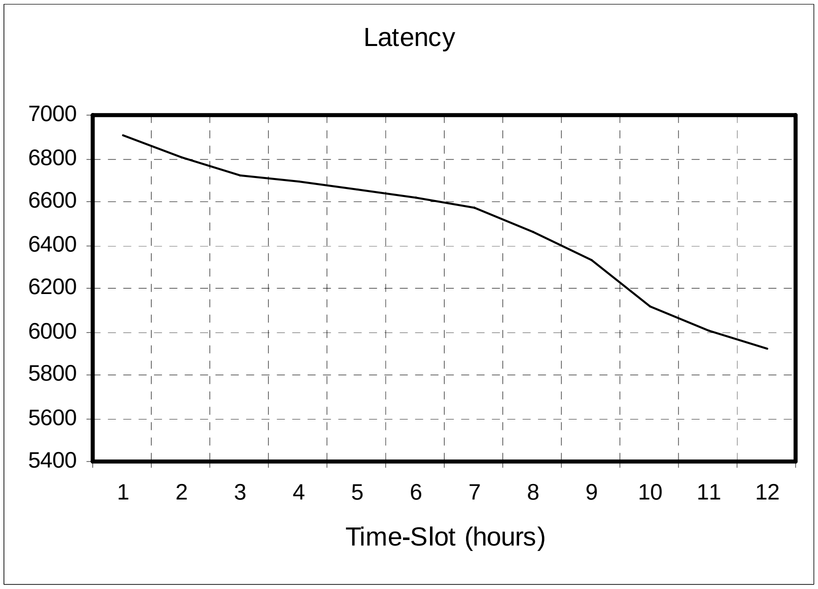


Figure 2.9.3 Latency decreases when TS increases

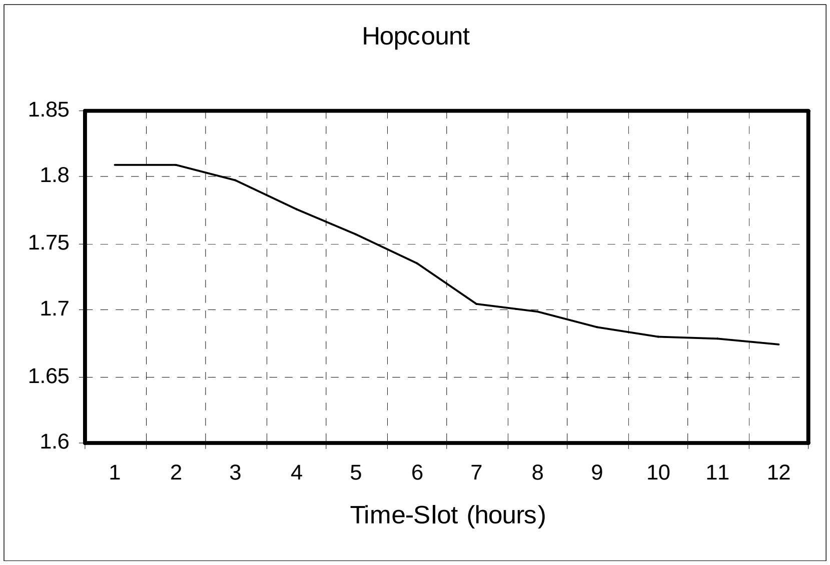


Figure 2.9.4 Hopcount decreases when TS increases

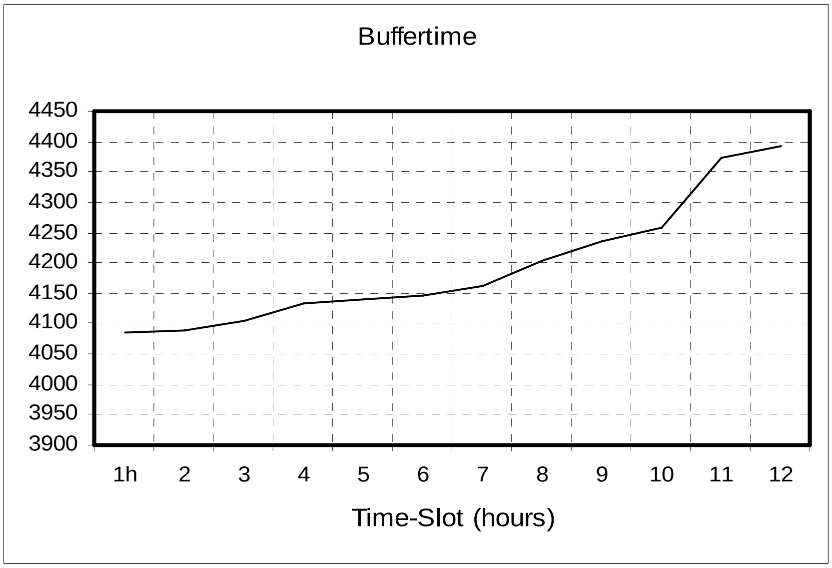


Figure 2.9.5 Buffertime increases when TS increases

2.8 Conclusion

In this chapter, we have presented our novel DTN-based probabilistic routing approach to achieve reliable communication in networks associated with intermittent connectivity. The challenge was to find a routing algorithm that can deal with dynamic environment causing networks to split and merge, considering nodes mobility. The new approach utilizes a DTN technique with the concept of the history of encounters to facilitate smooth information transfer between the heterogeneous nodes in Mobile Ad Hoc Network.

We designed our approach using the technique of History of Encounters forwarding procedure to present History of Encounters Probabilistic Routing Algorithm: HEPRA. Simulation results show that HEPRA achieved consistent performance in terms of delivery rate, overhead, latency, buffertime and average number of hopcounts over intermittent network. Furthermore through this chapter we illustrate and present Time-Slot HEPRA (TS-HEPRA) that proofs the harmony in the performance of HEPRA. We analyze the performance of TS-HEPRA in terms of behaviors like delivery rate, delay, overhead buffer size, and number of hops.

Chapter 3

Performance Analysis of HEPRA in Delay/Disruption Tolerant Mobile Ad Hoc Networks

3.1 Motivation

In this chapter we present the progress and development of the performance of the History of Encounters Probabilistic Routing Algorithm, HEPRA. We analyze the performance of HEPRA routing protocol in terms of different network environment parameters. We select well-known DTN routing protocols in our evaluation to demonstrate how those protocols act comparing to our approach. We continue developing our algorithm, HEPRA, to provide a detailed analytical as well as simulation-based study.

Using simulation we considered in our analysis various parameters such as number of nodes, buffer size, speed of nodes, transmission range, time to live (TTL) and movement models.

HEPRA presents good and consistent performance in which is good enough compared to the other protocols. In the mean time, in this chapter we provide analysis and evaluation of the other DTN routing protocols.

We analyze the performance of HEPRA and common routing protocols: Epidemic, PROPHET, Spray and Wait, MaxProp.

3.2 Routing Protocols in DTN

Delay/Disruption Tolerant Networks have been proposed to address data intermittent communication challenges in networks where an instantaneous end-to-end path between a source and destination may not exist, and the links between nodes may be opportunistic, predictably connectable, or periodically-(dis)connected [24][25].

In this section we review routing protocols in DTN and presents common DTN routing protocols.

Vahdat and Becker [17] presented a routing protocol called Epidemic. Epidemic routing is flooding-based in nature, since nodes continuously replicate and transmit messages to newly discovered nodes that do not already possess a copy of the message. It utilized the theory of epidemic algorithm to ultimately deliver messages to their destination when nodes encounter each other by doing random pair-wise information of messages between the encountered nodes. If bath to destination is not accessible, the node will buffer the messages in index called summary vector. Each node maintains a buffer consisting of messages that it has originated in addition to messages that it is buffering on behalf of other hosts. Once two nodes meet they exchange the summary vectors. If the node finds any new messages, it requests them from the encountered node. This mechanism of swapping new messages continues as long as buffer space is available, and messages will spread similar to an epidemic of some diseases inside the network whenever infected node meets susceptible node, a copy is forwarded (flooding). In order to avoid duplicate messages during the exchange process each message has a globally unique message ID. Each message contains source and destination addresses. Also, to lower the utilization of nodes resources, each message has a hop counter to determine the maximum number of hops a message can travel to.

In [18] Anders Lindgren and et al presented a Probabilistic routing algorithm called PROPHET. PROPHET stands for Probabilistic ROuting Protocol using History of Encounters and Transitivity. Authors established a probabilistic metric called delivery predictability $P_{(a,b)} \in [0,1]$ at every node a for each known destination b. The procedure of PROPHET is like the Epidemic Routing, in which, two nodes exchange summary vectors when they meet. In addition to that, in PROPHET, it contains the delivery predictability information stored at the nodes. This information is used to update the internal delivery predictability vector and then the information in the summary vector is used to decide which messages to request from the other node. The forwarding strategy depends on the delivery predictability of the encountered nodes. If node a meets node b, a carried message destined for node m will be transferred from a to b only if $P_{(b,m)} > P_{(a,m)}$. PROPHET algorithm relies on calculation of delivery predictability to forward messages to the reliable node. The probability is used to decide if one node is more reliable than the other to forward message to the destination node. It includes three parts about the probability. First is to update the probability metric whenever a node is encountered, the node that is frequently encountered having higher delivery predictability than others. Second, if a pair of nodes do not encounter each others during an interval, they are less likely to be good forwarders of messages to each other, thus the delivery predictability values must be reduced. Third, there is a transitive property in delivery predictability. Based on the observation, if node a frequently encounters node b, and node b frequently encounters node c, then node c probably is a good node to forward messages destined for node a.

Thrasyvoulos Spyropoulos and et al proposed Spray and Wait protocol. Spray and Wait has phases: 1) spray phase and 2) wait phase. When a new message is created in the network, a number M is attached to the message indicating to the maximum allowable copies of the message in the network. In the first phase, spray, the originate node of the message is responsible for spraying, one copy to M intermediate nodes. When the intermediate node receives the copy, it go into the second phase, wait, where the intermediate node buffer that particular message until the destination is encountered directly. [19].

In [20] John Burgess and et al presented a routing protocol uses flooding technique called MaxProp. In MaxProp If a new node discovered, new messages to the node will attempt to be replicated and transferred. MaxProp determines first which messages should be transmitted and or dropped. It maintains an ordered-queue based on the message’s destination, and it ordered by the estimated likelihood of the future path to that destination. Path likelihoods estimated by each node in which is maintaining a vector of size n − 1, where n is the number of nodes in the network, consisting of the likelihood the node has of encountering each of the other nodes in the network. Encountered nodes exchange their estimated node-meeting likelihood vectors when they meet. The vectors are kept updated by every node. Each node can compute a shortest path via a depth-first search where path weights indicate the probability that the link does not occur. Path weights are added to determine the total path cost, and are computed over all possible paths to the desired destinations. The cost for any destination is determined by selecting the path with the least total weight. Then, messages are ordered by destination costs, and transmitted and or dropped in that order.

Authors in [21] proposed RAPID, Resource Allocation Protocol for Intentional DTN. RAPID can optimize a specific routing metric such as worst-case delivery delay is delivered within a deadline. It translates the routing metric into per-packet utilities which determine how packets should be replicated in the system.

Each packet in the network will assign a utility function to every packet, which is based on the metric being optimized. RAPID replicates packets first that locally result in the highest increase in utility. Therefore, the protocol replicates the packet that results in the greatest decrease in delay. RAPID, like MaxProp, is flooding-based, and will therefore attempt to replicate all packets if network resources allow.

Michael Demmer and Kevin Fall presented DTLSR, Delay Tolerant Link State Routing, in which is modeled on classic link state algorithms. DTLSR works similarly as OSPF. When the network state changes, link state announcements are flooded in the network. Nodes maintain a graph representing their current view of the state of the network, and use a shortest path computation to find routes for messages. Each node in the system is assigned to an administrative area, and a link state protocol operates only within a single area. Nodes that have neighbors in other areas learn the set of endpoint identifiers reachable via the other area and announce themselves as a gateway to those endpoint identifiers. [22].

Paolo Costa and et al in [23] present SocialCast, an interest-based routing protocol to support delay tolerant communication in human networks. Authors assumed that socially bound hosts are likely to be co-located regularly: The collocation patterns are used to efficiently route the messages from publishers to interested subscribers. The social ties selection is made by taking into account predictions about contextual parameters such as mobility patterns based on previous observations.

3.3 Simulation parameters

In this section we describe the simulation setup used to evaluate the performance of HEPRA and common DTN Routing Protocols. We select Epidemic, PROPHET, Spray and Wait (SnW), MaxProp and HEPRA since the first four protocols are included in the ONE simulator.[16].

Simulation settings and Parameters are demonstrated table 3.

Table 3. Simulation setting used in the evaluation

PARAMETERS	VALUE
Simulation Area (W x H) meter	4500 x 3400
Simulation duration (hr)	12
Number of nodes	50
Movement Model	Shortest Path Map Based Movement Random Waypoint Map Based Movement
Message TTL (minutes)	60-600
Host speed (m/s)	0.1 -50
Buffer size (Mbyte)	5-500
Transmission Range (meter)	1-50

3.4 Evaluation of DTN routing protocols

Simulation results are organized in table 4. The table illustrates the good and weak performances in terms of different network behaviors such as buffer size, speed of nodes, number of nodes, transmission range, Movement models, and packet time to live. In general, MaxProp and Spray and Wait outperform other protocols in terms of the pervious behavior whereas HEPRA’ performance is acceptable and outperform other protocol in overhead and latency.

Table 4. Simulation results of evaluation

Behavior	***Good performance***	***Weak performance***
Buffer size		
Delivery Rate	SnW & MaxProp	HEPRA
Overhead	SnW	Epidemic
Latency	SnW	PROPHET
Speed		
Delivery Rate	MaxProp	PROPHET & Epidemic
Overhead	HEPRA	Epidemic & MaxProp
Latency	SnW	MaxProp
Number of nodes		
Delivery Rate	MaxProp	Epidemic
Overhead	SnW	Epidemic
Latency	HEPRA	MaxProp & PROPHET
Transmission range		
Delivery Rate	MaxProp & SnW	Epidemic
Overhead	HEPRA	Epidemic & MaxProp
Latency	SnW	MaxProp
Shortest Path Movement		
Delivery Rate	MaxProp	Epidemic
Overhead	HEPRA	Epidemic
Latency	SnW	MaxProp

Behavior	***Good performance***	***Weak performance***
Random Way Movement		
Delivery Rate	SnW	Epidemic
Overhead	HEPRA	Epidemic
Latency	HEPRA & Epidemic	MaxProp
Map Based Movement		
Delivery Rate	PROPHET	Epidemic
Overhead	HEPRA	MaxProp & Epidemic
Latency	SnW	MaxProp
Time To Live (TTL)		
Delivery Rate	MaxProp	Epidemic
Overhead	SnW	Epidemic
Latency	SnW	MaxProp

In the above, table 4 reflects results obtained in figures 3.1 through 3.24 below.

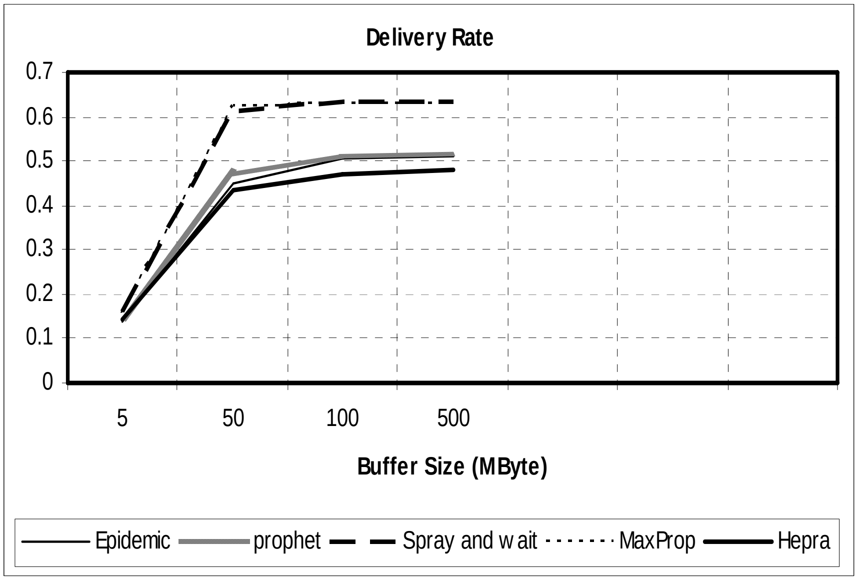


Figure 3.1 SnW and MaxProp delivers more messages when buffersize increases

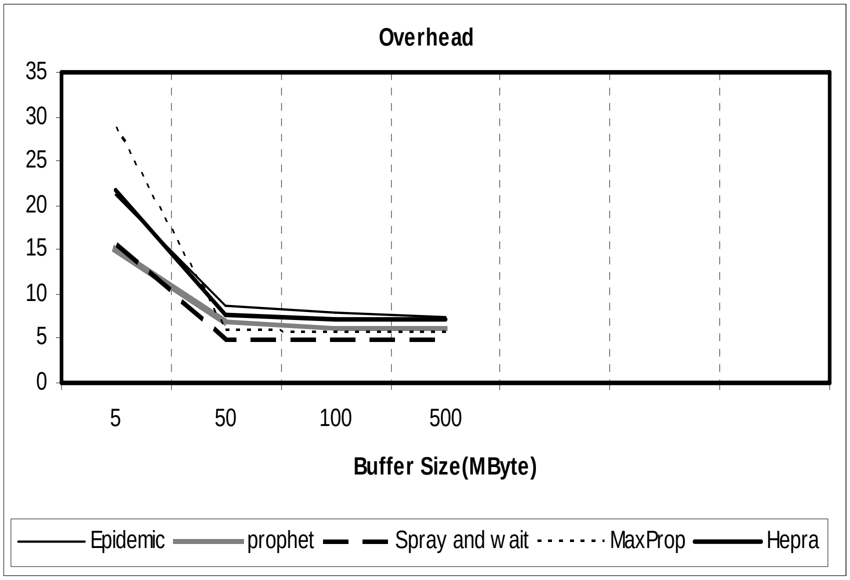


Figure 3.2 Overhead of Epidemic is higher than others

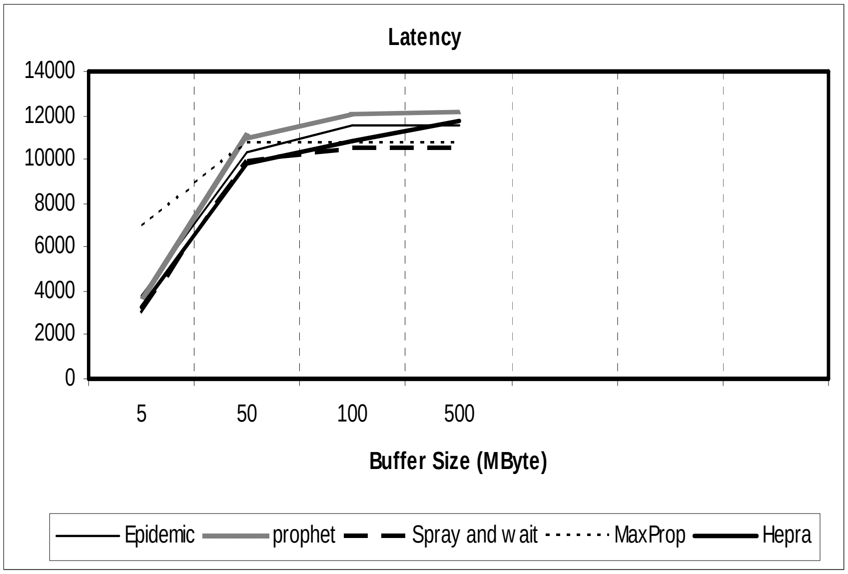


Figure 3.3. Latency of PROPHET has more delay

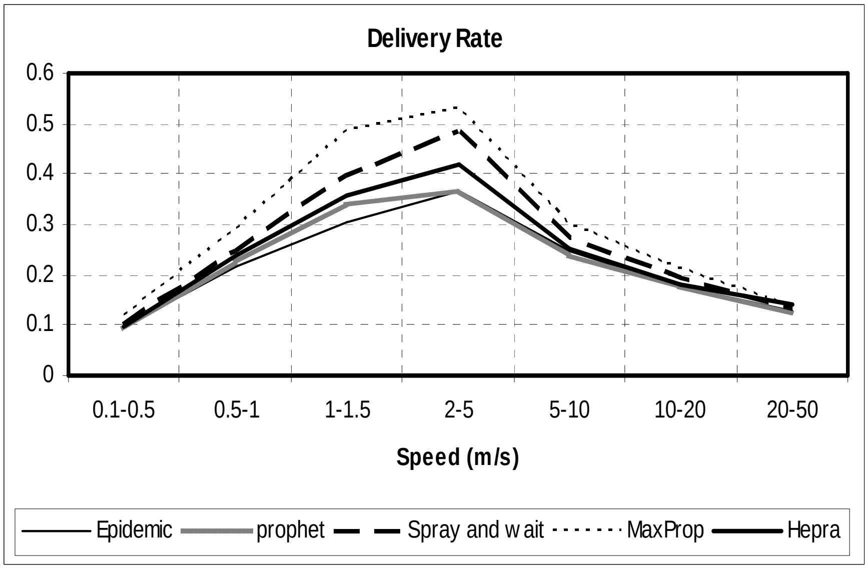


Figure 3.4. MaxProp deliver messages

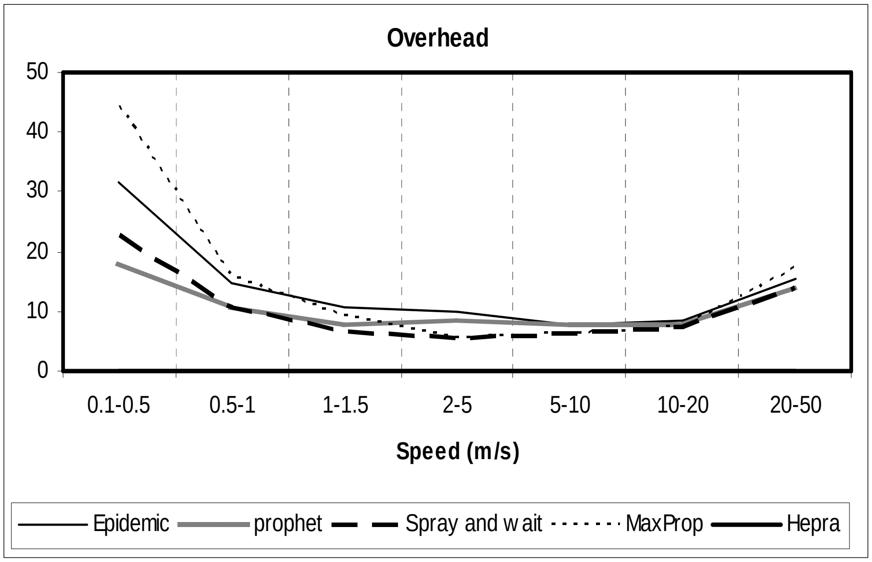


Figure 3.5 Overhead of Epidemic and MaxProp is higher than others

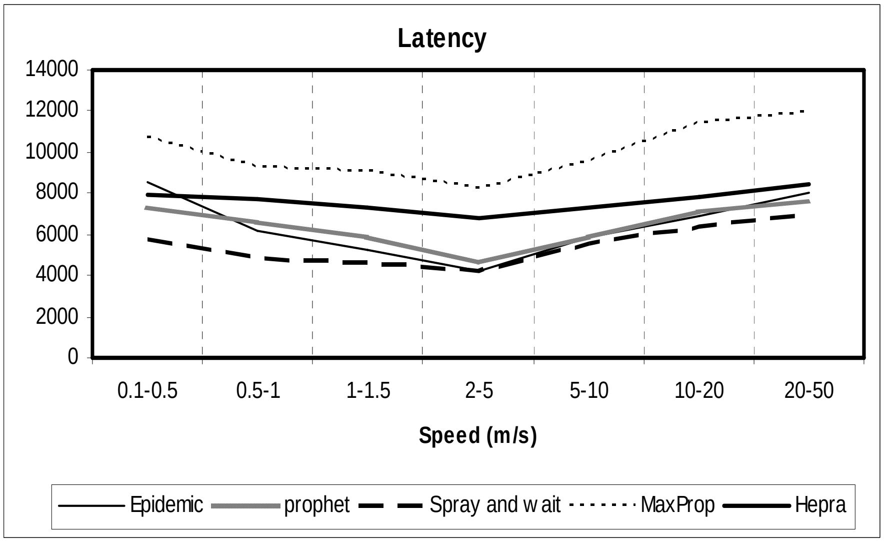


Figure 3.6 MaxProp has the highest average Latency when speed increases

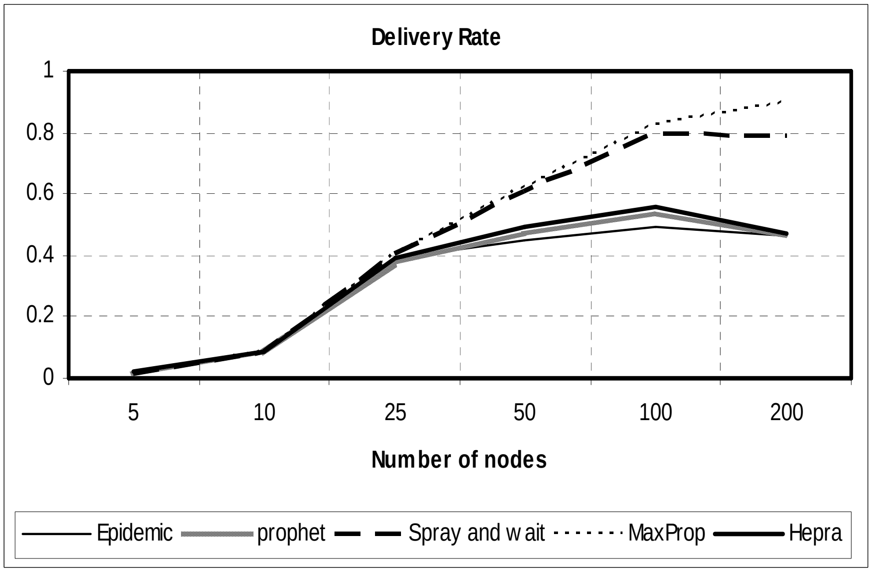


Figure 3.7 MaxProp delivers more messages when nodes' number increases

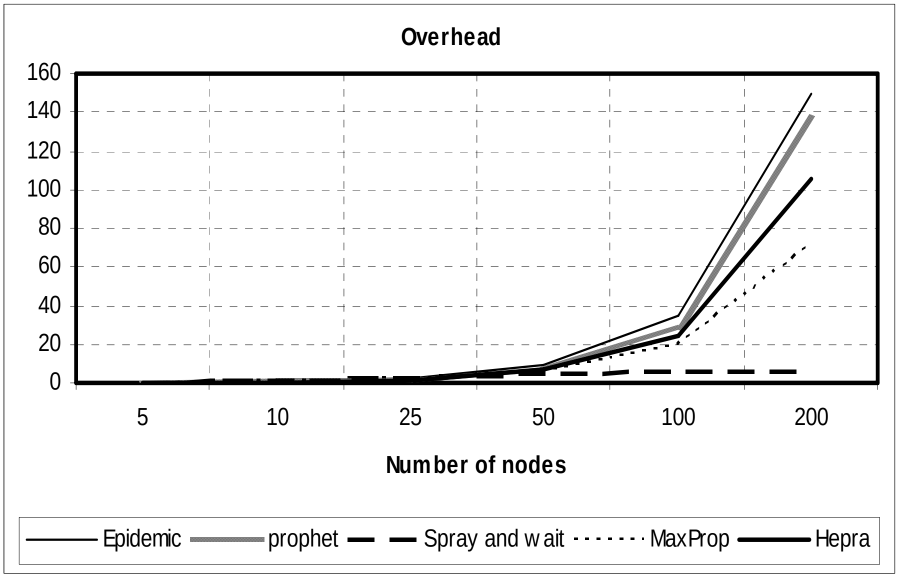


Figure 3.8 SnW has a low overhead

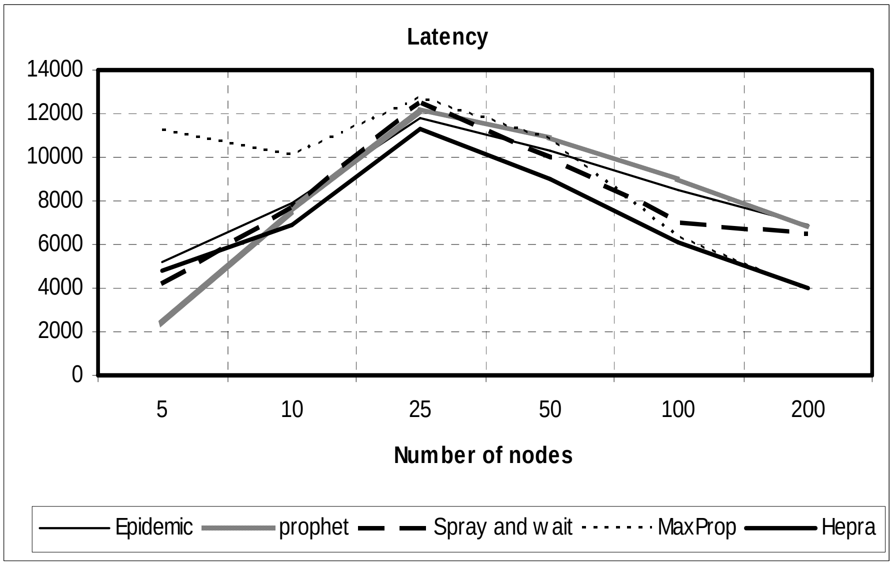


Figure 3.9 HEPRA outperform other in terms of latency number of nodes increases

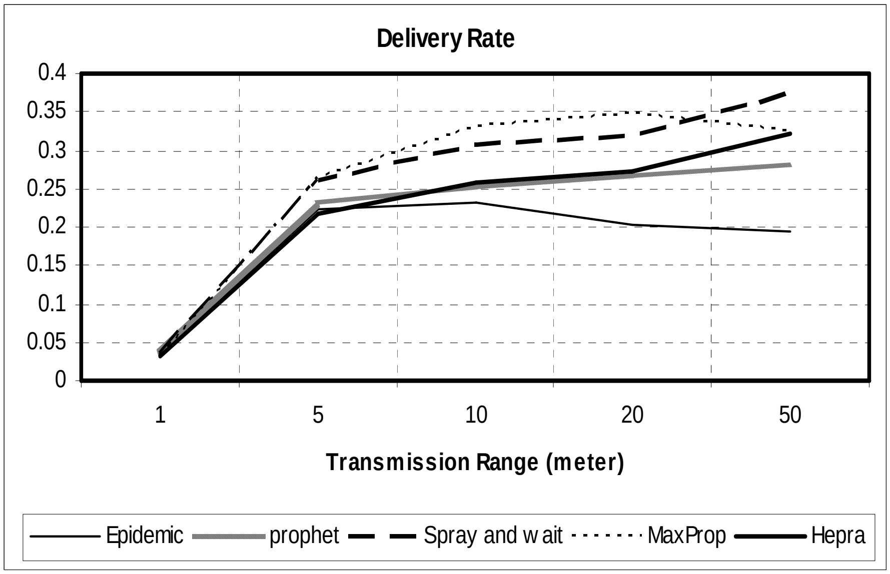


Figure 3.10 SnW and MaxProp delivers more messages when range increases

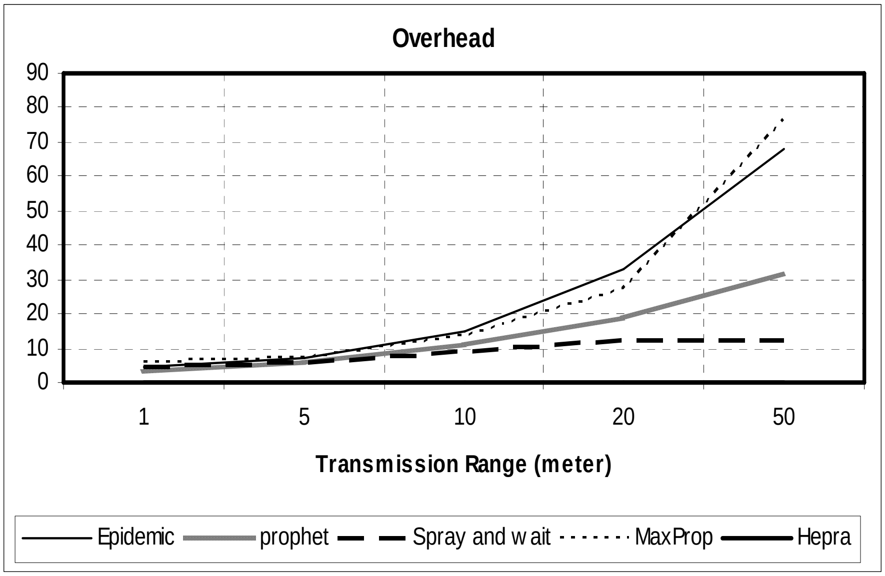


Figure 3.11 HEPRA’ overhead is perfect when range varies.

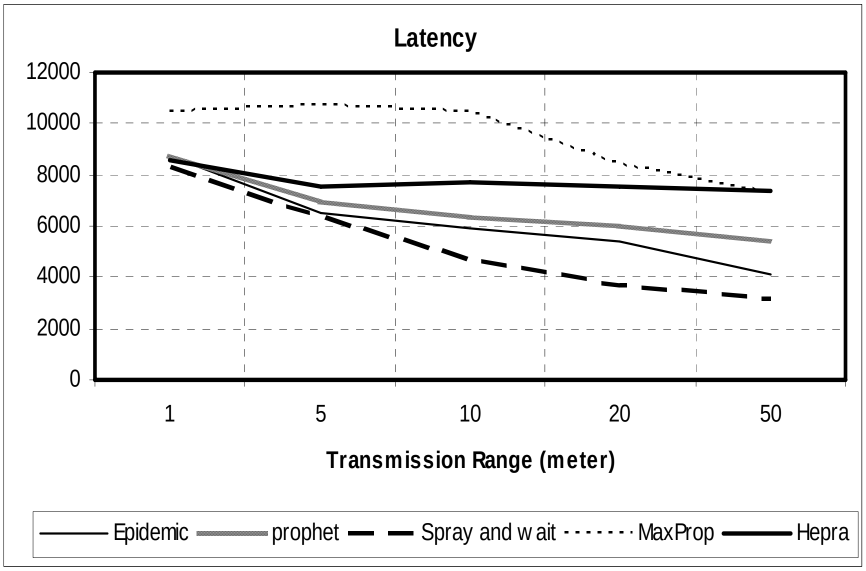


Figure 3.12 SnW has low delay and MaxProp has high delay.

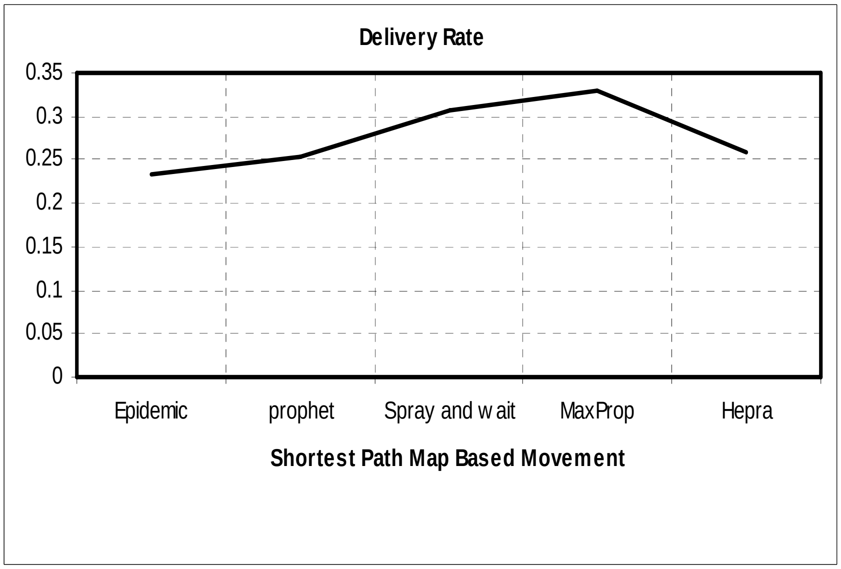


Figure 3.13 SnW has low delay.

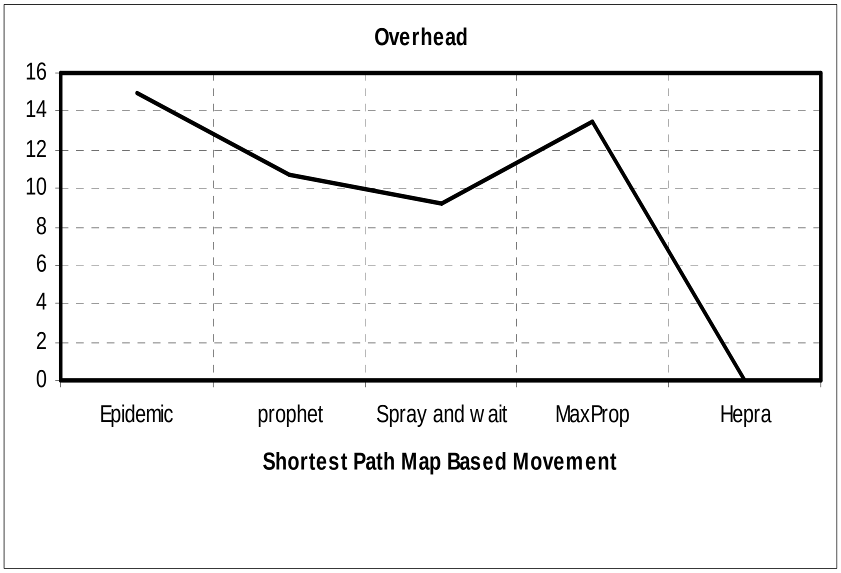


Figure 3.14 HEPRA has the lowest overhead in the shortest path movement.

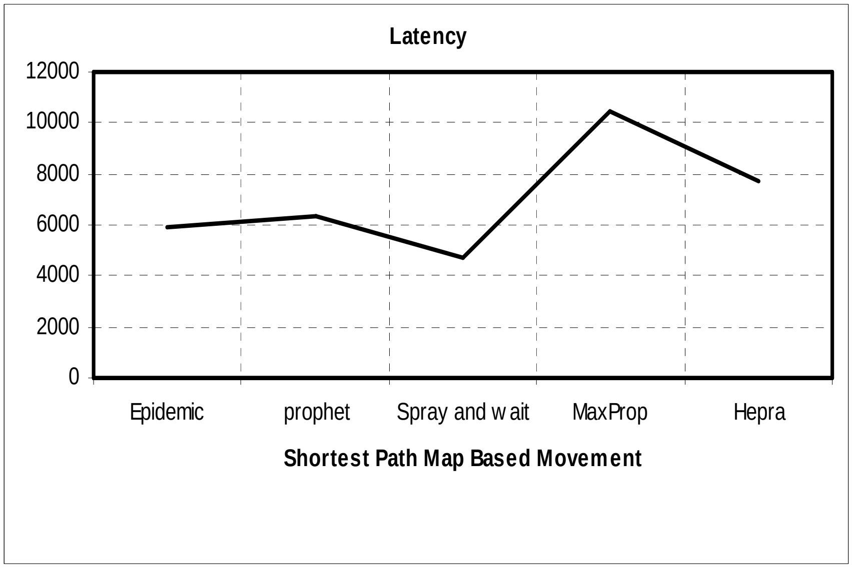


Figure 3.15 SnW's delay is the lowest in the shortest path movement.

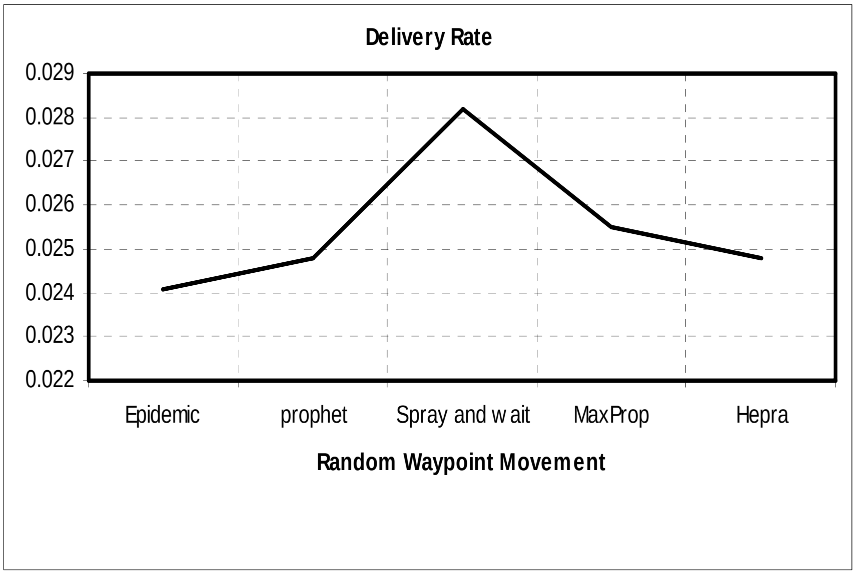


Figure 3.16 SnW delivers more messages than others in random waypoint movement

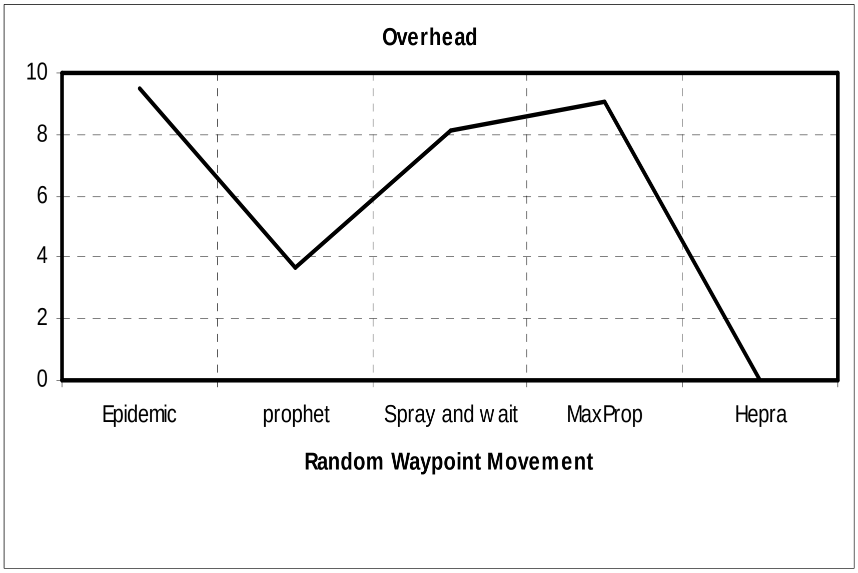


Figure 3.17 HEPRA has the lowest overhead in random waypoint movement

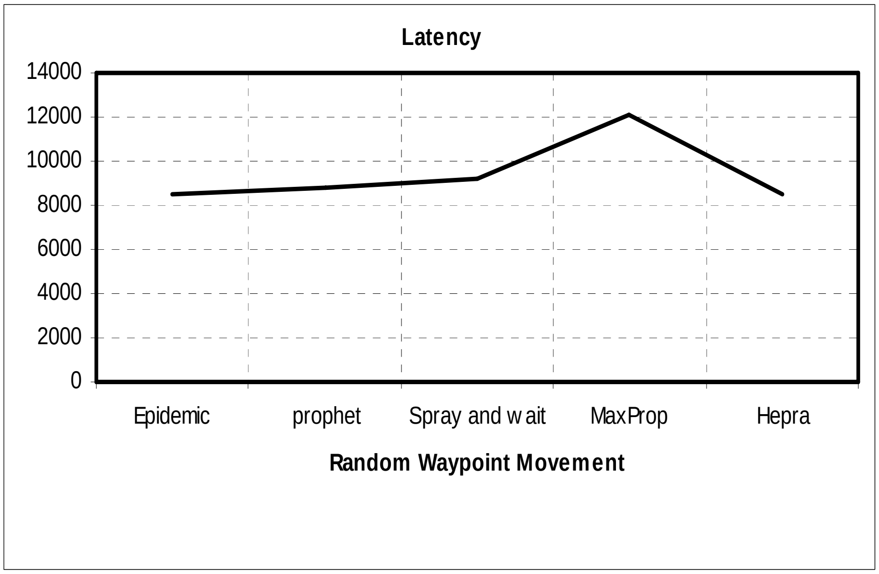


Figure 3.18 Delay of HEPRA and Epidemic is low in random waypoint movement

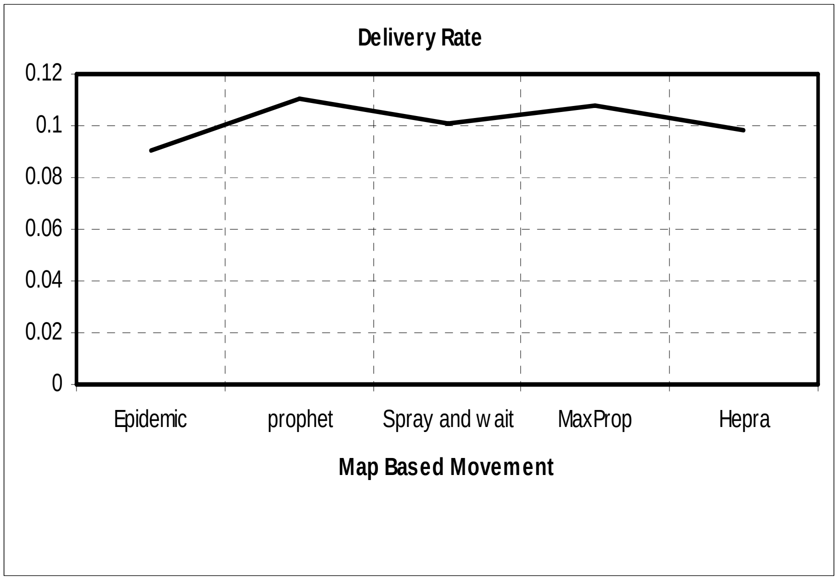


Figure 3.19 PROPHET delivers messages than others in map based movement

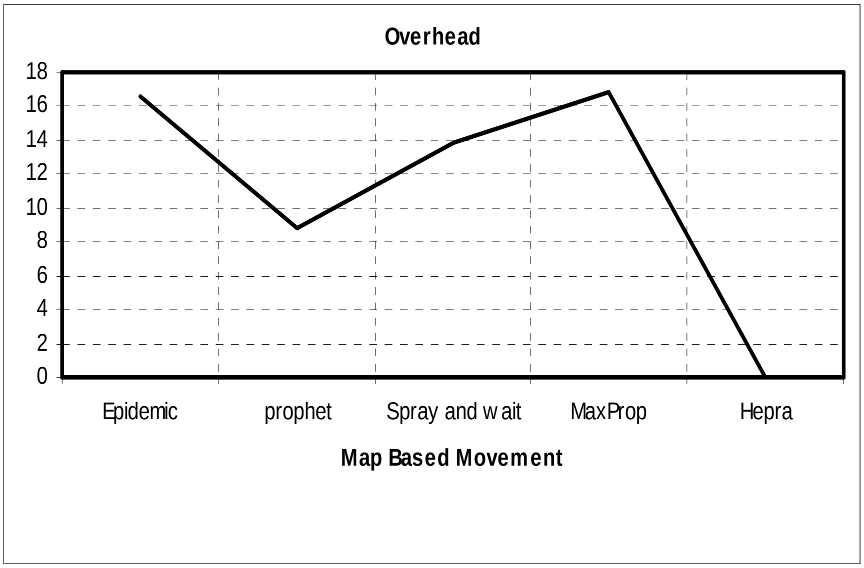


Figure 3.20 HEPRA has the lowest overhead in map based movement

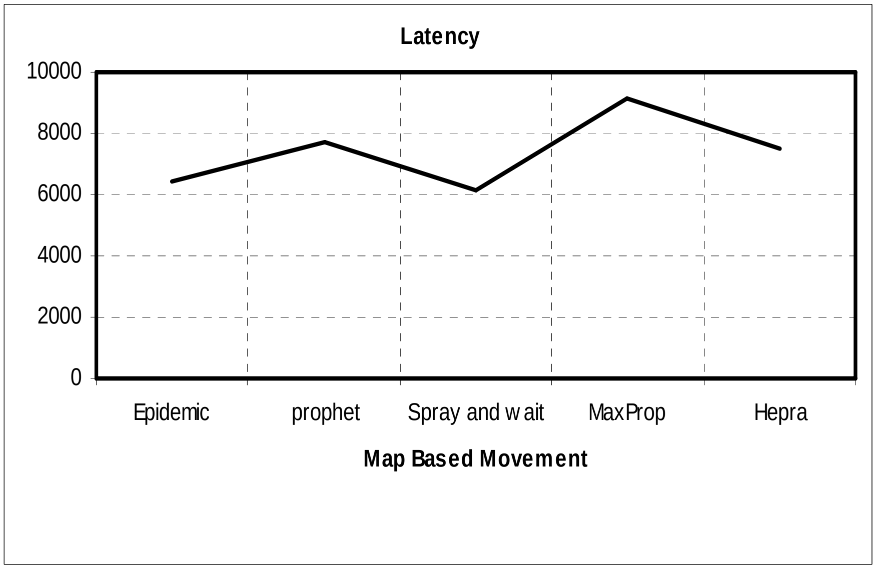


Figure 3.21 Delay of SnW is lower than others in map based movement

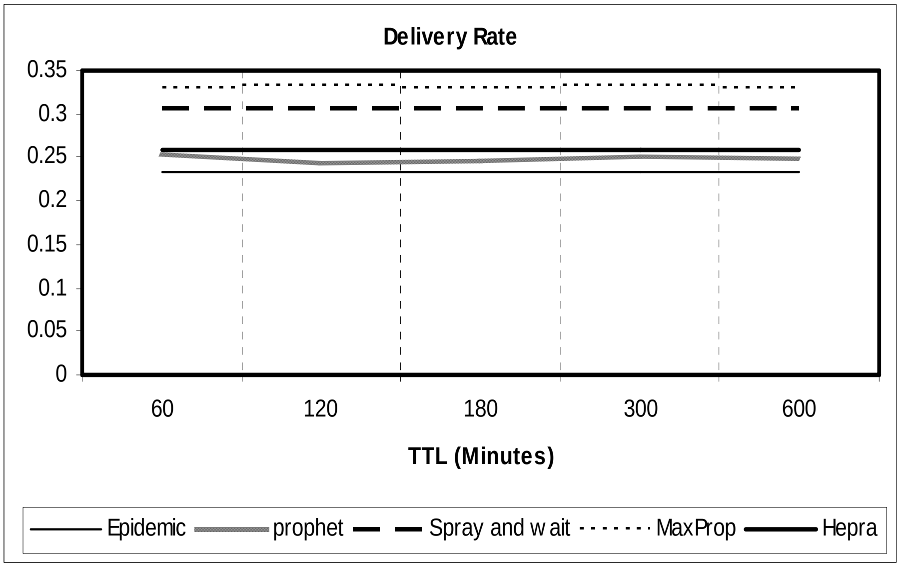


Figure 3.22 MaxProp delivers more messages but fixed when TTL increases

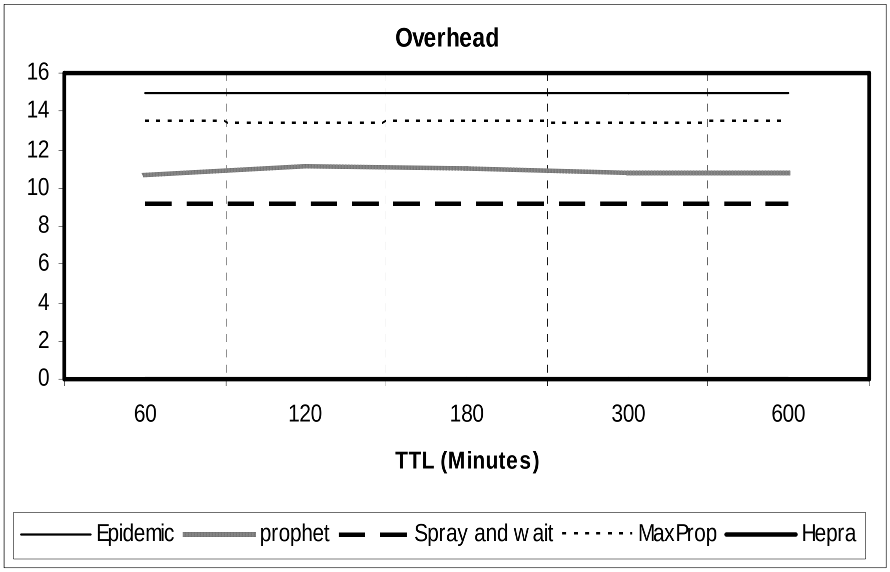


Figure 3.23 HEPRA’s overhead is perfect and fixed when TTL increases

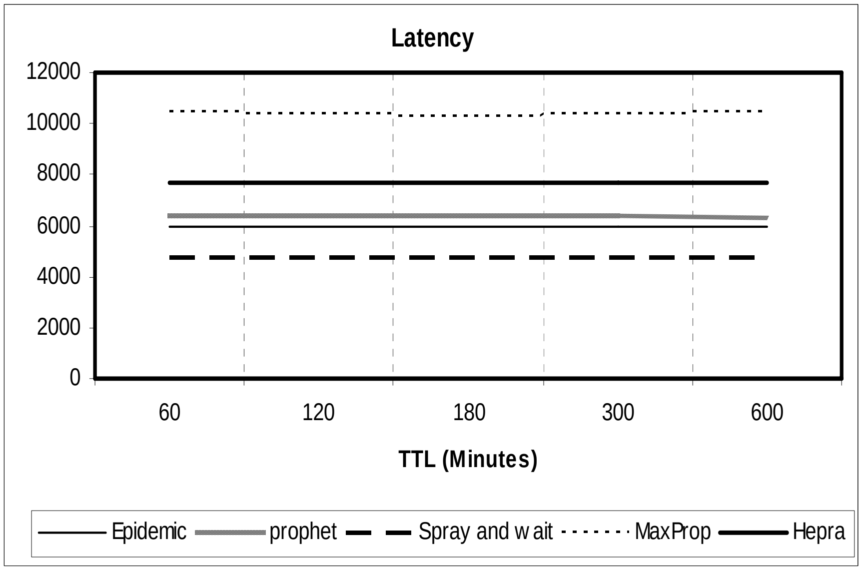


Figure 3.24 MaxProp's delay is lower than others when TTL increases

3.5 Discussion and Conclusion

We provide in this chapter an evaluation of the performance History of Encounters Probabilistic Routing Algorithm, HEPRA, and compare it to other common routing protocols in DTN. We illustrate the behaviors of the DTN routing protocols in terms of various parameters and variables. Each routing protocol has its own advantages and disadvantages in terms of parameters. HEPRA presents an acceptable performance in our environment model.

The main contributions of this chapter are as followings:

- Evaluation of performance of HEPRA and how HEPRA works with various network parameters.
- Analysis of performance of common DTN routing protocols including HEPRA in terms of different parameters in the MANET environment. The chapter will aid researchers who are new to the field to have a better overall understanding of the performance of those selected routing protocols.

The challenge was to find a routing algorithm that can deal with dynamic environment causing networks to split and merge, considering nodes mobility, transmission range, buffer size, movement models, and packet TTL.

We encourage researchers in the DTN research group to continue developing their routing protocols to achieve high quality performance.

Chapter 4

Study of the Impact of Link Availability on the Performance of DTN Routing Protocols

4.1 Motivation

Routing in Delay/Disruption Tolerant Networks (DTN) acquires the attention and interest of researchers as being the most adequate solution for the problem of intermittently connection in Mobile Ad hoc Networks (MANET).

Available simulation tools in DTN focus on evaluating performance of protocols in terms of network and application layers parameters. Unfortunately, implementation of physical layer parameters such as noise, fading, interference, link availability is not incorporated in those simulators.

Our aim in this chapter is to study the impact of link availability as a parameter of the physical layer environment on the performance of DTN routing protocols. We demonstrate through the simulation how those protocols act against changes in network environment.

4.2 Introduction

In MANET, the entire network is mobile where nodes move freely and arrange themselves randomly. Nodes may not be able to communicate directly and have to rely on each other in order to deliver messages. The contacts between nodes in the network do not occur very frequently. As a result, the network graph is rarely, if ever, connected and message delivery must be delay-tolerant. Those types of networks are refereed to multi-hop or store-forward networks. The topology in MANET is changing rapidly because of weather, terrain, highly variable delay links, error rate links, and jamming. Traditional MANET routing protocols requires that the network graph is fully connected and fail to route messages if there is not a complete route from source to destination at the time of sending. For this reason traditional ad hoc routing protocols cannot be used in environments with intermittent connectivity.

DTN is an end-to-end network architecture designed to provide communication in and/or through network environment characterized with intermittent connectivity, large and/or variable delays, and high bit error rates. DTN is a message-based store, carry and forward overlay network architecture where architecture is designed to provide communication in intermittently connected networks (ICN) by moving messages towards destination via store-carry-and-forward networking model that supports multi-routing algorithms to acquire best path towards destination.

Routing in DTN is active area of research and numerous routing protocols are proposed. The challenge is to create a technique that can present good delivery performance and low end-to-end delay in an intermittent network graph and opportunistic or scheduled intermittent links where nodes may move freely.

Researcher in DTN routing field focus on evaluating their design in terms of network layer parameter or application layer parameters whereas physical layer parameters has not yet implemented. Simulation tools in DTN field do not yet have implementation of parameters such as signal to noise ratio (SNR), bit error rate (BER), interference, fading and Doppler Effect. OPNET simulator has not implement DTN in its modules.[27]. Opportunistic Network Environment simulator (ONE-V1.4) does not have implementation of the physical layer parameters so there are no values for SNR or BER.

So if two nodes are within the radio range, they can communicate with the configured speed without any errors. [16]

In this chapter we evaluate the performance of some of well known DTN routing protocols with respect to link availability. The analysis considers the impact of link availability on the performance of those algorithms in terms of delivery rate, delay, overhead and buffer size.

4.3 MANET Environment Graph

MANET is made up of multiple nodes connected to each other by wireless links. Links are influenced by the node's resources such as:

- Available energy : supply, transmitter power and
- Behavioral properties: reliability, and
- Link properties: line-of-sight interference, length-of-link and signal loss, interference, link availability and noise.

Since new and old links can be connected or disconnected at any time, a network must be able to cope with this dynamic topology in timely, efficient, reliable, robust and scalable way. The network must allow any two nodes to communicate, often via other nodes that relay the information. A “path” is a series of links that connects two nodes. Overwhelmingly there are multiple paths between any two nodes. Nodes are often limited by transmission range and available energy resources. According to the inverse square law, it is more energy efficient to relay information across a network via multiple nodes. [26].

The topology in MANET environment is dynamic multi-hop graph G = (N, L), where N is a number of mobile nodes and L is a set of edges which represent wireless links. A link (i, j) Є L exists if and only if the distance between two mobile nodes is less than or equal to a transmission range r. In figure 4.1 the distance between nodes A and B is less than the transmission range so they are in contact whereas C and D are not.

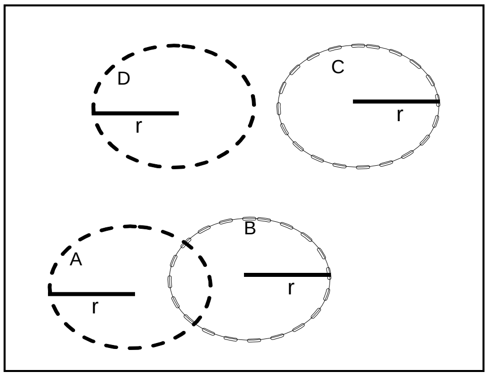


Figure 4.1 Nodes A & B in contact

The radio transmission range r depends on wireless channel characteristics including transmission power. Accordingly, the neighborhood of a node x is defined by the set of nodes that are inside a circle (assume that nodes are moving in a two-dimensional plane) with center at x and radius r, and it is denoted by:

$$N_r(x) = N_x = \{n_j \mid d(x, n_j) \leq r, x \neq n_f, \forall j \in N, j \leq |N|\}$$

, where *x* is an arbitrary node in graph *G* and d is a distance function.

A path (route) from node i to node j, denoted by Rij is a sequence of nodes Rij = $(i,n_1, n_2,\ldots,n_k, j)$ where (i,n_1), (n_k, j) and (n_y, n_{y+1}) for $1 \leq y \leq k-1$ are links.

A simple path from i to j is a sequence of nodes with no node being repeated more than once. Due to the mobility of the nodes, the set of paths (links) between any pair of nodes and distances is changing over time. New links can be established and existing links can vanish. [28], [29].

4.4 Impact of link availability

In MANET, node mobility may cause frequent network topology changes that makes link capacity continually varies because of the impacts from physical layer parameters such as transmission power, receiver sensitivity, noise, fading and interference. Additionally, wireless mobile networks have a high error rate, power restrictions and bandwidth limitations. [30].

Interference among wireless links significantly impacts the performance of multi-hop wireless networks. The need for routing protocols to take link interference into account has been highlighted in [31][32]. Information about link interference is also needed for optimal channel assignment. [33].

Two main forms of interference are adjacent channel interference and co-channel interference. In the adjacent channel interference case, signals in nearby frequencies have components outside their allocated ranges, and these components may interfere with on-going transmission in adjacent frequencies. It can be avoided by using guard bands between the allocated frequency ranges. Co-channel interference (narrow-band interference) is due to other nearby systems using the same transmission frequency. There are another type of interference called inter-symbol where distortion in the received signal is caused by the temporal spreading and the consequent overlapping of individual pulses in the signal. [34].

Traffic on a wireless link interferes with neighboring links, significantly reducing the performance of MANET. Providing bandwidth-guaranteed service in MANET requires consideration of the underlying interference model. [35].

In MANET environment nodes are mobile and links are created and broken as nodes move in and out of range of one another. During the life of the network, links are formed and paths are built over these links. The stability of the links is of essential when constructing a path.

Nodes may send to the known neighbors for the duration of this time, and assuming no interference (collisions), the packets should be properly received.

Link stability refers to the ability of a link to survive for certain duration. The higher the link stability, the longer the link duration. The stability of a link depends on how long two nodes, which form that link, remain as a neighbor. Two nodes are neighbors when they remain within each other's communication range, or the signal strength is above certain thresholds.[36].

4.5 Simulation Model

In DTN research field, simulation tool like ONE simulator [16] does not have implementation of those network environment parameters. ONE ignores the parameters of the physical and MAC layers. So if two nodes are within the radio transmission range, they can communicate with the configured speed without any errors and the link consider stable. In realty this is not accurate since interference affects the stability and availability of the links.

In our model, we used ONE simulator and since ONE does not support physical layer we employed the definition of co-channel interference. We create new nodes called interference nodes (IN) and consider the interference between neighboring links, or between multiple hops. Interference nodes have same characteristics of other nodes and share same network setting. If node a meets one of those interference nodes and be in their transmission range, node a can not communicate with any encountered node inside IN’ transmission range. Figure 4.2 illustrates our scenario: node A is an interference node

(IN) with blue-color transmission range. Node A meets node B (it means distance between them less than or equal to the transmission range) and in the same time C meets A and D.

C can not communicate with D since A interference with C. Node C will continue moving. The only case that any node forward messages if it is not situated in the transmission rage of IN. Figure 4.3 defines the necessary variables and contains the pseudo-code of our model.

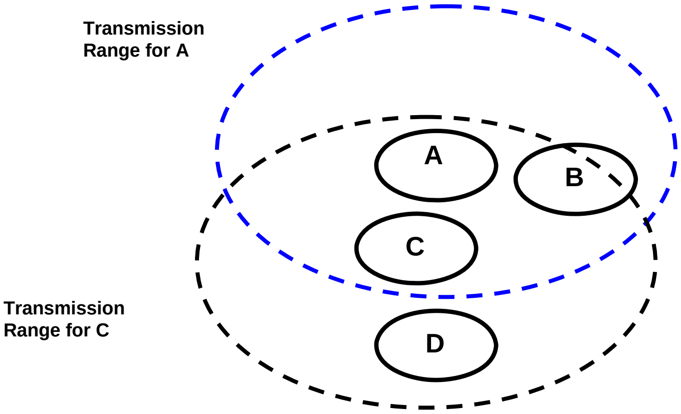


Figure 4.2. Interference node A affects the communication link between C and D.

```
Variables
--------
A-Interference Node
B,C,D-Regular Nodes
I-Interference node group
anotherInterface-interface of the node on the other side of connection.

Functions
---------
getHost()- gets the host on the other side of the interface.
getInterface()-gets the name assigned to that particular node.
getGroupId()- gets the group Id of the node.
isWithInRange(Interface X)- finds whether the Interface 'X' is with in transmission
                            range of this particular node.

Procedure
---------
Every node checks whether it is in the range of interference node before
  establising connection with another node.

  Node C (current node) before establishing connection with any node (Eg: D)

  C.createconnection(another Interface 'D')
   {
    C.iswithinrange('I'.gethost().getInterface())
    Note: All the interfaces of each interference node has to checked.
   }

If C is with in range of Interference node, connection is not established and
hence no message is transferred.
```

Figure 4.3 Pseudo-code used in our model

We assigned number of interference nodes in the network and study the impact of the link availability on the performance of routing protocols. In our study we analyze performance of DTN routing protocols that are implemented in ONE simulator. The study illustrates the impact of link availability in terms of deliver rate, overhead, delay and buffertime.

Table 5 shows the simulation setup used in our model. It describes the simulation setup used to evaluate the performance of selected DTN routing protocols. We select Epidemic, PROPHET, Spray and Wait (SnW), MaxProp and HEPRA.

Table 5. Simulation setting used in the study

PARAMETERS	VALUE
Simulation Area (W x H) meter	4500 x 3400
Simulation duration (hr)	12
Number of nodes	50
Movement Model	Shortest Path Map Based Movement
Message TTL (minutes)	60
Host speed (m/s)	0.5 -5
Buffer size (Mbyte)	5
Transmission Range (meter)	20

4.6 Simulation Results

In this study we analyze the impact of link availability on the performance of the DTN routing protocols, Epidemic, PROPHET, Spray and Wait (SnW), MaxProp, and HEPRA. Figures 4.4 - 4.7 show the performance of the routing protocols in terms of delivery rate, overhead, latency and buffertime with respect to increasing number of interference nodes (IN) in the networks.

Figure 4.4 shows the delivery rate and buffertime decrease when number of IN increase. Figure 4.5 depicts that the overhead increases when number of IN increases. It is clear from figure 4.6 that increasing number of IN does not effect latency. In figure 4.7, buffertime increases because nodes stores and carries messages for longer time to overcome the link availability problem.

Figures 4.8 – 4.11 illustrate the behaviors of the protocols with respect to increasing the buffer size. In those figures we increase the buffer size of nodes and make number of IN equals to fixed number. The performance of protocols enhances while buffer size increases since increasing the buffer size helps nodes to store more messages and reduces the impact of IN.

In figure 4.8 increasing buffersize reduce the impact of IN and delivery rate increases until it reach a certain point where it becomes fixed number. Figure 4.9 illustrates that overhead is decrease when buffersize increase to reach stable point. In figures 4.10 and 4.11 respectively, increasing buffersize does not enhance latency and buffertime since storing more messages in the buffer impact buffertime and increase the latency. Latency reaches stable case when the buffer size increases.

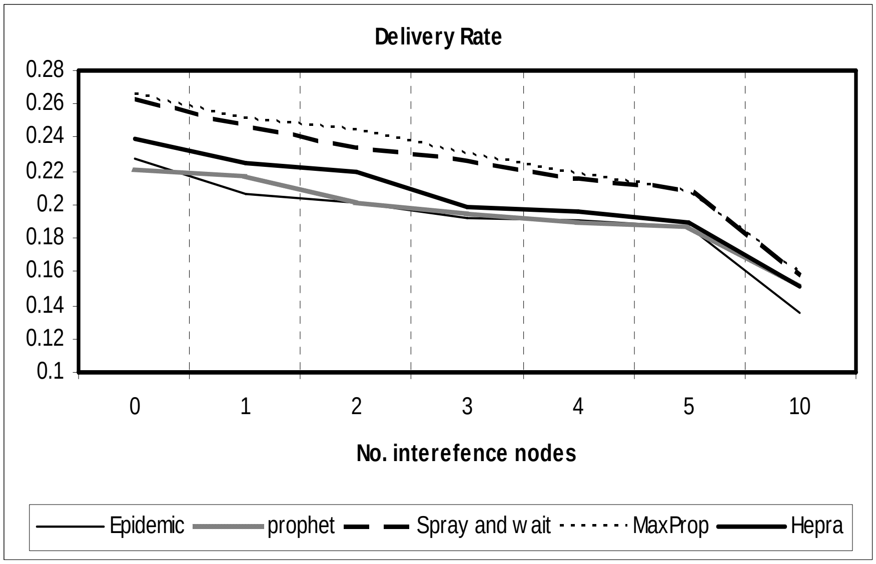


Figure 4.4 Delivery Rate decreases when No. IN increases

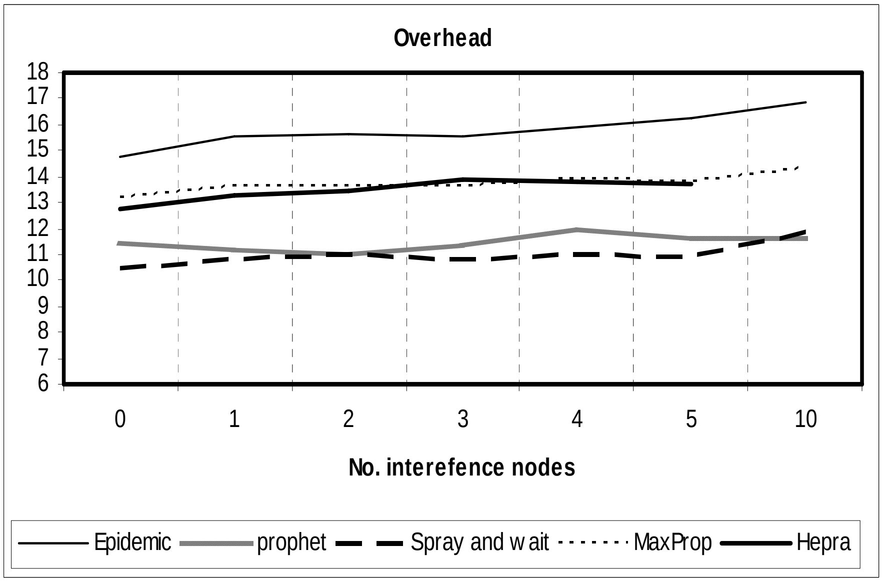


Figure 4.5 Overhead increases when No. IN increases

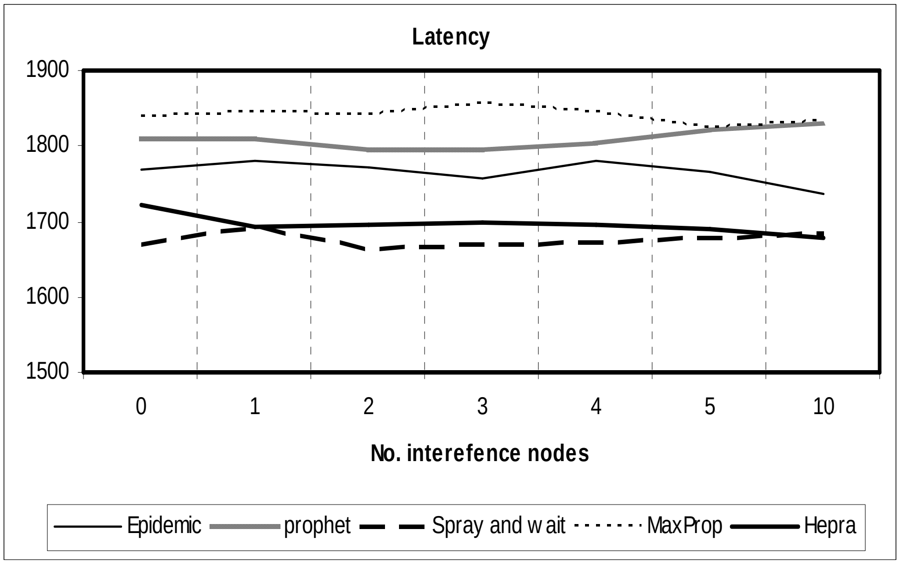


Figure 4.6 No impact on latency

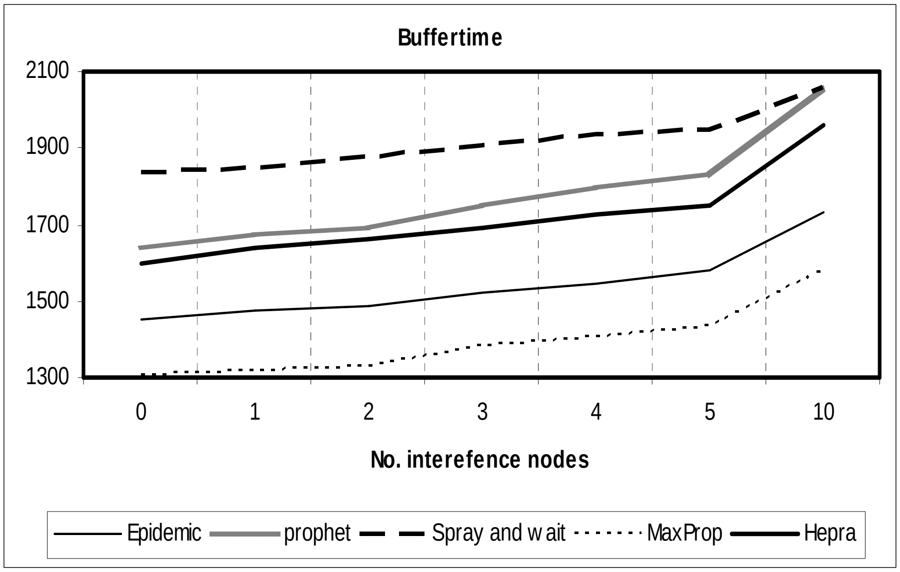


Figure 4.7 Buffertime increases when No. IN increases

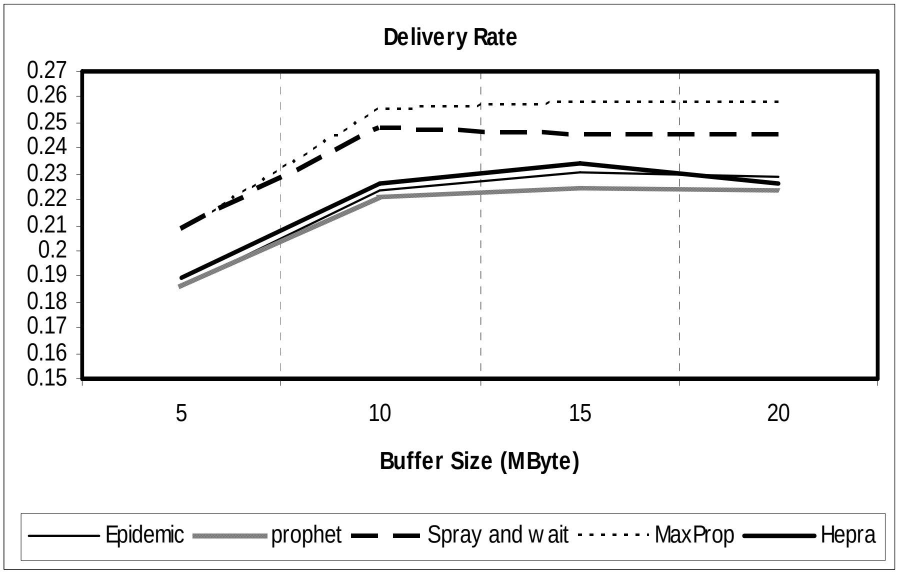


Figure 4.8 Increasing buffersize reduces the impact of IN on delivery rate

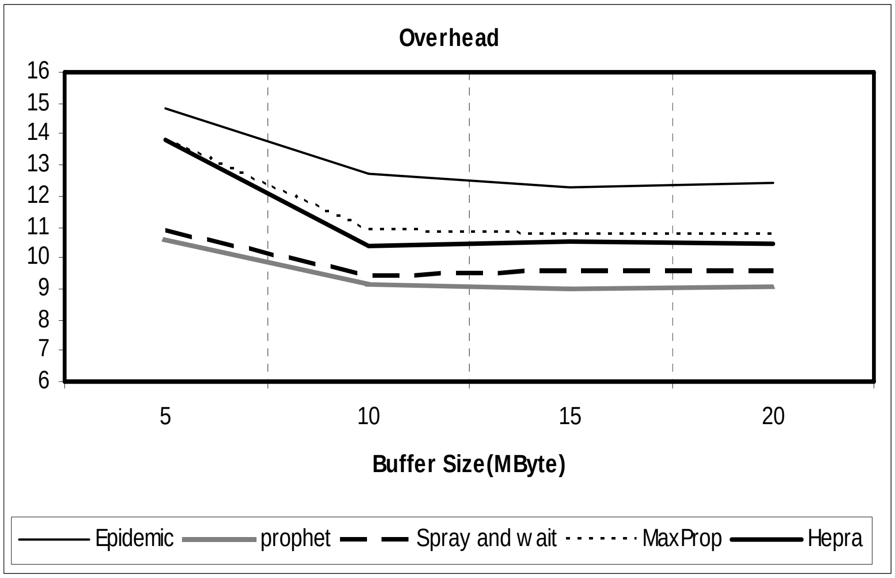


Figure 4.9 Increasing buffersize reduces the impact of IN on overhead

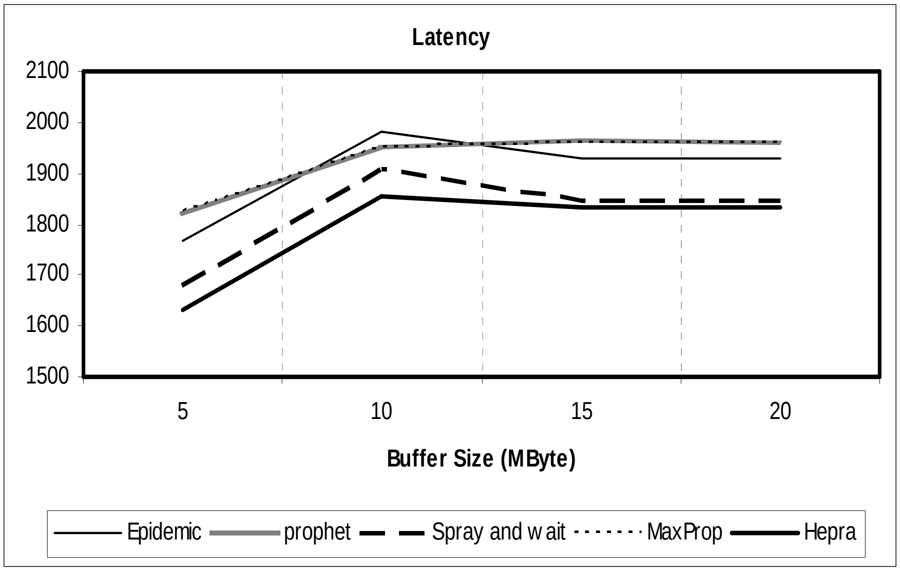


Figure 4.10 increasing buffer size makes latency reach stable case

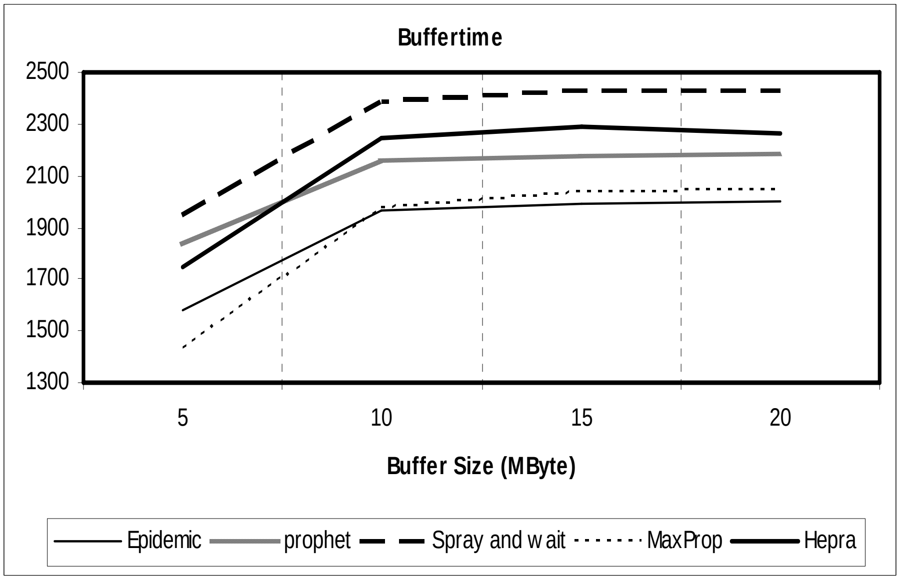


Figure 4.11 Buffertime increases when buffer size increases

4.7 Discussion and Conclusion

In this chapter we present a brief study of the impact of link availability as a parameter of the physical layer environment on the performance of DTN routing protocols.

Most of researchers focus on enhancing the performance of DTN routing protocols with respect to network layer or application layer. We design our model to illustrate the impact of link availability as physical layer parameter on routing performance. Simulation results illustrate that performance of DTN protocols degrades when number of interference nodes increase in network.

We evaluate the performance of well known DTN routing protocols including our approach, HEPRA, to show how those protocols act against changes in physical layer parameters.

This brief study will open the door to researcher to start including the impact of physical layer parameters in their design of routing protocol to achieve better results. Future work should continue to study the impact of other parameters such as Doppler Effect, fading, transmission power. Cross Layer Design (CLD) should be presented to overcome the impact of those parameters.

Chapter 5

SNR/RP Routing Model: Cross-Layer Design for MANETs

5.1 Motivation

Design a service-quality aware routing algorithm in Mobile ad hoc network (MANET) is difficult due to the nature of the environment where nodes are mobile and connectivity is intermittent that changes topology rapidly. In this chapter, we propose cross-layer design to attain a reliable data transmission in MANET.

In MANET environment, the challenge is to design a mechanism that can provide high quality of service with a high level of performance or to achieve service quality in terms of high delivery rate, low latency and low bit error. The key components of our approach include a cross-layer design (CLD) to improve information sharing between network and physical layers.

We present a model that allows the network layer to adjust its routing protocol dynamically based on Signal Noise Ratio (SNR) and Received Power (RP) along the end-to-end routing path for each transmission link to improve the end-to-end routing performance in MANET,.

We evaluate our model using well known MANET- routing protocols: AODV, DSR, OLSR to illustrate that our CLD improved their performances with respect to service quality. We analyze their performance in terms of: packet delivery rate, average End-to-End delay and overhead.

5.2 Routing in MANET

Routing in MANET using the shortest-path metric is not a sufficient condition to construct high-quality paths, because minimum hop count routing often chooses routes that have significantly less capacity than the best paths that exist in the network. [37]

Most of the existing MANET protocols optimize hop count to build a route selection. Examples of MANET protocols are Ad hoc On Demand Distance Vector (AODV) [38], Dynamic Source Routing (DSR)[39], and Optimized Link State Routing Protocol (OLSR) [40].

However, the routes selected based on hop count alone may be characterized with bad quality since the routing protocols do not ignore weak quality links which are typically used to connect to remote nodes. These links usually have poor signal-to-noise ratio (SNR), hence higher frame error rates and lower throughput. [41], [42].

The wireless channel quality among mobile nodes is time varying due to fading, Doppler Effect and pathloss. Known that the shortest-path metric does not take into account the physical channel variations of the wireless medium, it is desirable to choose the route with minimum cost based on some other metrics which are aware of the wireless nature of the underlying physical channel. In MANET, there are many other metrics to be taking into account: power, SNR, packet loss, maximum available bandwidth etc. These metrics should come from a cross-layer approach in order to make the routing layer aware of the local issues of the underling layers. [43].

The ability of MANET to provide acceptable quality of service (QoS) is restricted by the ability of the underlying routing protocol to provide consistent behavior despite the inherent dynamics of a mobile computing environment. [44] , [45].

Cross-Layer Design has enormous potential in wireless communication systems. By using Cross Layer Design (CLD) we try to offer dedicated QoS for dedicated applications.

Our objective is to design a mechanism to provide an efficient QoS routing protocol to enhance the performance of existing routing protocols in Mobile ad hoc network environment.

In this chapter we select AODV, DSR and OLSR as common MANET routing protocols to demonstrate our two models, Signal to noise Ratio (SNR) and Received

Power (RP), to enhance the quality of service of those protocols. We evaluate how the protocols differ in the methods they use to select paths, detect broken links, and buffer messages during periods of link outage. Our new approach is called Signal to Noise Ratio/Received Power Aware Routing Algorithm (SNR/RP). We computed differences in terms of packet delivery ratio, throughput, end-to-end latency, and overhead. We show that the performances of AODV, DSR, and OLSR protocols improved by using the proposed model.

5.3 Related work

Many proposals and models addressed quality of service (QoS) among mobile nodes of the wireless networks and considered the link quality in their designs and architectures. Wisitpongphan and et al. [46] proposed a bit error rate (BER)-based routing design, where the chosen route is the one which guarantees the lowest BER at the ending node. They considered providing QoS in terms of BER at the destination node.

[47] presented a mechanism to improve both the routing and data forwarding performance of DSR, with lesser power consumption. This mechanism involves intelligent use of the route discovery and route maintenance process thereby providing faster routing and reduced traffic as compared to the basic DSR. This mechanism enables faster data forwarding and reduced collisions with lesser power consumption.

In [43] authors modified DSR to work as three-state Markov model of the wireless channel instead of two-state Markov model (Gilbert-Elliot model) by applying a higher order of Markov chains. They applied their model to the Dynamic Source Routing protocol (DSR). In their proposed modified DSR, both the route discovery and route selection are based on physical layer parameter and the link monitoring function located at each node.

Authors in [48] proposed a simple extension of DSR. They presented a model to reduce routing overhead in request process and the anycast group management protocol is discussed.

In [49] work proposes using of link lifetime and channel quality as metrics in the selection of routes. They applied the model to the Optimized Link State Routing (OLSR) routing protocol and focused on multipoint relay (MPR) selection method, to find the most optimal routes between any pair of nodes.

5.4 MANET Routing Protocols

In MANET the entire network is mobile where nodes move freely and topology is changing rapidly because of weather, terrain, highly variable delay links and error rate links. Nodes may not be able to communicate directly and have to rely on each other in order to deliver packets. The contacts between nodes in the network do not occur very frequently that makes routing difficult because the network graph is episodically connected. A lot of routing algorithms have been proposed for MANET environment and some of them have been widely used. [50], [51].

In this section we review AODV, DSR and OLSR as selected MANET routing used in our design evaluation.

Ad Hoc On-demand Distance Vector Routing (AODV) protocol [38] is a reactive routing protocol. As a reactive routing protocol, it maintains only routing information about the active paths. Every node uses hello messages to notify its existence to its neighbors and maintains routing information in their routing tables to keep a next-hop routing table that contains the destinations to which it has a route. In AODV, when a source node wants to send packets to the destination but no route is available, it initiates a route discovery operation. In the route discovery operation, the source broadcasts route request (RREQ) packets. A RREQ includes addresses of the source and the destination, the broadcast ID, the last seen sequence number of the destination as well as the source node's sequence number. AODV uses sequences numbers to ensure loop-free and up-to-date routes. Each RREQ has Time-to-Live (TTL) and nodes maintain a cache to keep track of RREQs it has received and discards any RREQ has seen before. When intermediate or destination node receives RREQ, it checks destination sequence numbers to what it knows. Then, the node creates a route reply (RREP) packet and forwards back to the source node only if the destination sequence number is equal to or greater than the one specified in RREQ. The RREP follows the reverse path of the respective RREP and intermediate nodes update their next-hop table entries with respect to the destination node. When a node discovers a link disconnection, it broadcasts a route error (RERR) packet to its neighbors, which in turn propagates the RERR packet towards nodes whose routes may be affected by the disconnected link. Then, the affected source can re-initiate a route discovery operation if the route is still needed. [51]

Dynamic Source Routing (DSR) [39] stands as one of the common representatives of reactive routing protocols like all On-Demand routing algorithms, AODV, Dynamic MANET On-demand (DYMO). DSR applies source routing rather than hop-by-hop routing, in which each packet to be routed carrying in its header the full ordered list of nodes through which the packet should pass. The key benefits of source routing is that intermediate nodes do not need to maintain up-to-date routing information in order to route the packets they forward, since the packets themselves already contain all the routing decisions. This fact, coupled with the on-demand nature of the protocol, eliminates the need for the periodic route advertisement and neighbor detection packets present in other protocols. In DSR source node generates a route request packet when it has a new route to a destination. The route request is flooded through the network until it reaches some nodes with a route to that destination. Each route request packet holds the information of the route it has propagated. When the route request packet arrives at the destination or an intermediate node with a route to the destination, a route reply packet will be generated. This reply packet is then sent back to the source node following the reverse route contained in the route request packet. While transmitting the data traffic, the complete path is added to each data packet according to the routing table of the source node. The intermediate nodes forward packets according to the path provided in the packet. More clearly, in DSR routing protocol to send route reply packet, when current route breaks, destination seeks a new route. [50],[51],[52].

The Optimized Link State Routing protocol (OLSR) [40], [49] is a proactive routing protocol and operates as a table driven protocol. In OLSR, each node exchanges its link state information to all other nodes in the network and transmits its neighbor list regularly so nodes can know their two hops neighbors. Each node selects its multipoint relay (MPR) and the MPR nodes announce this information periodically using Topology control (TC) messages. When a node broadcasts a message, its neighbors will receive the message. The protocol uses MPRs to facilitate flooding of control messages and only the MPRs that have not seen the message before, rebroadcast the message in the network periodically. MPRs are used as intermediate nodes to route packets. Then, each node floods the link state information of its MPRs through the network and it obtains network topology information and constructs its routing table through link state messages. [51].

In this work we try to change route selection mechanism. We define a signal to noise ratio (SNR) and received power (RP) parameters as new metrics in which those values are considered in constructing routes. Given those features, source node can select the best and more stable route out of various available routes based on Signal to Noise Ratio

(SNR) or Received Power (RP) not number of hops or shortest path. In this work our aim is improving the Quality of Service (QoS) and the performance of the routing protocols in MANET environment.

5.5 SNR/RP aware routing Model

Routing in MANET is difficult due to the dynamic nature of network topology and the resource constraints. The issue of Link reliability in mobile ad hoc networks is a main problem to transmit messages through the wireless channels. Routing in multi-hop wireless networks using the shortest-path metric is not an adequate condition to build good quality paths, because minimum hop count routing often selects paths that have significantly less capacity than the best paths that exist in the network. [37].

Physical-layer limits of wireless channel because of: time-varying fading, multipath, co-channel interference, hostile jamming, mobility, dynamic network topology.
In technicality, information from the transmission links, such as Signal to Noise Ratio (SNR) and Received Power (RP), can furnish valuable information to the source node about the transmission paths as far as routing is concerned. Each wireless node can communicate with any other node within its transmission range, which depends on SNR and RP at the receiver node.

In our work we used OPNET simulator [27]. We modified the packet formats in OPNET simulator of AODV (figure 5.1), DSR (figure 5.2) and OLSR (figure 5.3) and added two extra fields to store the worst value of power strength (received power strength) and worst value of SNR (signal-to-noise ratio) along the route from destination to source.

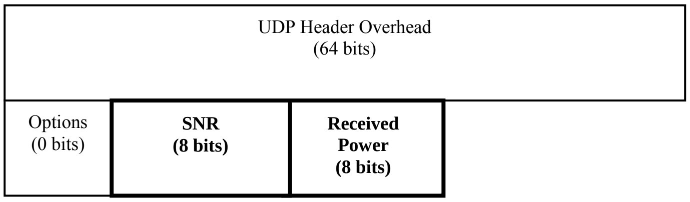


Figure 5.1 Modified Route Reply packet format in OPNET of AODV including metrics of SNR and RP.

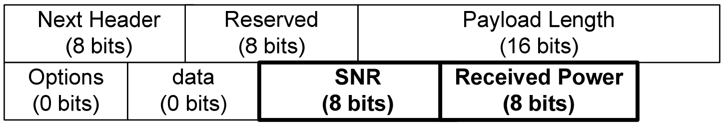


Figure 5.2 Modified Route Reply packet format of DSR including metrics of SNR and RP.

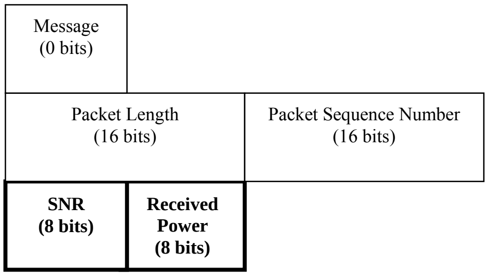


Figure 5.3 Modified packet format of OLSR to include metrics of SNR and RP.

Section 5.4 illustrates how original AODV, DSR and OLSR work. We modified also the mechanism of those routing protocols processes to include our SNR/RP model.

5.5.1 Modification in AODV and DSR (Reactive routing)

In case of DSR and AODV, the new mechanism will work as follows: when the route request packet arrives at the destination or an intermediate node with a route to the destination, a route reply packet will be generated. This reply packet is then sent back to the source node following the reverse route contained in the route request packet. Each intermediate node will update the SNR and RP values if its link values of SNR and RP lower than the existing recorded values in the route reply packet. If SNR/RP values of its link are greater than recorded value, the node will not update the value. The process will continue until the route reply packet reach the source node. Now, at the source node there are many of available routes with different values of SNR and RP. The Source node will select the route based on the value of best of worse available values of SNR or RP.

Figure 5.4 demonstrates the flow chart of how modified DSR and AODV routing protocols work after implementing the SNR/RP model. Dotted-line areas in the figure represent new process.

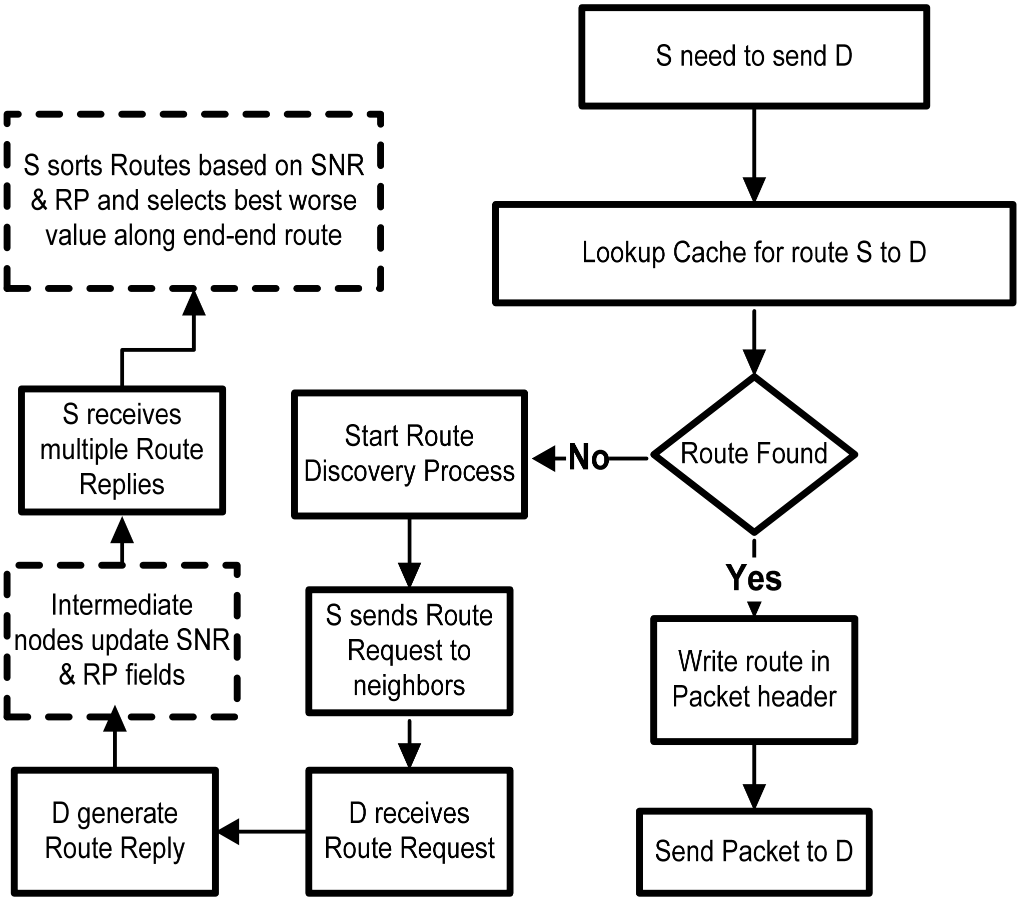


Figure 5.4 Flow chart shows how SNR/RP model works with DSR and AODV.

5.5.2 Modification in OLSR (Proactive routing)

Original OLSR uses hello and Topology Control (TC) messages to discover and exchange link state information throughout the network. Nodes compute next hop destination by using topology information received by neighbors considering shortest hop forwarding paths. OLSR makes use of "Hello" messages to find its one hop neighbors and its two hop neighbors through their responses. The sender node can then select its MPR based on the one hop node that offers the best routes to the two hop nodes.

In our SNR and RP model, we modified the selection process of MPR and makes nodes select MPR based on the SNR and RP values of each link connected to those MPR instead of the shortest paths. Modified OLSR constructs routing table for each node using the SNR/RP to guarantee the quality of service in the network.

Figure 5.5 illustrates the mechanism of our new approach, SNR/RP aware routing algorithm when it applies to DSR, AODV and OLSR routing protocols. The values on links represent the values of Signal to Noise Ratio of the link or values of received power of the link. When node S needs to send a packet to node R. Node S sends 2 route request packets along path 1 and path 2. Node R generates 2 route reply packets to node S along the reverse routes of paths 1 and 2. Now, at node S there 2 available routes to destination R, path 1 with 5 hops but the lowest value of SNR or RP found in the end-to-end path is 3, and path 2 with 4 hops but the lowest value of SNR or RP found in the end-to-end path is 2. Source node S will sort the two routes and select path 1 based on our new mechanism since the best worse value of path 1 is 3 is grater than the worse value of the other path which is 2. Traditional DSR, AODV and OLSR protocols will select Path 2 that has minimum number of hops eventhough the path has low-quality of service.

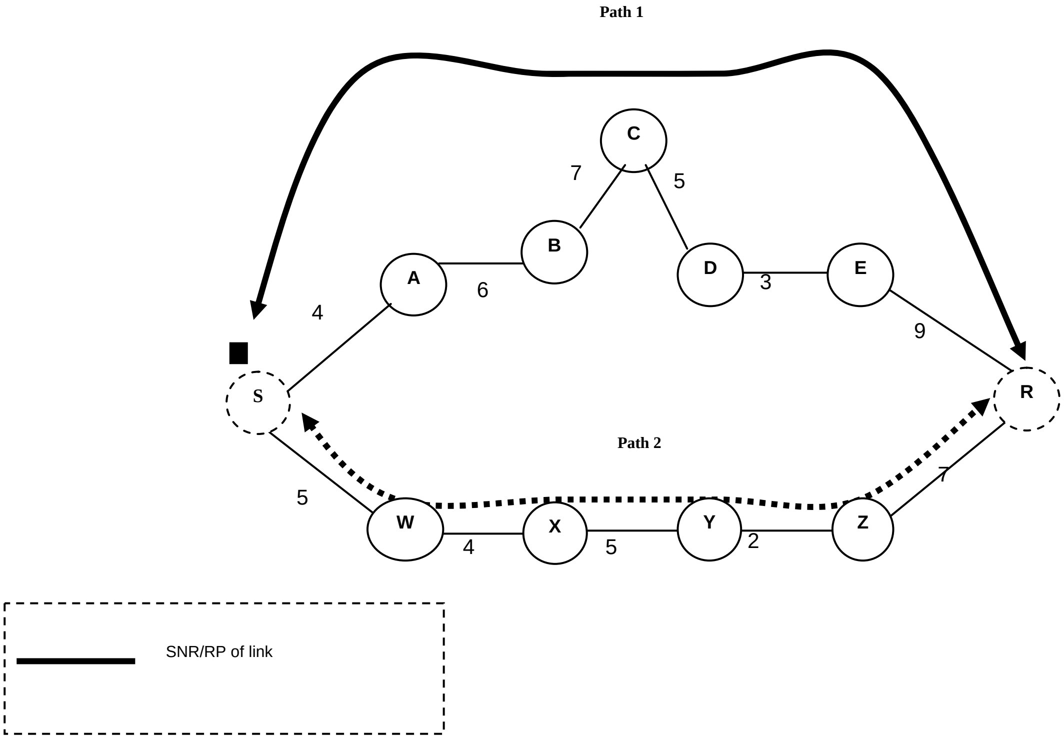


Figure 5.5 Scenario shows that modified DSR and AODV with SNR/RP will select path 1 (High QoS) rather than path 2 (minimum number of hops).

Wireless channels have high channel bit error rate and limited bandwidth. The high bit error rate degrades the quality of transmission and the network performance. A routing protocol that can not quickly recover from link breakage caused by mobility renders a QoS model incapable of meeting delivery requirements. [44].

Implementing our model will guarantee the Quality of service in the environment of MANET where is QoS is low. Any routing protocol should be smart enough to pick a stable and good quality communication route in order to avoid any unnecessary packet loss.

Routing in MANET is challenging due to the dynamic nature of network topology and the resource constraints. In our model, we create a mechanism that can provide good delivery performance and high quality of service in MANET environment that characterized with intermittent network and episodically connected and nodes get intermittently connected because of nodes mobility, terrain, weather, and jamming to reach a reliable data transmission.

5.6 Simulation environment

Our cross-layer model described above was implemented and evaluated in OPNET v 14.5 simulator [27]. Figure 5.6 shows snapshot of our model used in OPNET simulator. Table 6 shows the parameters used in our simulation.

The fading modules contributed in [53] are included into account. The modulation, BPSK, compute the BER under fading condition from the loop-up tables. We calculate the Doppler shift velocity according to the ground speed, pitch, and yaw of the transmitting node and the receiving node. Look up the fading amplitude according to the Rician K=5 factor. [54]. We consider in our network topology to include fading, Doppler Effect, various speed mobility.

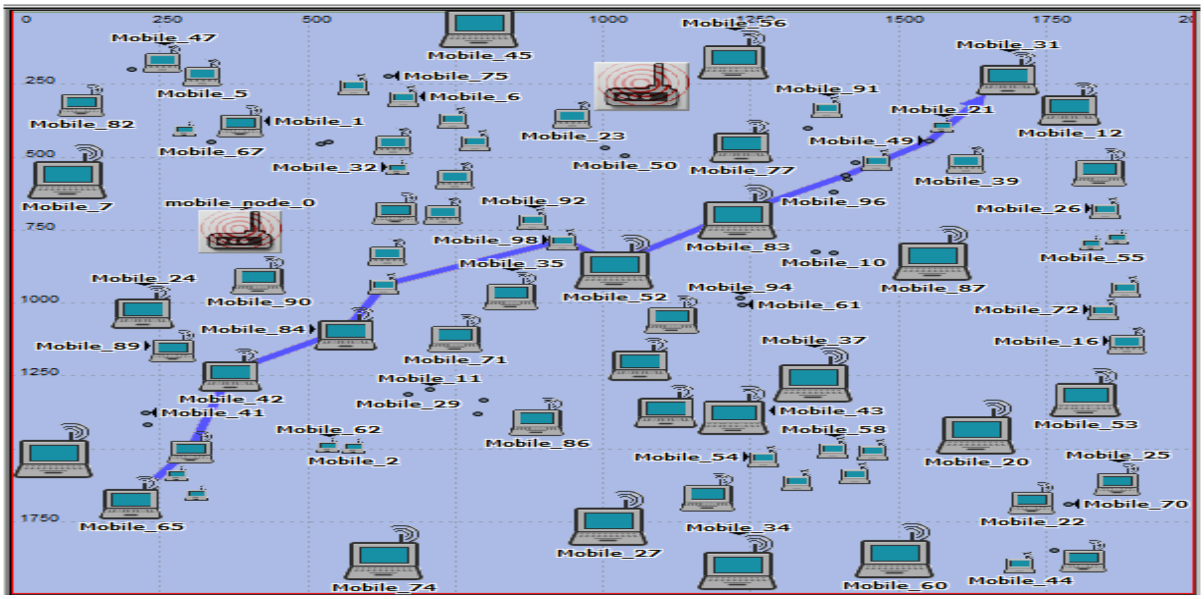


Figure 5.6 Snapshot of network design in OPNET simulator.

Table 6: simulation setup

Parameters	**Value**
Network Size	3 x 3 Km
Modulation Scheme	BPSK
Traffic rate	11 Mbps
Transmit Power	35 mW
Packet Reception-Power Threshold	-75 dBm
Mobility model	Random-Waypoint
Propagation–Path loss	Free space
Propagation fading model	Rayleigh, Rician
Rician K Factor	5
MAC protocol	802.11
Packet size	1024 bits
Routing protocol	AODV, DSR, OLSR
Carrier frequency	2.4 GHz
Nodes number	100
Transmission Range	300 - 400 m
Speed of nodes	3, 6, 9, 12 m/s

5.7 Results

Simulation results evaluate the performance of AODV, DSR and OLSR respectively, in terms of delay, traffic received, routing traffic received (overhead), throughput and retransmission attempts.

5.7.1 AODV evaluation

Figure 5.7 shows that traditional AODV and AODV-SNR models provide good performance in terms of delay. Figure 5.8 illustrates that the RP model enhance the performance of traditional AODV and increase packet delivery in the network. 5.9 shows that overhead reduced in the network with implementing the SNR and RP model separately with AODV. In terms of MAC layer throughput performance, figure 5.10 shows that traditional AODV, SNR model and RP model provide same performance. Finally, figure 5.11 shows that the SNR model and RP model reduce the retransmission attempt in layer 2.

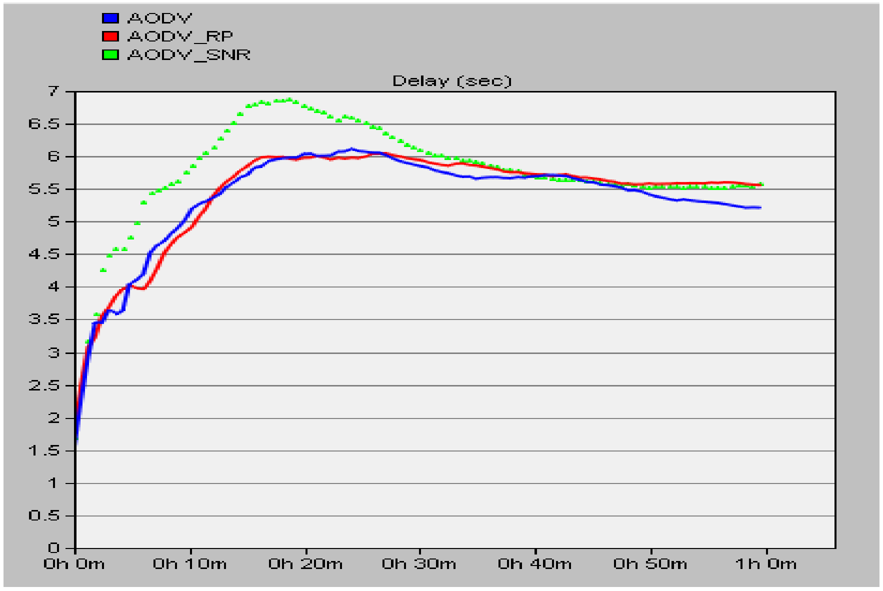


Figure 5.7 AODV and SNR model provide low delay in the network.

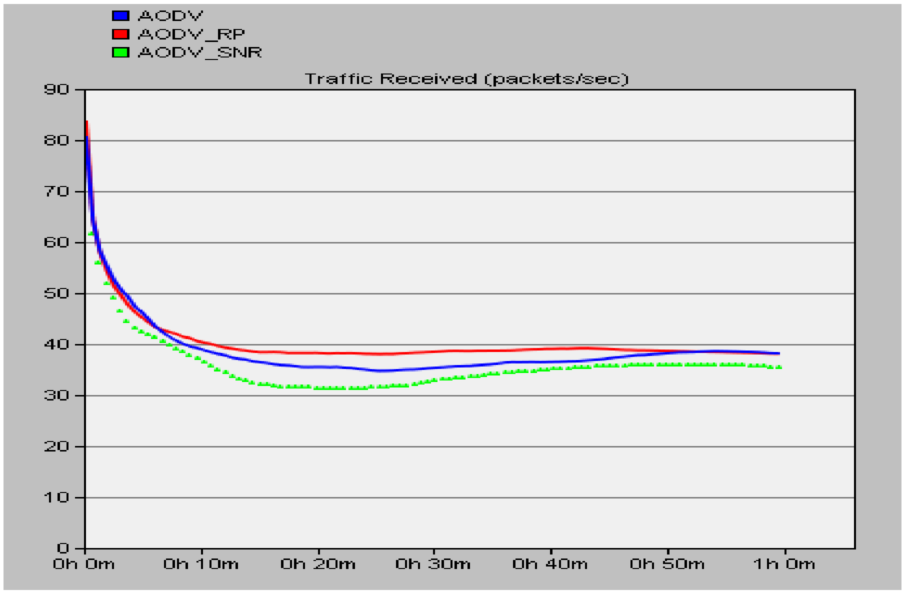


Figure 5.8 RP model increases the packet delivery.

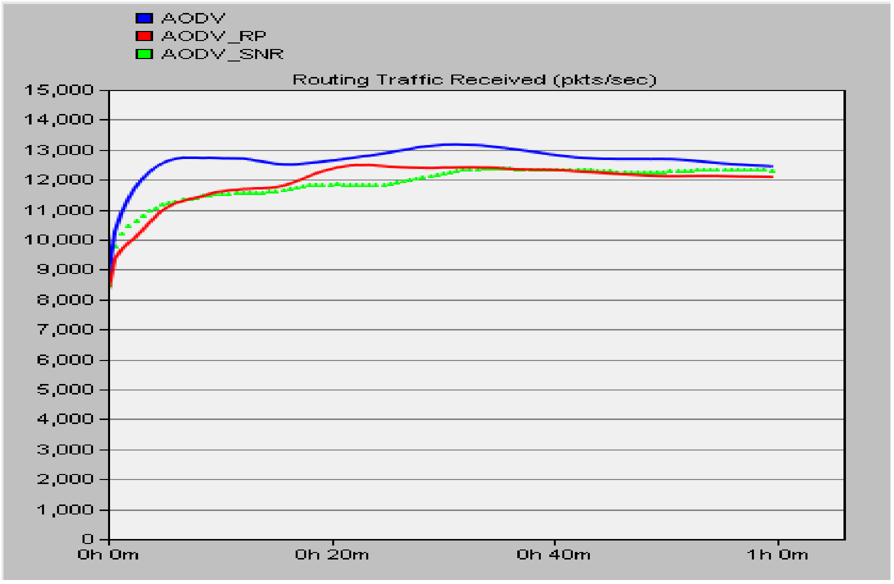


Figure 5.9 RP & SNR models reduce overhead

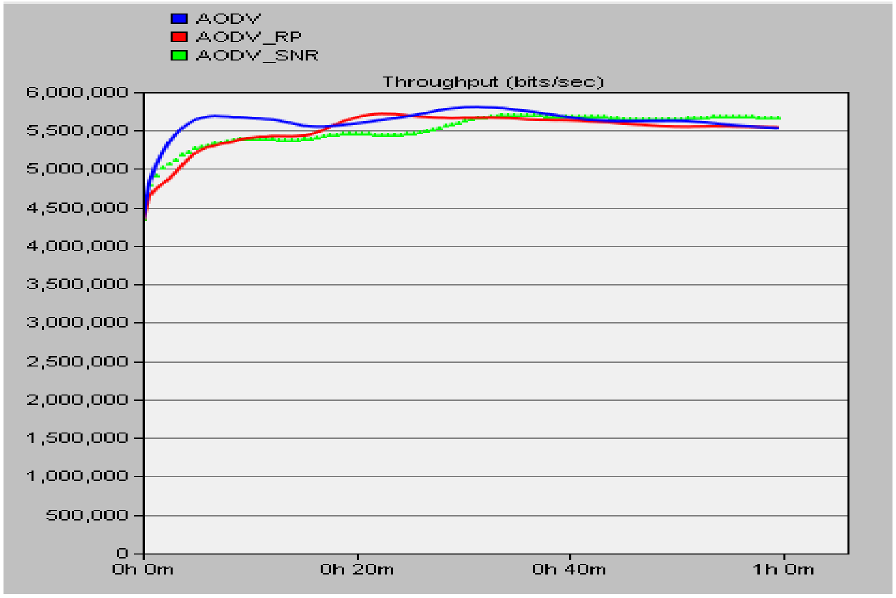


Figure 5.10 Traditional AODV, SNR and RP models have same throughput performance

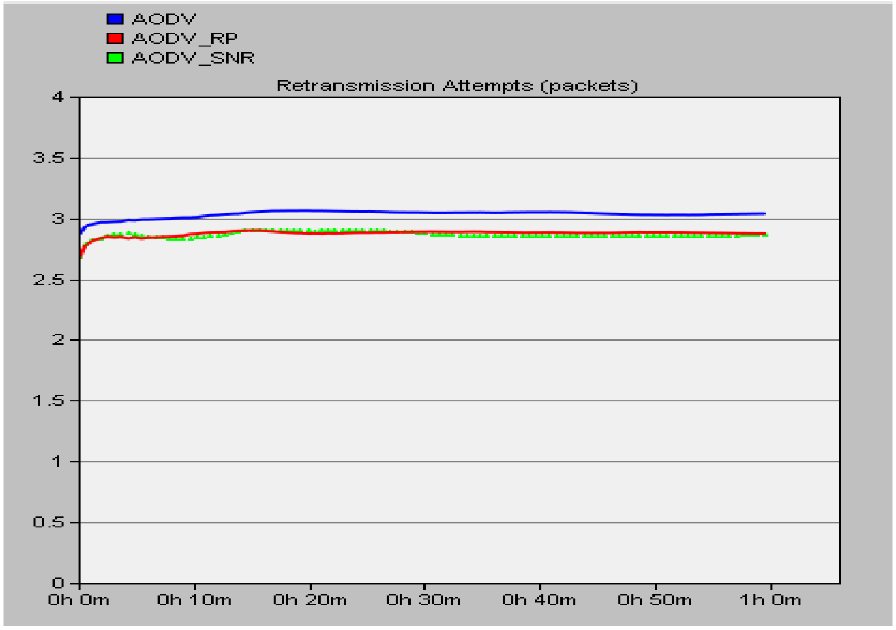


Figure 5.11 SNR & RP models improve numbers of destination's repliers

5.7.2 DSR evaluation

It is immediately evident from the results given in figure 5.12 that delay reduced when SNR or RP models used. Figure 5.13 shows that the traditional DSR and RP model perform equally with respect to packet delivery in the network. 5.14 illustrates that overhead reduced in the network with implementing the SNR and RP model separately with DSR. In terms of MAC layer throughput performance, figure 5.15 shows that traditional RP model provide excellent performance. Finally, figure 5.16 illustrates that the SNR model and RP model reduce the retransmission attempt in layer 2.

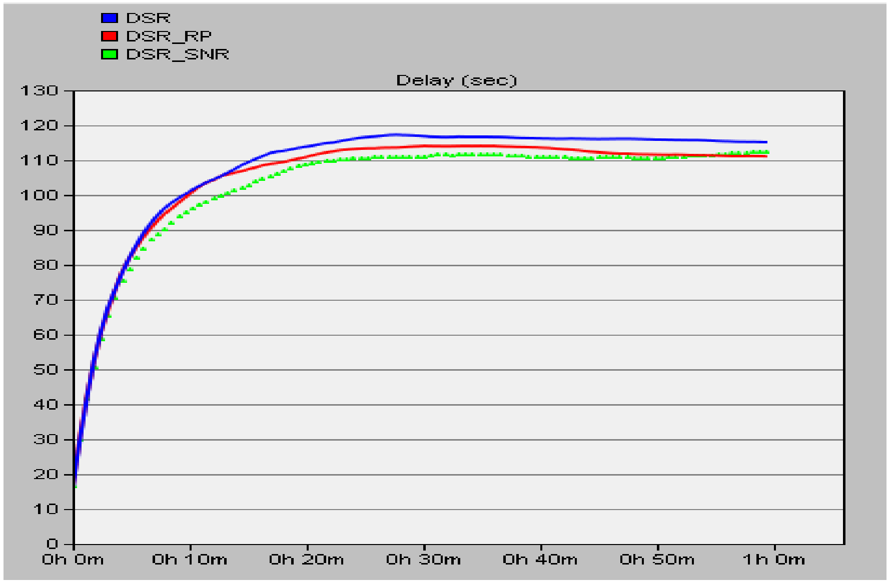


Figure 5.12 SNR & RP models reduce delay

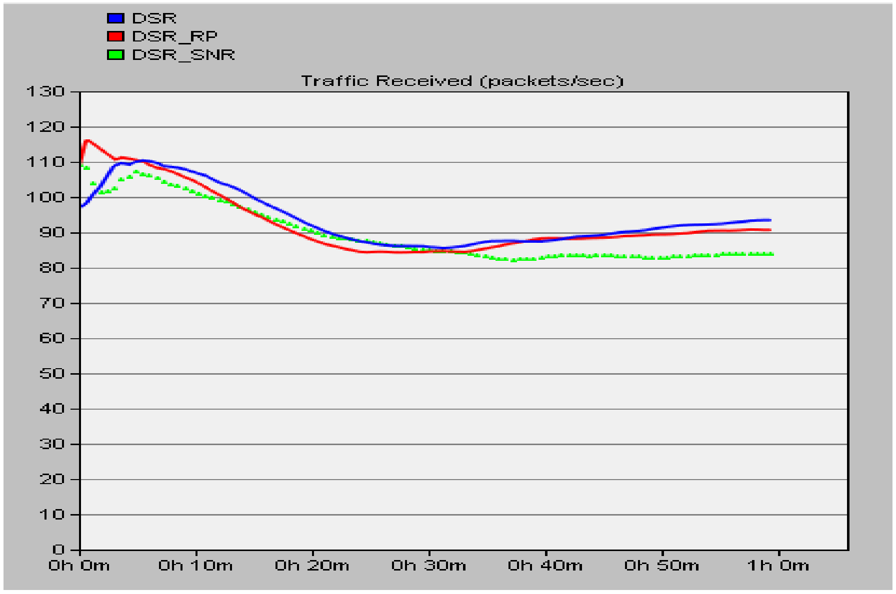


Figure 5.13 DSR & RP model provide good performance in terms of packet delivery

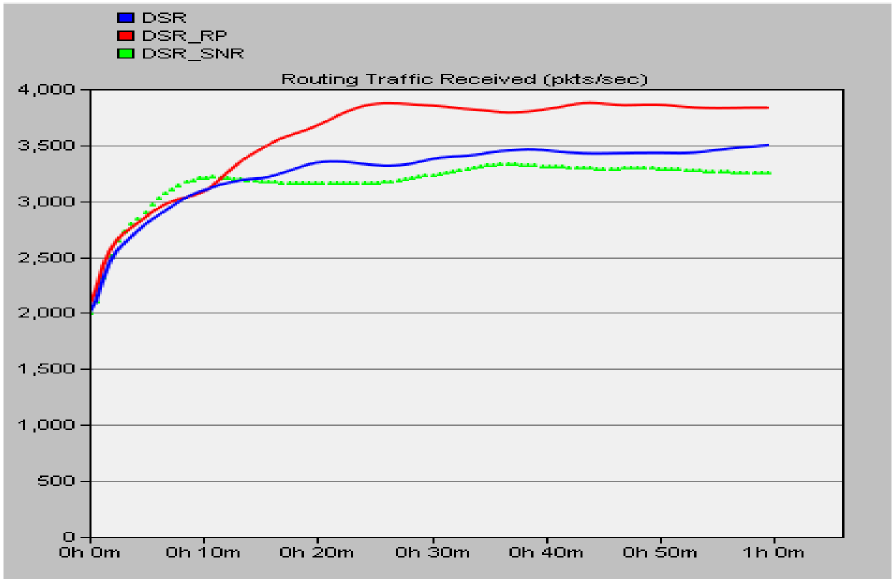


Figure 5.14 SNR & RP models reduce overhead

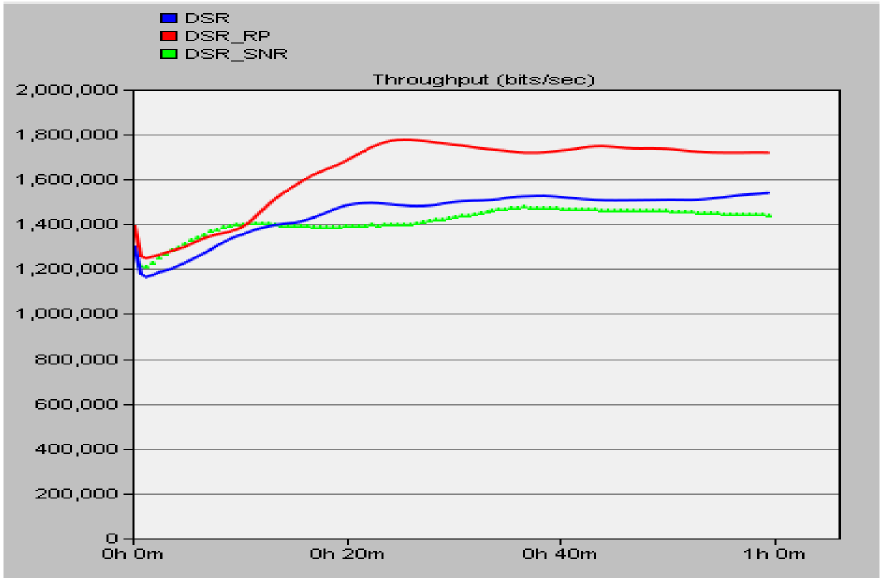


Figure 5.15 RP model increase layer 2 throughput

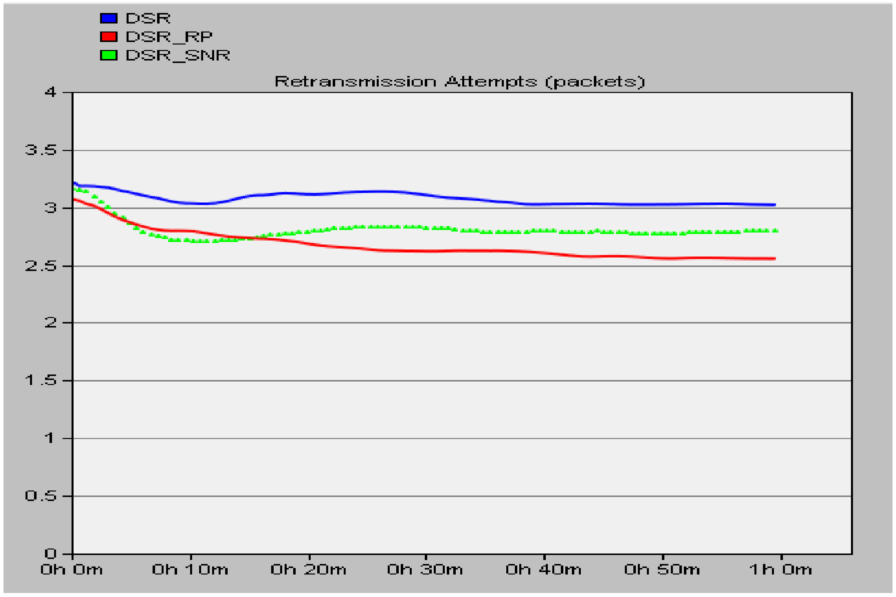


Figure 5.16 SNR & RP models reduced number of errors sent

5.7.3 *OLSR evaluation*

Figures 5.17- 5.19 show that traditional OLSR outperforms OLSR-SNR model and OLSR-RP in terms of delay, packet delivery and overhead. For MAC layer throughput performance, figure 5.20 shows that traditional OLSR, SNR model and RP model provide better performance than OLSR. Figure 5.21 shows that OLSR, SNR model and RP model same performance in terms of retransmission attempt.

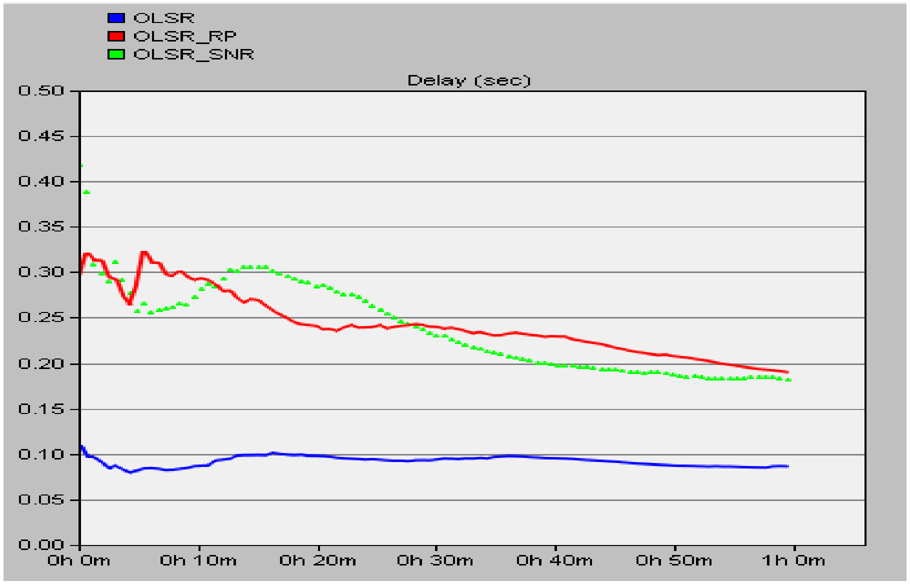


Figure 5.17 traditional OLSR provides low delay

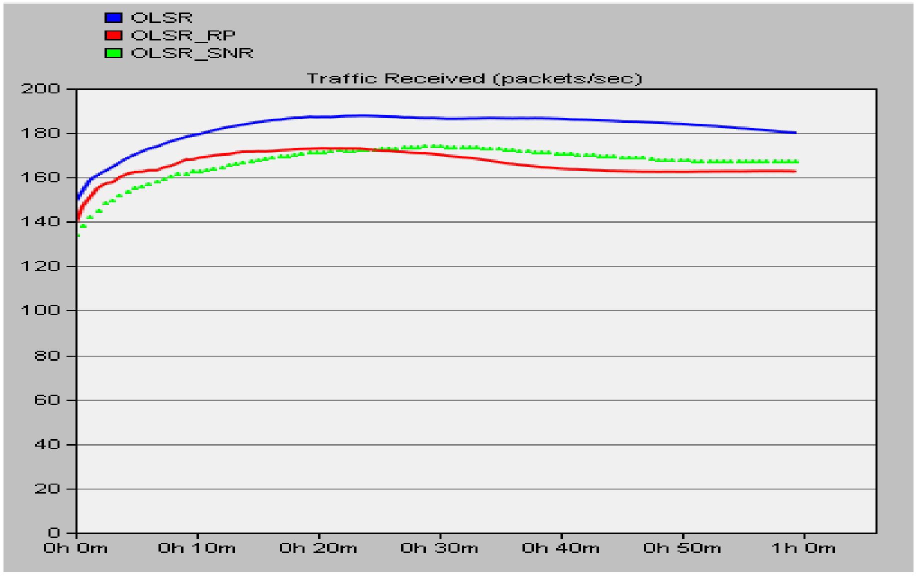


Figure 5.18 traditional OLSR delivers more traffic

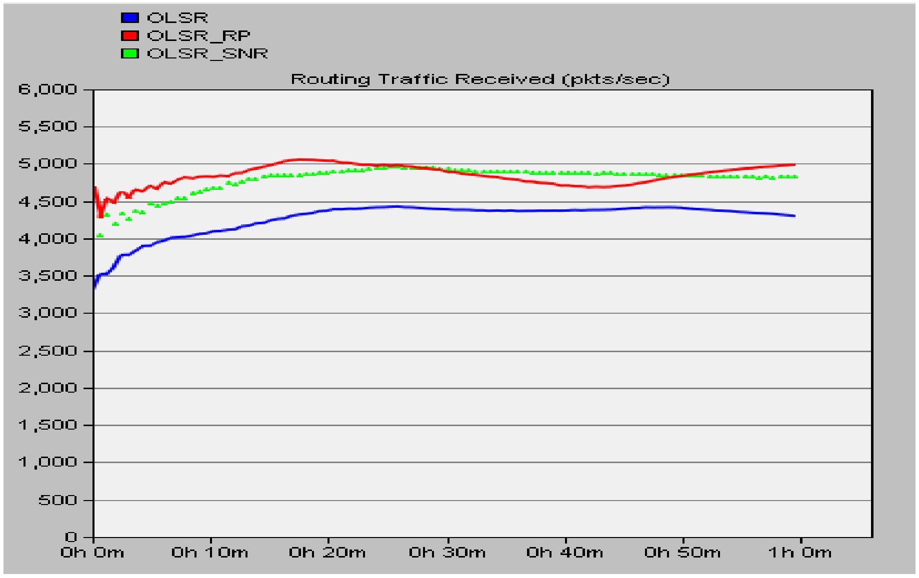


Figure 5.19 overhead in traditional OLSR is low

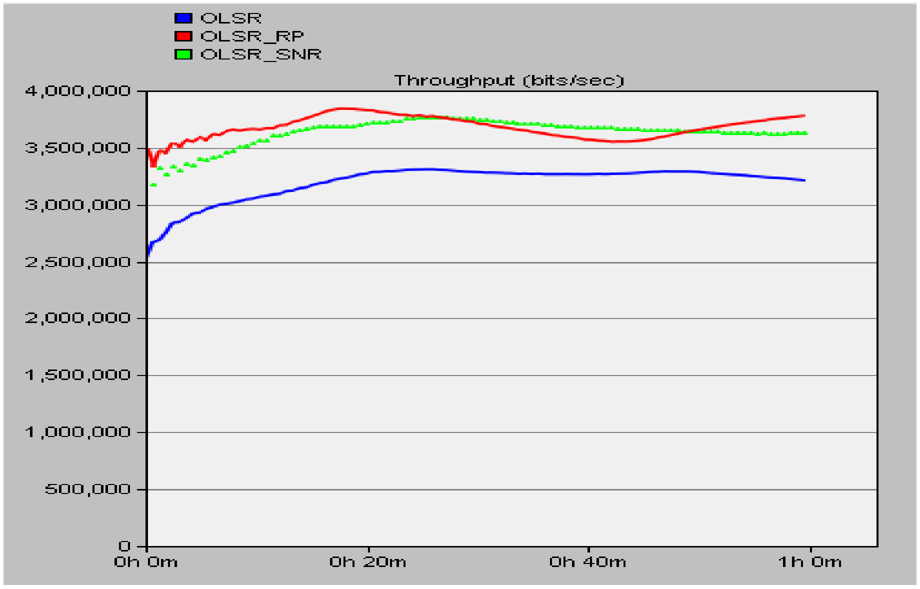


Figure 5.20 SNR & RP models increase throughput

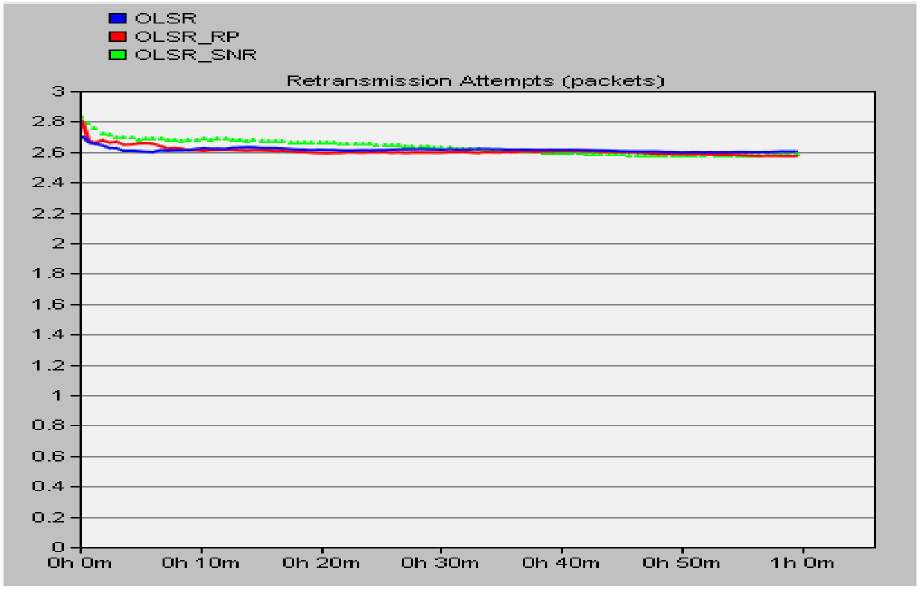


Figure 5.21 Identical performance in terms of retransmission attempts

5.7.4 General evaluation

We evaluate the performance of AODV, DSR and OLSR in terms of delivery rate with respect to time and number of nodes.

Figure 5.22 shows that AODV-RP increases the delivery rate. In figure 5.23, SNR and RP models enhance the delivery rate when time increases. Figure 5.24 illustrates that OLSR delivery rate is higher than the models.

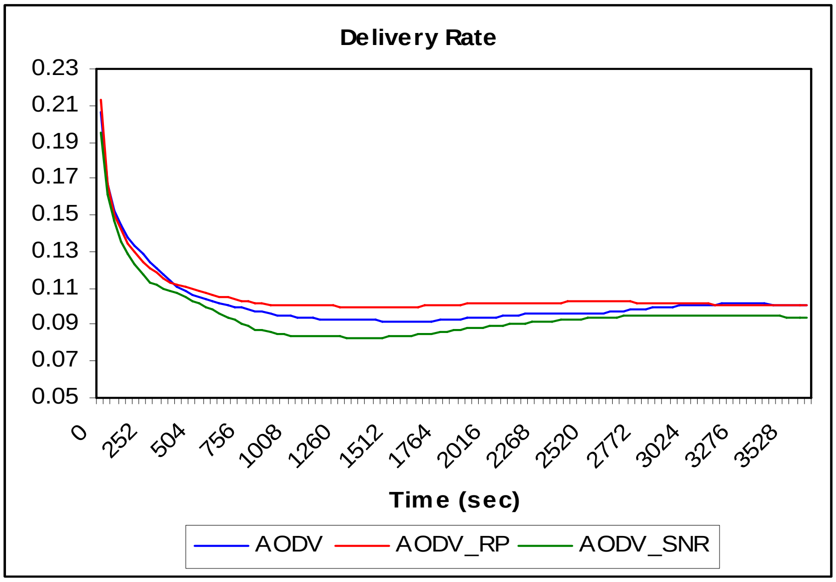


Figure 5.22 APDV-RP model increases delivery rate

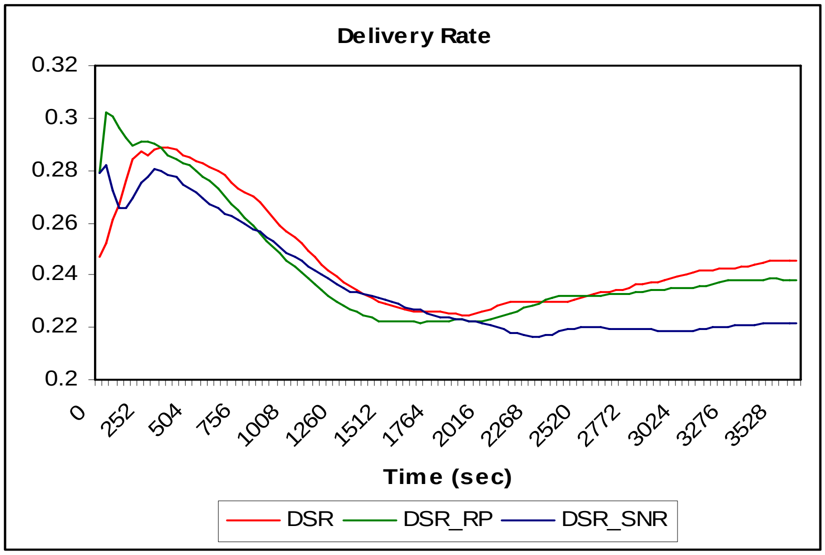


Figure 5.23 SNR & RP models presents better performance than traditional DSR

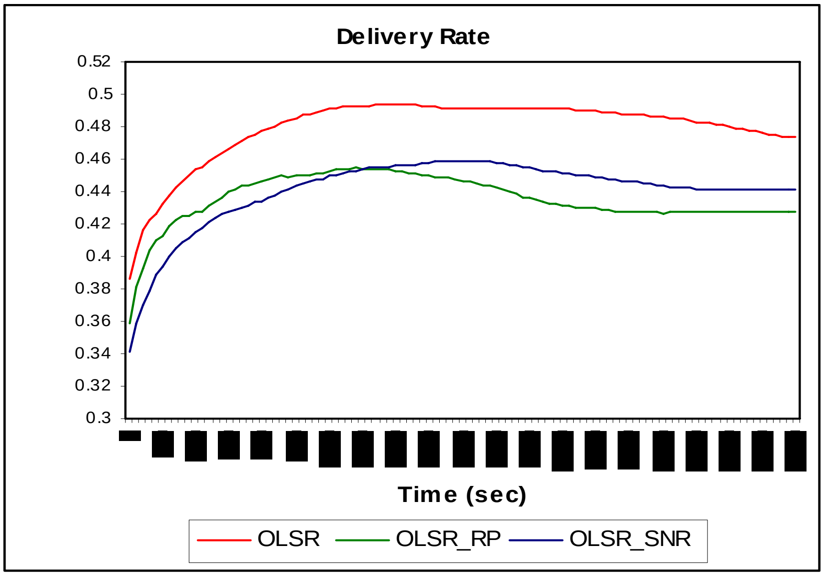


Figure 5.24 Traditional OLSR delivers more packets

Figures 5.25 - 5.27 evaluate delivery rate with respect to number of nodes. In figure 5.25 when number of nodes increases AODV-SNR model increases delivery date and outperforms traditional AODV. Figure 5.26 shows that DSR and models achieve approximately same performance. In figure 5.27, OLSR-RP presents high performance than other with small number of nodes.

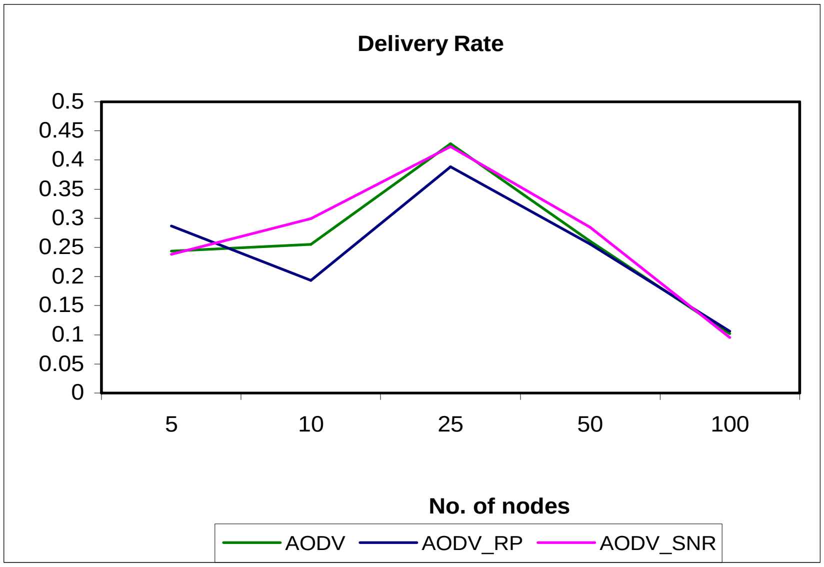


Figure 5.25 AODV-RP model increases delivery rate when No. nodes increases.

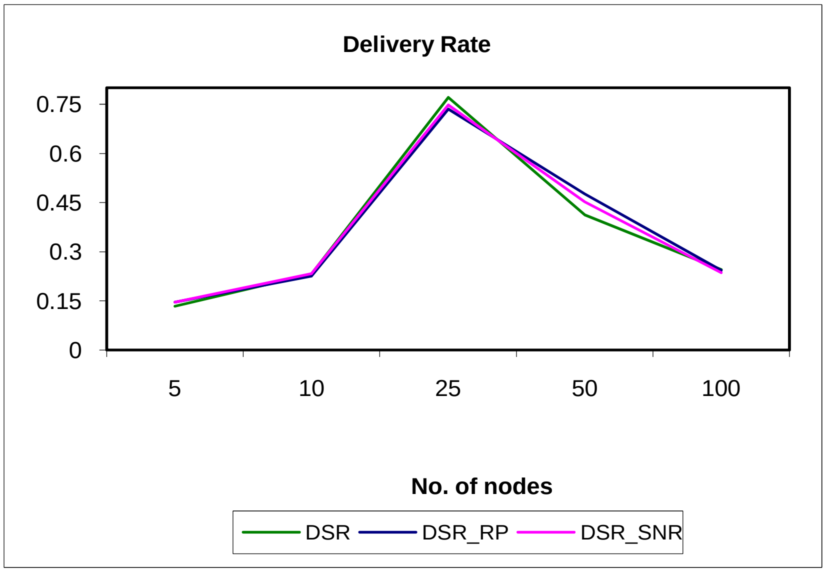


Figure 5.26 When No. nodes increases DSR and models have same performance

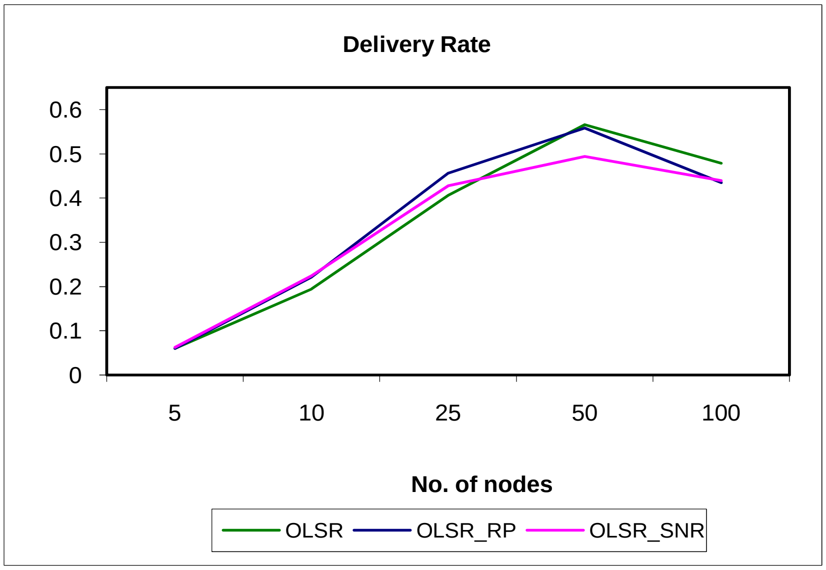


Figure 5.27 OLSR-RP presents good performance with small group of nodes

5.8 Discussion and Conclusions

In this chapter, we present our Cross-Layer Design (CLD) to improve the performance of well known MANET routing protocols, AODV, DSR and OLSR. We modified the protocols to choose routes according to the Signal to Noise Ratio (SNR) or a Received Power (RP) criterion which is characterized with the best value of SNR or RP of the weakest link along the route from destination to source to eliminate the routes with bad links that has very low SNR and to improve QoS.

We have presented our recent results of the SNR/RP aware routing design to achieve reliable communication in networks associated with intermittent connectivity. The challenge was to find a routing design that can deal with dynamic environment causing networks to split and merge, considering nodes mobility, fading, and Doppler Effect.

Simulation results present performance evaluation of the protocols with our CLD model. The evaluation illustrates how those protocols act in the network with and without our CLD model in terms of various network behaviors.

5.9 Future Work

We intend to continue on developing the proposed model and provide a detailed analytical as well as simulation-based study. Our future work will complete the research to implement SNR/RP aware routing design on GRP and TORA. Also, we will implement Delay/Disruption Tolerant Network (DTN) in our Model in OPNET simulator to study and analyze the impact of the physical layer parameters on the performance of DTN routing protocols. Also, our future work will complete the research by implement DTN based routing algorithms in Aerial/terrestrial Airborne Network environment.

Chapter 6

Conclusions

In this chapter we present and summarize our conclusion of the dissertation highlighting the contributions of our work, followed by a brief discussion of future research work.

6.1 Review

Mobile ad hoc network (MANET) presents complex challenges to routing because of the nodes mobility, the constrained bandwidth, terrain, weather, nodes' limited power and the changing wireless channel characteristics that cause topology changes frequently.

Routing protocols must construct and maintain multihop routes in this dynamic ad hoc network effectively and efficiently. Traditional MANET based routing protocols require that the network graph is fully connected from sender to receiver at the time sending messages and fail to route messages if there is not a complete route.

Delay/Disruption Tolerant Networks (DTN) architecture is designed to provide communication in intermittently connected networks (ICN) by moving messages towards destination via store-carry- and-forward technique.

6.2 Dissertation Contribution

We study DTN-MANET environment and its routing protocols in this dissertation. We design a routing protocol using DTN architecture to overcome the intermittent connection in MANET environment.

We summarize our contribution as follows:

- We design a probabilistic routing protocol, History of Encounter probabilistic routing protocol (HEPRA) to improve MANET performance.
- We conduct a performance evaluation of various DTN based routing protocols in terms of various network parameters. Protocols were analyzed in diverse network scenarios to assess their relative strengths and weaknesses.
- We study the impact of link availability on the performance of DTN routing Protocols. We perform a network simulation and evaluate the routing protocol scalability. Our study is the first study of the impact of physical parameters on DTN routing protocols.
- We propose a Cross-Layer Design (CLD) to enhance Quality of Service in MANET environment. We introduce a novel route selection metrics that considers the Signal to noise Ratio (SNR) and Received Power (RP) in lieu of shortest path. We applied our model, SNR/RP on three MANET routing protocols, AODV, DSR, and OLSR. Our results indicate that the new model enhance the performance of those protocols in terms of service quality.

6.3 Future Research

The goal is to design a probabilistic routing algorithm to be applicable to work in intermittently connected environments such as Airborne network (AN) to improve the end-to-end message delivery ratio in a multihop scenario where link availability can be low.

There are several interesting directions for future work based on the work described in this dissertation. Some of these are extensions of our work, while some others are derived by the more general problem of Cross Layer Design (CLD).

6.3.1 HEPRA in Aerial/terrestrial AN

Future work should focus on further enhancement of the DTN-based routing protocols in Aerial/terrestrial Airborne Network environment. Figure 6.1 demonstrates an Airborne Network scenario.

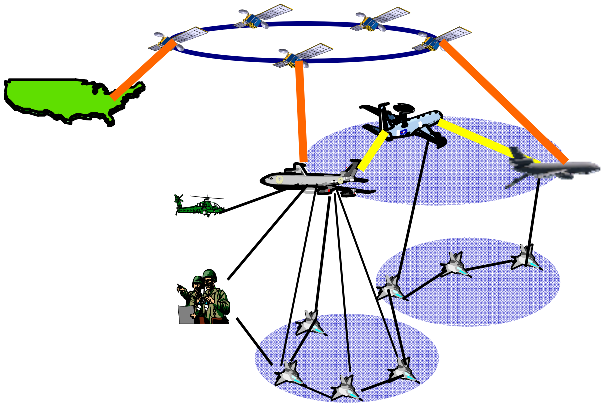


Figure 6.1 HEPRA in Airborne Network Scenario

6.3.2 Physical Propagation Parameters & DTN using OPNET simulator

It is essential to study and analyze the impact of the physical layer parameters on the performance of the DTN-based probabilistic routing protocols such as HEPRA. DTN model in OPNET simulator can be created to aid future research and development of DTN routing protocols. The model should include an airborne networking (AN) environment including airplanes' speed, encounter time window between planes, Doppler Effect, fading, etc.

6.3.3 Cross-Layer Design (CLD) for DTN protocols

It is vital enhancement to design cross-layer frame assists information exchanges between different network layers in DTN architecture, expedites upper layers response to quick changes of physical links and outside environment, and help to optimize link selections. The approach will consider the broad diversity of link types that exists in Airborne Networks.

Bibliography

[1] Jorg Ott, Dirk Kutscher, Christoph Dwertmann, Integrating DTN and MANET Routing, SIGCOMM Workshops, Pisa, Italy, September 11-15, 2006.

[2] Mooi-Choo Chuah, Peng Yang, Brian D. Davison, Liang Cheng, Store-and-Forward Performance in a DTN, Vehicular Technology Conference, 2006. VTC 2006-Spring. IEEE 63rd.

[3] Jeremie Leguay, Timur Friedman, Vania Conan, DTN Routing in a Mobility Pattern Space, SIGCOMM'05 Workshops, Philadelphia, PA, USA., August 22–26, 2005.

[4] DARPA website (http://www.darpa.mil/ATO/solicit/DTN/index.htm)

[5] Forrest Warthman, Delay-Tolerant Networks (DTNs): A Tutorial v1.1, Mar 2003

[6] John Seguí and Esther Jennings, Delay Tolerant Networking – Bundle Protocol Simulation. Proc. 2nd IEEE International Conference on Space Mission Challenges for Information Technology, WA, DC, 2006, 235–240.

[7] DTNRG website (www.dtnrg.org).

[8] Sushant Jain, Michael Demmer, Rabin Patra, and Kevin Fall, Using Redundancy to Cope with Failures in a Delay Tolerant Network, SIGCOMM 2005. August 21–26, 2005, Philadelphia, Pennsylvania, USA.

[9] NASA website (http://www.nasa.gov/mission_pages/station/science/experiments/DTN.html)

[10] Kevin Fall, A Delay-Tolerant Network Architecture for Challenged Internets. Intel Research, Berkeley February 26, 2003.

[11] A. Balasubramanian, B. Neil Levine and A. Venkataramani, DTN Routing as a Resource Allocation Problem, SIGCOMM'07, Kyoto, Japan, August 27–31, 2007.

[12] Bill Howard, ’’Analyzing Online Social Networks’’, Communications of the ACM, November 2008, Vol. 51 , no. 11

[13] Facebook website (www.facebook.com)

[14] Hi5 website (www.hi5.com)

[15] Twitter website (www.twitter.com)

[16] Ari Keranen and Jorg Ott, Increasing Reality for DTN Protocol Simulations, Technical Report, Helsinki University of Technology, Networking Laboratory, July 2007

[17] Amin Vahdat and David Becker, “Epidemic routing for partially connected ad hoc networks,” Technical Report CS-200006, Duke University, April 2000.

[18] Anders Lindgren, Avri Doria, and Olov Schel´en, Probabilistic routing in intermittently connected networks, Proc. The Fourth ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc 2003), June 2003.

[19] Thrasyvoulos Spyropoulos, Konstantinos Psounis, and Cauligi S. Raghavendra. Spray and wait: An efficient routing scheme for intermittently connected mobile networks. In WDTN ’05: Proceeding of the 2005 ACM SIGCOMM workshop on Delay-tolerant networking, 2005

[20] John Burgess, Brian Gallagher, David Jensen, and Brian Neil Levine. MaxProp: Routing for vehicle-based disruption-tolerant networks. In Proc. IEEE INFOCOM, April 2006.

[21] Aruna Balasubramanian, Brian Neil Levine, and Arun Venkataramani. DTN routing as a resource allocation problem. In Proc. ACM SIGCOMM, August 2007.

[22] Michael Demmer and Kevin Fall, DTLSR: Delay Tolerant Routing for Developing Regions ACM SIGCOMM Workshop on Networked Systems in Developing Regions (NSDR), August 27, 2007, Kyoto, Japan.

[23] Paolo Costa, Cecilia Mascolo, Mirco Musolesi, and Gian Pietro Picco, Socially-Aware Routing for Publish-Subscribe in Delay-Tolerant Mobile Ad Hoc Networks, IEEE Journal on selected areas in communications, VOL. 26, No. 5, June 2008.

[24] Qun Li and Daniela Rus, Communication in disconnected ad-hoc networks using message relay, Journal of Parallel and Distributed Computing, 2003.

[25] Zhensheng Zhang, Routing in Intermittently Connected Mobile Ad Hoc Networks and Delay Tolerant Networks: Overview and Challenges, IEEE Communications Surveys & Tutorials, 1st Quarter 2006, Volume 8, No. 1.

[26] Michelle Effros, Andrea Goldsmith and Muriel Medard, The Rise of Instant Wireless Networks, Scientific American Magazine, April 2010, p.73

[27] The OPNET simulator www.opnet.com

[28] Anuj K. Gupta, Harsh Sadawarti, Anil K. Verma, Performance analysis of AODV, DSR & TORA Routing Protocols, IACSIT International Journal of Engineering and Technology, Vol.2, No.2, April 2010

[29] N. Nikaein, H. Labiod, and C. Bonnet. DDR-Distributed Dynamic Routing Algorithm for Mobile Ad hoc Networks. First Annual Workshop on Mobile and Ad Hoc Networking and Computing (MobiHOC), 2000.

[30] Changling Liu, Jorg Kaiser , A survey of Mobile Ad Hoc network Routing Protocols, The University of Magdeburg; the University of Ulm Tech. Report Series, Nr. 2003-08.

[31] D. De Couto, D. Aguayo, J. Bicket, and R. Morris. High-throughput path metric for multi-hop wireless routing. In MOBICOM, 2003.

[32] R. Draves, J. Padhye, and B. Zill. Routing in multi-radio, multi-hop wireless mesh network. In MOBICOM, 2004

[33] J. Padhye, S. Agarwal, V. N. Padmanabhan, L. Qiu, A. Rao, and B. Zill. Esitmation of link interference in static multi-hop wireless networks. In Proceedings of Internet Measurement Conference (IMC), pages 305–310, 2005.

[34] C. Siva Ram Murthy and B.S. Manoj, Ad hoc Wireless Networks Architecture and protocols, Prentice Hall Communications Engineering and Emerging Technologies Series, 2004.

[35] Rajarshi Gupta, Zhanfeng Jia, Teresa Tung, and Jean Walrand, Interference-aware QoS Routing (IQRouting) for Ad-Hoc Networks

[36] NZ Ali, R. B Ahmad, S.A.Aljunid, Link Availability Estimation for Routing Metrics in MANETs : An Overview, 2008 International Conference on Electronic Design December 1-3, 2008, Penang, Malaysia

[37] Wing Ho Yuen, Heung-no Lee and Timothy D. Andersen "A Simple and Effective Cross Layer Networking System for Mobile Ad Hoc Networks", in: PIMRC 2002, vol. 4, September 2002, pp. 1952-1956

[38] C. E. Perkins and E. M. Royer, "Ad-hoc on-demand distance vector routing," in Proc. IEEE Workshop on Mobile Comp. Sys.and Apps., Feb. 1999, pp. 90-100.

[39] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks," in Mobile Computing, 1996, pp. 153-181.

[40] P. Jacquet, P. Muhlethaler, T. Clausen, A. Laouiti, A. Qayyum, L. Viennot. Multi, Optimized link state routing protocol for ad hoc networks, IEEE INMIC 2001. August 2002, pp. 62-68.

[41] H.M. Tsai, N. Wisitpongphan, and O.K. Tonguz, "Link-Quality Aware AODV Protocol," in Proc. IEEE International Symposium on Wireless Pervasive Computing (ISWPC) 2006, Phuket, Thailand, January 2006

[42] E. Royer and C.-K. Toh, "A Review of Current Routing Protocols for Ad Hoc Mobile Wireless Networks," IEEE Personal Communications Magazine, vol. 6, No. 2, April 1999.

[43] Merlinda Drini & Tarek Saadawi .”Modeling Wireless Channel for Ad-Hoc Network Routing Protocol”, ISCC Marakech Marocco, July 2008, Page(s): 549-555

[44] John Novatnack , Lloyd Greenwald & Harpreet Arora, “Evaluating ad hoc routing protocols with respect to quality of service”, Wireless And Mobile Computing, Networking And Communications, 2005. Volume 3, 22-24 Aug.2005, Pages: 205-212

[45] Frank Aune “Cross-Layer Tutorial” NTNU 2004.

[46] N. Wisitpongphan, G. Ferrari, S. Panichpapiboon, J.S. Parikh, and O.K. Tonguz, "QoS provisioning using BER-based routing for ad hoc wireless networks", IEEE Vehicular Tech. Conf. (VTC Spring 2005), PP. 2483-2487.

[47] Arun kumar .B.R, C. Lokanatha Reddy and P.S. Hiremath, “High performance Modified DSR with Power Consumption Optimization for Mobile Adhoc Networks.” IJCSNS International Journal of Computer Science and Network Security, VOL.7 No.5, May 2007.

[48] Vivek Gulati, Aman Garg and Nitin Vaidya, “Anycast in Mobile Ad Hoc Networks,” Technical Report, Texas A&M University, April 2001.

[49] Merlinda Drini, Tarek Saadawi, Link Lifetime Based Route Selection in Mobile Ad-Hoc Networks, International Journal of Communication Networks and Information Security (IJCNIS), Vol. 1, No. 3, December 2009

[50] Anuj K. Gupta, Harsh Sadawarti, Anil K. Verma, Performance analysis of AODV, DSR & TORA Routing Protocols, IACSIT International Journal of Engineering and Technology, Vol.2, No.2, April 2010

[51] Changling Liu, Jorg Kaiser , A survey of Mobile Ad Hoc network Routing Protocols, The University of Magdeburg; the University of Ulm Tech. Report Series, Nr. 2003-08.

[52] Josh Broch, David A. Maltz, David B. Johnson, Yih-Chun Hu, Jorjeta Jetcheva, “A Performance Comparison of Multi-HopWireless Ad Hoc Network Routing Protocols”, Proc. of the Fourth Annual

ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom'98),October 25–30, 1998, Dallas, Texas, USA.

[53] R. J. Punnoose, P. V. Nikitin, and D. D. Stancil. "Efficient simulation of ricean fading within a packet simulator". September 2000. Code available at http://www.ece.cmu.edu/wireless/downloads/ns2 ricean dist.tgz.

[54] Theodore Rappaport, Wireless Communications: Principles and Practice, Prentice Hall PTR, Upper Saddle River, NJ, 2001