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Enhancing the scalability of heterogeneous MANET routing protocols

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ENHANCING THE SCALABILITY OF HETEROGENEOUS MANET ROUTING PROTOCOLS

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by

Huda Al Amri

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CERTIFICATION

I, Huda Al Amri, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Electrical. Computer and Telecommunications Engineering, Faculty of Informatics, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Huda Al Amri
August 2012

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List of Abbreviations

AODV	Ad-hoc On-Demand Distance Vector
BSP	Broadcast Storm Problem
CBR	Constant Bit Rate
CTS	Clear-To-Send
DSR	Dynamic Source Routing
DYMO	Dynamic MANET On-demand
EED	End-to-End Delay
EUDA	Early Unidirectionality Detection and Avoidance
FSR	Fisheye State Routing
GPS	Global Positioning System
HC	Hop Count
HMANET	Heterogeneous MANET
HR	Heterogeneity Ratio
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
LAR	Location-Aided Routing
LBU	Location-Based Utilisation
LPAR	Location-based Point-to-Point Adaptive Routing
MAC	Medium Access Control
MANET	Mobile Ad hoc Networks
mJ	milli Joule

MPR	Multi-Point Relays
NCO	Normalised Control Overhead
OLSR	Optimised Link State Routing
OTRP	On-demand Tree-based Routing Protocol
OTRP_HA	On-demand Tree-based Routing Protocol Heterogeneity-Aware
OUBRP	On-demand Utility-Based Routing Protocol
PDR	Packet Delivery Ratio
PN	Powerful Nodes
RDMAR	Relative Distance Micro-discovery Ad-hoc routing
RERR	Route Error
RREQ	Route REQuest
RTS	Request-To-Send
SLURP	Scalable Location Update Routing Protocol
TC	Topology Control
TOF	Tree-based Optimised Flooding
TTL	Time-To-Live
ULE	Uni-directional Link Elimination
ULE-NL	Uni-directional Link Elimination-Neighbour List
WLAN	Wireless Local Area Networks
WMN	Wireless Mesh Network
WRP	Wireless Routing Protocol
ZRP	Zone Routing Protocol

ABSTRACT

Ad hoc networks consist of a set of de-centralised end-user nodes which perform routing in a distributed manner over the wireless medium. This distinct feature of these networks has created a number of new and challenging research issues in the wireless data networking paradigm. One such issue is routing, which has consequently received significant attention in particular, the problem of creating routing protocols that scale well in large networks. This has led to the proposition of various categories of routing protocols. These routing protocols have been classified into three classes according to the strategies for discovering and maintaining routes: proactive, reactive, and hybrid. Each routing protocol reacts differently to node mobility and density.

On-demand routing protocols have the potential to provide scalable information delivery in large ad hoc networks. The novelty of these protocols is in their approach to route discovery, where a route is determined only when it is required by initiating a route discovery procedure. Much of the research in this area has focused on reducing the route discovery overhead when prior knowledge of the destination is available at the source or by routing through stable links. Hence, many of the protocols proposed to date still resort to flooding the network when prior knowledge about the destination is un-available. In addition, the issue of node heterogeneity is not considered in current MANET routing protocols. Although most current MANET routing protocols assume homogeneous networking conditions where all nodes have the same capabilities and resources, in practice MANETs may consist of heterogeneous nodes that have diverse capabilities and resources, for example military (battlefield) networks and rescue operations systems. Homogeneous networks are easy to model and analyse, but tend to exhibit poor scalability compared with heterogeneous networks. Therefore, scalability and heterogeneity in MANETs are issues that significantly affect the performance of routing protocols. Hence, this dissertation examines the scalability properties of ad hoc routing protocols in homogeneous and heterogeneous MANETs.

The research begins with a review of the scalability characteristics of several different classes of routing protocols. This is followed by an extensive study of the performance of current on-demand routing protocols in heterogeneous networks that consist of different nodes with different resources. The study shows that while all protocols perform reasonably well in homogeneous networking conditions, their performance suffer significantly over heterogeneous networks.

This dissertation presents two scalable routing protocols. The first is proposed to improve scalability of homogeneous ad hoc networks when there is no prior knowledge about the destination. This protocol is called On-demand Tree-based Routing Protocol (OTRP) . It combines the idea of hop-by-hop routing (as used by Ad-hoc On-Demand Distance Vector (AODV) with an efficient route discovery algorithm called Tree-based Optimised Flooding (TOF) . In this protocol, route discovery overheads are minimised by selectively flooding the network through a limited set of nodes, referred to as branching nodes. The key factors governing the performance of OTRP are theoretically analysed and evaluated, including the number of branch nodes, location of branching nodes and number of Route REQuest (RREQ) retries. It was found that the performance of OTRP (evaluated using a variety of well-known metrics) improves as the number of branching nodes increases and the number of consumed RREQ retries is reduced. Additionally, theoretical analysis and simulation results shows that OTRP outperforms AODV, Dynamic MANET On-demand (DYMO) , and Optimised Link State Routing (OLSR) with reduced overheads as the number of nodes and traffic load increases.

The second protocol is On-demand Tree-based Routing Protocol Heterogeneity-Aware (OTRP_HA) . It utilises node heterogeneity and optimises route discovery to reduce overheads while ensuring connectivity between different types of nodes with different interfaces.

A node heterogeneity model is developed which can be used to describe common types of node heterogeneity. Nodes in this model are identified by: number of radio interfaces, types of interfaces, and types of power that provides energy for nodes. A strategy called Location-Based Utilisation (LBU) is then introduced to detect unidirectional links and resolve them in a timely fashion. This strategy is based on utilising locations of nodes to filter and cache incoming RREQ packets to find reliable paths to the destination when unidirectional links exist. This strategy is evaluated by applying it on top of ADOV and OTRP. Simulation results show that LBU outperforms existing strategies in homogeneous and heterogeneous MANETs.

Finally, a new approach to route discovery is proposed based on the node heterogeneity model. Each node makes its own decision as to whether or not to participate in the route discovery process according to its location, local density, and available resources. This route discovery strategy is combined with LBU. Theoretical analysis and simulation results show that OTRP_HA outperforms OTRP and AODV while reducing overhead as a the number of nodes and traffic volume increase, while also further prolonging the lifetime of battery-powered single-interface nodes when compared to AODV.

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Chapter 1

Introduction

1.1 Background

Wireless communication has became an integral part of computing and communication over the last ten years. This is because it uses electromagnetic waves to transmit data through space without any wires, which is inexpensive and more practical compared to wired communication. Such type of communication has been recently adapted with mobile devices to facilitate network connectivity. Mobile devices, like laptops, Personal Digital Assistant (PDA) and mobile phones are computing systems, which can easily move from one place to another. Mobility and capabilities of such kinds of devices and the idea of wireless communication have resulted in the introduction to wireless data mobile networks. Recently wireless mobile networks have drawn a lot of attention in the research community. Location awareness, network connectivity, quality of service (QOS), limited power supply, limited device capability, routing protocols, and medium access protocols are among the most important issues under investigation with respect to wireless mobile networks.

Wireless mobile networks are classified in two categories: infrastructure networks and ad hoc networks. A wireless network from the infrastructure category is a network with fixed and wired gateways called base stations. A node in this network can communicate with the nearest base station in its coverage area. Wireless local area networks (WLAN) belong to this category. While ad hoc networks are infrastructureless mobile networks which do not use fixed routers. Each node can act as a router to discover and maintain routes to other nodes in the network. Emergency search-and-rescue operations constitute an application area for ad hoc networks.

Mobile Ad hoc Networks (MANETs) consist of a set of de-centralised end-user nodes which perform routing in a distributed manner over the wireless medium. This distinct feature of such networks has created a number of new and challenging research issues in the wireless data networking paradigm. One such issue is routing, which has consequently received significant attention. The scalability issue is one of the main problems researched in routing. This has led to the proposition of various types of routing protocols such as reactive (or on-demand) routing protocols. These routing protocols improve the scalability by reducing the amount of routing overheads introduced through the network by limiting route calculations to occasions when a route is required. Consequently, a significant amount of reduction in routing overhead can be achieved at a cost of extra delays [1] [2] [3]. Moreover, most current routing protocols assume homogeneous networking conditions where all nodes have the same capabilities and resources. Although homogeneous networks are easy to model and analyses, they exhibit poor scalability compared with heterogeneous networks consisting of different nodes with different resources and capabilities.

1.2 Summary of Open Research Issues Identified in Current Literature about Scalability of MANETs Routing Protocols in Homogeneous and Heterogeneous Environments

There is significant number of existing researches that focus on the scalability with on-demand routing protocols in homogeneous MANETs by reducing control overheads. However, these researches have attempted to tackle scalability and overhead problems through the use of routing strategies that require pre-existing knowledge of destination nodes as in [21, 27, 1]. The use of pre-existing knowledge is, in reality, not applicable to the majority of mesh network scenarios nor is it feasible to disseminate or acquire global knowledge of nodes. This will raise a question:

- How can on-demand MANET routing protocols be scalable by having:
    1. No pre-existing knowledge about the destination.
    2. Reduce control overheads without increasing delay.

This question is answered in Chapter 3, where a new routing strategy is proposed to improve the scalability while reducing route discovery overhead, hence solving the Broadcast Storm Problem without the need for a source node to have pre-existing knowledge of the destination node. This strategy has been extended in Chapter 4, by studying and improving the performance factors of this strategy.

Current MANET routing protocols do not adapt well to heterogeneous conditions. The lack in existing research regarding the issue of MANET routing protocols and node heterogeneity is that:

- Most of published works on MANETs routing protocols and node heterogeneity have not modeled the heterogeneity clearly [41, 42, 43, 44, 45, 46].

- The unidirectional link problem that occurs because of differences of transmission powers have not been addressed well in existing literature [43, 47, 49].

- Assigning most of the routing load to the powerful nodes, as they possess more resources and communication capabilities. This approach eliminates number of hops and can reduce delay; however, this strategy can create network traffic bottlenecks and potential single point of failure for one or more routes.

For the above reasons, my thesis will focus on developing a routing protocol for heterogeneous MANET based a new model for Heterogeneous MANETs. This model includes different node resources: interfaces (multi interfaces, single interface), power (battery and continuous power), and transmission range. Therefore, the direction of my research is to answer the following questions.

1. What are the performances of the current MANET routing protocols on new proposed architecture for Heterogeneous MANETs?

2. What are the expected problems in presence of node heterogeneity?

3. How can the current routing protocols be improved to adapt our HMANET architecture where:

    - Solving unidirectional links
    - Routing data through different interfaces
    - Utilizing the node heterogeneity to achieve scalability by reducing number of broadcasting nodes.
    - Avoiding nodes with low battery in routing process

- Balancing the routing loads on powerful nodes to avoid any congestion.
- Selecting path according reliable links

These questions are answered in Chapters 5, 6 and 7.

1.3 Thesis Structure and Summary Contributions

The main objective of this thesis is to improve scalability of homogeneous and heterogeneous MANET routing protocols. This research has two main parts. The first part is to develop a routing protocol to reduce control overheads in homogeneous environment. The second part aims to utilise nodes heterogeneity to enhance the scalability of the networks. In this section, we outline the following chapters and briefly describe their contents and key contributions.

Chapter 2 introduces the current literature related to MANET routing protocols. Then scalability issue with current routing protocols is explained in detail. It continues with a discussion of the routing process in heterogeneous MANET. This discussion includes a summary of different techniques to enhance route discovery process to adapt heterogeneity environment. This work resulted in the following publication:

- H. Al Amri, M. Abolhasan and T. Wysocki: ”Scalability of MANET Routing Protocols for Heterogeneous and Homogenous Networks”, In the international Conference on Signal Processing and Communication Systems (ICSPCS ’07), Australia, Gold Coast, 17-19 December 2007. [4]

Chapter 3 describes and evaluates a new strategy to reduce control overheads and improve the performance of on-demand routing when previous knowledge of the destination is unavailable at the source. A new routing protocol is proposed which is called On-demand

Tree-based Routing Protocol (OTRP). This protocol combines the idea of hop-by-hop routing such as Ad hoc On-Demand Distance Vector (AODV) with an efficient route discovery algorithm called Tree-based Optimised Flooding (TOF). TOF minimises control overheads by selectively flooding the network through a limited set of nodes, referred to as branching nodes. This algorithm is explained with theoretical analysis. AODV, DYnamic MANET On-demand (DYMO), and Optimised Link State Routing (OLSR) are used to evaluate the performance of OTRP in homogeneous MANETs. Theoretical analysis and simulation results show that OTRP significantly reduces routing overheads and achieves higher levels of data delivery than the other protocols. This work resulted in the following publication:

- H. Al Amri, M. Abolhasan and T. Wysocki: ”On Optimising Route Discovery in Absence of Previous Route Information in MANETs”, In IEEE 69th Vehicular Technology Conference VTC2009-Spring (IEEE VTC), 2629 April 2009, Barcelona, Spain. [5]

Chapter 4 presents a comparative study of the factors that affect the performance of OTRP. These factors are the number of branch nodes, the location of the branching nodes and number of RREQ retries. Each factor is individually tested with different parameters in term of different nodes density and mobility. The best parameters of each factor are used to improve the performance of OTRP. This work resulted in the following publication:

- H. Al Amri, M. Abolhasan, D. Franklin, J. Lipman: ”Optimised Relay Selection for Route Discovery in Reactive Routing”. To appear in Elsevier Ad Hoc Networks Journal 2012. [10]

Chapter 5 studies the issue of heterogeneity under MANET routing protocols. The misbehaviour of these protocols in Heterogeneous MANET (HMANET) is described by simulating and evaluating different MANET routing protocols in heterogeneous and homogeneous MANET. Then it describes unidirectional links problem in HMANET. This problem is solved by proposing a strategy which is called Location-Based Utilisation (LBU). Although LBU is based in nodes locations, it focuses on detecting and utilising unidirectional links in route discovery process for on demand routing protocols. LBU is applied on top of AODV and OTRP then it is evaluated by comparing to current strategies like black list and neighbours list. This work resulted in:

- Huda Al Amri, Mehran Abolhasan, and Tadeusz Wysocki. 2010. Scalability of MANET routing protocols for heterogeneous and homogenous networks. Comput. Electr. Eng. 36, 4 (July 2010). [8]
- H. Al Amri, F. Safaei, M. Abolhasan, D. Franklin, J. Lipman: ”Location-Based Utilization for Unidirectional Links in MANETs”. To appear in the Eighth International Conference on Wireless and Mobile Communications (ICWMC 2012) June 24-29, 2012 - Venice, Italy. [9]

Chapter 6 extends the idea of OTRP to be applied on HMANET. It proposes a network model for heterogeneous MANET which considers different nodes resources: Interfaces (multiple interfaces, single interface), power (battery and external power), and transmission range. Then new routing discovery process is presented to work in heterogeneous MANET. This routing protocol considers and utilises different nodes resources to reduce control overheads by adjustig and determining:

1. Transmitting power of mobile nodes according to their remaining battery capacities.
2. Distribution of powerful nodes to balance the traffic loads on the network.
3. Node types according to their resources: powerful or limited.
4. How much routing loads can be distributed on powerful nodes.
5. Which interface must be used in case of nodes with multi interfaces.

Then a new routing metric is proposed for heterogeneous MANETs to utilise node heterogeneity to route data efficiently. This metric balances the use of shortest path with minimal hop count and path with the best quality with high number of powerful nodes.
Ths work resulted in:

- AlAamri, H.; Abolhasan, M.; Wysocki, T.; Lipman, J.; , ”On Optimising Route Discovery for Multi-interface and Power-Aware Nodes in Heterogeneous MANETs,” Wireless and Mobile Communications (ICWMC), 2010 6th International Conference on on Wireless and Mobile Communications, vol., no., pp.244-249, 20-25 Sept. 2010. [6]
- AlAamri, H.; Abolhasan, M.; Wysocki, T.; , ”Routing metric for multi-interface and power-aware nodes in heterogeneous MANETs,” Communications, 2009. APCC 2009. 15th Asia-Pacific Conference on , vol., no., pp.372-375, 8-10 Oct. 2009. [7]

Chapter 2

Literature Review

2.1 Introduction

Mobile Ad-hoc networks began in the form of packet radio networks in the 1970s when medium access control approaches and a kind of distance-vector routing were used. In 1980s , this form was developed into the packet-switched network for the mobile battlefield in an environment without infrastructure. The commercial Ad-hoc networks arrived in 1990s when new wireless technologies such as IEEE 802.11 became capable of providing high bandwidth for mobile data communication. This led to new paradigms of wireless networks such as Mobile Ad-hoc Network (MANETs) [11].

MANETs are composed of a set of arbitrarily distributed and potentially mobile wireless nodes where any node may act as an information source, either a sink or a router. In other words, MANET can be defined as a dynamic network of autonomous mobile nodes where wireless links are used without existing infrastructure. This kind of network leads to a high rate of topology changes which occur rapidly. Therefore, these networks present a number of challenging research issues - in particular, those of continuously achieving optimised routing. This subject has received significant research attention and led to the development of numerous routing protocols. MANET has many applications in real life such as tactical networks, sensor networks, emergency services, commercial environments, and home and enterprise networking.

This chapter introduces the current literature related to MANET routing protocols. MANET routing protocols categories are described in details with description of several representative routing protocols in each protocol category in the next section. The scalability issue of MANET routing protocol is discussed in Section 3. Section 4 discusses routing in heterogeneous MANETs.

2.2 Review of Routing Protocols in MANET

MANET can be referred to multi hops wireless Ad-hoc network where each node can carry a routing packet from source to destination. Accordingly, each node behaves as a router as it must assist in route discovery and maintenance processes. Therefore, a set of instructions and algorithms are needed to manage a routing process in such networks using a routing protocol. As a result, the routing issue has received significant attention which, this has led to the proposition of various types of routing protocols. According to the strategies of discovering and maintaining routes, these protocols can be classified into three different categories: proactive, reactive and hybrid. This section outlines the main features of each class and the following terms are used to describe the performance of the routing protocols: delay and protocol overhead. Network delay is the time taken for data to travel from source to destination. On the other hand, protocol overhead is network routing information which includes protocol overhead and application-specific information that is not part of the data contents as it uses a portion of available communication channel capacity. If delay and overhead are low, the performance of the protocol is good.

2.2.1 Proactive Routing Protocols

Pro-active routing protocols, are examples of early attempts at providing end-to-end routes in Ad-hoc networks. They are generally based on the traditional distance vector and link state algorithms which were primarily designed for wired networks, and as such, operated only in small Ad-hoc networks. Because in these protocols routes are maintained periodically regardless of whether they are required or not [12, 13, 14, 15]. Furthermore, routes updates may propagate globally using blind flooding which results in the Broadcast Storm Problem (BSP) [16]. In high node density networks, overhead caused by BSP can reduce the available bandwidth significantly. However, the proactive routing protocols have lower latency in sending data through the network because the path to destination has already been established.

The differences among the protocols in this class are routing structure, number of tables, frequency of updates, use of hello messages and the existence of a central node; therefore, each protocol reacts differently to topology changes. The current proactive routing protocols are inherited from either distance-vector or link-state routing algorithms. In link state routing, each node periodically maintains link-state cost of its neighbours [17], e.g. Optimised Link State Routing (OLSR) [13] and Fisheye State Routing (FSR) [15]. In distance vector routing, each node periodically maintains a set of routes of shortest distances to each destination e.g. Destination Sequenced Distance Vector (DSDV) [12] and Wireless Routing Protocol (WRP) [18].

DSDV [12] is one of the earliest proactive routing protocols based on Bellman-Ford routing algorithm. The main contribution of DSDV is to solve the routing loop problems by using sequence number for each route to destination in the routing table. This number is assigned by destination where the route with the most recent sequence number is used to route data to destination. Two type of packets are used to reduce the control overhead being flooded across the network. The first type is called full dump and it carries all the available routing information. Incremental packet is the second type, a shorter one, sent more frequently and carrying the updated information that has been changed since the last full dump.

WRP [18] is similar to DSDV. However, one of the differences is that, in WRP, each node maintains four routing tables and as the network increases, this protocol consumes significant amount of memory to maintain multiple tables. In addition, hello messages are used to ensure the connectivity with neighbours. Consequently, more bandwidth and power are consumed.

FSR [15] is a link-state proactive routing protocol. This protocol frequently updates network information for nodes that are within its scope only, thus controlling the control overhead. However, FSR is not characterised by high mobility because of inaccurate routing information to destination.

OLSR [13] is a point to point flat routing protocol. The main feature of OLSR is the use of Multi-Point Relays (MPR) to reduce the BSP. It also minimises the number of the required control packets when compared to DSDV. The MPR set is an optimised set of neighbouring nodes that are selected to re-broadcast link state information. MPR are selected when each node has link to at least one MPR node as first hop neighbour. OLSR uses Hello and Topology Control (TC) messages to discover and disseminate link state information.

2.2.2 Reactive Routing Protocols

On-demand (Reactive) routing protocols were introduced to improve scalability and overhead issues related to proactive routing protocols. This was only achieved by performing route discovery when a route is needed, rather than periodically maintaining routes as with proactive protocols. Consequently, a significant amount of reduction in routing overhead can be achieved at a cost of extra delays [1, 2, 3, 19]. Reactive routing generally occurs in two phases: route discovery and route maintenance. When a node has data to send and a pre-existing route is not available, route discovery is initiated. In this phase, the source node initiates a blind flood of RREQ packets throughout the network. When a RREQ packet reaches a node with an active route to the destination (or it reaches the destination itself), a route reply is sent back to the source either using blind flooding or link-reversal (unicast). The use of blind flooding in route discovery makes reactive protocols subject to the BSP. A route maintenance phase is initiated when an active route, which is transporting data, is broken. Using a local route repair strategy, a broken route may be repaired locally by the node that detects that broken link. Alternatively, a Route Error (RERR) packet is sent to the source and a new route discovery initiated. A disadvantage of reactive routing compared with proactive routing is that there may be a delay in data delivery due to the initial route discovery.

Reactive routing protocols can be classified into two groups: source routing and hop by hop routing. In source routing, data packet headers carry the entire path to destination, and intermediate nodes do not care about maintaining the routing information. On the other hand, this kind of protocols may experience high level of overhead per packet as the number of intermediate nodes increases and they also have a higher chance of a route failure. Packets in the second group of reactive protocols have to carry only destination and next hop addresses which means that nodes have to maintain and store routing information for active routes. Ad-hoc On-Demand Distance Vector (AODV), Dynamic Source Routing (DSR) , Dynamic MANET On-demand (DYMO), and Location-Aided Routing (LAR) are well-known reactive routing protocols.

AODV [20, 1] is a hop-by-hop routing protocol, which introduces a more dynamic strategy to discover and repair routes compared to DSR. Destination sequence numbers are used to avoid the problem of infinite loops. AODV maintains only active routes to reduce overheads and contention.

DSR is a reactive source routing protocol [20,3]. It discovers routes on demand using a route discovery and maintenance strategy. Multiple routes are applied to achieve load balancing and to increase robustness.

DYMO [19] is based on DSR and AODV. DYMO can adapt to network topology changes and mobility patterns by detecting and determining unicast routes to destinations as needed. This protocol can control different patterns of traffic in large networks by allowing nodes to communicate with groups of other nodes. The performance of DYMO is improved by using accumulative routing that reduces RREQs in contrast with AODV and DSR.

LAR [20, 21] uses GPS information to detect the location of nodes - all nodes must have GPS receivers thus reducing overhead due to flooding. This protocol has two strategies for route discovery. Firstly, it limits RREQ propagation to a defined area (i.e. Request Zone); secondly, it stores the coordinates of a destination node enabling a RREQ to be directed toward the destination coordinates, thereby avoiding the BSP and reducing overhead.

2.2.3 Hybrid Routing Protocols

Hybrid routing strategies can be both reactive and proactive in nature. These protocols use proactive and reactive properties in cases which would increase the scalability of the network. For example, proactive routes may be used to maintain connectivity to nearby nodes, whereas routes to more remote (or far away) nodes may be determined reactively. Therefore, periodically propagating global routing information is minimised and routes become more accurate as the data travels towards the destination. Furthermore, these protocols introduce different hierarchical schemes, which group nodes into clusters, zones or trees to minimise the number of rebroadcasting nodes in the network [22] [23] [24]. The performance of hybrid routing protocols in very large networks is still an open research question, hybrid routing protocols are more complex in nature than purely reactive or proactive protocols. Additionally, significant levels of computing power is required to study their performance in realistic simulation scenarios. Therefore, much of the development and implementation trials currently developed are based on proactive and reactive protocols. Zone Routing Protocol (ZRP) can serve as one example of hybrid routing protocols. In ZRP [24], nodes are grouped into zones and communications between them depend on their locations in the zone. Another example of hybrid routing protocol that can adapt to changes in node density and mobility is Scalable Location Update Routing Protocol (SLURP) [23]. It uses GPS information to manage node location and eliminates global routing. Each node is associated with a home region and sends its new location to its home region as it moves. Hence, when a route is required, the source node only has to query the home region of the destination. This protocol is suitable for large networks where the number of nodes and their mobility are high [20] [23].

2.2.4 Routing Structures

According to routing structures, MANET routing protocols can also be divided into flat routing protocols, hierarchical routing protocols, and geographic position information assisted routing protocols [25] [26]. Each protocol routes data proactively or reactively or uses the combination of the two strategies. Flat protocols can be tables driven (proactive) like DSDV or on demand protocols (reactive) like DSR. Those protocols have been described previously.

The target of wireless hierarchical routing protocols is to group mobile nodes to reduce the area of flooding. The nodes are grouped in terms of clusters, trees or zones where there is a leader that manages routing in its area. Each node has different functionality depending on its location inside or outside the group. This strategy reduces the size of routing tables and the routing information [25]. An example of a wireless hierarchical routing protocol is the ZRP [20]. The advantages of those protocols are reduction of overheads and improvement of scaling large networks compared to flat routing protocols. However, when node mobility is high, hierarchical routing may introduce more overhead due to cluster re-calculation. In addition, a cluster head is a critical node and communication breaks if it goes down.

Geographic position information assisted routing protocols improve routing by using Global Position System (GPS) receivers built into the nodes to get their location information [25]. Those protocols route the data using Geographic Addressing and Routing (GeoCast) where messages are sent to all nodes in specific geographical area. GeoCast uses the geographical information rather than logical addresses. Geographical information about nodes eliminates propagation of routing information. Hence, geographical protocols have more efficiency in adapting to changes in node density compared to other protocols. Examples of geographic routing are DREAM and SLURP [27] [23]. However, mapping address to location produces more overheads. In addition, using GPS consumes the power of a mobile node.

2.3 Comparison of Different Classes of Routing Protocols for MANETs

In this subsection, comparison of proactive, reactive and hybrid protocols is outlined by combining their published theoretical performance [28, 29]. The comparison is further verified through the published simulation results [30, 31, 29, 32, 33, 34]. The following metrics are used to evaluate the performance of routing protocol:

1. Packet Delivery Ratio (PDR) : Ratio of received packets at the destination to packets sent by the source node.
2. End-to-End Delay (EED) : Average end-to-end delay for transmitting data packets from source to destination.
3. Normalised Control Overhead (NCO) : Total number of control packets to the total number of data packets transmitted.

Proactive protocols are the oldest protocols that have been derived from wired network routing protocols to work in the wireless environment, therefore, they possess many features of wired routing protocols, such as, routing tables used to keep the routing information and which are periodically updated even if not needed. As the node moves, it produces a flooding of packets containing the topology changes which cause high overheads. Hence, in general, proactive protocols produce more overheads resulting in a lower throughput in case of high mobility as illustrated in theoretical and model based analysis below. In order to compare the protocols, the following set of parameters is usually defined:

- N=number of nodes,
- L=average path length (in hops),
- R=average number of active routes per node,
- μ=average number of link breakage per second (reflect mobility degree),
- α=route activity, which shows how frequently the node generates new route requests,
- ρ=route concentration factor that monitors traffic hot-spots in MANET.

Proactive, reactive and hybrid protocols have been evaluated theoretically in [29] . It has been found that asymptotic overhead for proactive is $O(N^{1.5})$ due to the process of maintaining and forwarding tables to keep periodic updates. In reactive protocols, route requests and reply messages create overhead of cost $O(N^2)$, while in hybrid protocols this is $O(N^{1.66})$. The number of packets that are produced by proactive protocols per second is $\mu * L * N^2$ while for reactive protocols it is $(\alpha + \rho * R * \mu) * L * N^2$. Reactive protocols are found to perform better than proactive ones if $\mu * L * N^2 > (\alpha + \rho * R * \mu) * L * N^2$. It has been concluded in [23] that proactive protocols can be used mostly in static or quasi-static networks; reactive protocols are preferred in more dynamic networking and hybrid protocols are more efficient in adapting to changes in network conditions.

Analytical model that compared control overhead with mobility and data traffic for proactive and reactive protocols for MANETs has been presented in [28]. It has been found that the number of packets produced by optimised reactive protocols in MANET is $O_r \mu a L N^2$ and for optimised proactive protocols it is $O_p \mu A N_p N^2$, where

- O_r= route request optimisation factor,
- AN_p=active next hops ratio,
- a= number of active routes per node (activity),
- O_p= broadcast optimisation factor.

In [28], these two analytic approaches of proactive and reactive protocols have been compared with existing simulations and it has been observed that OLSR is more scalable than DSR. It has also been found that reactive protocols are better than proactive in high mobility if they use routes that do not share links.

Hierarchical routing protocols, geographic position information assisted routing protocols, and hybrid routing protocols are more adaptable to various node density than flat protocols [20, 23]. In [20], hierarchical routing protocols have been found to be more scalable than flat protocols because they limit the propagation area by structuring the network nodes. However, overheads are increased with those routing schemes due to location management. Therefore, hierarchical protocols are suitable for scenarios with high density but low mobility. Geographic routing protocols also perform well in high density because of the simplicity of location management in the route discovery.

2.4 Scalability of MANET Routing Protocols

The scalability of MANET routing protocols measures the efficiency of the routing protocol to work in high nodes density. On-demand routing protocols have the potential to achieve high levels of scalability in Ad-hoc networks;but before this can be realised, two major issues need to be resolved: the first is route discovery overhead caused by the blind flooding

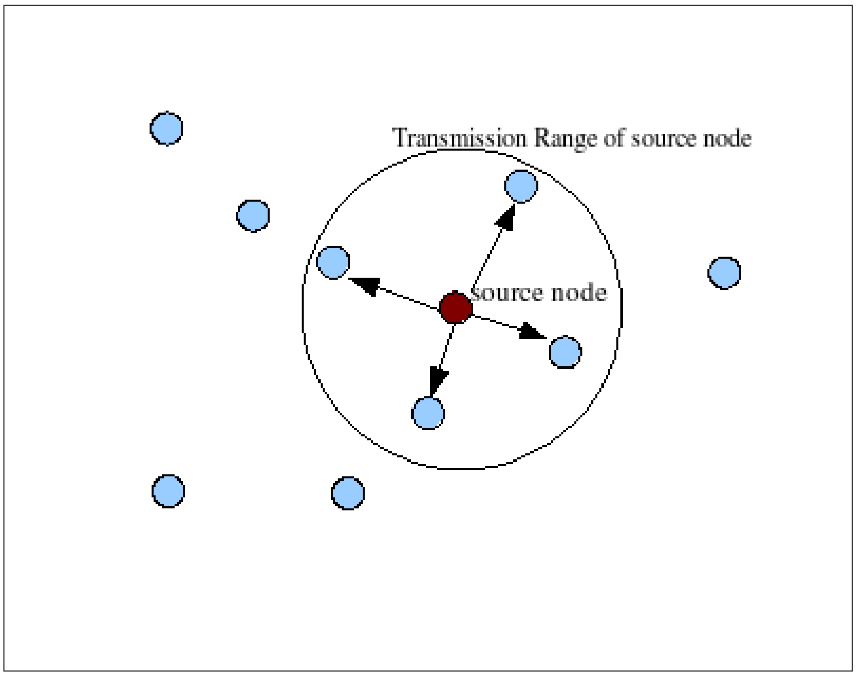


Figure 2.1: Broadcasting.

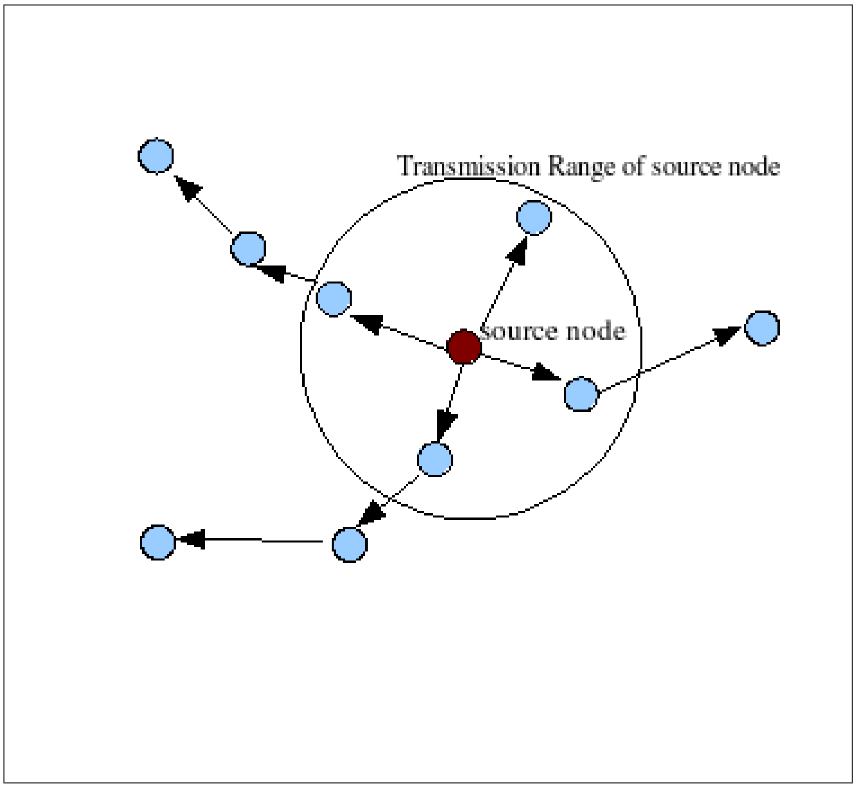


Figure 2.2: Blind Flooding.

of RREQ packets; the second is delay caused by the initial route discovery process. However, reducing overhead can also reduce the amount of delays introduced into the network, because as overhead increases, so does the number of data packets waiting in queues. Thus increasing the amount of delay experienced by each packet before it is sent to its destination. Flooding is the simplest method to disseminate information in Ad-hoc networks. Flooding within neighbourhood is called broadcasting when a source node sends information packet to all its 1-hop neighbours (see Figure2.1 and Figure2.2). If all nodes rebroadcast flooding occurs.

In MANETs, the simplest method for disseminating information to all nodes in the network is blind flooding, when each node rebroadcasts a received packet at least once, thereby propagating the packet throughout the network. Blind flooding is utilised by AODV and other routing protocols to perform route discovery. However, blind flooding suffers from the broadcast storm problem (BSP). The BSP may result in redundant broadcasts regardless of whether neighbours have already received a broadcast from another node or not. Further, the BSP may cause several periods of medium contention in wireless networks resulting in increased control overhead and delay.

Eliminating control overheads can be achieved either by reducing the number of route recalculations or reducing rebroadcasting area and the number of rebroadcasting nodes.

2.4.1 Reducing the Number of Route Recalculations

Route recalculation mainly occurs if there is a link failure and consequently a new route is required. To reduce the number of route recalculation, several approaches have been proposed such as stable routing, multi-path routing and routing based on pre-existing knowledge of the network.

In stable routing only routes that exhibit some form of stability such as remaining active for a longer period of time are selected. A variety of strategies have been proposed to quantify the stability of routes [35, 36, 37, 38]. In [37], AODV has been modified to reduce overhead by determining a Route Fragility Coefficient (RFC) for use as a route metric, calculated directly as a function of the RSSI for each potential router. The most stable route between source and destination is selected to reduce the number of route recalculations. The destination node replies only to RREQs received through the most stable route with the lowest RFC. Simulation results in small networks show that this strategy significantly reduces routing overheads when compared to standard AODV.

In multipath routing, more than one route for data transmission is utilised, so that if a single route should fail, additional backup routes are available, thereby avoiding the need for route recalculation. Dynamic Source Routing (DSR) and Split Multipath Routing (SMR) are on-demand routing protocols that use this strategy [3, 39]. In [40], a mechanism called Controlled Flooding (CF) is proposed to reduce control overheads due to route recalculation. CF is used to discover alternate paths based on previous knowledge about the approximate location of the destination and the search is limited to within one hop of any existing routes.

A number of different strategies that make use of pre-existing network knowledge to improve route repair due to link failure have been proposed. In AODV [1], source nodes use an expanding ring search along with the last hop count to the destination to minimise RREQ propagation. In LAR [21] scheme 1, the source node limits RREQ propagation to a localised region in which the destination is expected to be. In LAR scheme 2, RREQ packets travel only towards the destination after each hop. Relative Distance Micro-discovery Ad-hoc routing (RDMAR) [27] minimises RREQ propagation within a localised region by utilising hop count. Similarly, Location-based Point-to-Point Adaptive Routing (LPAR) protocol [2] uses pre-existing knowledge to limit the number of RREQ packets propagated through the network. However, unlike LAR and RDMAR, LPAR introduces a three-phased route discovery approach. In the first phase the source node performs route discovery through unicasting a RREQ toward the known location of the destination. If the first phase of route

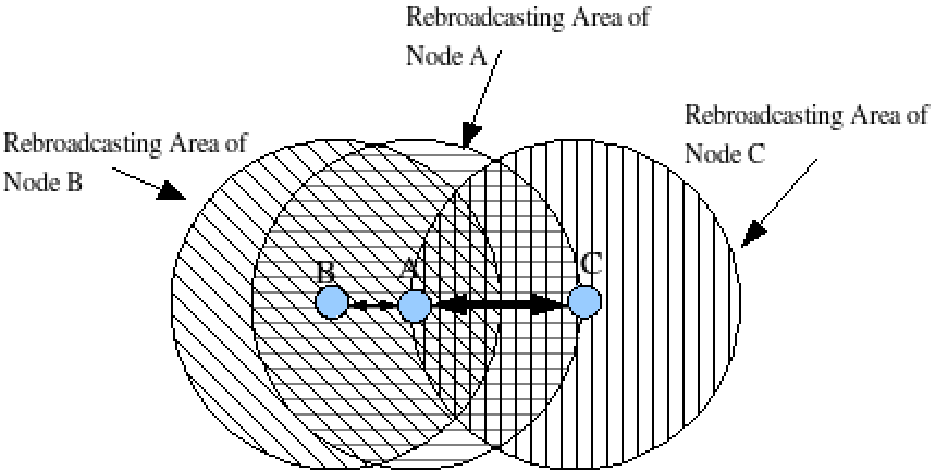


Figure 2.3: Rebroadcasting Area.

discovery fails, LPAR uses a strategy similar to LAR scheme 1 and AODV, in the subsequent route discovery phases.

2.4.2 Eliminating Rebroadcasting

Eliminating the number of rebroadcasting nodes and areas is another way to reduce control overhead in MANETs when not all nodes in the network are rebroadcasting. Figure3.6 shows the rebroadcasting area. Heuristic-based flooding is a mechanism to make a rebroadcasting decision based on parameters and thresholds that are related to the network environment. Several schemes are introduced in [39] which are:

- **Count-based scheme:** rebroadcasting decision is made based upon a threshold value of the duplicated packet. If a node receives a number of duplicated packets which is less than the count threshold, then it will rebroadcast; otherwise it will not.

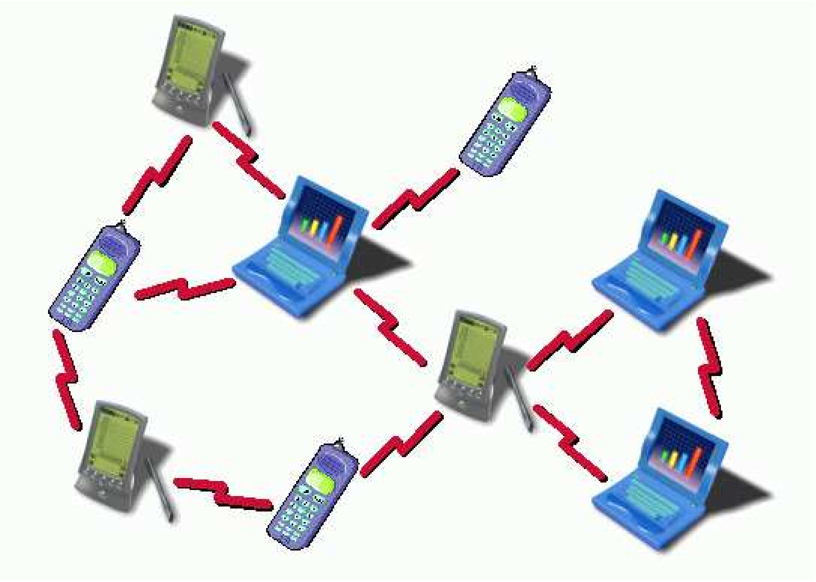


Figure 2.4: Heterogeneous MANET.

- **Distance-based scheme:** it considers relative distances between the nodes and decides whether they provide a larger broadcasting coverage. If the distance between the receiving node and the source is greater than some distance threshold *D*, then the receiving node will rebroadcast the message. In Figure3.6, node C provides larger rebroadcasting area to node A because the distance between nodes A and C is larger than the distance between nodes A and B.

- **Location-based scheme:** it requires a GPS to calculate the additional coverage area that is provided by the receiving node. It has been proved that additional coverage area can be achieved if boundary nodes are selected as relay nodes. However, this may create unstable links if boundary nodes are included in the path.

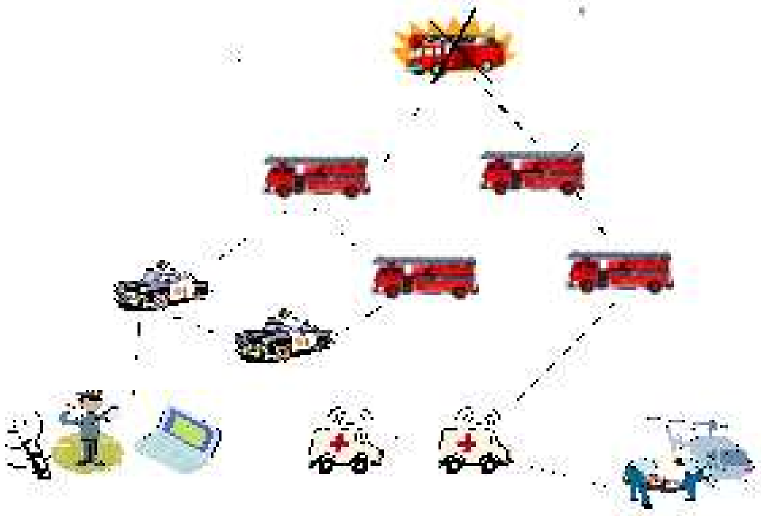


Figure 2.5: Heterogeneous MANET in rescue operations system.

2.5 Heterogeneity of Nodes and MANETs Routing Protocols

The issue of node heterogeneity is not considered in current MANET routing protocols. Although most current MANET routing protocols assume homogeneous networking conditions where all nodes have the same capabilities and resources, in real life MANET can consist of heterogeneous nodes that have different capability and resources such as military (battlefield) networks and rescue operations systems. Although homogeneous networks are easy to model and analyse, they exhibit poor scalability compared with heterogeneous networks. As Figure2.4 shows, heterogeneous MANET (HMANET) comprises of mobile devices that have different communication capabilities such as radio range, battery life, data transmission rate, etc. Figure2.5 shows a rescue operations system where there are limited mobile devices that are provided to individual rescuers, ambulances, police vehicles and helicopters. Limited mobile devices have the lowest communication capabilities, while the helicopter is the most powerful communication device forming the backbone of the rescue team. Therefore, heterogeneity of nodes is one of the main issues that needs to be considered in constructing and developing routing protocols for MANETs.

Recently, a few publications have introduced strategies to develop routing protocols to accommodate HMANETs [41,42,43,44,45,46]. Existing literature on the routing issue and heterogeneity of nodes has focused on: developing clustering algorithms, improving existing routing protocols and proposing new protocols with weight metrics of node resources.

2.5.1 Clustering and HMANET

Node heterogeneity in MANET and the issues of stability and scalability have been considered using clustering scheme in [41, 42, 43]. The concept of clustering is to group nodes located in nearby region or hop into one routing area. Each cluster has a leader which is elected by nearby nodes based on its capability. Other nodes in cluster are called member nodes. The leader of a cluster is responsible for the communication with outside nodes. In HMANET, different routing strategies have been proposed to utilise heterogeneity of nodes resources using clustering. The differences among these strategies mainly include methodology of cluster constructing, leader election process, and cluster maintenance. In [41], random Competition based Clustering (RCC) strategy has been proposed to achieve stability and simplicity of cluster by using structure of backbone nodes and local subnets in HMANET where backbone nodes form cluster heads. There also are so the called backbone capable nodes which act as redundancy nodes that will replace cluster leaders if there is any fault. The heterogeneity has been represented by having different protocols to route data inside cluster and outside it. Local nodes in a cluster use a proactive routing protocol to route data while an on-demand routing protocol is used to route a packet among backbone nodes. The simulation has been carried out by using DSDV as a proactive routing protocol and AODV as an on-demand routing protocol, DSDV-AODV. This strategy has been compared to flat AODV and hierarchical AODV. DSDV-AODV had a better packet delivery ratio and the lowest delay.

The idea in [42] targeted to find optimal partition that explicitly takes into account the heterogeneity of the network, as an integer linear programming (ILP) problem using clustering approach. The paper uses heterogeneity characteristics of nodes such as memory, battery capacity, traffic load, mobility, and nodes stability in forming clusters and electing cluster head. This scheme has the following two phases: finding appropriate clusters based on ILP, and developing heuristic and optimal solution to ILP. Some constrains have been applied to form cluster and routing process based on heterogeneity and clustering rules. The simulation showed that applying heterogeneity characteristics can reduce the overheads are produced by the process of maintaining clusters.

This was the first paper to consider mobility in HMANET as a parameter in the routing process. A Stable Clustering Algorithm (SCA) was proposed in [43] to adapt stability of cluster and the topology changes of HMANETs by considering different resources of nodes. The input parameter for the cluster head election algorithm is the cluster radius. SCA has three different steps: weight estimation, cluster formation and cluster maintenance. Weight estimation process is used to form clusters and to elect cluster heads. Weight function is based on an ILP formulation as in [42] where each node evaluates its weight according to its criteria and capabilities. Therefore, each node broadcasts its weight with its ID. The node with the highest weight is then selected as a cluster head. Simulation results showed that SCA is scalable for the large HMANET. It also achieved stability of clusters as the number of nodes increased.

2.5.2 Improving Existing MANET Routing Protocols for HMANET

Current MANET routing protocols misbehave when they are used in heterogeneous networks. Few existing protocols such as OLSR [44], Ant-based Routing Protocol [45], LANMAR [46], and AODV [47] have been improved to work effectively with HMANET. In [44], scalability issue of OLSR in MANET has been studied. The study showed that OLSR does not differentiate distinct nodes with different communication capability and resources and the paper proposes a strategy to optimise OLSR by making it scalable over large HMANET when OLSR is improved by organising nodes in hierarchical structure. Hierarchical OLSR (HOLSR) has eliminated overheads and reduced the size of routing table. With HOLSR, the nodes are organised on a logical level where nodes with the lowest resources are in a lower level. Each level has many clusters, where the cluster head is a powerful node with the highest communication capability. HOLSR and flat OLSR have been compared in terms of control overhead, computations overhead, and end-to-end delay. HOLSR shows significant performance improvement compared to OLSR. It also performs well in large HMANETs.

In [45], an Ant-based Routing Protocol is proposed for HMANETs by extending ANTHocNet protocol to use unidirectional link and multipath routing strategies to achieve good reliability and connectivity. The following three mechanisms are used to detect link failure of unidirectional link: detouring unidirectional links, blind retransmission and detection of link by ants. The unidirectional link is enhanced by finding reactive multipaths to a destination and maintaining them in a proactive way. An Ant-based Routing Protocol, AntHocNet, and AODV have been simulated with a static network of homogeneous nodes, static network of heterogeneous nodes and a dynamic network of heterogeneous nodes. It has been found that the proposed protocol in a static network of heterogeneous nodes achieves higher network connectivity, higher data delivery ratio and shorter path establishment.

AODV is enhanced (HAODV) in [47] to work well with heterogeneous interfaces of nodes in MANET. Current AODV routes data through nodes that have the same type of interfaces and discards nodes with different interfaces. In the paper, an algorithm is proposed to route data with different interfaces. The load of a node, its stability and time to convert packets between different interfaces are calculated to evaluate the weight of each link between two nodes.

2.5.3 Developing Routing Discovery for HMANET

Developing new strategies for routing discovery is another issue for HMANET. For example, Utility- based MultiPoint Relay flooding (UMPR) for heterogeneous mobile Ad-hoc networks is introduced in [48]. UMPR acts as an extension of MultiPoint Relay (MPR) to reduce blind flooding. This strategy is a significant improvement compared to complete broadcasts and blind flooding of MPR to extend the life of HMANET. Heterogeneous Biased Route Discovery (HBRD) is introduced in [49] as an on-demand route discovery strategy for HMANET. In this strategy, RREQ packets are delayed in poor devices to avoid using them in the route discovery process, with a delay value being inversely proportional to the remaining battery power to achieve balanced energy consumption. Hence, the routes that include poor devices will not be chosen as the destination replies only when the first RREQ is received and the strategy is implemented on the top of AODV. A testbed experiment and a simulation of AODV and AODV with HBRD have been carried out to compare their performances. In simulation, the nodes were classified into three groups: powerful nodes that do not delay RREQs, limited nodes that have certain delay value, and weak nodes that are excluded from routing process by having the highest delay value. AODV-HBRD demonstrated excellent results in delivering data packets successfully through powerful nodes. However, the delay value is a static value and does not reflect the real conditions of the network.

Another strategy for the routing discovery process in HMANET, On-demand Utility-Based Routing Protocol (OUBRP) strategy is proposed in [50] to develop reactive routing protocols to efficiently utilise the node heterogeneity. A utility-based route discovery algorithm is used to choose the richest nodes with the highest level of resources during route discovery stage. The utility level of resources is reduced if the route was not found and OUBRP reduces the number of re-broadcasting nodes. The unidirectional links are eliminated here using two schemes: the first one is Uni-directional Link Elimination (ULE) to use GPS where each node stores its location information in RREQ packet; the receiving node checks if the forwarding node is in its transmission range or not; If it is, then the receiving node forwards RREQ packet; otherwise the packet is deleted. The second scheme appends neighbour list to RREQ packets (ULE-NL) ; the receiving node checks if it is in the neighbour list; if yes, then the receiving node forwards the packet, otherwise the packet is deleted. OUBRP is implemented over AODV. It has been found that this strategy improves routing discovery and reduces effect of route failure. However, powerful nodes will have most of routing load. The source node initiates the preferred utility on RREQ packets which means that the route will be chosen according to these values only. Moreover, if there is a unidirectional link between two nodes, the RREQ packet is not forwarded.

HMANETs have the potential of reducing the amount of power used by user nodes. In [51], authors state that the supply of power in heterogeneous wireless Ad-hoc networks can affect the lifetime of the network. They propose a cross-layer strategy for Device Energy Load Aware Relaying (DELAR) to utilise powerful nodes. This strategy suggests introduction of a schedule to use different transmission powers in different periods. They also propose a routing and Asymmetric MAC (A-MAC) to support link level acknowledgements with unidirectional links. The unidirectional link in a routing level is solved by using backward paths from limited devices to powerful nodes. Backward paths are set up when powerful nodes broadcast a query message with a certain transmission power. The limited devices will reply and some, which can not reach the powerful node, will relay their replies. The simulation of DELAR showed that this strategy can reduce power consumption and increase the lifetime of the network. The performance of DELAR strategy has been improved in [52] using multiple-packet transmission scheme to reduce delay of DELAR. The concept of this scheme is to transmit multiple packets from powerful node P towards different receivers in one transmission where the transmission is implemented with hierarchical modulation scheme to ensure BER requirements at all receivers. The simulation showed that DELAR with multiple packets improves the energy efficiency and packet delivery ratio and reduces the packet delay comparing to original DELAR.

2.5.4 New Routing Protocols for HMANET

New routing protocols were proposed to make use of node heterogeneity in MANET. A hybrid routing protocol ,referred to as location and power-aware (A4LP), is proposed in [53] to support asymmetric link in heterogeneous networking. The concept of this protocol is to reduce the flooding by implementing m-limits forwarding when the receiver can rebroadcast packets which have a certain flag value that is specified by the sender. Transmission latency and power consumption per packet are used as base to choose the best path to route packets. With A4LP, the neighbours of a node i are classified into four groups according to the type of link and its direction: Out-bound, In-bound, Out/In bound and Not neighbours. If node i has a unidirectional link to node j, then node j is the the out-bound neighbour of i. If j has unidirectional link only to i then j is in-bound neighbour of i. If i and j have bidirectional links, then j is Out/In bound neighbour of i. If there is no link between them then they are not neighbours. The source node sends and forwards packets to only Out-bound and Out/In bound neighbours. There are six phases to discover route from source to destination that are: forward path request, backward path request, forward path reply, backward path reply, forward path request acknowledgement and forward path reply acknowledgement. These phases may consume more bandwidth and increase the delay of data if source node is powerful. A4LP has been improved in [54] to solve the problem of asymmetric connection. A MAC protocol with asymmetric link (AMAC) is introduced to reduce the number of collisions by characterising the ability of a medium access control protocol to silence nodes which could cause collisions. A series of experiments were carried out to compare the pairing of AMAC with A4LP as the upper layer protocol against two well established protocols pairs: AODV/IEEE 802.11 and OLSR/IEEE 802.11 in heterogeneous environment for nodes. AMAC reduced the average packet loss ratio and the average latency. This MAC protocol can provide good functionality of routing protocols in HMANETs compared to IEEE802.11 MAC protocol.

2.6 Chapter Summary

This chapter discusses existing routing protocols for MANET . Each routing protocols class has different behaviours and performance according to MANETs environment such as node density, mobility and traffic. The scalability issue is one of the main problems researched in routing. This has led to the proposition of various types of routing protocols such as reactive (or on-demand) routing protocols. These routing protocols improve the scalability by reducing the amount of routing overheads introduced through the network by limiting route calculations to occasions when a route is required. Consequently, a significant amount of reduction in routing overhead can be achieved at a cost of extra delays. Several approaches have been proposed to reduce the routing overheads of on-demand routing protocols. These approaches are outlined below with their disadvantages:

- Stable routing: generally, in MANETs with highly variable link quality and node mobility, stable routing strategies can't out-perform traditional flooding strategies significantly.

- Multi-path routing: in highly mobile environments, multipath strategies show limited performance improvement over single path routing algorithms, since alternative or backup routes may become invalid just as quickly as the primary routes. Hence, a complete route recalculation would still be required, with all of the overhead that this entails.

- Routing based on previous knowledge: it is efficient if there is knowledge about destination only.

Another issue to be considered is node heterogeneity which is one of the main network conditions that significantly affects the performance of the routing protocols. Current MANET routing protocols do not adapt well to heterogeneous conditions. The common approach to dealing with node heterogeneity in existing research, is to assign most of the routing load to the powerful nodes, as they possess more resources and communication capabilities . This approach eliminates the number of hops and can reduce delay; however, this strategy can create network traffic bottlenecks and potential single points of failure for one or more routes. For example, in a battlefield network scenario, if a vehicle or a tank possessing more powerful communication capabilities were destroyed, the communication with other resources such as soldiers and vehicles could be lost but most research has not considered this situation. There should be alternative strategies to recover any fault in powerful nodes that have been assigned as routers . Furthermore, most of published works on MANETs routing protocols and node heterogeneity have not modelled the heterogeneity clearly. In Section 4, only different transmission powers have been used to simulate node heterogeneity on MANET. Moreover, some publications suggest to have only two types of nodes, while in reality the network may have more than two types of nodes with different resources. Therefore, there should be a real modelling of node heterogeneity to take the advantages of HMANETs and clarify the problems that affect the performances of existing routing protocols. Furthermore, the unidirectional link problem that occurs because of differences in transmission powers have not been addressed well. For example in [50], the unidirectional link is avoided in route discovery process to route packets on path consisting of only bidirectional links . The node heterogeneity on MANETs can be seen as two different architectures. In the first architecture , all nodes begin as homogeneous and as time goes on, the resources of identical nodes deplete differently and thus creating heterogeneity in the network. The second architecture involves different nodes with different resources (CPU, memory, interfaces, battery capacity, disk size, etc) and characteristics (mobility and loads). Most current research considers the first architecture to be the HMANET architecture ;however, in real life HMANETs are considered to be closely related to the second architecture.

Chapter 3

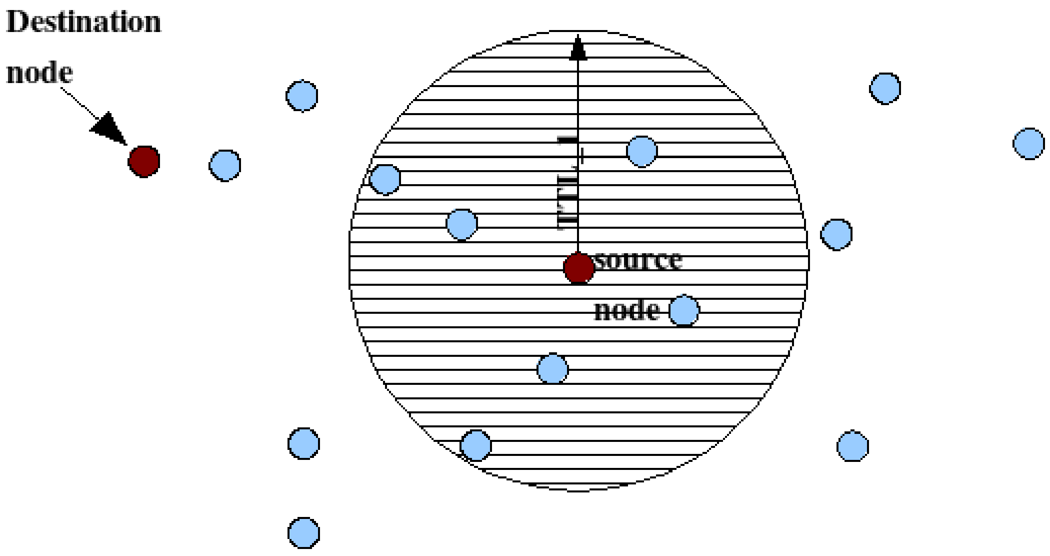
Optimised Relay Selection for Route Discovery in Reactive Routing

3.1 Introduction

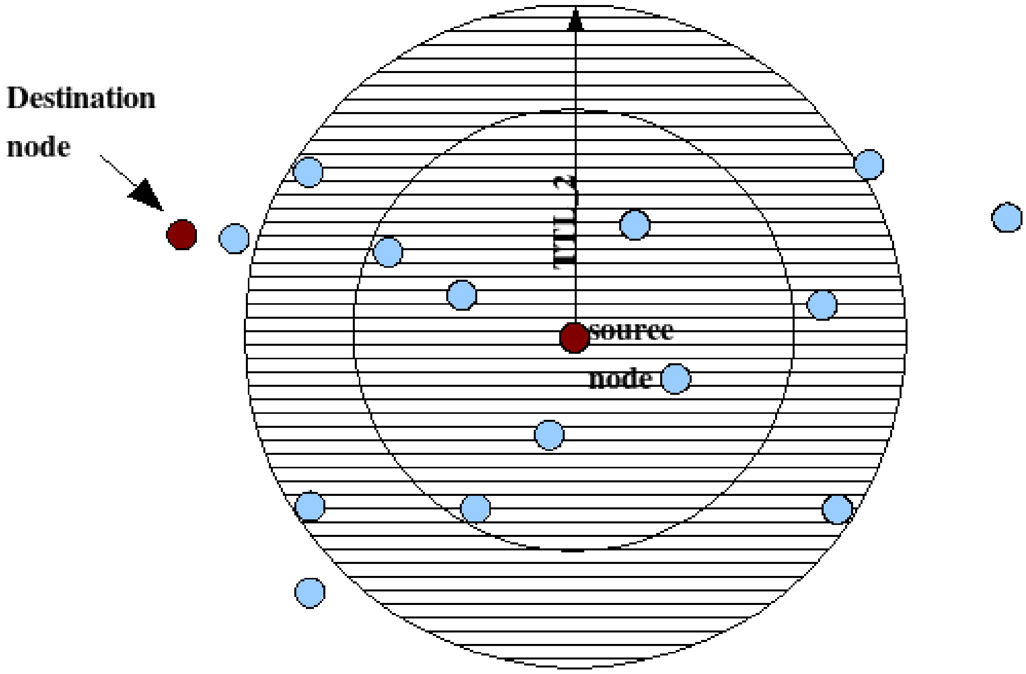
Reactive routing protocols have the potential to provide scalable information delivery in large ad hoc networks. The novelty of these protocols is in their approach to route discovery, where a route is determined only when it is required by initiating a route discovery procedure. Much of the research in this area has focused on reducing the route discovery overhead when prior knowledge of the destination is available at the source or by routing through stable links as discussed in the previous chapter. Some on-demand routing protocols use routing based on the previous knowledge approach to fix link failure of an existing path. Therefore, often a source node is required to re-calculate routes to the same destination. To minimise the level of route re-calculation due to route failures, a number of different strategies have been proposed, which attempt to minimise the number of re-broadcasting nodes during the route discovery process. However, many of the protocols proposed to date still resort to flooding the network when prior knowledge about the destination is un-available. In AODV, an expanding ring search strategy is used to minimise the scope of Route Request (RREQ) propagation, hence reducing control overhead and scaling the network [1]. In this strategy when a source node searches for a path to a destination node, RREQ packets traverse the search ring. This search ring is expanded for each retransmission of the RREQ packets by increasing their Time-To-Live value (TTL) (see Figure 3.1). If there is pre-existing knowledge about the destination, the source node uses an expanding ring search along with the last hop count to the destination. Otherwise, it may use blind flooding to find a path to the destination node.

In LAR scheme 1 (Figure 3.2(a)), the source node limits the RREQ propagation to a localised region in which the destination is expected to lie [21] . In LAR scheme 2 (Figure 3.2(b)), the RREQ packets travel only towards the destination at each hop. Relative Distance Micro-discovery Ad hoc routing (RDMAR) also minimises the RREQ propagation to a localised region [27]. However, unlike LAR, this protocol uses hop count to define a local region. Similarly, the Location-based Point-to-point Adaptive Routing (LPAR) protocol uses previous knowledge to limit the number of RREQ packets propagated through the network to a localised region [2]. However, unlike the previous two protocols, LPAR introduces a three-phase route discovery approach.In the first phase, the source node attempts to find a route by unicasting a RREQ towards the known location of the destination. If the first phase of route discovery fails, LPAR uses a similar strategy to LAR1 and AODV to find a route in the subsequent route discovery phases. While reducing the scope of flooding either in direction or range does reduce the flooding overhead, topographic changes to the network may result in sub-optimal routes.

On-demand routing protocols have the potential to achieve high levels of scalability in MANETs. However, before this can be realised, two major issues need to be resolved. The first is the route discovery overhead caused by blind flooding RREQ packets. The second is the delay caused by the initial route discovery process, the increase in a node's outbound

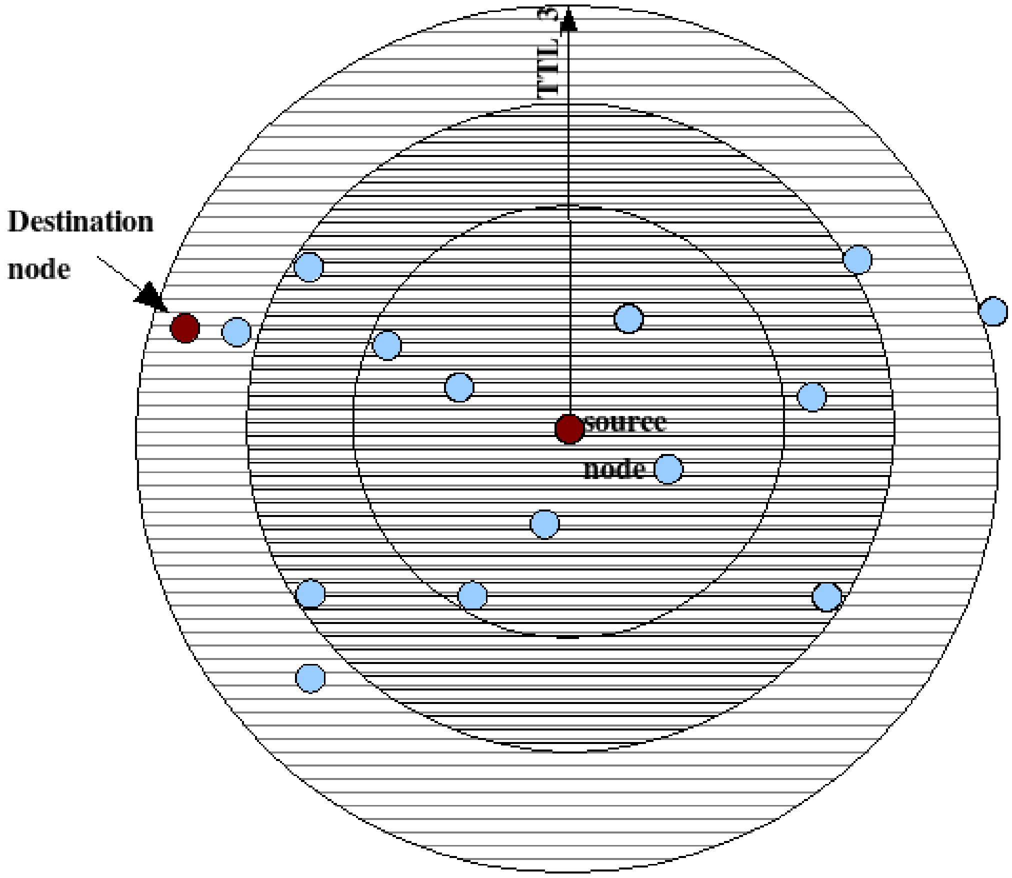


(a) First RREQ Transmission with Search Ring



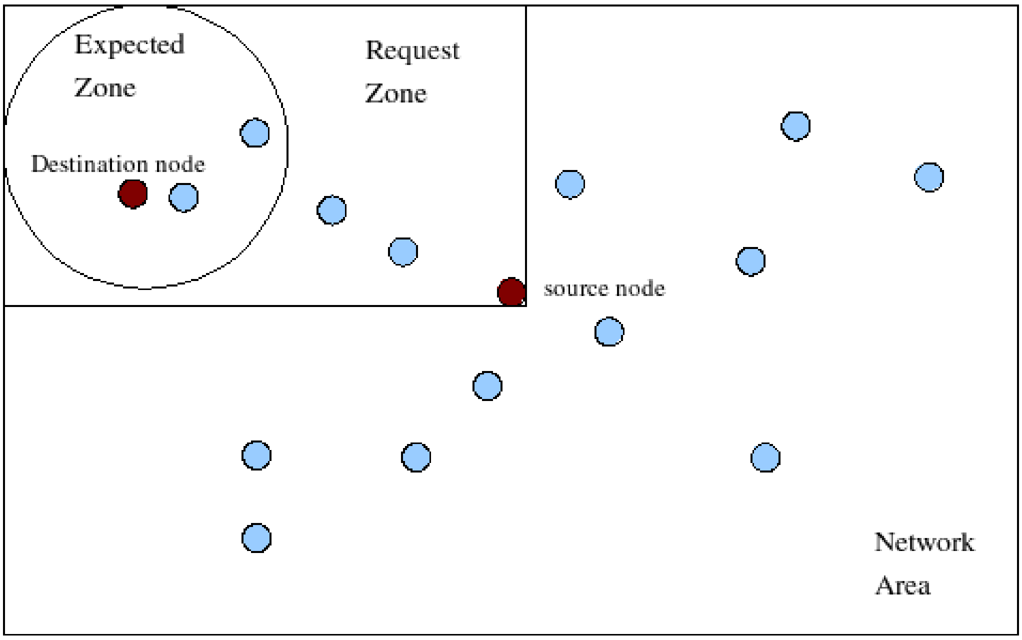
(b) Second RREQ Transmission with Expended Search Ring

Figure 3.1: Expanding Ring Search

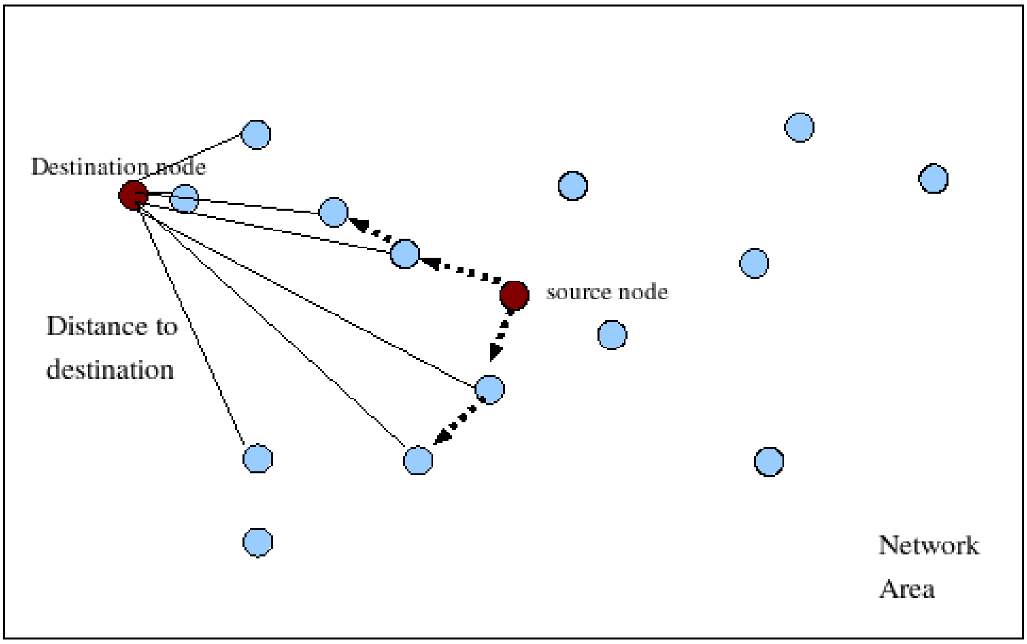


(c) Third RREQ Transmission with Expended Search Ring

Figure 3.1: Expanding Ring Search



(a) LAR with scheme 1 using localised region



(b) LAR with scheme 2 using distance

Figure 3.2: LAR routing schemes

packet queue and the wireless contention due to exponential binary backoff. In addition, existing research about on-demand routing has attempted to tackle scalability and overhead problems through the use of routing strategies that require pre-existing knowledge of destination nodes [21, 27, 1]. The use of pre-existing knowledge is, in reality, not applicable to the majority of mesh network scenarios nor it is feasible to disseminate or acquire global knowledge of nodes. In this chapter, a novel on-demand routing protocol called OTRP (On-demand Tree based Routing Protocol) is proposed that improves the scalability while reducing route discovery overhead, hence solving the BSP without the need for a source node to have pre-existing knowledge of the destination node. This is achieved by applying a novel, highly efficient route discovery algorithm called Tree-based Optimized Flooding (TOF) which floods the network through a limited set of nodes, referred to as branching nodes (described in Section 3.2). In section 3.2.1, the selection of branching nodes is described based on its geometric location related to the parent nodes using the Global Positioning System (GPS). Theoretical analysis and simulation results show that OTRP outperforms AODV, DYMO, and OLSR and it reduces control overheads as the number of nodes and amount of traffic increase (see 3.3).

3.2 OTRP Algorithm

In MANETs, the simplest method for disseminating information to all nodes in the network is blind flooding, in which each node rebroadcasts a received packet at least once, thereby propagating the packet throughout the network. Blind flooding is utilised by AODV and other routing protocols to perform route discovery. However, blind flooding suffers from BSP. The BSP may result in redundant broadcasts when neighbours have already received the broadcast from other nodes. Further, the BSP may cause several periods of medium contention in wireless networks, resulting in increased delays.

To address the BSP during route discovery, OTRP attempts to optimise flooding by re-

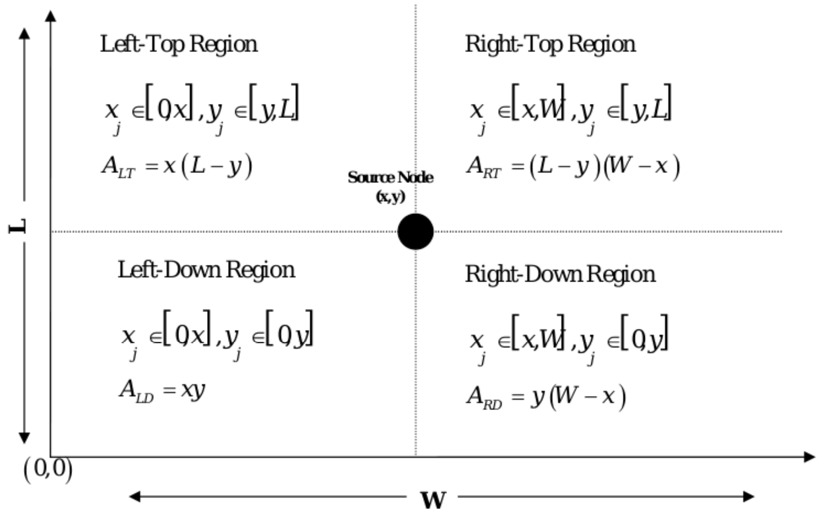


Figure 3.3: Neighbour area of rebroadcasting node with OTRP

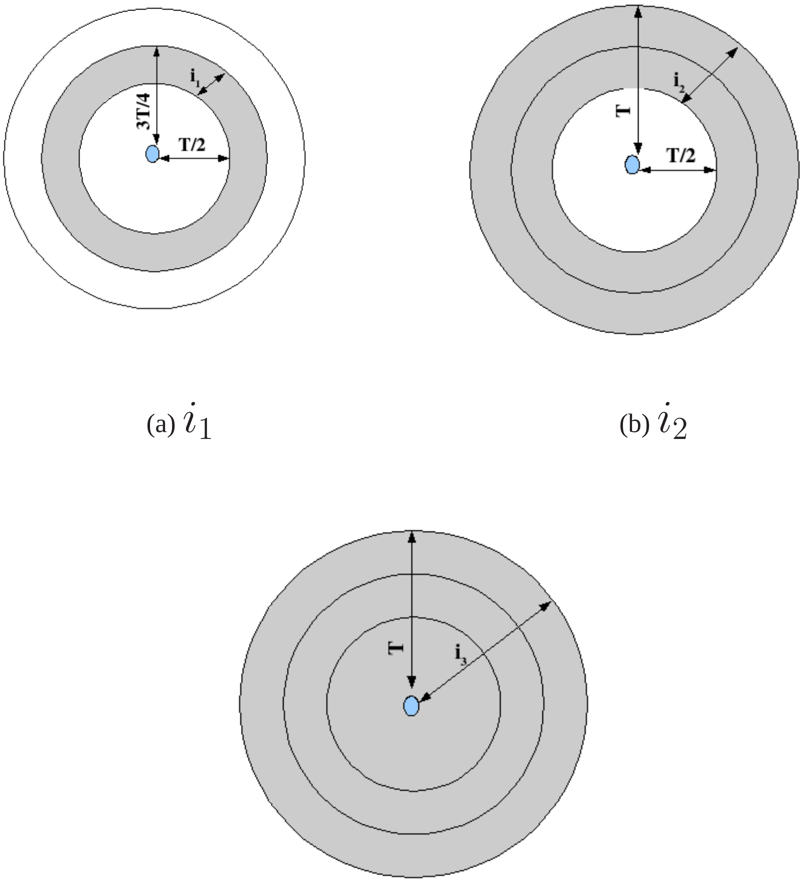
ducing redundant broadcasts when pre-existing knowledge about a destination is not available. This is achieved through a new algorithm called Tree-based Optimised Flooding (TOF) which strategically selects forwarding nodes during the route discovery phase. Algorithms 1 and 2 describe TOF in detail.

To ensure the most nodes in the network receive RREQ packets, rebroadcasting nodes are selected based on their location and distance related to parent node. The locations are obtained by using a GPS receiver. Rebroadcasting nodes are selected based on their locations if:

- They can increase the rebroadcasting coverage;
- They avoid the problem of localisation of RREQ flooding; and if
- RREQ packets will be received by most nodes in the network.

More details about location of rebroadcasting nodes are presented in the next chapter.

The transmission area of the parent node is called the *neighbour area*. This area is divided into four quadrants, labelled Right_Top (RT), Left_Top (LT), Left_Down (LD) and Right_Down (RD) (see Figure 3.3). The rebroadcasting node is located at position (x, y) in



(a) i_1 (b) i_2

(c) i_3

Figure 3.4: Division of the transmission range of a rebroadcasting node in OTRP

a region with dimensions $W \times L$. This node selects one neighbour j located at (x_j, y_j) in each quadrant. The area of each quadrant is shown in Figure 3.3. Assuming the transmission range is T, then the transmission area of a rebroadcasting node I is partitioned into three annular regions i_1, i_2, and i_3:

$$i_1 = [\frac{T}{2}, \frac{3T}{4}]; \;\; i_2 = [\frac{T}{2}, T]; \;\; i_3 = [0, T]$$

These ranges are shown in Figure 3.4. Selected forwarding nodes are called *branching*

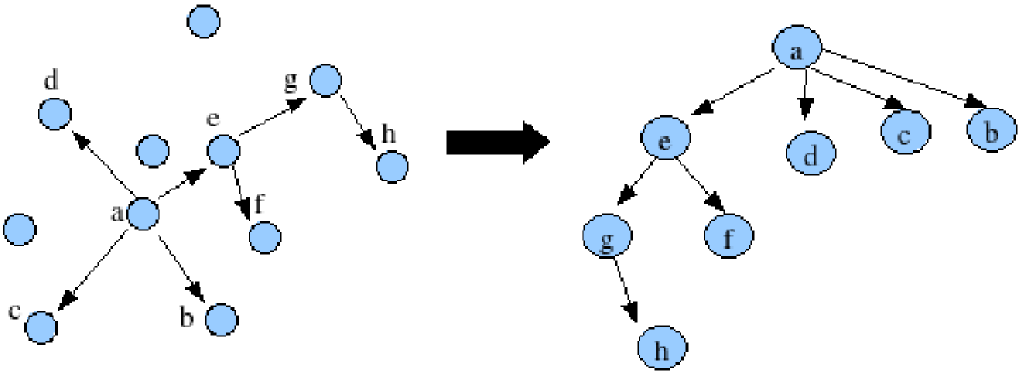


Figure 3.5: OTRP tree structure

nodes, since they form a tree-like structure to scan the network[1]. The resulting structure of the tree can be seen in Figure 3.5. The tree structure is described as follows:

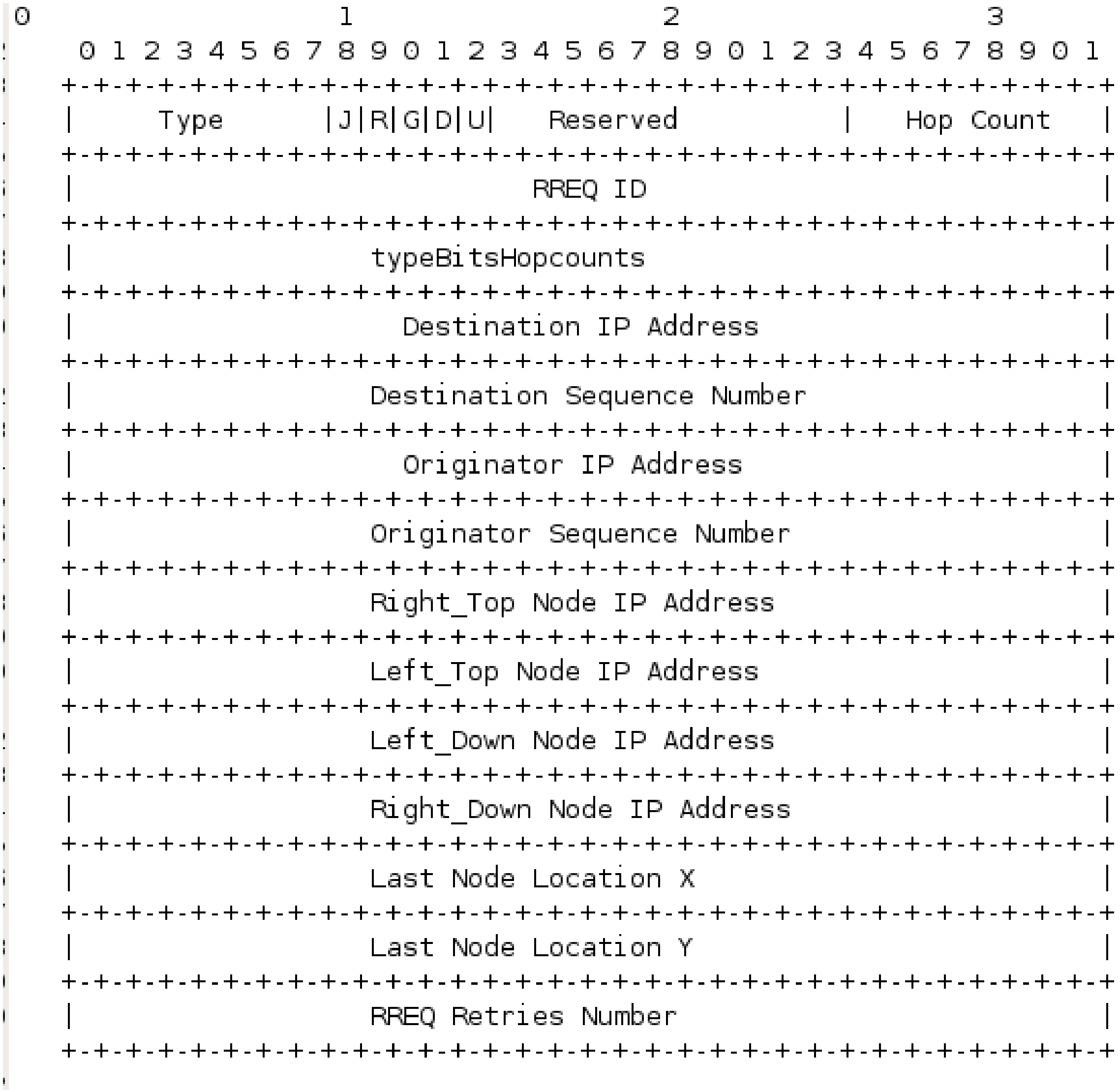
- The root a of the tree is the source node with at most four branches;
- A parent node (e.g e and g) is a relay node and has at most three branches; and
- A branching node (e.g b, c, d, f, and h) is a one hop neighbour of a parent node which forwards RREQ packets (in this thesis, the terms *rebroadcasting node* and *relay node* are used to refer to branching node).

The output of the TOF algorithm is a selected set of rebroadcasting nodes in the form of a tree; a root or source node may have a differently structured tree for each route discovery process.

The parent node appends its location, the IP address of each of the four branching nodes that will rebroadcast the RREQ packet, and the RREQ Retry value to the RREQ packet.The

---

[1] Note: in this context, the term ‘tree’ only refers to the structure of the network, rather than any sort of data structure.



```
0                   1                   2                   3
  0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |     Type      |J|R|G|D|U|   Reserved          |   Hop Count   |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                            RREQ ID                            |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                  typeBitsHopcounts                            |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                    Destination IP Address                     |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                  Destination Sequence Number                  |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                    Originator IP Address                      |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                  Originator Sequence Number                   |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                  Right_Top Node IP Address                    |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                  Left_Top Node IP Address                     |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                  Left_Down Node IP Address                    |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                  Right_Down Node IP Address                   |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                  Last Node Location X                         |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                  Last Node Location Y                         |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
 |                  RREQ Retries Number                          |
 +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3.6: The format of a Route Request (RREQ) packet in OTRP

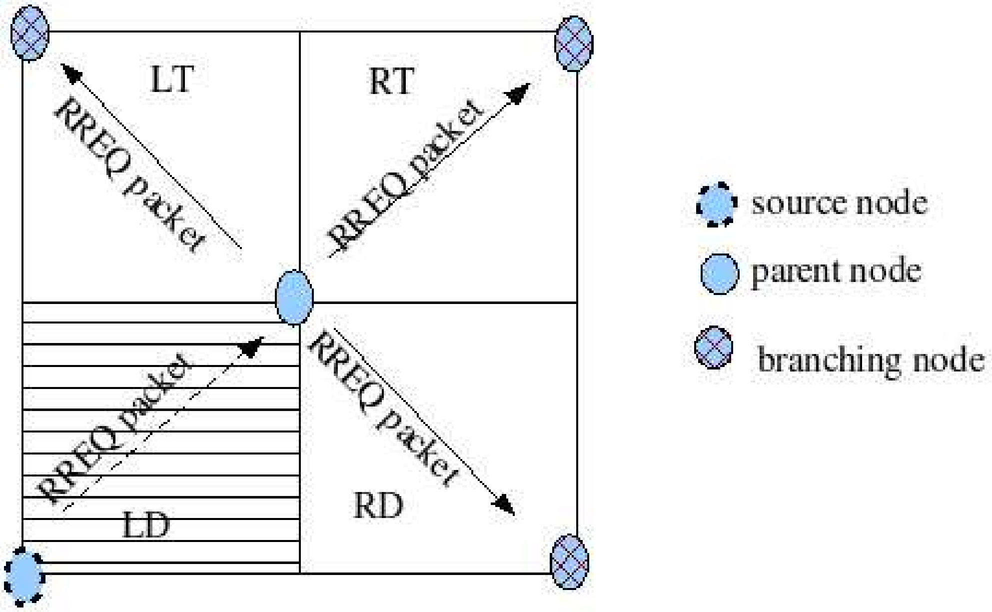


Figure 3.7: Excluding the LD region from the broadcasting of the RREQ packet

RREQ Retry value is the retry number to find the path to destination. The detailed structure of the OTRP RREQ packet is shown in Figure 3.6.

Algorithms 1 and 2 outline the TOF algorithm. In Algorithm 1, if no route reply is received after two RREQ retries, a normal AODV route discovery (blind flooding) will be performed. Each receiving node checks whether it is a branch node as indicated in the RREQ packet; if it is, then it will process the packet; if not, the packet is ignored. A branch node that processes a received RREQ packet must select its own branch nodes, update the RREQ packet and then rebroadcast it.

Algorithm 2 describes how a parent node finds its branching nodes. In this algorithm, branch nodes are selected in each region through at most three iterations according to the transmission range of the source or the parent nodes and the locations of neighbour nodes. The algorithm starts by setting the search range (shown in Figure 3.4) and initialising the attribute values for each region. The parent node then searches its routing table to find the location of its one-hop neighbours with active links in each region (lines 14 to 34 of Algorithm 2). During this process, it is assumed that the distance between source/parent node and its neighbour is D and that $D < T$. The source or parent node will firstly search for branching nodes whose D is between half and 3/4 of the transmission range, i.e. within transmission zone i_1. This zone is searched first for branching nodes because nodes in this region are unlikely to move out of range in the near future (i.e. they are not too far from the source/parent node), yet will provide a considerable increase in coverage without excessively adding to the route hop count (i.e. they are not too close to the source/parent node). If no node is found in i_1, the search area will be extended to i_2 to include the periphery of the transmission range. Finally, the source/parent node will choose any neighbour nodes available within the entire coverage range, extending the search to the nearest region as well. Thus preference is given to nodes which are intermediate in distance from the source/parent node.

Once branching nodes are selected, the RREQ is updated by replacing the value of the node location with the current node and updating the addresses of the next three branching nodes that will rebroadcast the RREQ packet in each of the four regions. A selected relay node does not need to direct RREQ packets toward the region where the RREQ came from. Therefore only three branching nodes are needed (an example is shown in Figure 3.7). The parent node address is assigned to the node address in the Address_Four_Branches_Nodes field in the RREQ packet either if its region is excluded from broadcasting or if no node has been found in that region. If there are unreachable nodes or no route was found through the above procedure, then all nodes will rebroadcast the RREQ packet. OTRP will resort to blind flooding in the final route request retry to solve the problem of unreachable nodes in the event that the destination was not reached in the previous two TOF iterations. However, the probability of finding destination nodes using TOF is expected to be quite high. This is because rebroadcasting nodes are selected optimally to forward RREQ packets to all nodes (this is demonstrated in next chapter).

The process of maintaining a route is the same as in AODV. The location of one-hop neighbours of the parent nodes are considered to be valid as long as the link between two nodes remains active. As node mobility degrades the accuracy of the the stored location information over time, the locations of neighbours are updated passively using control packets (i.e. RREQ, RREP, and RERR). When a node receives a control packet, it copies the location of the node that forwarded the packet to its routing table. It then replaces the location values in the control packet with its own location information.

Algorithm 1 Tree-based Optimised Flooding (TOF)

Input: Received RREQ Packet.
Output: 4 Branching Nodes.

```
if $retries < 3$ then
    if $(Node\_Add = Address\_Four\_Branches\_Nodes)\&(Node\_Add \neq Node\_SRC)$ then
        $Find\_Branch\_Nodes(Node\_Loc, Last\_Node\_Location, SRC\_Add, Routing\_Table)$
        $Update\_RREQpacket$
        $Broadcast\_RREQpacket$
    else
        $ignore\_RREQpacket$
    end if
else if $(retries \geq 3)\&(No\_Route\_Found)$ then
    $All\_Nodes\_Broadcasting$
end if
```

3.2.1 Theoretical Analysis of OTRP

In this section, the overhead of OTRP is compared with that of AODV. To simplify the analysis, a grid-based node distribution is assumed, as shown in Figure 3.8. Simulations are later presented with a more general node distribution. The transmission range of all nodes is assumed to be T, and each node has four neighbours (branch nodes) in each quadrant (Top, Left, Right and Bottom). The minimum distance between adjacent nodes is $\frac{T}{2}$.

Algorithm 2 Algorithm for selecting branching nodes

```
function FIND_BRANCH_NODES($N\_Loc, L\_Loc, SRC\_Add, RT$)
    $i_1 \leftarrow [\frac{T}{2},\frac{T}{2}+(\frac{T-\frac{T}{2}}{2})]$
    $i_2 \leftarrow [\frac{T}{2}\ ,T]$
    $i_3 \leftarrow [0\ ,T]$
    $I \leftarrow [i_1\ ,i_2,i_3]$
    for $j \leftarrow 0, 3$ do                                        ▷ Initialization
        ▷ R is a boolean set to represent four areas as R=[LT ,RT,RD, LD]
        $R_j \leftarrow FALSE$
            ▷ Bran_Node represents addresses of four branching nodes as Bran_Node =
            [LT_add, RT_add, RD_add,LD_add]
        $Bran\_Node_j \leftarrow SRC\_Add$
    end for
    $ER \leftarrow ExcArea(N\_Loc, L\_Loc)$
        ▷ exclude the area where the RREQ packet came from
    $R_{ER} \leftarrow TRUE$

    $z \leftarrow 1$
    $found \leftarrow FALSE$
    while $(found \neq TRUE)\&(z \leq 3)$ do
        $Node \leftarrow First\_Node\_RT$
        while $(found \neq TRUE)\&(Node \neq Null)$ do
            if $NOT(Node\_active)\|(Node\_hopcount \neq 1)$ then
                $Node \leftarrow Next\_Node$
                continue
            end if
            $x \leftarrow Node\_loc.x$
            $y \leftarrow Node\_loc.y$
            $D \leftarrow \sqrt{(N\_Loc.x - x)^2 + (N\_Loc.y - y)^2}$

                    ▷ BranchNode function validates if a node is a branch node and in
                which area. The function returns the index of the area in R, otherwise it
                returns a -1.
            $j \leftarrow -1$
            $j \leftarrow BranchNode(Node, D, i_z, R)$
            if $(j > -1)\&NOT(R_j)$ then
                $Bran\_Node_j \leftarrow Node\_Add$
                $R_j \leftarrow TRUE$
                $found \leftarrow AreAllFound(R)$
            end if
            $Node \leftarrow Next\_Node$
        end while
        $z++$
    end while
    return(Bran_Node)
end function
```

Let the source node be located at (x, y) in a network of dimensions $W \times L$ with N being the total number of nodes. For the grid-based distribution shown in Figure 3.8,

$$N = \frac{W}{T/2} \cdot \frac{L}{T/2} \tag{3.1}$$

The source node initiates the route discovery process by searching for four branching nodes (one per quadrant). Figure 3.8 shows this distribution and the subsequent path of the RREQ packets through branch nodes.

With reference to Figure 3.3 and Figure 3.8, consider the nodes in the Top Right region. The distribution of nodes will form a rectangular region whose area is equal to $A_{RT} = (L - y)(W - x)$. Let N_{RT} be the total number of nodes in this region:

$$N_{RT} = \left(\frac{W - x}{T/2}\right)\left(\frac{L - y}{T/2}\right) \tag{3.2}$$

In the case of blind flooding in AODV, all N nodes will rebroadcast the RREQs. Therefore, the number of nodes that will rebroadcast in the Top Right quadrant using AODV $B_{RT-AODV} = N_{RT}$.

However, if OTRP is used, the number of nodes that will rebroadcast in the Top Right quadrant is reduced to:

$$B_{RT-OTRP} = \frac{1}{2}\left(\frac{W - x}{T/2}\right)\left(\frac{L - y}{T/2}\right) \tag{3.3}$$

where each selected node will choose only one neighbour in each direction at distance T/2. By combining Equation 3.2 and Equation 3.3, the total number of rebroadcast nodes in the Top Right quadrant for OTRP will be:

$$B_{RT-OTRP} = \frac{1}{2} B_{RT-AODV} \tag{3.4}$$

Equation (3.4) is illustrated in Figure 3.8 where $W = 7$, $L = 5$, $T = 2$, $x = 3$, and

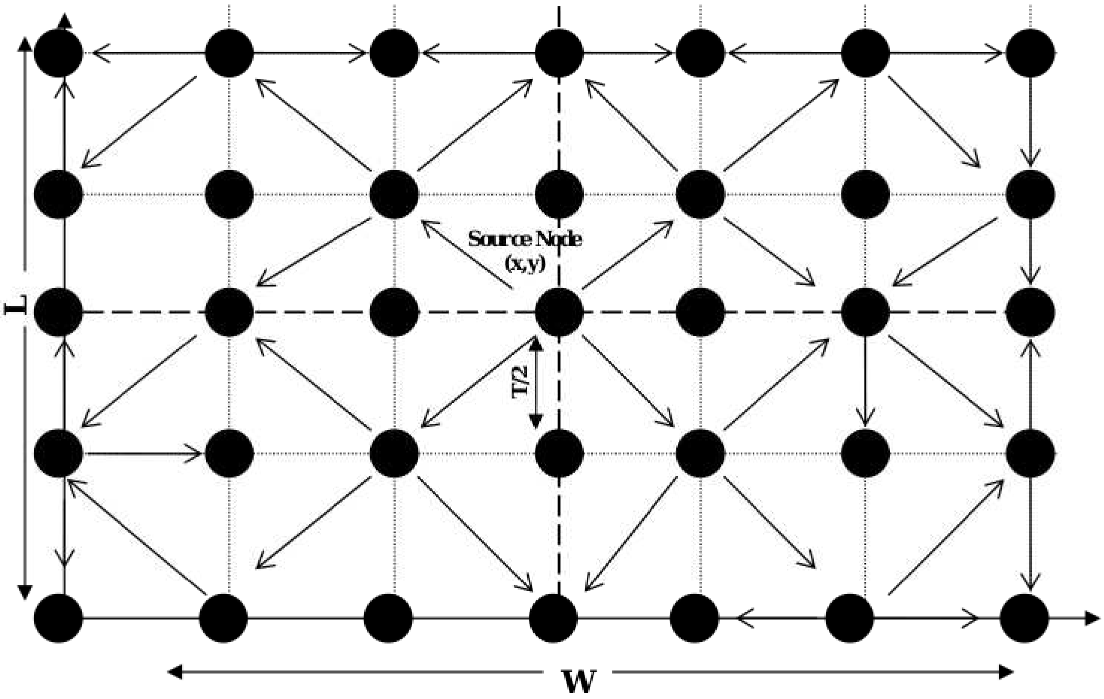


Figure 3.8: OTRP with grid distribution of nodes

$y = 2$. In this case,

$$\begin{aligned} N_{RT} &= (7-3)(5-2) \\ &= 12 \end{aligned}$$

and $B_{RT-OTRP} = 6$ according to Equation (3.3). Hence, for a fully-populated grid distribution, OTRP reduces the number of rebroadcast nodes by 50%. A simple extension of this idea to the remaining three quadrants results in the total number of rebroadcasting nodes with OTRP:

$$B_{RT-OTRP} = \frac{1}{2}\left((W-x)/(\frac{T}{2})\right)\left((L-y)/(\frac{T}{2})\right)$$

$$\begin{aligned}
B_{LT-OTRP} &= \frac{1}{2}\left(x/(\frac{T}{2})\right)\left((L-y)/(\frac{T}{2})\right)\\
B_{LD-OTRP} &= \frac{1}{2}\left(x/(\frac{T}{2})\right)\left(y/(\frac{T}{2})\right)\\
B_{RD-OTRP} &= \frac{1}{2}\left((W-x)/(\frac{T}{2})\right)\left(y/(\frac{T}{2})\right)
\end{aligned}$$

By summing the above 4 equations the total number of rebroadcasting nodes with OTRP is obtained:

$$\begin{aligned}
B_{OTRP} &= \frac{1}{2}\left(\frac{W}{T/2}\right)\left(\frac{L}{T/2}\right)\\
&= \frac{N}{2}
\end{aligned} \tag{3.5}$$

A similar expression may be obtained for AODV:

$$\begin{aligned}
B_{RT-AODV} &= \left((W-x)/(\frac{T}{2})\right)\left((L-y)/(\frac{T}{2})\right)\\
B_{LT-AODV} &= \left(x/(\frac{T}{2})\right)\left((L-y)/(\frac{T}{2})\right)\\
B_{LD-AODV} &= \left(x/(\frac{T}{2})\right)\left(y/(\frac{T}{2})\right)\\
B_{RD-AODV} &= \left((W-x)/(\frac{T}{2})\right)\left(y/(\frac{T}{2})\right)
\end{aligned}$$

By summing the above 4 equations the total number of rebroadcasting nodes with AODV is obtained:

$$\begin{aligned}
B_{AODV} &= \frac{4}{T^2}(W \cdot L)\\
&= (\frac{W}{T/2} \cdot \frac{L}{T/2})\\
&= N
\end{aligned} \tag{3.6}$$

Comparing Equation 3.5 and Equation 3.6 yields the same result as in Equation 3.4:

$$B_{OTRP} = B_{AODV}/2 \tag{3.7}$$

This means that OTRP reduces the number of rebroadcasting nodes by 50% in a grid-based node distribution. Overheads will correspondingly reduce by the same fraction. The worst-case overhead for AODV is [29]:

$$OH_{AODV} = N^2 \tag{3.8}$$

Hence,

$$OH_{OTRP} = \frac{1}{\lambda} \cdot OH_{AODV} \tag{3.9}$$

where $\frac{1}{\lambda}$ is a node-distribution-dependent factor. In the case of a grid distribution as in Figure 3.8, λ is equal to 2 (Equation 3.7). From Equation 3.8 and Equation 3.9, it may be concluded that the density of nodes directly affects the overhead in OTRP. With AODV, all nodes participate in rebroadcasting RREQ packets during route discovery as shown in Equation 3.6. Therefore, increasing the number of flows means increasing the load on all nodes in the network. Consequently, it will increase overheads significantly. However, with OTRP, only rebroadcasting nodes will be affected. Hence, the effect of increasing the number of flows in OTRP will be much less than for AODV. The effect of increasing the number of flows that affect the overheads may be illustrated for the worst case as follows:

$$OH_{AODV} = \alpha \cdot N^2 \tag{3.10}$$

$$OH_{OTRP} = \frac{\beta}{\lambda} \cdot N^2 \tag{3.11}$$

where $\alpha \geq 1$, $\beta \geq 1$ and $\alpha > \beta$ with the same number of flows.

3.3 OTRP Performance Comparison

In this section, the performance of OTRP is compared to AODV [1], DYMO [19], and OLSR-INRIA [13]. Although OLSR-INRIA is a proactive routing protocol, it uses Multi-Point Relaying (MPR) to reduce flooding overheads. Consequently, two flooding strategies (TOF and MPR) are compared here. The simulations are conducted using the QualNet4.5 simulator [55]. The following parameters are used:

- Simulations are run for 200 seconds with five different seed values;
- 200 nodes are randomly distributed over a 1000 x 1000 m^2 terrain;
- A random waypoint mobility model is used with five different values of pause time (0, 50, 100, 150, and 200 s);
- Node speed is varies from 0 m/s to 20 m/s;
- Each simulated protocol is evaluated with 30 Constant Bit Rate (CBR) data traffic flows, each generating one 512-byte packet per 250 ms;
- IEEE 802.11b is used as the MAC protocol with a constant transmission rate of 2 Mbps;
- Transmission power is set to 15 dBm and transmission range is 370.968 m for all nodes.

All figures are shown with 95% confidence intervals.

The following metrics are used to evaluate the performance of routing protocols:

1. Packet Delivery Ratio (PDR): Ratio of the number of packets received at the destination to the number of packets sent by the source node;

2. End-to-End Delay (EED): The average end-to-end delay for transmitting data packets from source to destination;

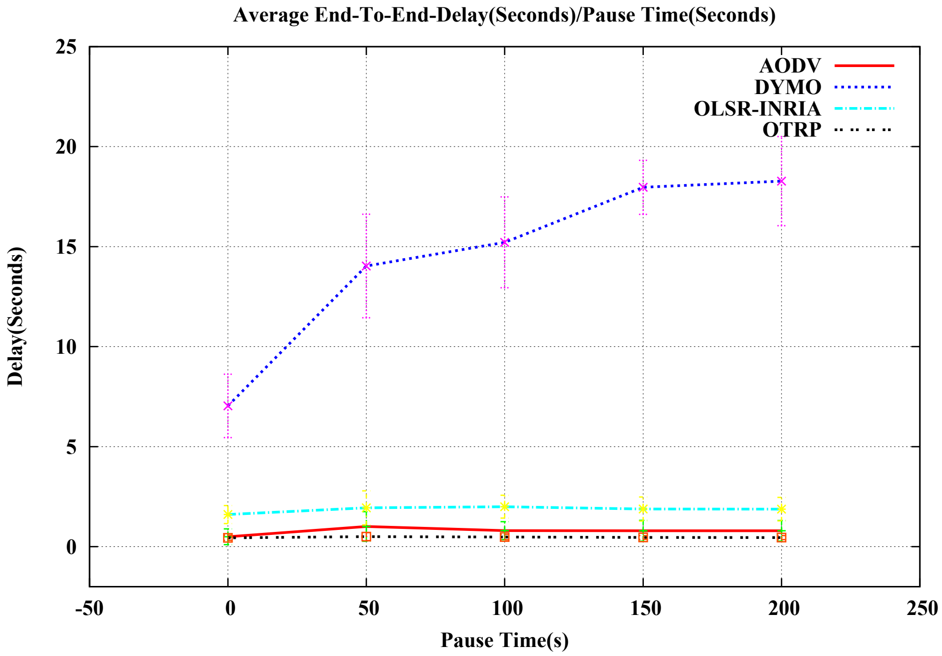
3. Normalised Control Overhead (NCO): The ratio of the total number of control packets to the total number of data packets transmitted;

Figure 3.9 and Figure 3.10 demonstrate that OTRP provides significant performance improvements over AODV, DYMO and OLSR-INRIA. OTRP provides the highest PDR with the lowest EED and NCO in both 100 and 200 node scenarios.

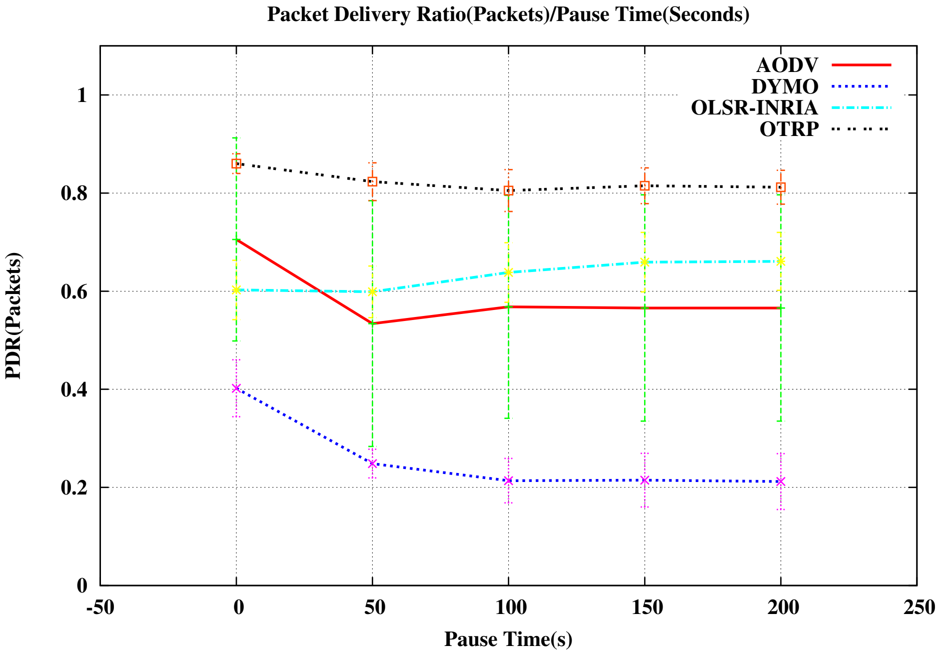
The use of TOF to replace blind flooding for route discovery enables OTRP to find routes more efficiently (hence the significantly lower NCO) compared with AODV and DYMO. Further, TOF's constant number of branch nodes results in an approximately constant NCO for both the 100-node and 200-node scenarios. This demonstrates the fact that TOF significantly contributes to OTRP's scalability (confirming the behaviour predicted by Equation 3.9).

The number of branch nodes used by TOF is related to the node transmission range and the area covered by the network. Therefore, an increase in node density has little effect on the performance of the algorithm. By contrast, the use of blind flooding in AODV results in progressively higher NCO as density is increased, thereby limiting the scalability - a direct result of the BSP. OLSR-INRIA's use of MPR for link state dissemination helps to reduce NCO, however periodic link state dissemination and neighbour discovery still results in a high NCO compared with OTRP. OLSR-INRIA's NCO increases four-fold as the network scales from 100 to 200 nodes.

The consistently low NCO for OTRP directly translates to fewer issues associated with the BSP (contention, collision, overhead). Thus OTRP is able to achieve a PDR above 80% and 70% for the 100-node and 200-node scenarios respectively; by contrast, AODV is only able to achieve a PDR of 50% and 10% for the 100-node and 200-node scenarios respectively.

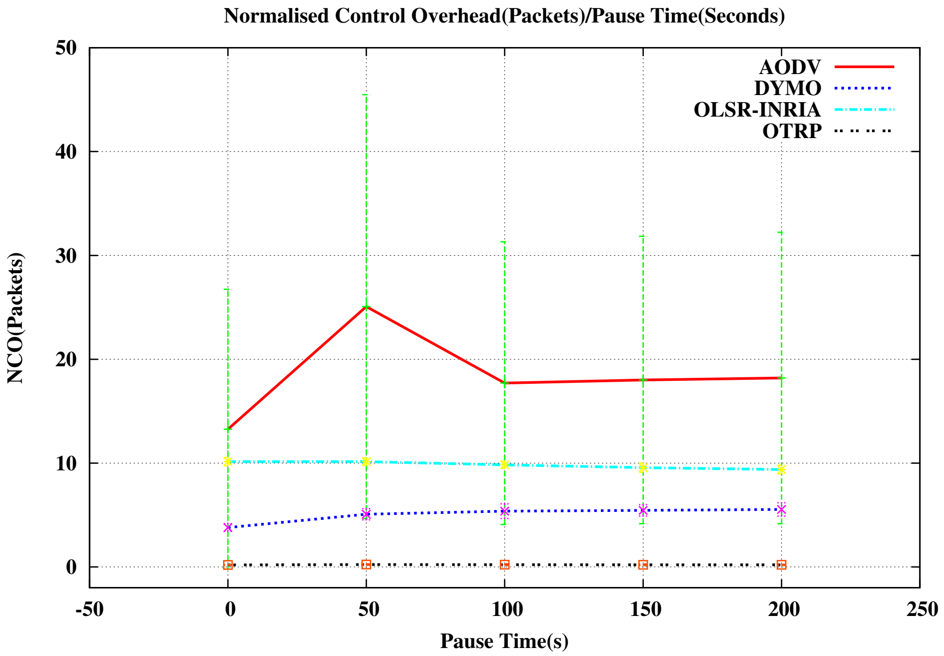


(a) Average End-to-End Delay



(b) Packet Delivery Ratio

Figure 3.9: Comparison of OTRP to AODV, DYMO, and OLSR-INRIA with 100 nodes and 30 Traffic Flows.

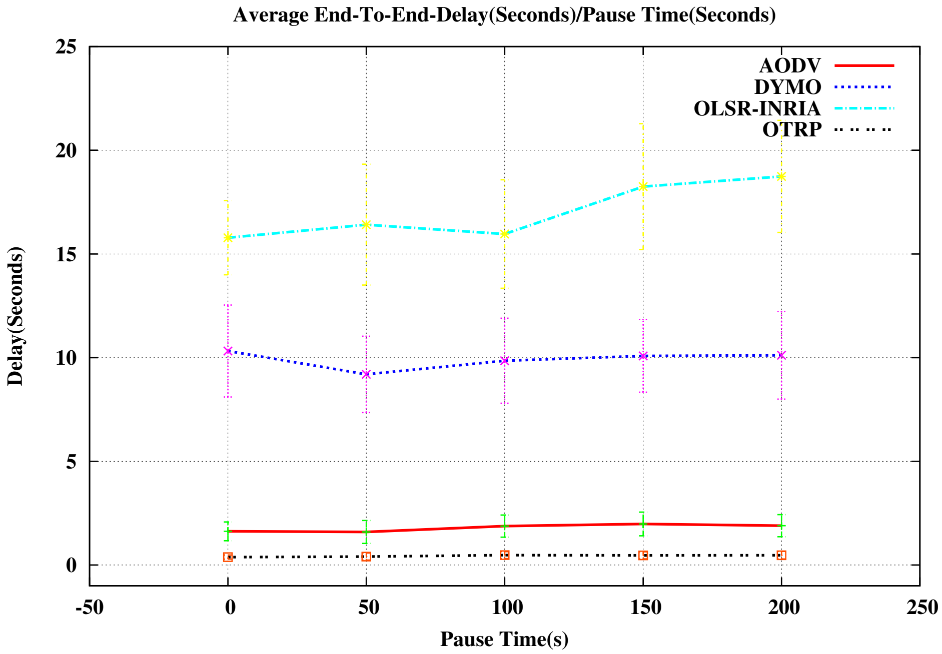


(c) Normalised Control Overhead

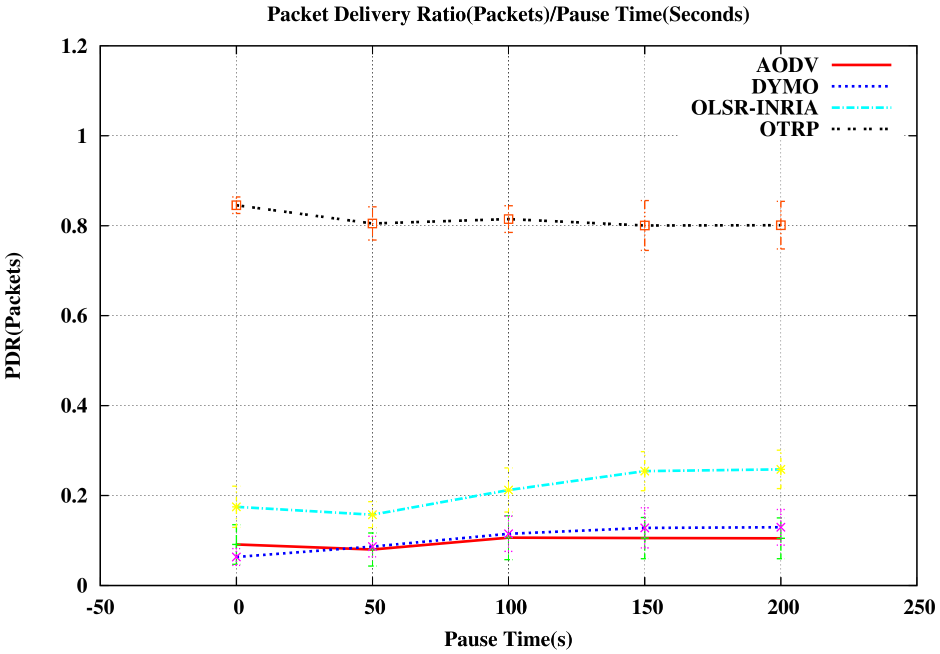
Figure 3.9: Comparison of OTRP to AODV, DYMO, and OLSR-INRIA with 100 nodes and 30 Traffic Flows.

The use of blind flooding for route discovery as in AODV enables all possible routes between two points to be discovered, and theoretically should always find the shortest route between two given points. In the absence of other overheads, AODV would therefore be expected to exhibit lower average end-to-end delay compared to OTRP. However, it is evident from Figure 3.9 and 3.10 that OTRP actually offers lower average end-to-end delay than AODV as the network increases in size from 100 nodes to 200 nodes. This is because even though TOF may not always identify the optimal route, its lower NCO greatly reduces the impact of the BSP (medium contention in particular) leading to an overall reduction in average end-to-end delay compared to AODV. This result demonstrates the excellent scalability characteristics of OTRP.

It is observed that that both OLSR and OTRP outperform AODV, however OTRP outperforms OLSR in dense networks subject to high traffic load. Although OLSR and OTRP both reduce overheads by selecting a subset of nodes to forward control packets, in dense

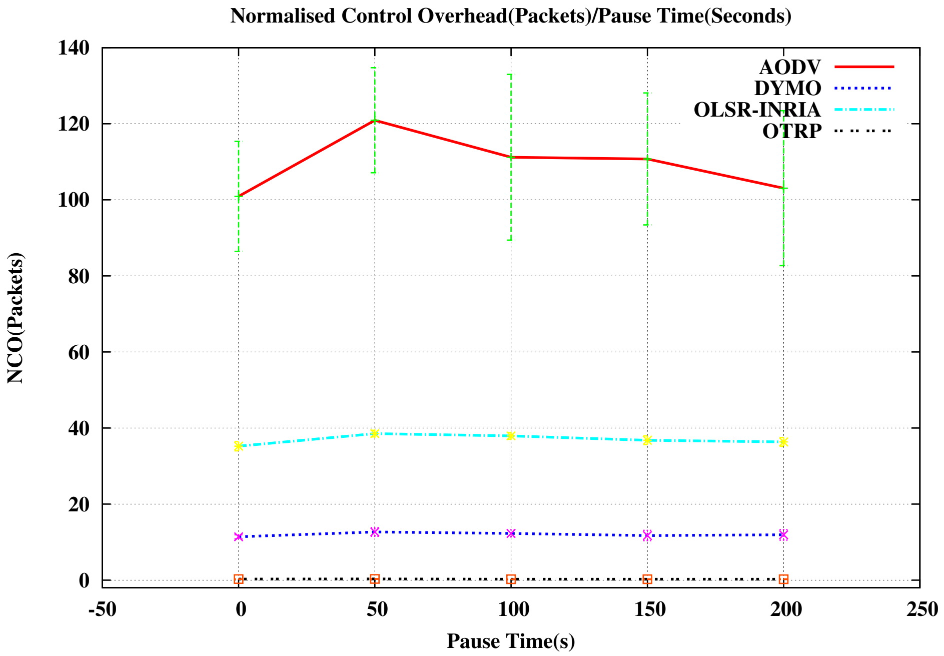


(a) Average End-to-End Delay



(b) Packet Delivery Ratio

Figure 3.10: Comparison of OTRP to AODV, DYMO, and OLSR-INRIA with 200 nodes and 30 Traffic Flows.



(c) Normalised Control Overhead

Figure 3.10: Comparison of OTRP to AODV, DYMO, and OLSR-INRIA with 200 nodes and 30 Traffic Flows.

networks, OTRP selects a *constant* number of branching nodes regardless of node density. However, in OLSR, the number of MPRs continues to increase as the number of nodes increases, resulting in a corresponding increase in overhead and delay. This is avoided in OTRP.

In the simulation results, DYMO is shown to have a greater NCO than OTRP, but lower NCO than AODV due the elimination of local repair and hello messages. However, DYMO has a greater average end-to-end delay than AODV as it exhibits some fragility with respect to timers. Further, when compared with OTRP it has a significantly lower PDR.

3.4 Conclusion

In this Chapter, a new on-demand routing protocol called OTRP (On-demand Tree based Routing Protocol) has been proposed to improve scalability of MANETs. This is achieved by an efficient route discovery algorithm called Tree-based Optimised Flooding (TOF) which reduces the routing overhead of on-demand routing protocols when previous knowledge of destination is not available. Particular nodes (branching-nodes) are selected to forward RREQ packets.

The performance of OTRP was compared with two reactive protocols (AODV and DYMO) and one proactive routing protocol (OLSR) with varying degrees of node density and mobility. Simulation results show that OTRP significantly reduces routing overheads and achieves higher levels of data delivery than the other protocols.

In the next chapters, the performance of OTRP in heterogeneous networks will be explored, as OTRP's advantages are even more significant in such networks.

Chapter 4

Factors Affecting OTRP Performance

4.1 Introduction

In the previous chapter, the OTRP algorithm is proposed to improve scalability of Ad hoc networks by selectively choosing rebroadcasting nodes. Selection of branch nodes (rebroadcasting nodes) is affected by several factors which, in turn, affect the performance of OTRP. The factors to be considered are:

- The number of branch nodes;
- The location of branching nodes;
- Node density; and
- The number of RREQ retries.

Generally routing protocols assume that the network is fully connected. There have been different approaches to estimate the minimum number of rebroadcasting/neighbouring nodes that are needed for scalability and connectivity in wireless network. It has been argued that the optimal number is between five and eight [56], [57]. In [58], it is shown that 95% of the potential connectivity is achieved if there are nine neighbors for each node in the network.

In OTRP, four neighbors are selected to rebroadcast RREQ packets. In the previous chapter, theoretical analysis and simulation results showed that OTRP outperforms AODV, DYMO, and OLSR and reduces overhead as the number of nodes and traffic increase. This suggests that four rebroadcasting neighbours for each node in the network is sufficient in the routing process of on-demand routing protocols. This can firstly be shown from the geometrical distribution model of branching nodes which is discussed in Section 4.2. The effects of the choice of branching scheme on the performance of OTRP are studied according this model in Section 4.3.

Locations of branch nodes relative to the sender is one parameter that can accelerate route discovery process [39]. In OTRP, nodes which can provide additional rebroadcasting coverage and simultaneously conserve network connectivity are given the highest priority to rebroadcast. Three locations are studied and tested to find the best location for branch nodes to rebroadcast. These are the annular regions between: $[0, \frac{T}{2}]$, $[\frac{T}{2}, \frac{3T}{4}]$, and $[\frac{3T}{4}, T]$ (See Section 4.4).

Node density can directly affect the process of selecting nodes; in sparse networks there is an insufficient number of nodes to effectively rebroadcast. Accordingly, node density must be considered in the process of selection of branch nodes. There are three classes of nodes density that are to be considered: low, medium and high. This is discussed in more detail in Section 4.5.

On-demand routing protocols have configuration parameters which directly affect their scalability. The performance of AODV may be affected by fixed values of the parameters that are shown in Table 4.1 [59]. These parameters control and optimise the route discovery process. In this Chapter, the effects of using different values of RREQ_RETRIES parameter on the scalability of OTRP are studied(see Section 4.6). This parameter specifies the number of times OTRP and AODV will repeat an expanded ring search for a destination if no RREP Packet is received within the specified amount of time. The default value of

Configuration Parameter	**Default Value**
AODV_DEFAULT_ACTIVE_ROUTE_TIMEOUT	3000 * MILLI_SECOND
AODV_DEFAULT_ALLOWED_HELLO_LOSS	2
AODV_DEFAULT_HELLO_INTERVAL	1000 * MILLI_SECOND
AODV_DEFAULT_NET_DIAMETER	35
AODV_DEFAULT_NODE_TRAVERSAL_TIME	40 * MILLI_SECOND
AODV_DEFAULT_RREQ_RETRIES	2
AODV_DEFAULT_ROUTE_DELETE_CONST	5
AODV_DEFAULT_MESSAGE_BUFFER_IN_PKT	100

Table 4.1: Configuration parameters of AODV

RREQ_RETRIES in AODV is 2. With OTRP, the maximum value of RREQ_RETRIES is 3.

Few research papers have discussed the impact of choosing different values of configuration parameters on the performance of on-demand routing protocols in MANETs. In [59], the RREQ_RETRIES parameter of AODV was varied during simulation to find the optimal value to achieve the fastest convergence of the routing tables. The optimal value for RREQ_RETRIES in AODV was found to be 2, which achieved high goodput ratio and low route acquisition latency with 50 and 100 nodes. Therefore, the default value of

RREQ_RETRIES in AODV is 2. However, this value is optimal only for network conditions that have been used in this paper; it is not optimal for all scenarios. Other authors have concluded that the default value of RREQ_RETRIES of AODV is too conservative and a more appropriate value is 5 [60]. In this paper, AODV and DSDV have been implemented and deployed on a real five nodes network to evaluate the performance of the two protocols in real-world environment. In [61], a new flooding strategy has been proposed to reduce the number of redundant broadcasting nodes in on demand routing protocols. A node can rebroadcast RREQ packet with a certain probability. Retry-times or RREQ_RETRIES of route discovery is one of the parameters that has been used to find the probability for a node to rebroadcast a received RREQ packet. It was stated that as the number of retry-times increases then this probability is increased. This strategy has been implemented in AODV. Simulation results showed that this strategy outperforms the default flooding strategy of AODV. In [62], AODV has been modified to dynamically adjust its configuration parameters (e.g NET_DIAMETER, RREQ_RETRIES,...) to the conditions of the network. The performance of AODV has improved as its configuration values are modified to search for reliable routes during the route discovery process.

The objective of studying this configuration parameter is to answer the following questions:

1. What are the effects of increasing the number of RREQ_RETRIES on discovery route process in on-demand routing protocols?
2. Does optimising the RREQ_RETRIES in terms of optimised flooding and the number of retries improves scalability?
3. What is the optimal value for RREQ_RETRIES with OTRP to achieve high scalability?

Finally, Section 4.7 presents simulation-based validation of results of the theoretical analysis.

4.2 Branching Node Distribution

Branch nodes are selected to rebroadcast RREQs in a distributed manner using TOF. Therefore, the method by which they are selected is of critical importance to the operation of OTRP. Given the number of branch nodes required, the transmission range of rebroadcasting nodes is divided into sub-areas to search for the most efficient relay nodes.

In Section 3.2, only 4 nodes were selected as first hop neighbours of a source node. The transmission region of a source node was divided into four quadrants as shown in Figure 4.1b. In this section, the performance of OTRP with 3, 4, 6 and 8 branch nodes is compared. It is assumed for each case, the location of a source node is (x_0, y_0) and the location of the next rebroadcasting node is (x_i, y_i). B is the number of branch nodes that are used to rebroadcast. P_i is the search sub-area for rebroadcast nodes where $1 \leq i \leq B$. A rectangular grid-based node distribution is assumed in the analysis[1]. If the transmission range of each node is assumed to be a circle of radius T, then the search sub-area is a sector of this circle. The area of this sector is $\frac{1}{2}\frac{2\pi}{B}T^2 = \frac{\pi T^2}{B}$ where $\frac{2\pi}{B}$ is the angle between each of the two lines that divides the transmission range of the rebroadcasting node.

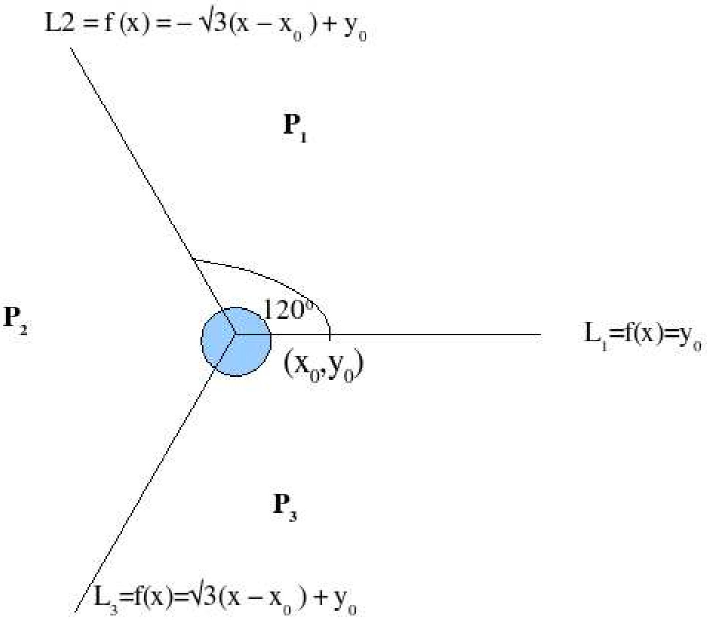
The following parameters are used to decide which sector a given node belongs to.

- node's location (x_i, y_i)
- parent location (x_0, y_0)
- the angle θ_i formed between the parent location and node location

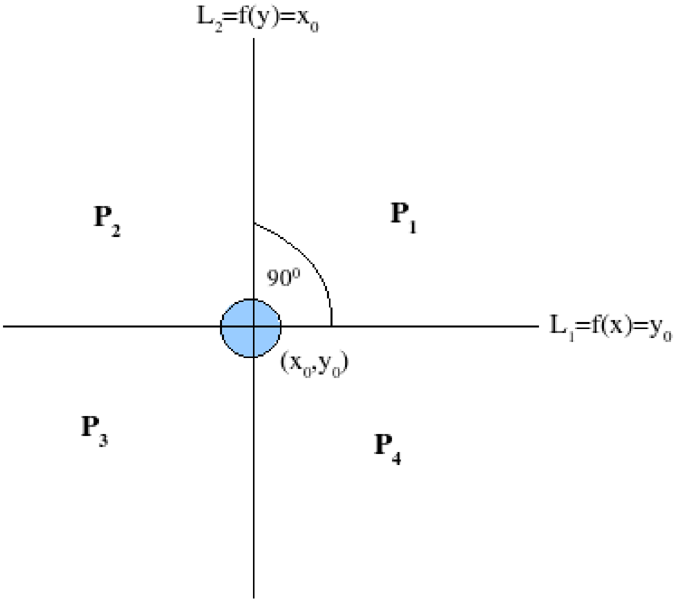
θ_i is computed by using the following equation:

---

[1] This distribution is assumed for simplicity of analysis; the result is confirmed to apply to more general spatial distributions in Section 4.7

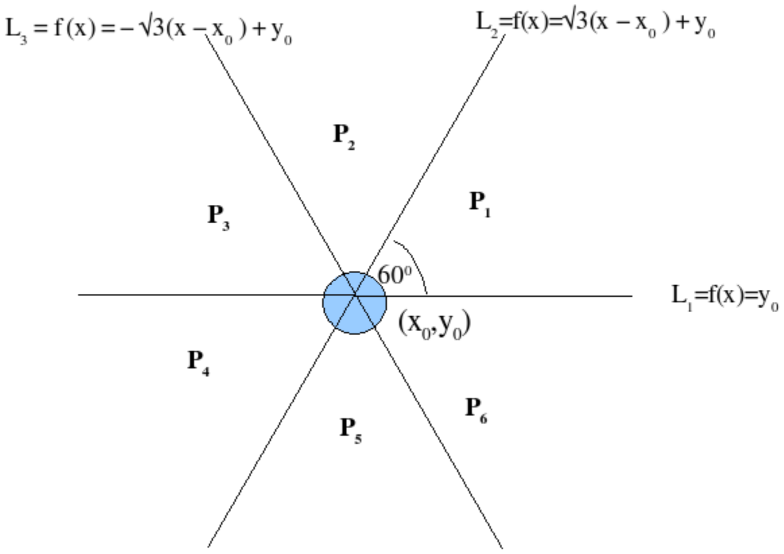


(a) 3 branching nodes

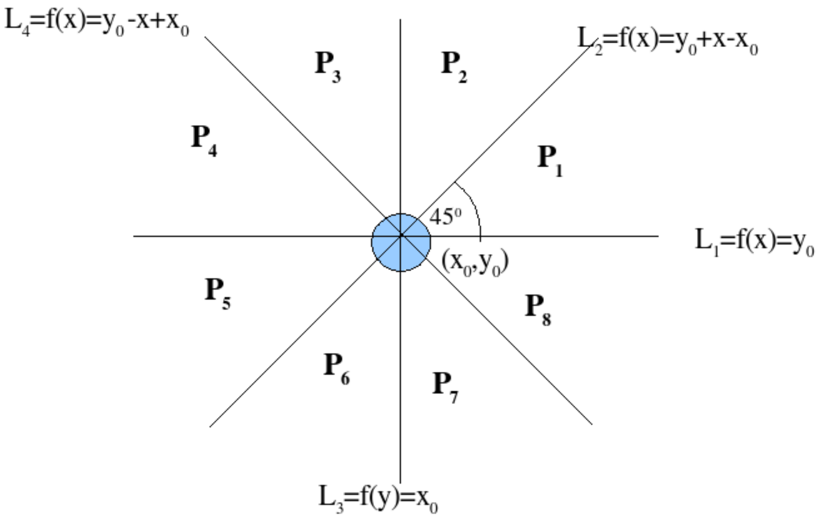


(b) 4 branching nodes

Figure 4.1: Selecting different numbers of branching nodes



(c) 6 branching nodes



(d) 8 branching nodes

Figure 4.1: Selecting different numbers of branching nodes

$$\theta_i = \arctan(y_i - y_0, x_i - x_0) \times \frac{180}{\pi}$$

if $\theta_i < 0$ then we can add 360 to convert it to its equivalent positive angle. Then, the sector S is calculated in below equation:

$$S = \lceil \frac{B \times \theta_i}{360} \rceil$$

where B is the number of branching nodes.

4.3 Number of Branching Nodes

The main benefit of increasing the number of branching nodes is that this results in an increase in the rebroadcast area of the parent node. Consequently, most nodes will receive each RREQ packet at least once, which accelerates the route discovery process.

To find the relationship between the number of branch nodes and the need for additional rebroadcast coverage to reduce the number of rebroadcast nodes, the following assumption will be used (Figure 4.2:

- The transmission ranges C_{P_i} of all nodes are equal;
- The distance between each horizontally or vertically adjacent pair of nodes is D;
- $\widetilde{A}(C_{P_i})$ is the area of the transmission circle C_{P_i} of node P_i; and
- P_R is a rebroadcasting node.

Moreover, as in AODV, if a node receives multiple copies of a RREQ packet that it has already seen, the packet will be dropped regardless of whether the received node has

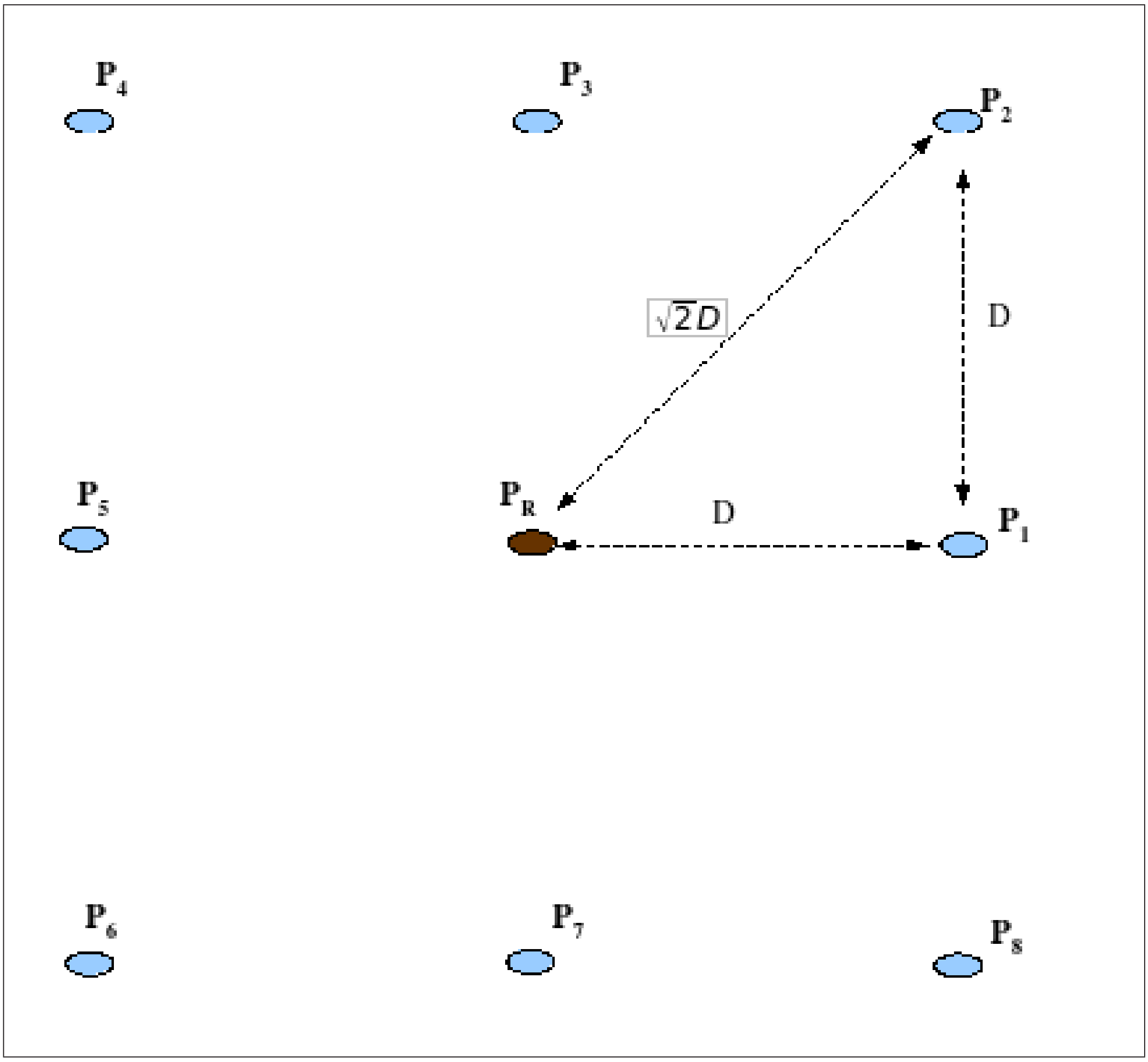


Figure 4.2: Rebroadcast area of branch nodes

been selected as a rebroadcast node. To model this scheme, it is assumed that the current rebroadcasting node is P_{R_i} and it has been selected by $P_{R_{i-1}}$. The next rebroadcast nodes are thus:

$$R_{i+1} = \{P_{R_{i+1}} : P_{R_{i+1}} \in C_{P_{R_i}} \quad \& \quad P_{R_{i+1}} \notin C_{P_{R_{i-1}}}\} \tag{4.1}$$

Therefore, if the rebroadcasting area, $\widetilde{A}(C_{P_{R_i}}) - (\widetilde{A}(C_{P_{R_i}}) \cap \widetilde{A}(C_{P_{R_{i-1}}}))$ which is covered by node P_{R_i} but not by $P_{R_{i-1}}$, is larger than $(\widetilde{A}(C_{P_{R_i}}) \cap \widetilde{A}(C_{P_{R_{i-1}}}))$ then this increases the probability of finding more branch nodes. Therefore, according to Figure 4.2 and using union notation $\bigcup$ which meanes union between multiple regions :

Theorem 1.

$$\begin{aligned}\bigcup_{i=1}^{4}(\widetilde{A}(C_{P_i}) - (\widetilde{A}(C_{P_i}) \cap \widetilde{A}(C_{P_R}))) &< \bigcup_{i=1}^{6}(\widetilde{A}(C_{P_i}) - (\widetilde{A}(C_{P_i}) \cap \widetilde{A}(C_{P_R})))\\ &< \bigcup_{i=1}^{8}(\widetilde{A}(C_{P_i}) - (\widetilde{A}(C_{P_i}) \cap \widetilde{A}(C_{P_R})))\end{aligned}$$

Proof. By using Figure 4.2:

$$\overline{P_{2i+1}P_R} < \overline{P_{2i}P_R} \rightarrow D < \sqrt{2}D$$

where $1 \leq i \leq B/2$. Then as distance between each pair of nodes increases, the total rebroadcast area is increasing. Then,

$$\begin{aligned}&\widetilde{A}(C_{P_R}) \cup \widetilde{A}(C_{P_1}) > \widetilde{A}(C_{P_R})\\ &\Rightarrow \widetilde{A}(C_{P_R}) \cup \widetilde{A}(C_{P_1}) \cup \widetilde{A}(C_{P_2}) > \widetilde{A}(C_{P_R}) \cup \widetilde{A}(C_{P_1})\\ &\widetilde{A}(C_{P_R}) \cup \widetilde{A}(C_{P_1}) \cup \widetilde{A}(C_{P_2}) \cdots \cup \widetilde{A}(C_{P_B}) > \widetilde{A}(C_{P_R}) \cup \widetilde{A}(C_{P_1}) \cdots \cup \widetilde{A}(C_{P_{B-1}})\end{aligned}$$

$$\therefore \bigcup_{i=1}^{8} \widetilde{A}(C_{P_i}) \cup \widetilde{A}(C_{P_R}) > \bigcup_{i=1}^{6} \widetilde{A}(C_{P_i}) \cup \widetilde{A}(C_{P_R}) > \bigcup_{i=1}^{4} \widetilde{A}(C_{P_i}) \cup \widetilde{A}(C_{P_R})$$

Then,

$$\bigcup_{i=1}^{8} \widetilde{A}(C_{P_i}) > \bigcup_{i=1}^{6} \widetilde{A}(C_{P_i}) > \bigcup_{i=1}^{4} \widetilde{A}(C_{P_i})$$

Therefore,

$$\begin{aligned} &\bigcup_{i=1}^{8}(\widetilde{A}(C_{P_i}) - (\widetilde{A}(C_{P_i}) \cap \widetilde{A}(C_{P_R}))) > \\ &\bigcup_{i=1}^{6}(\widetilde{A}(C_{P_i}) - (\widetilde{A}(C_{P_i}) \cap \widetilde{A}(C_{P_R}))) > \\ &\quad \bigcup_{i=1}^{4}(\widetilde{A}(C_{P_i}) - (\widetilde{A}(C_{P_i}) \cap \widetilde{A}(C_{P_R}))) \end{aligned}$$

□

This means that using 8 branch nodes can increase the availability of rebroadcast nodes by increasing the rebroadcast area in a different direction from the parent node.

4.4 Location of Branching Nodes and OTRP

The location of branching nodes is a very important factor in the performance of OTRP. Choosing branch nodes that are located near each other can localise the dissemination of a RREQ to one direction. This may partition the network such that some nodes do not receive the RREQ, consequently degrading the performance of OTRP. Therefore, the location of branch nodes directly influences the scalability and reliability of OTRP. Generally, as the distance between the parent node and its branching node increases, the additional rebroadcast coverage is increased too. A node which is located on the boundary of the parent node's coverage area will provide the maximum possible rebroadcast coverage [39]. Therefore,

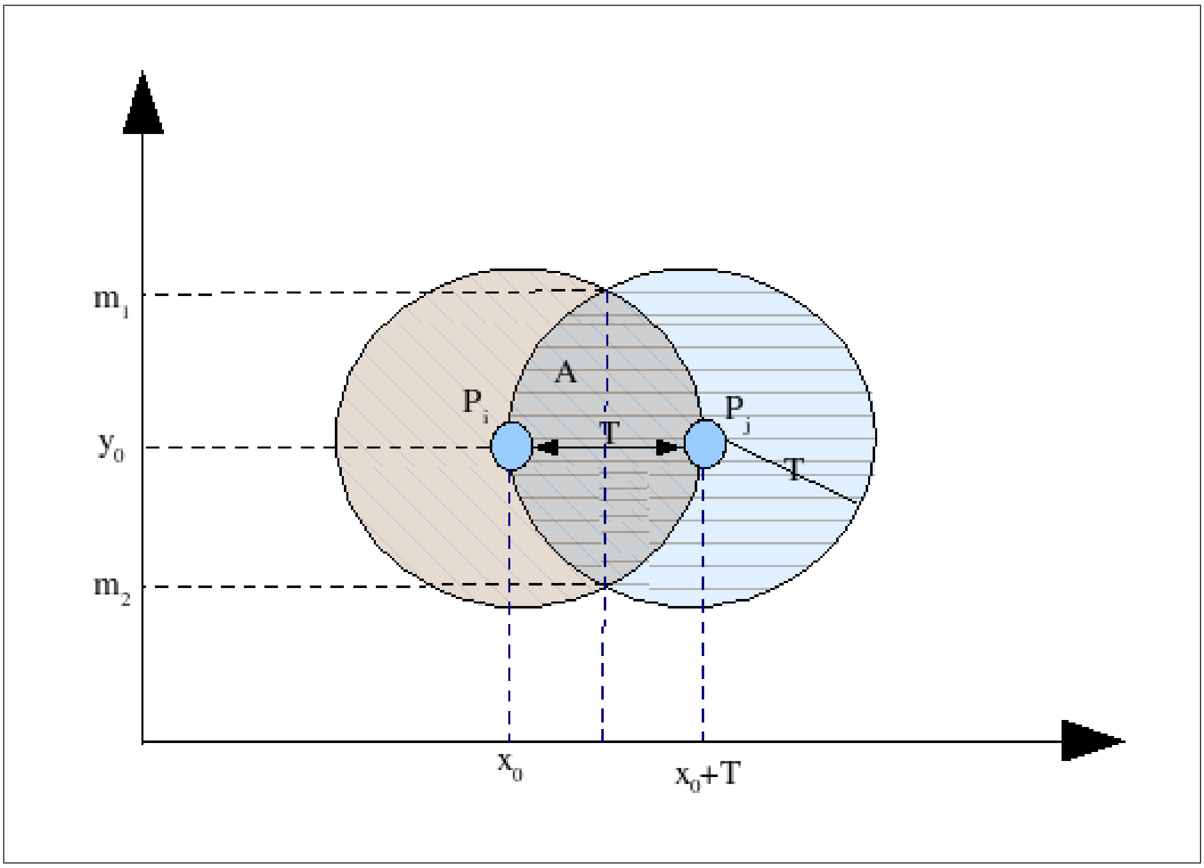


Figure 4.3: The intersection between the coverage areas of two nodes

Theorem 2. *The additional rebroadcast coverage area that can be provided by a branch node which is located at boundary of a parent node, where the distance between the two is* T*, is given by*

$$\left(\frac{\pi}{3} - \frac{\sqrt{3}}{2}\right) T^2$$

Proof. To determine the largest rebroadcast coverage area that can be provided by a branch node j which is located at boundary of a parent node i, where the distance between two is T (see Figure 4.3). The transmission area for each node is πT^2. Therefore, the largest coverage area that is covered by P_j but not by P_i is $\pi T^2 - (\widetilde{A}(C_{P_i}) \cap \widetilde{A}(C_{P_j}))$. To find the intersected area A between two nodes i and j (see Figure 4.3), the equations of the circles are computed:

$$(x - x_0)^2 + (y - y_0)^2 - T^2 = 0 \tag{4.2}$$

$$(x - (x_0 + T))^2 + (y - y_0)^2 - T^2 = 0 \tag{4.3}$$

To find the points of intersection of two circles, m_1 and m_2, Equations 4.2 and 4.3 are solved simultaneously:

$$m_1 = \left(\frac{2x_0 + T}{2}, y_0 + \frac{\sqrt{3}T}{2}\right); \;\; m_2 = \left(\frac{2x_0 + T}{2}, y_0 - \frac{\sqrt{3}T}{2}\right) \tag{4.4}$$

To find the area of intersection A, equations (4.2) and (4.3) can respectively be rewritten as:

$$x = \sqrt{T^2 - (y - y_0)^2} + x_0; \;\; x = \sqrt{T^2 - (y - y_0)^2} + x_0 + T \tag{4.5}$$

Using the information in Figure 4.3 and the equations above, A may be determined:

$$\begin{aligned} A &= 2T^2 \cos^{-1}(\frac{T}{2T}) - \frac{1}{2}T\sqrt{4T^2 - T^2} \\ &= T^2 \left(\frac{2\pi}{3} - \frac{\sqrt{3}}{2} \right) \\ \therefore A &= 1.2283697 \ \ T^2 \end{aligned} \tag{4.6}$$

The total area of P_j is πT^2. Hence, the additional coverage area that P_j provides by rebroadcasting is:

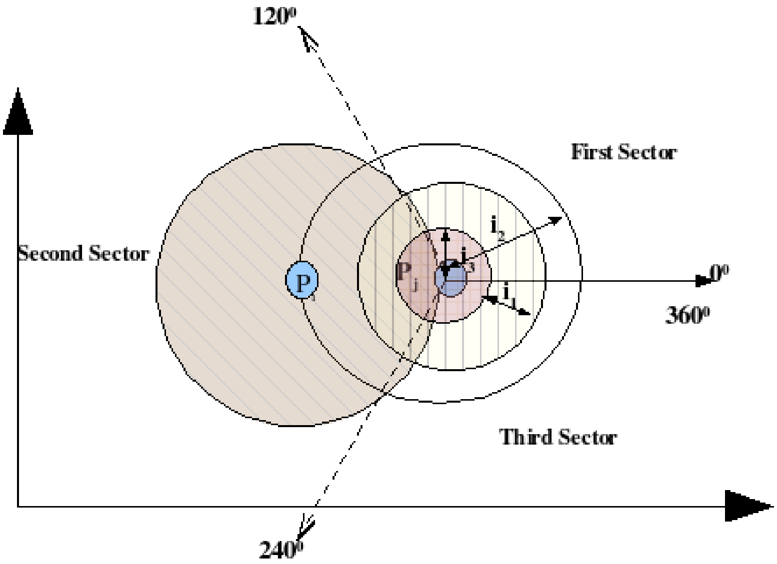
$$\begin{aligned} &\pi T^2 - \left(\frac{2\pi}{3} - \frac{\sqrt{3}}{2} \right) T^2 \\ &= \left(\frac{\pi}{3} - \frac{\sqrt{3}}{2} \right) T^2 \\ &= 1.9132222 \ \ T^2 \end{aligned} \tag{4.7}$$

which is approximately 61% of the total area of P_j.

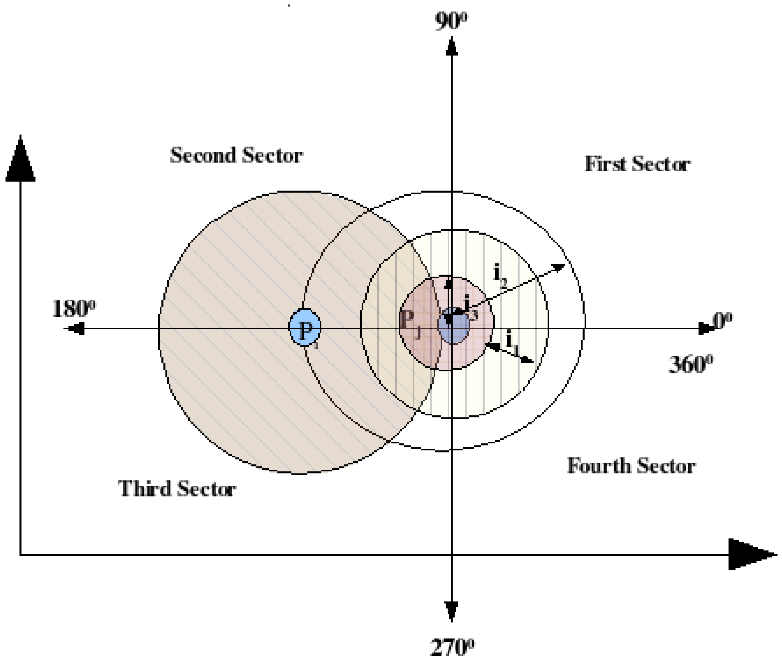
□

According this theorem, the following conclusions can be stated:

- A boundary node will provide the greatest additional coverage area, which is 61% of its total area.
- Table 4.2 summarises the additional coverage areas that can be provided by the selected node at specific distances. The third column of the table represents the ratio of additional coverage area to largest additional coverage area which is found in the previous point.

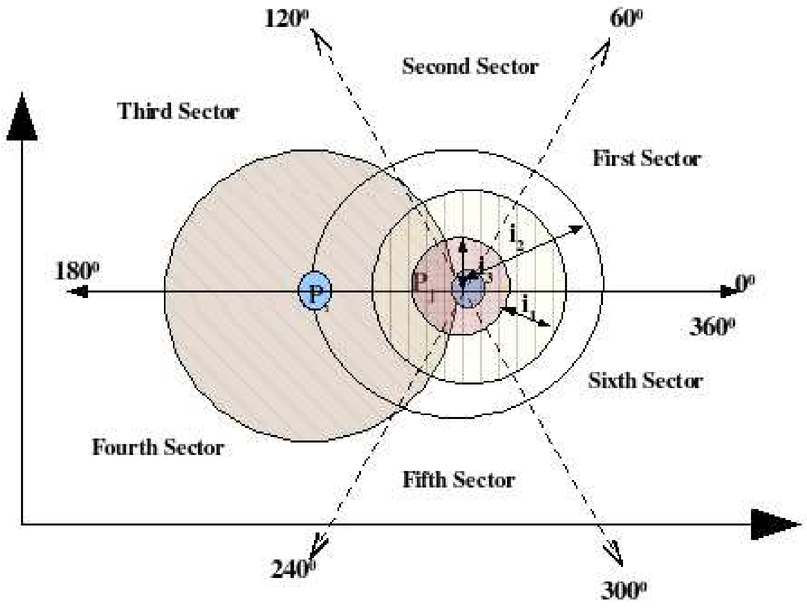


(a) 3 branching nodes

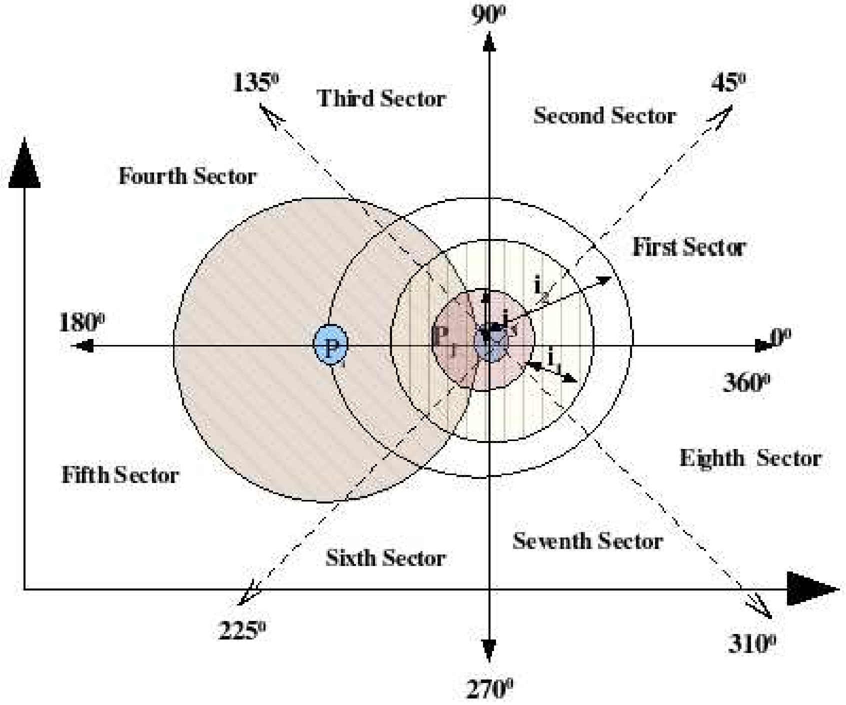


(b) 4 branching nodes

Figure 4.4: Expected number of rebroadcasting nodes for different branch schemes.



(c) 6 branching nodes



(d) 8 branching nodes

Figure 4.4: Expected number of rebroadcasting nodes for different branch schemes.

Distance	**Additional Coverage Area(%)**	**Ratio Additional Coverage/ 61% (%)**
$\frac{T}{2}$	31.5%	51.7%
$\frac{3T}{4}$	46.5%	76.5%
T	61%	100%

Table 4.2: Additional rebroadcasting area based on locations of nodes

Hence, using the branching node distributions shown in Figure 4.1 and the fact that the multiple copies of a RREQ packet will be dropped regardless of whether the received node has been selected, six nodes at most will be selected to rebroadcast in a scheme using 8 branch nodes, four in a scheme using 6 branch nodes, and two in a scheme using 3 branch nodes, for the cases where the branch nodes are located on the boundary of the parent node's transmission range (see Figure 4.4). However in OTRP, the transmission area of a parent node is partitioned into three sub-areas to search for relay nodes as shown in Figure 3.4. Thus the source node or parent node will search for branching nodes in three locations as stated in Algorithm 1, where the area between $[\frac{T}{2}, \frac{3T}{4}]$ is searched first (I_1 in Figure 4.1), followed by the region $[\frac{T}{2}, T]$ (I_2) and finally $[0, T]$ which is equal to $[0, \frac{T}{2}]$ (I_3). Hence, the probability that the selected node is within one of the search regions is calculated as in Table 5.1. Assume that the probability P of finding a node in a particular region (as in Figure 4.5) is proportional to the area of the region. As a result, the probability that the selected node is near the boundary of the parent node is the highest at $\frac{7}{16}$. Therefore, the number of branch nodes in each scheme is reduced if the distance between each rebroadcast node and its parent is less than T.

To conclude, it is expected that rebroadcast schemes using 8 branch nodes will perform best,

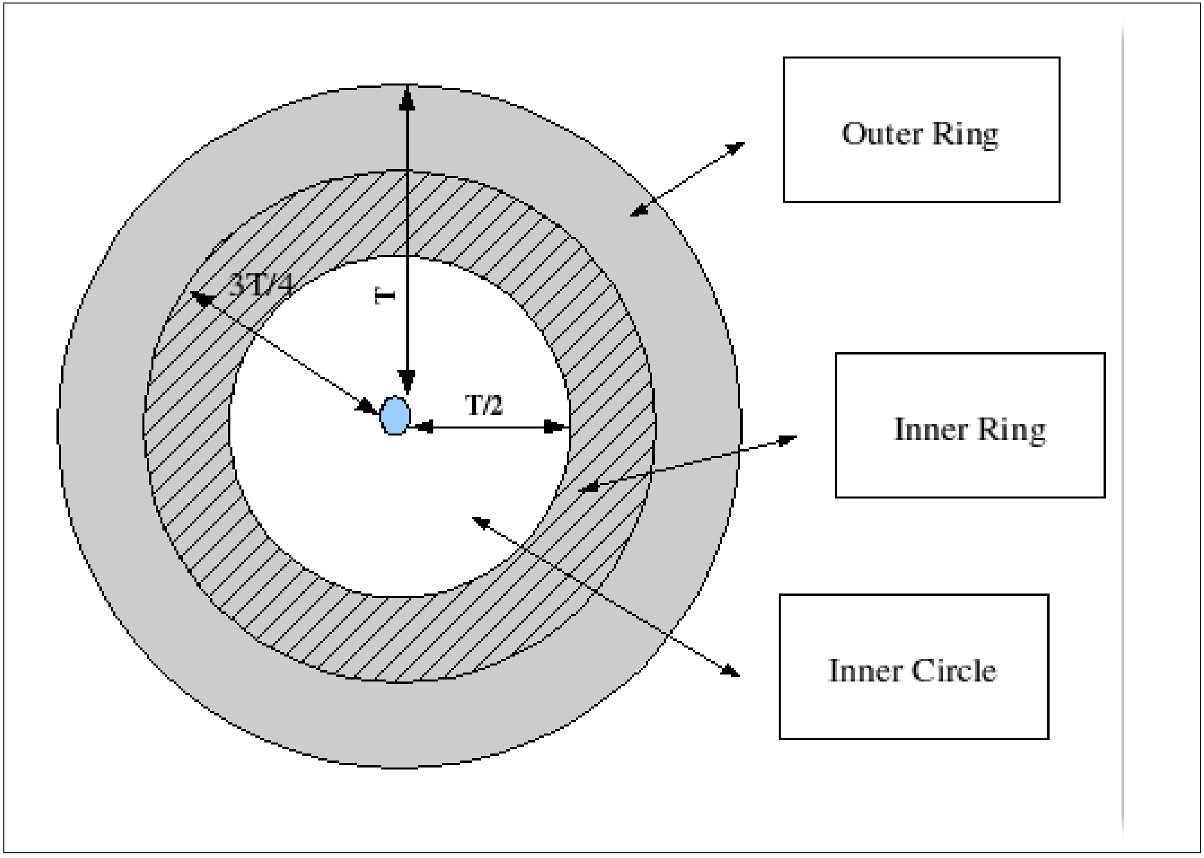


Figure 4.5: Probability of the location of the selected node.

Region	**Area**	**P**
Inner Circle	$\frac{4\pi T^2}{16}$	$\frac{4}{16}$
Inner Ring	$\frac{5\pi T^2}{16}$	$\frac{5}{16}$
Outer Ring	$\frac{7\pi T^2}{16}$	$\frac{7}{16}$

Table 4.3: Probability of the selected node being in a specific region

especially in low or medium node density networks because they provide more rebroadcast nodes and effectively act as a blind flood.

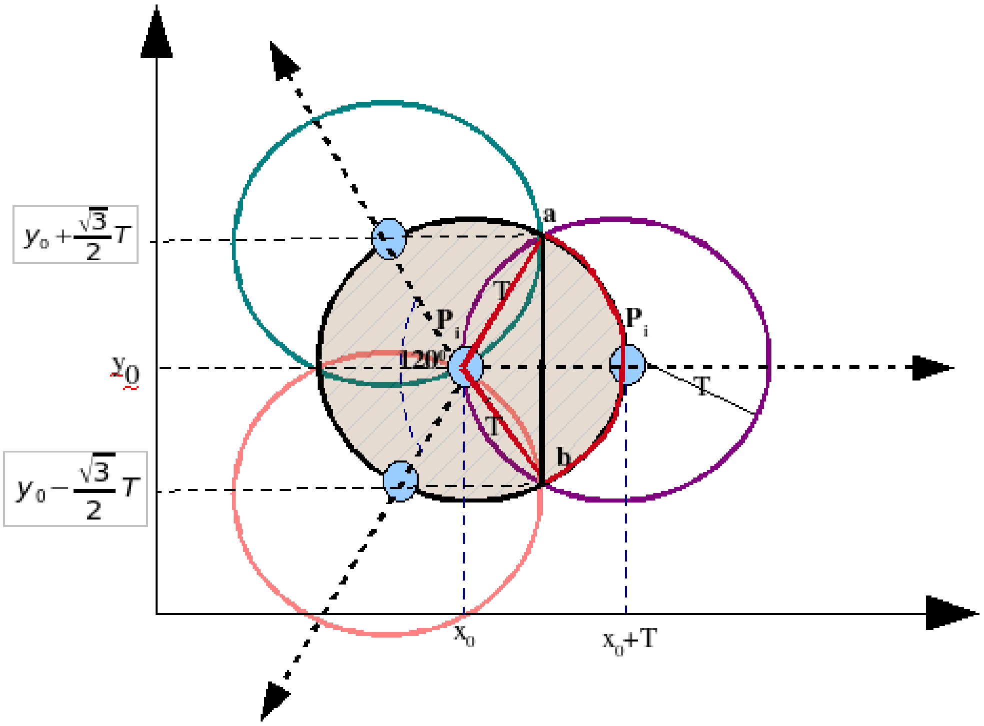


Figure 4.6: OTRP efficiency with 3 branch nodes.

Theorem 3. *Using OTRP and a uniform node distribution, 3 branch nodes positioned on the boundary of a parent a node are sufficient to provide boundary cover for the parent.*

Proof. As in the previous section, in the 3 branch strategy, the transmission range area is divided by three lines where each line starts from a source node. The angle between two lines is 120° (see Figure 4.1(a)). In Figure 4.6, it is assumed that all nodes have the same transmission range T and and 3 branching nodes are located on the boundary of parent node P_i where the distance between each node and the parent is T. Therefore, the intersected areas are the same as in equation (4.6). According to the following lemma, we find that the length of the sector $\overline{ab}$ in Figure 4.6 is

$$\overline{ab} = \frac{1}{3} 2\pi T$$

which means that each intersected sector of branch nodes covers $\frac{1}{3}$ of the transmission range of P_i. According to the distribution of 3 branch nodes, 3 nodes can cover the transmission range of P_i. Therefore, three branch nodes are sufficient to direct the rebroadcast of a RREQ in different directions from the parent node to reach most of the nodes in the entire network.

□

Lemma 1. *According to Figure 4.6, the length circular arc of the intersected sector is equal to 1/3 of the circumstance of the transmission zone of P_i.*

Proof. The circumstance of transmission range of P_i is $2\pi T$. According Figure 4.6 and equation (4.4), $a\hat{P_i}b = \frac{2\pi}{3}$.
Therefore, the length of the sector $\overline{ab}$ is $\frac{1}{3} 2\pi T$.

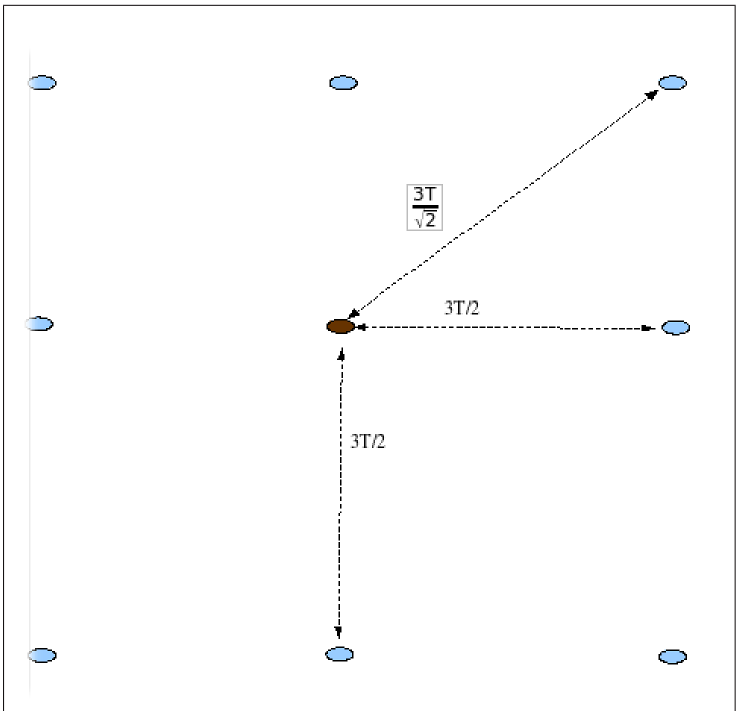
□

4.5 Effects of local density on selection of branching nodes

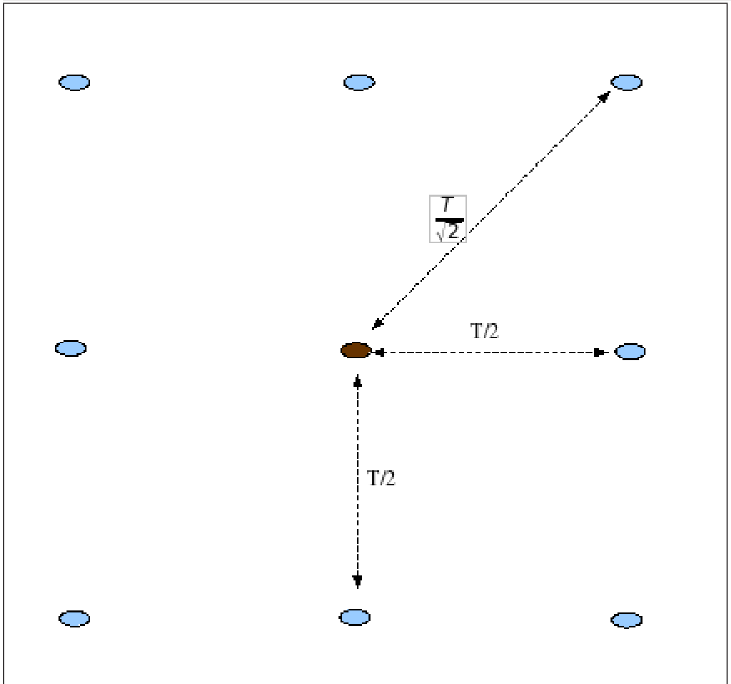
The local density is the total number of neighbours that surround the rebroadcast node. The main effect of local density on OTRP is on choosing branching nodes with OTRP. In Equation (3.9) it was found that:

$$OH_{OTRP} = \frac{1}{\lambda} \cdot OH_{AODV}$$

where $\frac{1}{\lambda}$ is a factor that depends on the distribution of nodes and local density to reduce control overheads. Uniform node distribution is assumed in our analysis, arbitrary distribu-

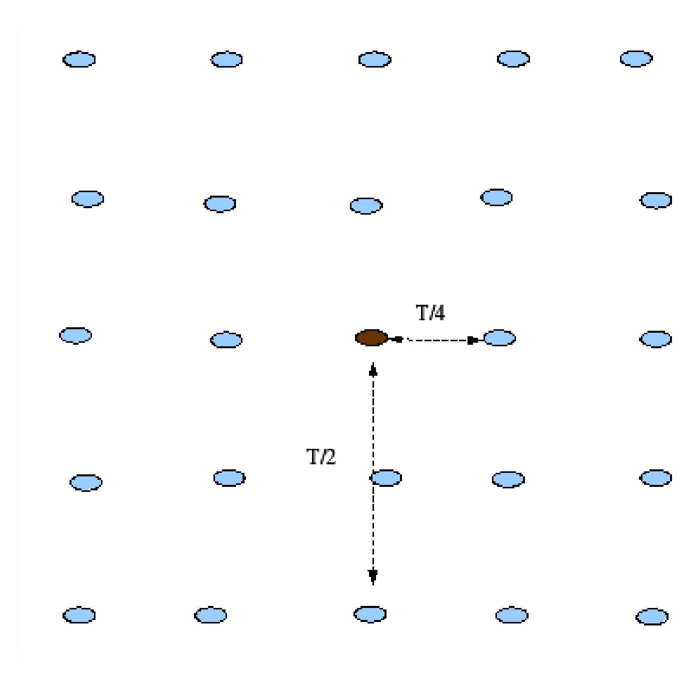


(a) Low nodes density



(b) Medium nodes density

Figure 4.7: Selecting rebroadcasting nodes with different node density, uniform distribution.



(c) High nodes density

Figure 4.7: Selecting rebroadcasting nodes with different node density, uniform distribution.

tion of nodes are used later simulation work. We will study three classes of local density: low, medium, and high (see Figure 4.7). Assume that the number of rebroadcasting nodes with AODV for three cases are: B_{AODV_1}, B_{AODV_2}, and B_{AODV_3} respectively while the notations $B_{OTRP_3}, B_{OTRP_4}, B_{OTRP_6}$, and B_{OTRP_8} referee to total numbers of rebroadcasting nodes with OTRP with different number of branching nodes.

4.5.1 Low Local Node Density

In this sparse network scenario, a sufficient level of control overheads is needed to successfully find a route to the destination. If there are 8 or 6 branching nodes to rebroadcast then OTRP performs well. However , if there is an inadequate number of nodes for rebroadcasting then it is useless to vacate 6/8 addresses for 6/8 branches within the RREQ packet. In Figure 4.7a, there are only 4 reachable neighbours around the source; in such scenarios, there are insufficient neighbours to select 6 or 8 branching nodes for rebroadcasting. This means that OTRP with 3 and 4 branching nodes schemes will behave as AODV and may consume all number of trails to discover the path to destination. Hence, using 3 and 4 branches schemes are better than using 8 branches in such scenarios.

4.5.2 Medium Local Node Density

In Chapter 3 it was found that where nodes are distributed uniformly, the number of rebroadcasting nodes using 4 branches with OTRP (B_{OTRP_4}) as a function of the number of rebroadcasting nodes with AODV (B_{AODV_2}) is given by:

$$B_{OTRP_4} = 0.5 B_{AODV_2}$$

where 4 nodes out of 8 are selected to rebroadcast as shown in Figure 4.7b. When Using 4 branches with OTRP, the ratio of nodes to the total existing nodes is $4/8 = 0.5$. If 3 or 6 or 8 nodes are selected, then the ratio is $3/8 = 0.375$, $6/8 = 0.75$, and $8/8 = 1$ respectively:

$$B_{OTRP_3} = 0.375 B_{AODV_2},$$
$$B_{OTRP_6} = 0.75 B_{AODV_2},$$
$$B_{OTRP_8} = B_{AODV_2}$$

Although the number of rebroadcasting nodes increases as the number of branches increases, this doesn’t mean that overhead with a higher number of branches will also increase. This is because the network may need a sufficient level of control overheads in order to reach the destination with minimal delay and high packet delivery ratio. This can be achieved by providing more rebroadcasting area for the RREQ packet to travel by increasing number of branching nodes to forward RREQ packet in medium local density.

4.5.3 High Local Node Density

For the high local density case there is a node every $T/4$ as shown in Figure 4.7c. Now:

$$
\begin{aligned}
B_{OTRP_3} &= 3/24 B_{AODV_3} \\
B_{OTRP_4} &= 4/24 B_{AODV_3} \\
B_{OTRP_6} &= 6/24 B_{AODV_3} \\
B_{OTRP_8} &= 8/24 B_{AODV_3}
\end{aligned}
$$

High local density of rebroadcasting nodes reduces the effects of increasing rebroadcasting area with increasing number of branching nodes. This is because in such scenarios, the availability of branching nodes is very high; consequently using 3 or 4 nodes to rebroadcast efficiently to reduces control overheads and quickly finds optional routes to destination.

4.6 Number of RREQ Retries and OTRP

Control overhead can also be reduced by reducing the number of route discovery retries that are consumed to find a path to the destination. This occurs naturally when the number of branching nodes is increased, since in general, increasing the number of branching nodes results in a smaller number of retry attempts being needed to discover the path to the destination. An example is shown in Figure 4.8, where node 0 has been selected to rebroadcast a RREQ to find node 9. The notation $B_{OTRP_3}, B_{OTRP_4}, B_{OTRP_6}$, and B_{OTRP_8} refer to instances of OTRP using different numbers of branching nodes. Node 0 will then select nodes:

- 2, 6, and 8 to rebroadcast in the case of $OTRP_3$,
- 1, 3, 6, and 8 to rebroadcast in the case of $OTRP_4$,

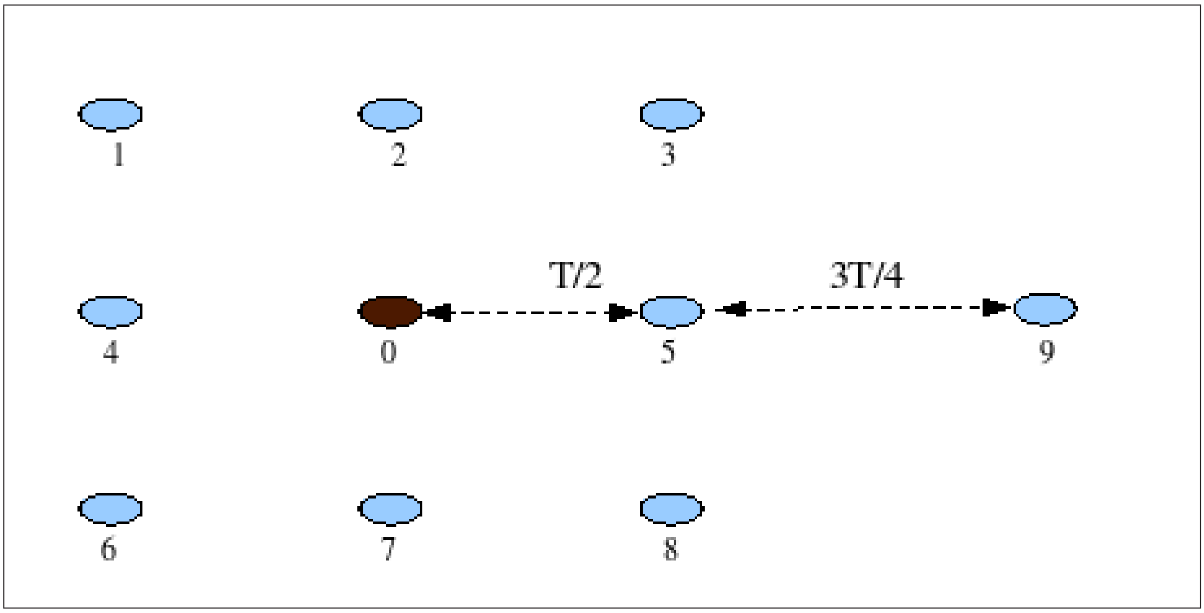


Figure 4.8: OTRP efficiency with 8 branch nodes

- 1, 2, 3, 6, 7, and 8 to rebroadcast in the case of $OTRP_6$,
- 1, 2, 3, 4, 5, 6, 7, and 8 to rebroadcast in the case of $OTRP_8$,

In this example, the RREQ will fail to reach the destination on the first attempt with $OTRP_3$, $OTRP_4$ and $OTRP_6$, while $OTRP_8$ *is* able to reach the destination. Therefore, B_{OTRP_8} accelerates the process of finding a route to the destination by providing more rebroadcasting area and reducing the required number of retries. Consequently, this can reduce the number of rebroadcasting nodes, which reduces overheads and delay, and can increase packet delivery ratio due to reduced medium contention.

In this section, the effect of varying the value of the maximum number of route request retry attempts (represented by the constant parameter RREQ_RETRIES) on the scalability of OTRP is studied. In OTRP, the final RREQ retry is a blind flood which attempts to search for nodes which have not been reached during the previous RREQ attempts. Therefore, it is important to understand how OTRP performs when all RREQ retries are optimised and only the selected nodes are rebroadcasting. It is also important to determine the effect of changing the maximum number of the optimised RREQ retries. Hence, the performance of OTRP is compared with 3 cases:

1. Case 1: using 3 rebroadcast attempts where all nodes rebroadcast in the final attempt;
2. Case 2: using 3 rebroadcast attempts where *only branching nodes* rebroadcast in the final attempt; and
3. Case 3: using 5 trials to rebroadcast, where only branching nodes rebroadcast in all trials. Here the value of RREQ_RETRIES is changed to 5.

To study the performance of OTRP theoretically under those three cases, the following conventions and assumptions are used:

- $OTRP_{case1}$, $OTRP_{case2}$, and $OTRP_{case3}$ denotes OTRP under Case 1, Case 2, and Case 3 respectively;
- α_i branching nodes are used to rebroadcast in each optimised trial OT_i of the given value of RREQ_RETRIES;
- Similarly, in each flooding trial FT_i of the given value of RREQ_RETRIES, there are β_i nodes that are rebroadcasting where $\beta_1 \geq \sum_{j=3}^{5} \alpha_j$, and $i \leq RREQ\_RETRIES$; and
- Each trial OT_i takes a maximum time t_i to reach the limit where the new RREQ retry is initiated by source node.

Given these assumptions, OTRP performance may be expressed in terms of the number RREQ retries for each case as follows:

$$
\begin{aligned}
T_{OTRP_{case1}} &= \sum_{i=1}^{2} OT_i + FT_1 \\
T_{OTRP_{case2}} &= \sum_{i=1}^{3} OT_i \\
T_{OTRP_{case3}} &= \sum_{i=1}^{5} OT_i
\end{aligned}
$$

Therefore, the number of rebroadcasting nodes for each case with OTRP $(B_{OTRP_{case1}})$ can be calculated as follows:

$$
\begin{aligned}
B_{OTRP_{case1}} &= \sum_{i=1}^{2} \alpha_i + \beta_1 \\
B_{OTRP_{case2}} &= \sum_{i=1}^{3} \alpha_i \\
B_{OTRP_{case3}} &= \sum_{i=1}^{5} \alpha_i
\end{aligned}
$$

From the preceding equations, it is expected that:

1. $OTRP_{case1}$ has the highest number of rebroadcasting nodes and $OTRP_{case2}$ has the lowest. Therefore, $OTRP_{case1}$ will have the highest control overheads while $OTRP_{case2}$ has the lowest; and
2. $OTRP_{case3}$ has the highest maximum number of RREQ retries, which means it should take the longest time to find a path if all RREQ_RETRIES are consumed, hence leading to a larger end-to-end delay. Although $OTRP_{case1}$ and $OTRP_{case2}$ have the same number of RREQ_RETRIES, $OTRP_{case1}$ is expected to exhibit a higher delay than $OTRP_{case2}$ because in last trial *all* nodes are rebroadcasting.

Therefore, it is expected that $OTRP_{case2}$ will have the highest packet delivery ratio and the lowest delay and control overheads when compared to $OTRP_{case1}$ and $OTRP_{case3}$.

To conclude this theoretical analysis, the optimal value for RREQ_RETIES of OTRP is expected to be 3 where all RREQ retries are optimised and only selected nodes are rebroadcasting. This will be demonstrated through simulation in next section.

4.7 Experimental Optimisation of OTRP Parameters

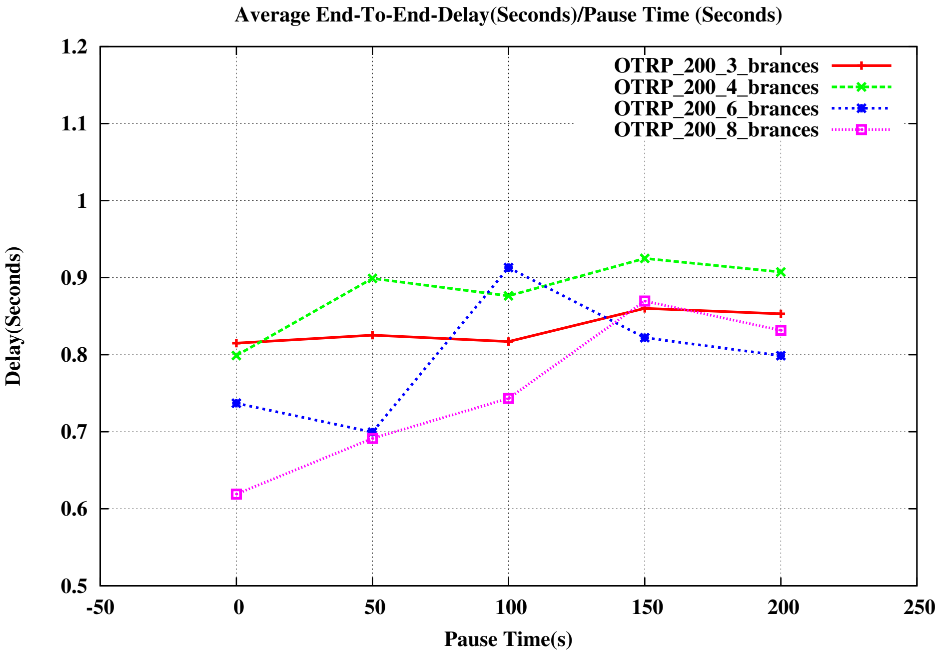
In this section, the theoretical analysis described in previous sections is evaluated and validated in order to determine optimal parameters for the OTRP algorithm. The simulations parameters and performance metrics are the same as stated in Section 3.3 in previous chapter.

4.7.1 Effect of Number of Branching Nodes

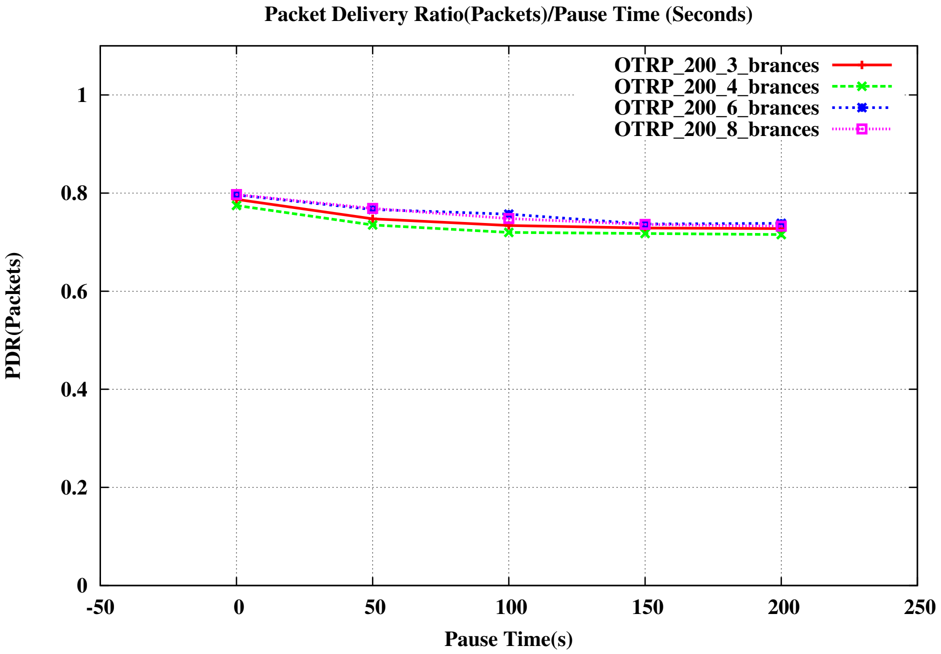
The performance of OTRP is evaluated with several different values for the number of branching nodes (3, 4, 6, and 8); see Figure 4.9. According to the theoretical analysis in previous sections, six rebroadcasting nodes should be sufficient for the 8-node branching scheme.

End-to-end delay is greater when 3 or 4 branching nodes are used than for 6 or 8, as shown in Figure 4.9a. This is because when a smaller number of branching nodes is used, more RREQ retries are needed to find destination as shown in Figure 4.9d. Therefore, as the number of RREQ retries increases, the delay increases too. Consequently, the NCO *increases* as the number of branching nodes *decreases* (see Figure 4.9c).

Selection of a larger number of branching nodes provides additional rebroadcasting reach, as predicted by Theorem 1. As discussed in Section 4.6, the route discovery process is accelerated when the number of route discovery retries is reduced as the number of

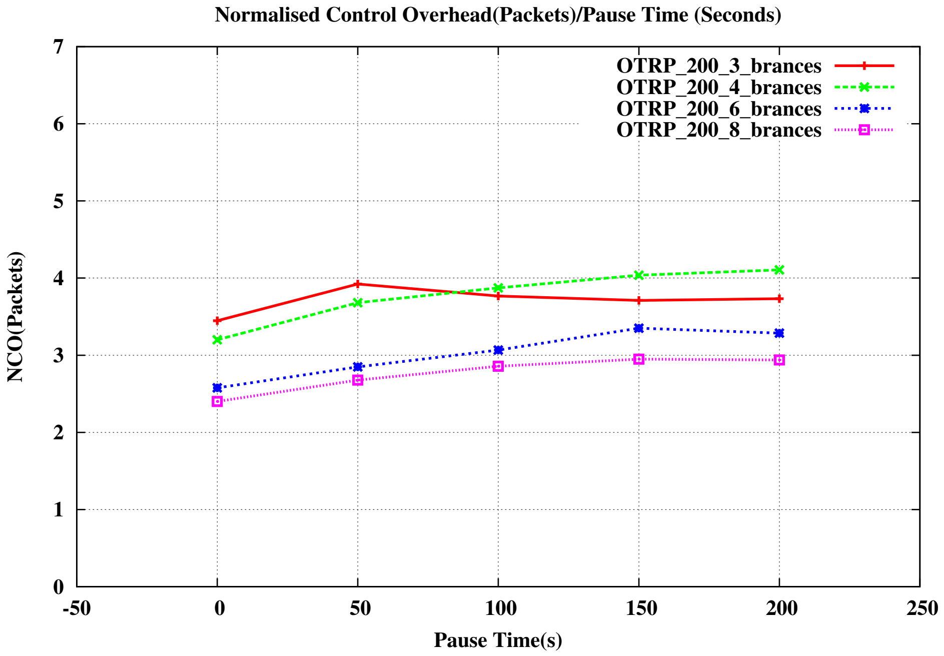


(a) Delay

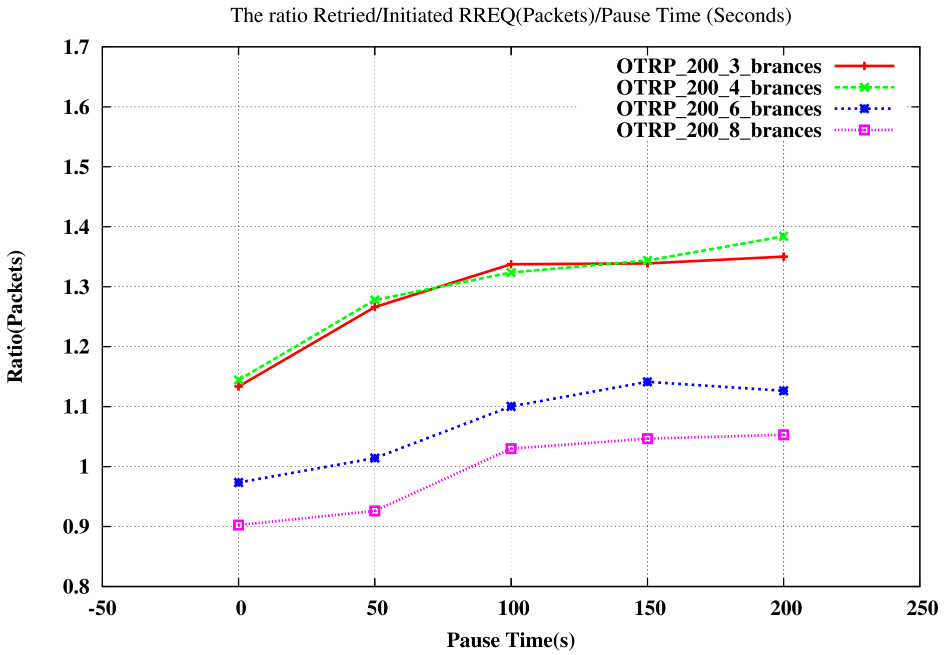


(b) PDR

Figure 4.9: Performance of OTRP with different number of branching nodes with 200 nodes and 30 traffic flows



(c) NCO



(d) Retried Ratio

Figure 4.9: Performance of OTRP with different number of branching nodes with 200 nodes and 30 traffic flows

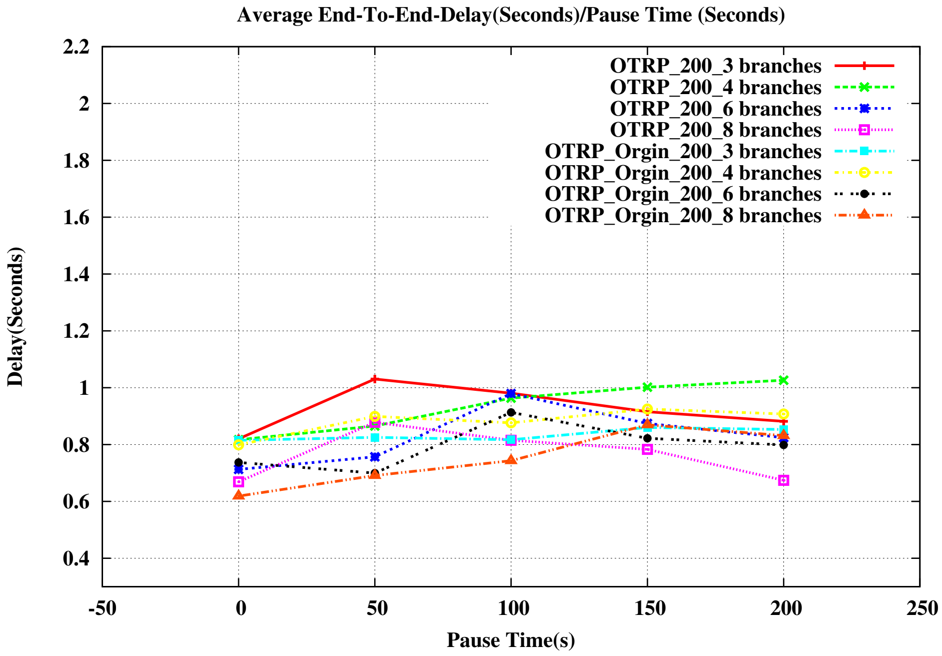
branching nodes is increased. In other words, the network requires a certain minimum level of control overheads in order for a given RREQ packet to reach most nodes without heavy consumption of network resources. From these simulations it may be concluded that 3 or 4 branching nodes are unable to provide sufficiently complete RREQ distribution. However, 6 or 8 branching nodes are clearly sufficient to distribute RREQs without saturating the network with a broadcast storm.

When 3, 4, 6, and 8 branching nodes are used with OTRP, the packet delivery ratio (PDR) is observed to be almost identical (see Figure 4.9b). This is because the strategy that is used to select the relay nodes in OTRP effectively distributes the RREQ packets throughout the entire network regardless of the number of branching nodes or the number of route discovery retries that have been used. Therefore, the ratio of the number of received packets in the destination to the number of the packets that are sent by the source is similar for different number of branching nodes.

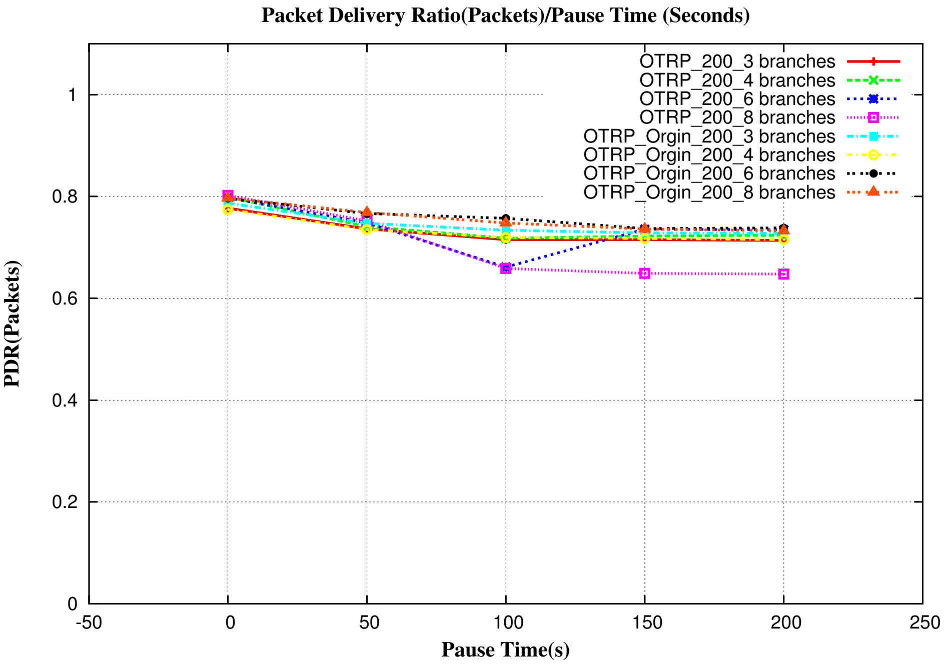
4.7.2 Effect of Branching Node Location

To evaluate the effects of the *locations* of selected branching nodes on the performance of OTRP, Figure 4.10 and Figure 4.11 present simulation results with 200 nodes where OTRP selects nodes that are located in range of $[\frac{T}{2}, T]$ and $[0, \frac{T}{2}]$ respectively. The term *OTRP_Origin* represents the original strategy that is used to select branching nodes in OTRP. The simulation results justify the *OTRP_Origin* strategy; when this selection method is used, the performance of OTRP is clearly better than for the other two cases tested.

If only boundary nodes located within $[\frac{T}{2}, T]$ are selected as branching nodes, this will result in unreliable links under high-mobility conditions, leading to high delay and NCO as shown in and Figure 4.10c. Furthermore, PDR drops from 80% to less than 65% as shown in Figure 4.10b. Generally, 3 and 4 branches nodes have higher EED and NCO regardless of the branching node selection strategy. This is because 3-node and 4-node branching schemes

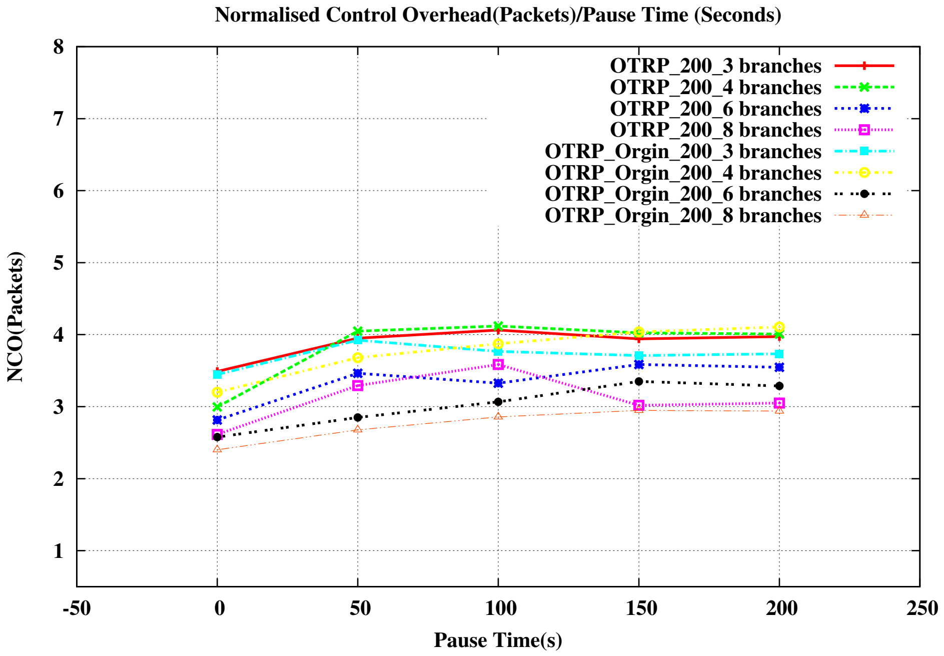


(a) Delay

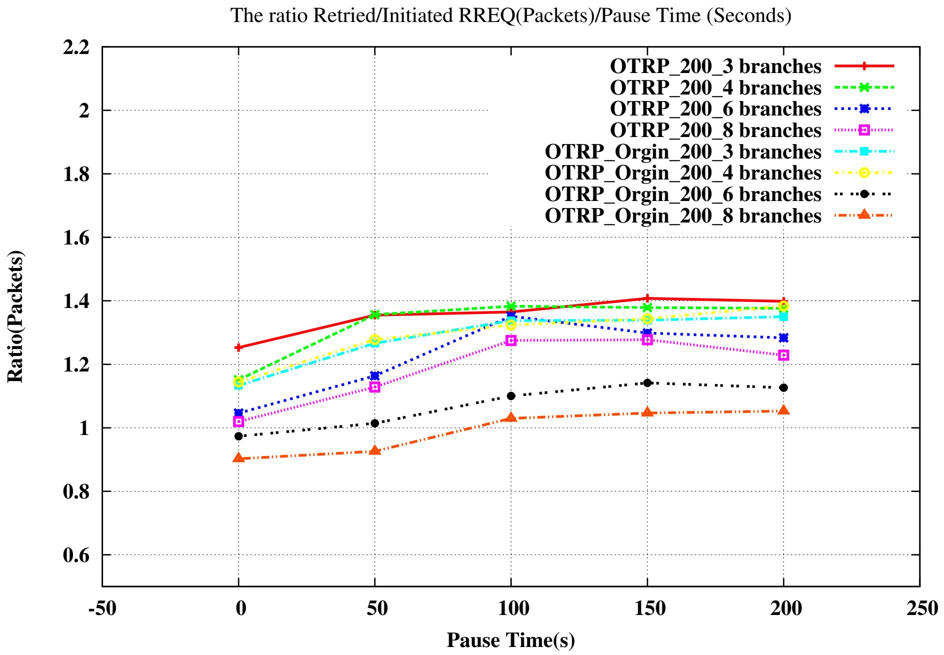


(b) PDR

Figure 4.10: Selecting branching nodes between $[T/2, T]$ in OTRP with 200 nodes and 30 traffic flows

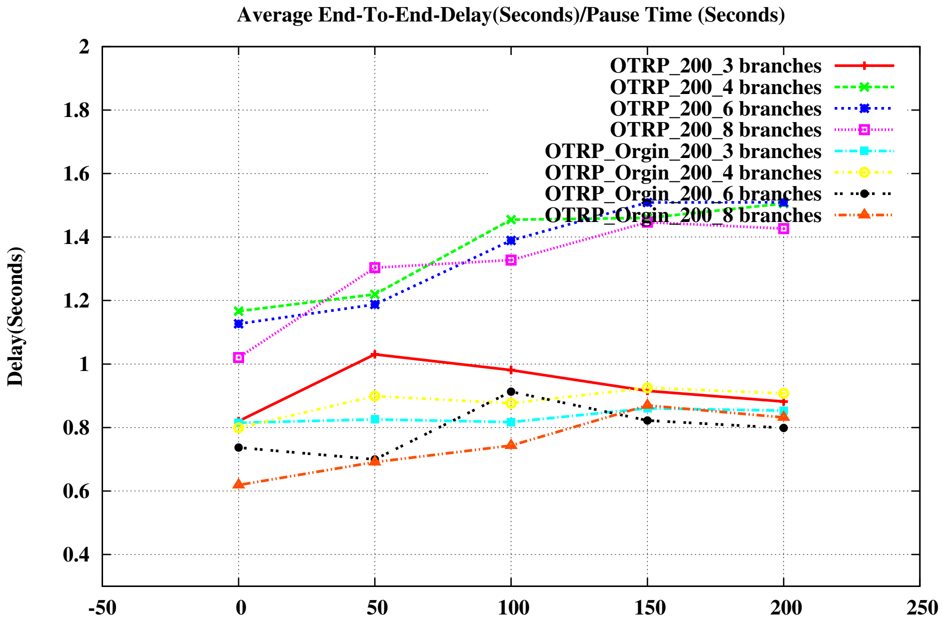


(c) NCO

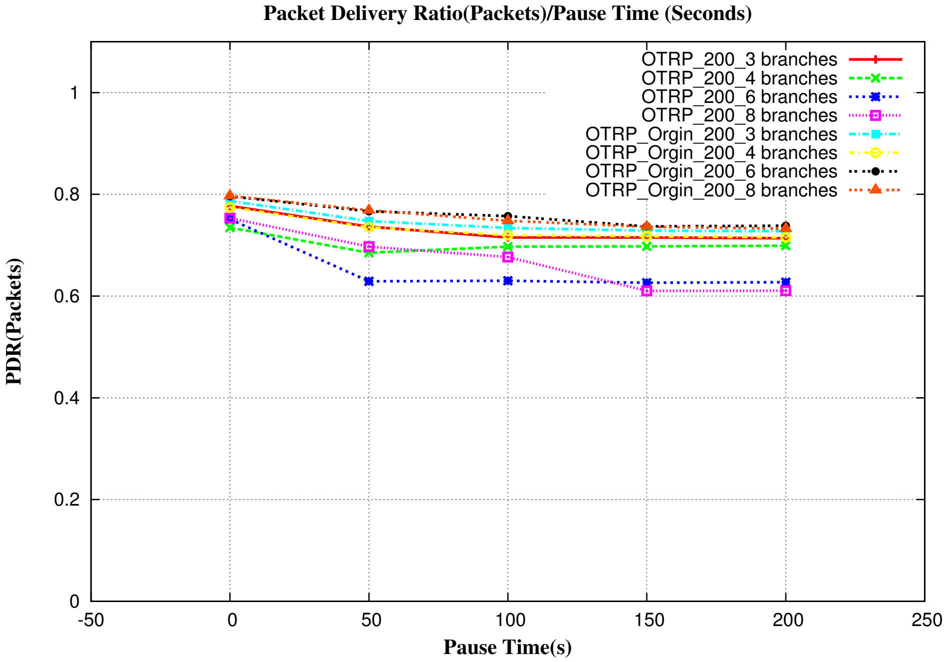


(d) Retried Ratio

Figure 4.10: Selecting branching nodes between $[T/2, T]$ in OTRP with 200 nodes and 30 traffic flows

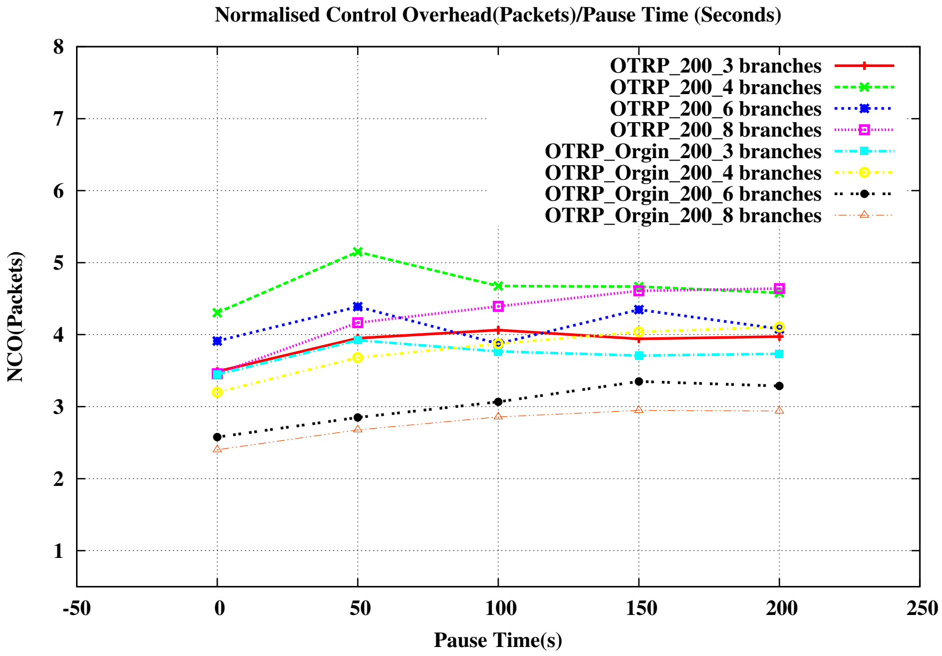


(a) Delay

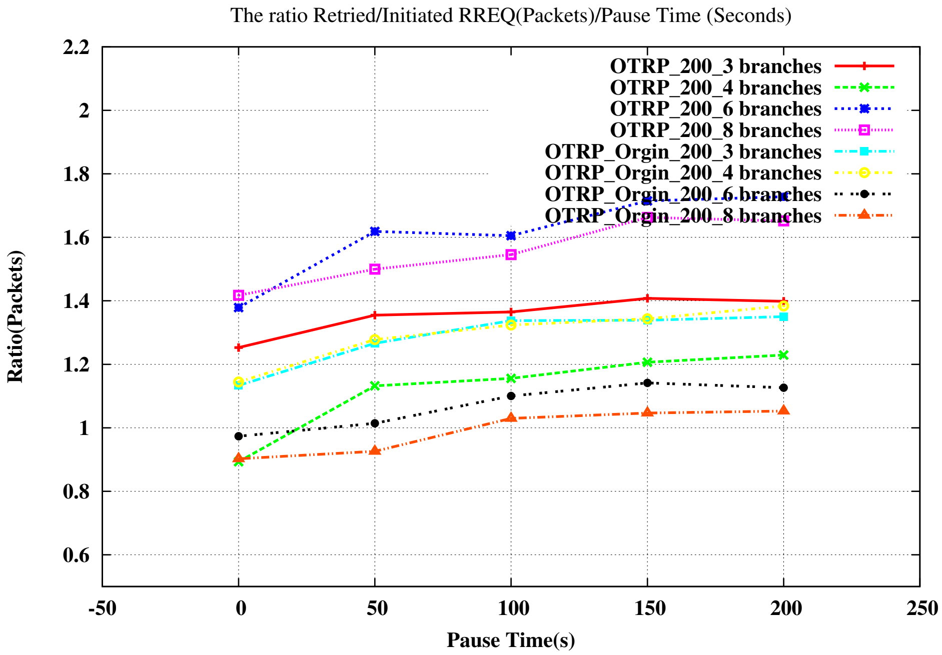


(b) PDR

Figure 4.11: Selecting branching nodes between $[0, T/2]$ in OTRP with 200 nodes and 30 traffic flows



(c) NCO



(d) Retried Ratio

Figure 4.11: Selecting branching nodes between $[0, T/2]$ in OTRP with 200 nodes and 30 traffic flows

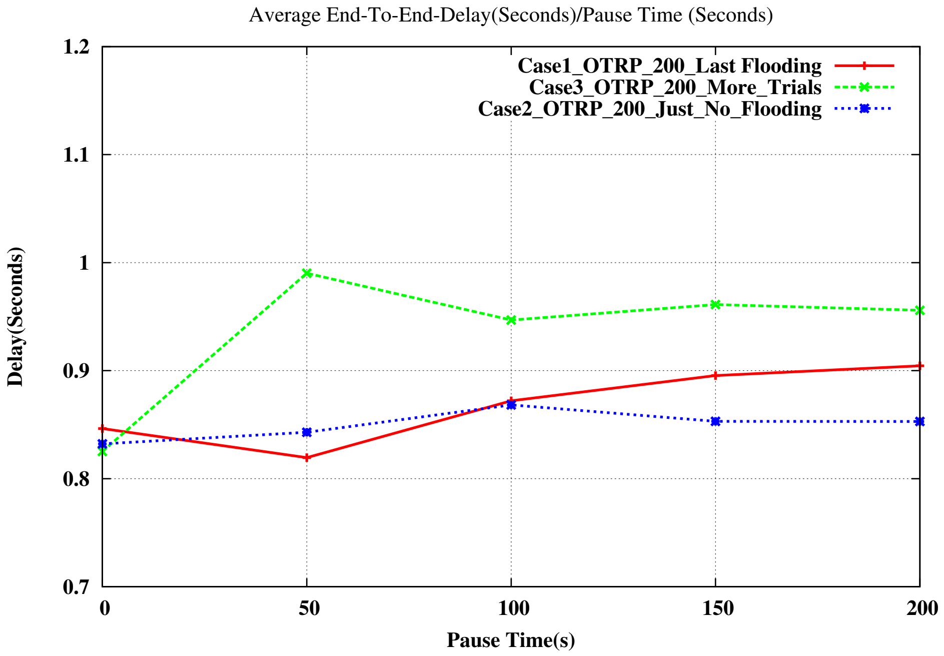
need a larger number RREQ retries to find destination compared to when 6 and 8 branching nodes are used.

Selecting branching nodes within range $[0, \frac{T}{2}]$ degrades the performance of OTRP more seriously than when the range $[\frac{T}{2}, T]$ is used, as shown in Figure 4.11. Here, parent node selects nearby branching nodes, with the result that where they do not provide much additional rebroadcasting coverage. This will frequently lead to a failure in the route discovery process, this is demonstration of Theorem 2. Also, it may result in interference between nodes which causes the loss of RREQ packets. All branching nodes require more RREQ attempts to find the path to the destination as shown in Figure 4.11d. Consequently, EED and NCO are sharply increased in comparison to the *OTRP_Origin* strategy used with OTRP as shown in Figure 4.11a and 4.11c. Moreover, the PDR of OTRP is reduced by 20% if this selection range is used. This is because many of the selected branching nodes do not provide a significant amount of additional rebroadcasting coverage.

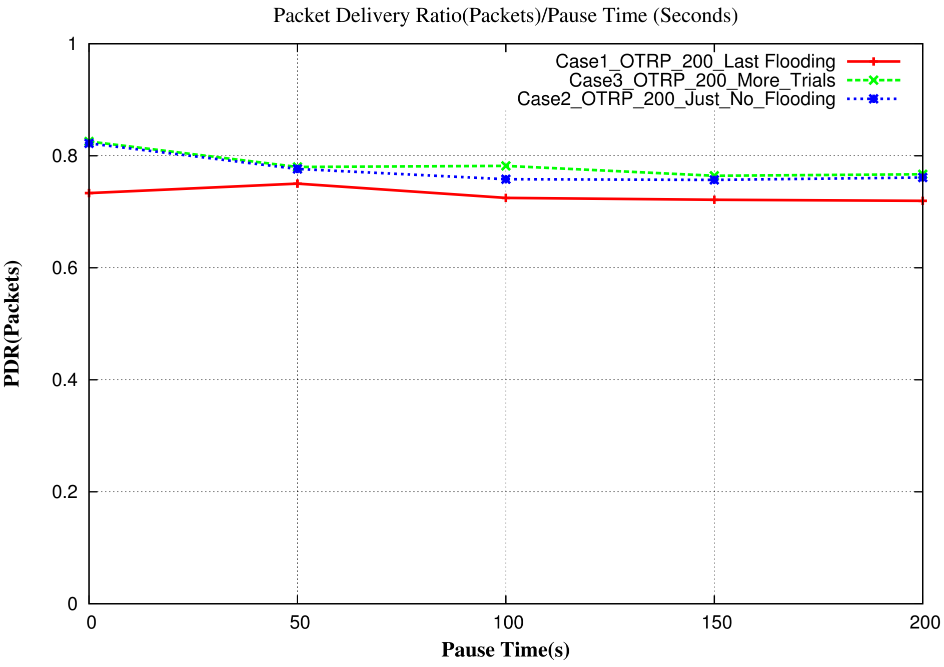
4.7.3 Effect of Number of RREQ Retries

Figure 4.12 presents simulation results for OTRP for each of the cases described in Section 4.6 using 200 nodes and 4 branching nodes. The PDR observed for $OTRP_{case2}$ and $OTRP_{case3}$ is higher by 10% in each case as shown in Figure 4.12b. While the PDR for $OTRP_{case3}$ is slightly higher than for $OTRP_{case2}$, this marginal improvement comes at the cost of higher end-to-end delay. $OTRP_{case1}$ has the highest NCO (more than 6 times the NCO of $OTRP_{case2}$ and $OTRP_{case3}$) as shown in Figure 4.12c. Overall, $OTRP_{case2}$ outperforms the others under 200 node density as it achieves near-maximum PDR with low delay and normalised control overhead. The simulation results are in agreement with the equations derived in Section 4.6 (where $OTRP_{case2}$ was predicted to outperform $OTRP_{case1}$ and $OTRP_{case3}$).

It is noted that the performance of $OTRP_{case3}$ is nearly the same as $OTRP_{case2}$ in terms

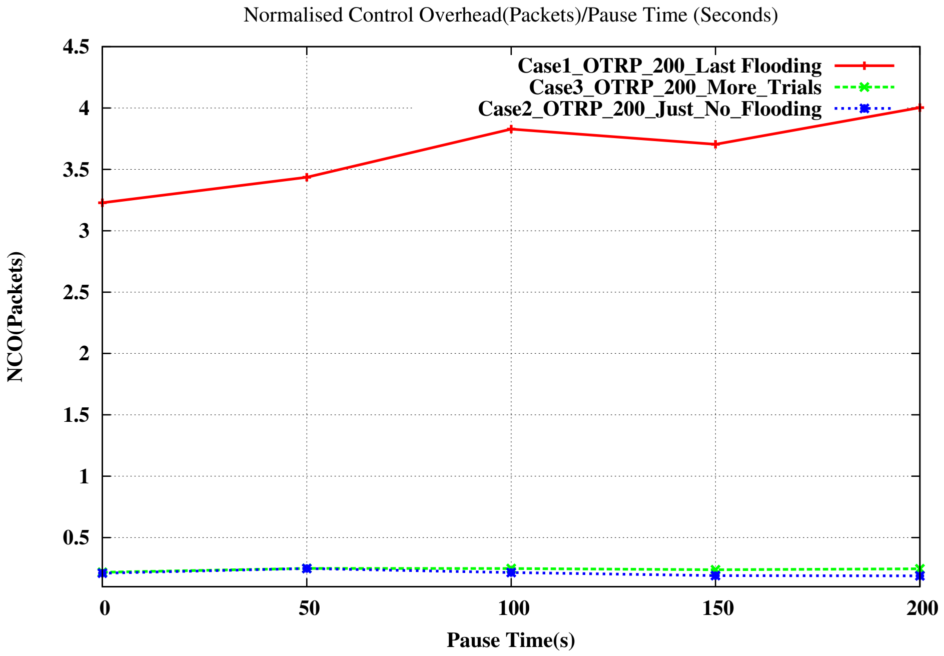


(a) Delay

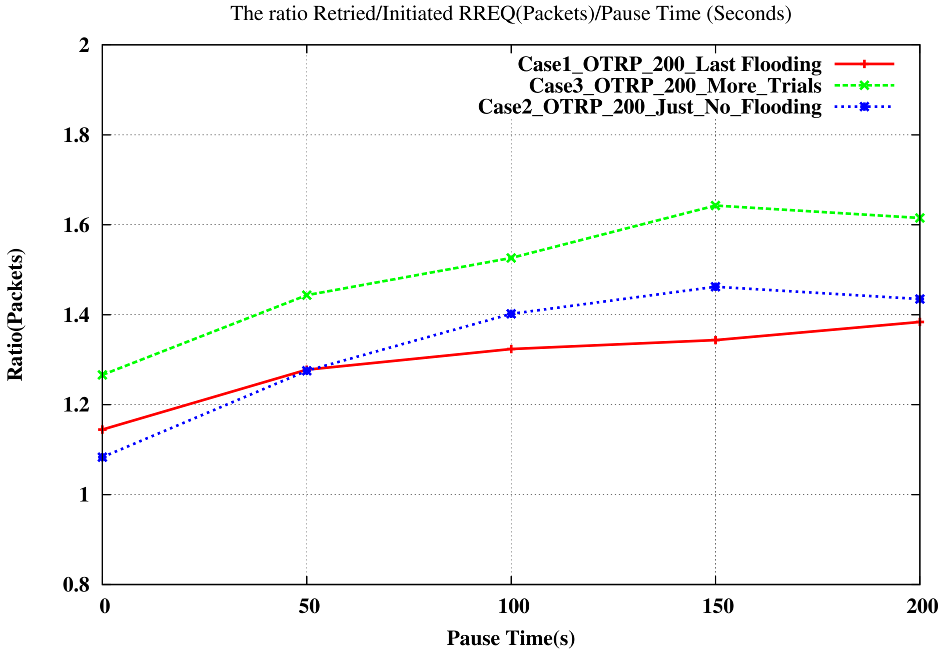


(b) PDR

Figure 4.12: Performance of OTRP for each of the three cases with 200 nodes and 30 traffic flows



(c) NCO



(d) Retried Ratio

Figure 4.12: Performance of OTRP for each of the three cases with 200 nodes and 30 traffic flows

of PDR and NCO, however $OTRP_{case3}$ suffers from very high end-to-end delay. This higher delay is a result of some source nodes requiring all 5 RREQ_RETRIES to find a path to the destination, which delays the process of route discovery. Consequently, as number of RREQ_RETRIES is increased, delay also increases. Although $OTRP_{case2}$ has the same number of RREQ_RETRIES as $OTRP_{case1}$, $OTRP_{case2}$ performs significantly better than $OTRP_{case1}$. This is because only branching nodes are rebroadcasting with $OTRP_{case2}$ in the last RREQ retry attempt, compared to $OTRP_{case1}$ where *all* nodes are rebroadcasting. Hence, optimising the last RREQ retry significantly improves the performance of OTRP. This means that most nodes in the network are reached by OTRP without the need to either use blind flooding in the last retry or increase the maximum number of RREQ retries.

4.7.4 Summary of Experimental Performance Optimisation

In conclusion, using three RREQ retries where all RREQ retries are optimised improves the performance of OTRP especially under conditions of high node density. The following results were obtained:

1. Using an 8-node branching scheme (which actually uses 4 or 5 nodes to rebroadcast) is optimal for OTRP;
2. The strategy of choosing branching nodes in OTRP is more efficient than selecting nodes that are located either at the edge of the parent node's transmission range or in close proximity to it; and
3. Decreasing number of branching nodes and increasing the maximum number of RREQ retries results in greater overhead compared to increasing the number of branching nodes while reducing the number of RREQ retries.

4.8 Conclusion

In this Chapter, the factors that affect the performance of OTRP have been theoretically analysed and evaluated. The key parameters are the number of branch nodes, the location of the branching nodes and number of RREQ retries. It was found that increasing the number of branching nodes with a low number of RREQ retries can improve the performance of OTRP. Moreover, the strategy of choosing branching nodes in OTRP is more efficient than selecting nodes that are located at the boundary of parent node or very close to it.

Chapter 5

Nodes Heterogeneity and MANET Routing Protocols

5.1 Introduction

In MANETs, mobility, heterogeneity, traffic and node density are the main network conditions that significantly affect the performance of routing protocols. Node heterogeneity is one of main issues that needs to be considered in constructing and developing routing protocols for MANETs. Node heterogeneity of MANETs can be explored via two different architectures. In the first architecture, all nodes are initially homogeneous and then as time goes on, the resources of identical nodes deplete differently, creating heterogeneity in the network. The second architecture involves different nodes with different resources (CPU, memory, interfaces, battery capacity, disk size, .. etc) and characteristics (mobility and network loads). This Chapter focuses on the first architecture. In this architecture, as time progresses, the resources such as power depletes differently for each node and consequently the transmission power must be reduced. This eventually creates unidirectional links between nodes as shown in Figure 5.1. Node A has higher transmission range than node B, which means that A includes B in its transmission area while node B does not include node

A. Consequently, the link between A and B is unidirectional from A to B only. However, most MANET reactive routing protocols, assume that all links between two nodes are bidirectional. In heterogeneous scenario, this assumption gives incorrect routing information, resulting in higher delays and greater level of packet loss in heterogeneous networks. In Section 5.2 different MANET routing protocols are evaluating based on the first heterogeneous MANET (HMANET) architecture and compared to the homogeneous MANET scenario.

The unidirectional link problem has not been addressed well in existing literature [43,47,49]. The authors in [63] have been suggested solving the unidirectional link problem between a cluster head and its members by making member nodes move closer to their cluster heads which is not a practical solution for this problem. In [64], unidirectional links were excluded from the route discovery process, which leads to routes consisting of bidirectional links only. However, in [65], the authors suggested that unidirectional links can be utilised to increase packet delivery ratio and hence increase reliability. Therefore, in Section 5.3 a strategy to detect and solve unidirectional links problem according the scenario of the first heterogeneous MANET architecture is proposed.

5.2 Performance of MANET Routing Protocols in Homogeneous and Heterogeneous Environments

In this section results of simulations that have been carried out to compare the performance of different protocols from different classes in heterogeneous and homogeneous MANETs are presented. In homogeneous MANETs, all nodes have identical capabilities and resources while in heterogeneous MANETs different nodes have different transmission range and power supply resources.

GloMoSim[1] [66] package has been used to simulate five different protocols under homo-

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[1] GloMoSim is the predecessor to QualNet

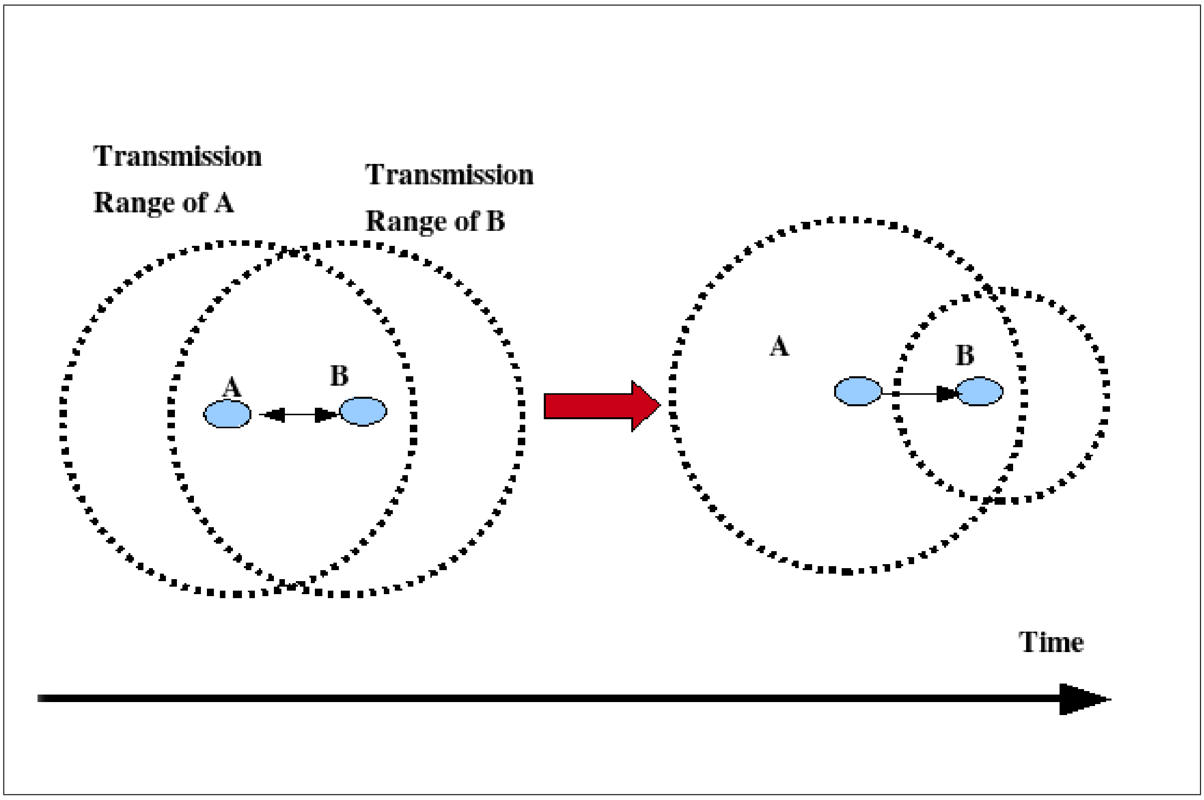


Figure 5.1: Unidirectional Link in First Architecture of Heterogeneous MANET

Simulation Parameter	**Value**
Simulation Time	200s
Number of seeds	10
Number of Nodes	50,100 and 200, randomly distributed
Simulation Area	1000 x 1000 m^2
Node Mobility Model	Random way point
Nodes Speed Range	0-20m/s
Pause Times	0s, 50s, 100s, 200s, 300, 500, 700 and 900s
Number of Traffic Flows	10
Traffic Details	10 flows, Constant Bit Rate (CBR) , 4 packets per second, 512 bytes/packet
MAC Protocols	IEEE 802.11b
Transmission Power	15 dBm in homogeneous MANETs, 10 dBm - 25 dBm in heterogeneous MANETs

Table 5.1: Simulation Parameters

geneous and heterogeneous conditions. These protocols are DSR, AODV, LAR1, FSR and WRP. Packet delivery ratio (PDR), End-to-End Delay, packet loss percentage, and control overhead were used as performance metrics for each protocol. The simulations parameters are listed in Table 5.1.

In this section, only the results of simulating AODV and FSR are presented as representative reactive and proactive routing protocols within heterogeneous and homogeneous networks. DSR, AODV and LAR1 were simulated with 50, 100 and 200 nodes while FSR were simulated with 50 and 100 nodes and WRP with 50 only. This is because FSR and WRP are not scalable to a large number of nodes. Simulation results of DSR, LAR1 and WRP are provided in AppendixA.1.

Figure 5.2a and Figure 5.3a show end-to-end delay for the AODV and FSR protocols. It is clear from the figure that all protocols behave differently with heterogeneous nodes. The delay with 50 and 100 homogeneous nodes remains nearly stable compared to the behaviour in heterogeneous MANETs. All protocols experience higher delay in heterogeneous MANETs compared to homogeneous MANETs for a given number of nodes. For example, the end-to-end delay in AODV was less than 0.02s with 50 homogeneous nodes while it is more than 0.03s with 50 heterogeneous nodes. FSR has higher delays with 100 nodes for both homogeneous and heterogeneous networks. All these reflect the fact that current routing protocols are not appropriate for heterogeneous nodes.

PDR for all protocols is close to 1 in homogeneous networks with different numbers of nodes as shown in Figure 5.2b and It decreases with heterogeneous networks as the number of nodes increases. The difference between the PDR in homogeneous and heterogeneous networks with the same number of nodes is higher in proactive protocols like FSR. This difference is about 20% for reactive protocols while it is nearly 50% for proactive protocols. This shows that proactive protocols are unable to make use of different resources that different nodes have in homogeneous networks.

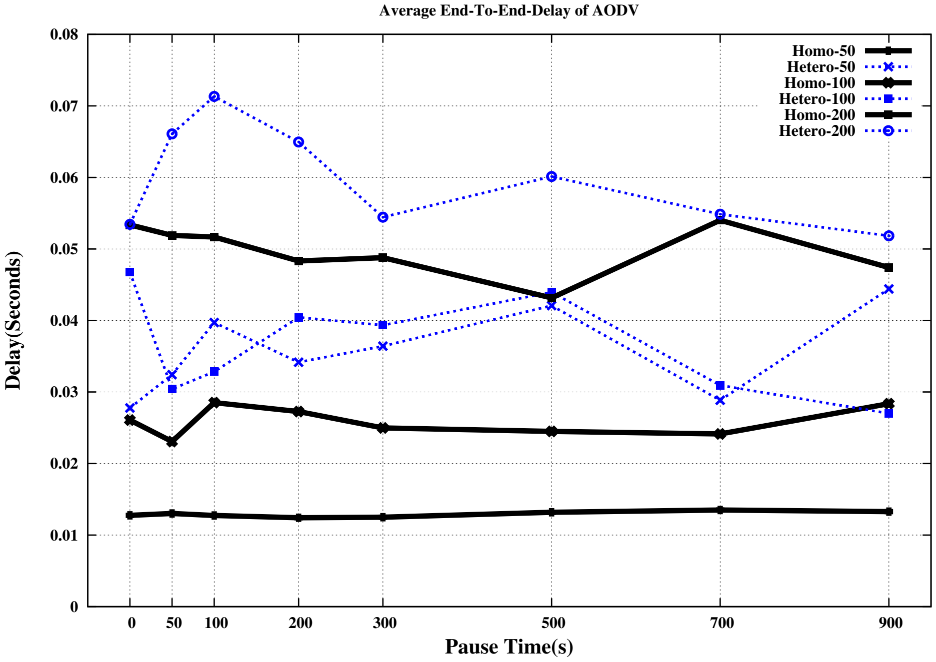
Packet loss rates are illustrated in Figure 5.2c and Figure 5.3b. In homogeneous network, the rate of packet loss is very low compared to heterogeneous network. The packet loss rates in heterogeneous networks with reactive protocols is between 20% and 25% while it ranges from 60% to 70% for proactive protocols.

Control overhead is illustrated in Figure 5.2d and Figure 5.3c. Overhead is higher with heterogeneous networks. Proactive protocols as expected have the highest overhead in both homogeneous and heterogeneous networks. This is because of periodical updates of routing information.

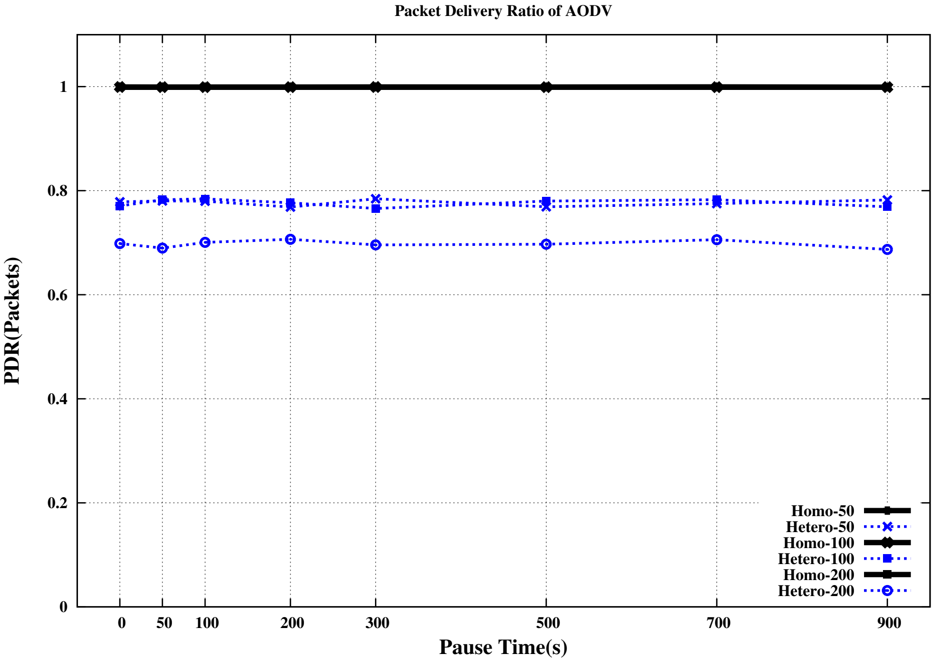
In summary, the performance of all simulated protocols deteriorates in heterogeneous networks. They suffer from higher delays and achieve very low PDR as compared to the homogeneous case. More work needs to be carried out to investigate the problems that arise with routing protocols in heterogeneous networking. In the next section, the unidirectional link problem and its effects on the performance of routing protocols in heterogeneous networks will be investigated.

5.3 Avoiding Unidirectional Links in MANETs using Location-Based Strategies

Commonly, unidirectional links in MANETs are detected either at the MAC layer or network layer. The two way Request-To-Send (RTS) and Clear-To-Send (CTS) handshake is the most common approach in MAC layer to avoid unidirectional links [67]. Network layer approaches use feedback mechanisms either to detect and avoid unidirectional links or to

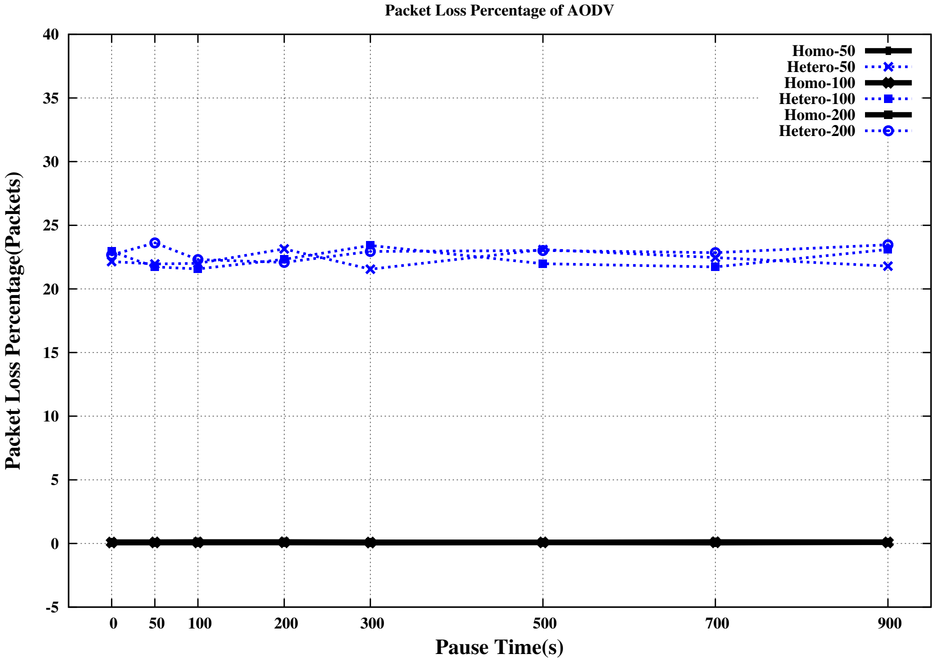


(a) Delay

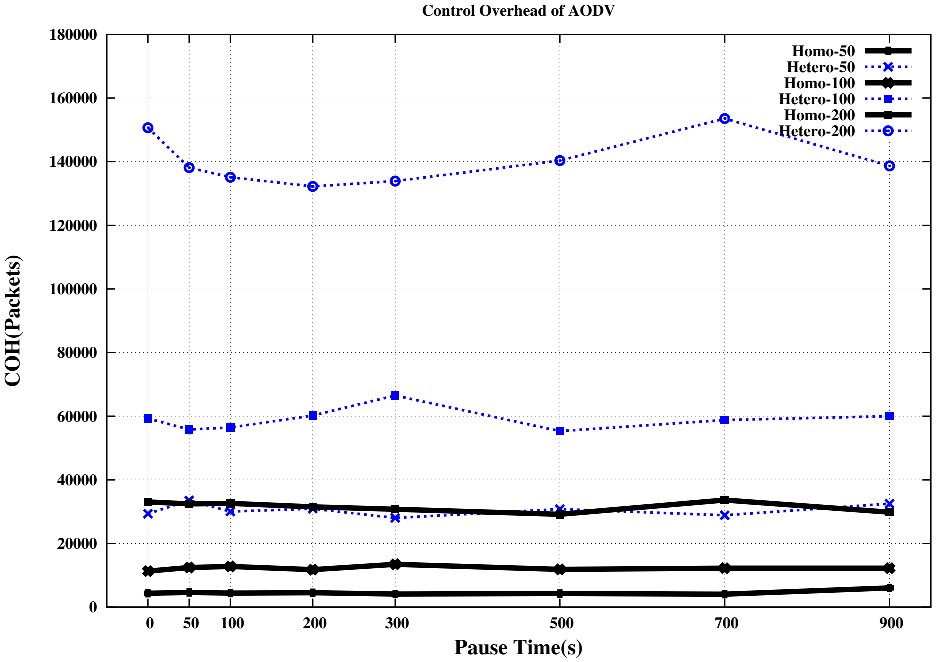


(b) PDR

Figure 5.2: The performance of AODV for 50, 100, and 200 nodes in both homogeneous and heterogeneous networks.

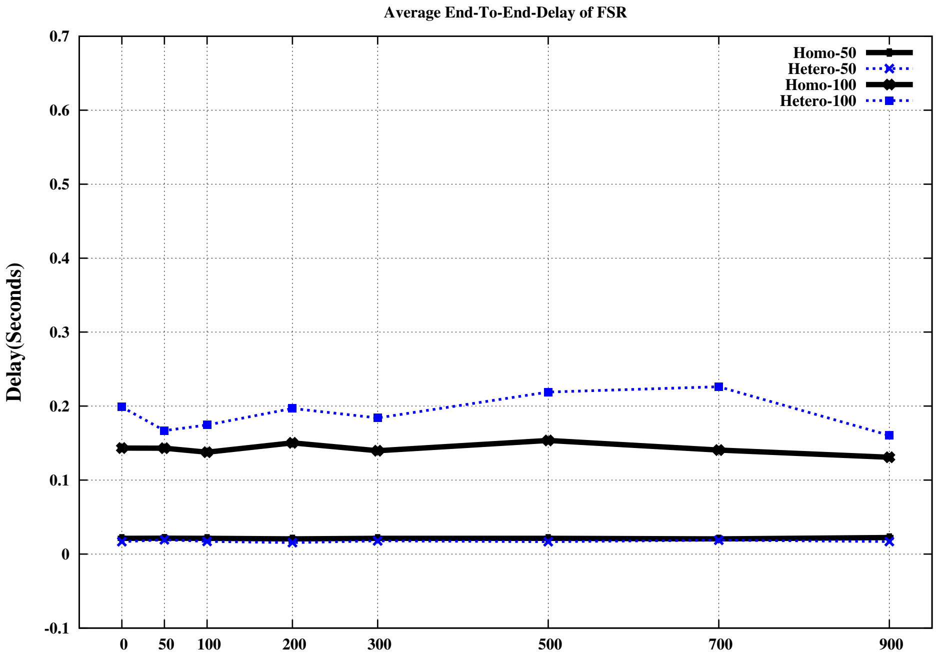


(c) Packet Loss



(d) OH

Figure 5.2: The performance of AODV for 50, 100, and 200 nodes in both homogeneous and heterogeneous networks.

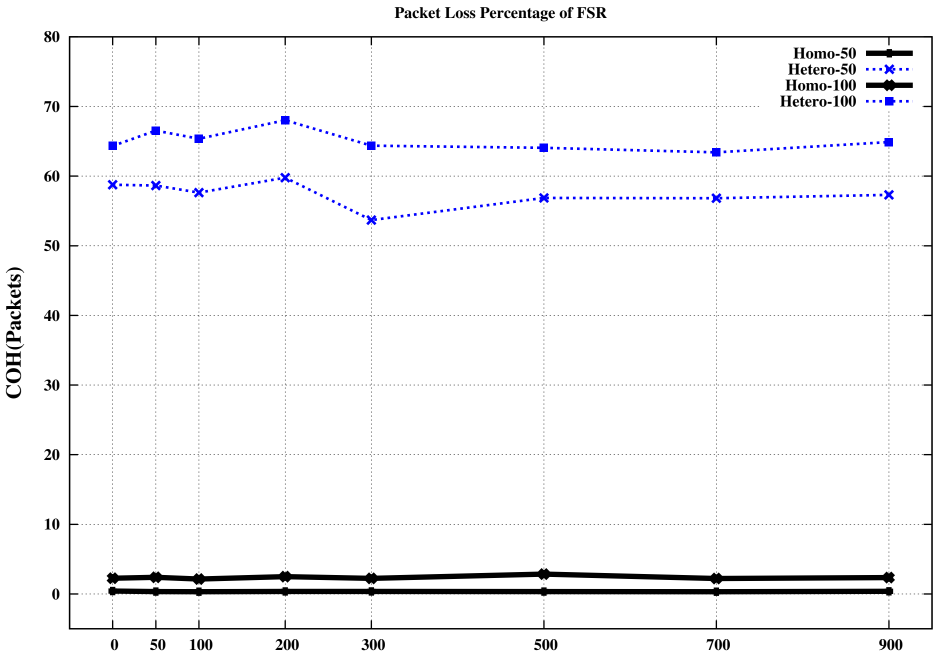


(a) Delay

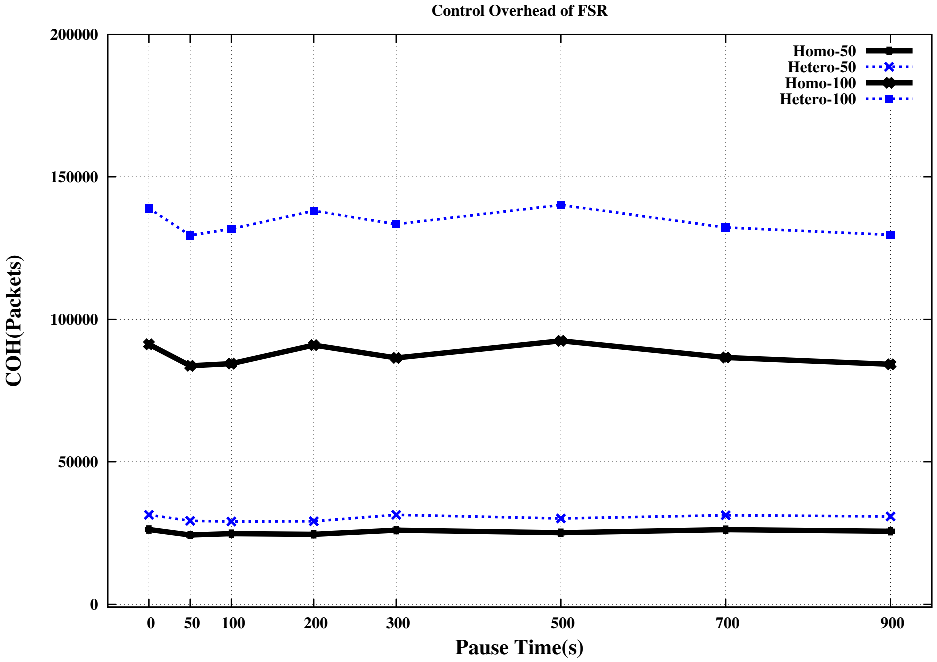
Figure 5.3: The performance of FSR for 50, 100, and 200 nodes in both homogeneous and heterogeneous networks.

utilise them to improve the effectiveness of routing processes. Different strategies have been developed to enhance the performance of routing protocols in the presence of unidirectional links [1, 65, 67, 68]. In AODV-Blacklist [1], when the destination node sends RREP (or any node relays RREP) to the next hop in the reserve path, it waits for an ACK from the node receiving the RREP. If it fails to receive the ACK because of a unidirectional link, then this node is added to the blacklist. Next, when a node receives a RREQ from node in the blacklist, the packet will be dropped. AODV-BlackList avoids unidirectional links but with cost of a high level of control overheads and increased delay since nodes may consume all RREQ_RETRIES to set up a path to destination nodes.

In [68], the Early Unidirectionality Detection and Avoidance (EUDA) mechanism has been proposed to detect and avoid unidirectional links in ad hoc networks. This mechanism appends the location of the forwarding node in RREQ packet. When a node receives a RREQ packet for the first time, it compares the transmission range to the distance to the forward-



(b) Packet Loss



(c) OH

Figure 5.3: The performance of FSR for 50, 100, and 200 nodes in both homogeneous and heterogeneous networks.

ing node using location information embedded in the RREQ. If there is a unidirectional link, then the packet is dropped without any processing. In the worst case where there are no bidirectional routes, all RREQ_RETRIES are consumed. Consequently, the number of control packets increases and the packet delivery ratio decreases as the path to destination can not be established. In [64], Unidirectional Link Elimination using Neighbour List (ULE_NL) is proposed to to eliminate Unidirectionality. NL is appended to the RREQ packet by the forwarding node. The receiving node checks if its address exists in the list. If it does, then the node processes the packet, otherwise the packet is dropped because there is a unidirectional link from the forwarding node to the receiving node. Including the neighbour list in a RREQ packet may increase control overhead. To reduce the size of the list, duplicated neighbour nodes in the NL are excluded.

In [65], a powerful and simple strategy to enhance AODV-Blacklist is proposed. Here, RREP is rebroadcasted to the first hop nodes, the unidirectional link is detected and no nodes are blocked. To avoid inefficient exchanging of ACKs during RREP rebroadcasting, the TTL is set to 1. Also the source node ID and destination ID are cached to avoid duplication of the same RREP packets. Simulation results have shown some improvement of AODV performance in term of packet delivery ratio and control overhead [65].

In this section, a new strategy called Location-Based Utilisation (LBU) is proposed to detect and utilise unidirectional links in the route discovery process of reactive routing protocols. This strategy utilises the locations of forwarding nodes of RREQ packets to resolve the unidirectionality problem. All received RREQ packets are cached and filtered before they are processed or dropped.

In Figure 5.4, a number of nodes with different transmission powers are shown. Source node 1 initiates route discovery to find a path to node 7. Node 2 will rebroadcast the RREQ packet. Node 8 will receive the packet and has a path to destination 7. However,

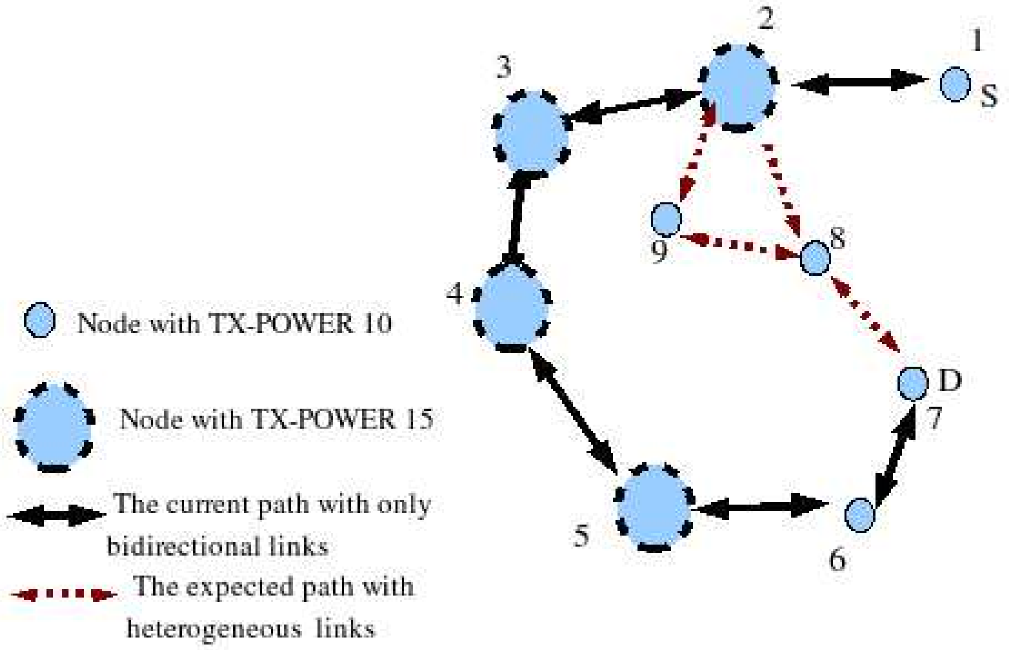


Figure 5.4: Routing through bidirectional links.

it fails to unicast its RREP to node 2 because of the unidirectional link. Because duplicated RREQ packet are ignored, the received RREQ from node 9 is ignored at node 8. In AODV-BlackList, rebroadcasting will continue until the destination is found or RREQ retries limit is reached. In Figure 2, node 8 will consider node 2 unreachable and then inserts node 2 in its blacklist. Therefore, when node 8 receives any packet from node 2, it will be ignored. Source node 1 will have long path $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7$ to reach destination 7, which is only 3-hops distant. This long path can degrade the reliability of network and delay data compared to the expected path $1 \rightarrow 2 \rightarrow 9 \rightarrow 8 \rightarrow 7$. One of the strategies to resolve this problem is that, when node 8 detects unidirectional link to previous forwarding node of RREQ, it rebroadcasts its RREP to its first hop neighbours. As node 9 hears rebroadcasting of RREQ and RREP packets, it will unicast a RREP packet to node 2. This idea is similar to that is proposed in [65]. However, this may create a large number of paths and increases control overheads, which may degrade network performance. Instead of re-

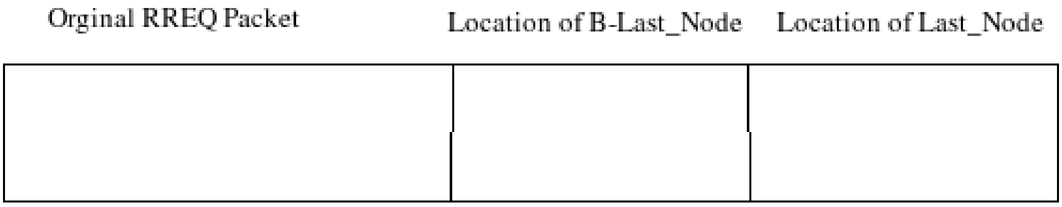


Figure 5.5: RREQ packet for mate

broadcasting RREP as in [65], each node (e.g., node 8) starts caching all RREQ packets of the same source and flood ID to resolve any unidirectional links. The description of how to detect and utilize unidirectional links is described in the following subsections.

5.3.1 Location-Based Utilisation (LBU) of Unidirectional Links

In LBU, the concept of detecting unidirectional link using location information is applied as in [68]. However, LBU differs from EUDA by utilising the unidirectionality to improve the routing process in reactive routing protocols using 2 hops node locations.

To detect the unidirectionality, each RREQ packet will have two more fields (see Figure 5.5). These two fields carry locations of last hop nodes in the path (see Figure 5.6). When node receives a RREQ packet, the following procedure is performed:

1. The node calculates the distance to the forwarding node by using the location information in the RREQ packet;
   $curr_{loc}$=(x_{curr}, y_{curr})
   $lastloc$=$getLastLoc(Recived\_RREQ\_Packet)$
   $Distance$=$\sqrt{(x_{curr} - x_{lastloc})^2 + (y_{curr} - y_{lastloc})^2}$
2. The node calculates its transmission range as Transmission_Range_CurrNode; and

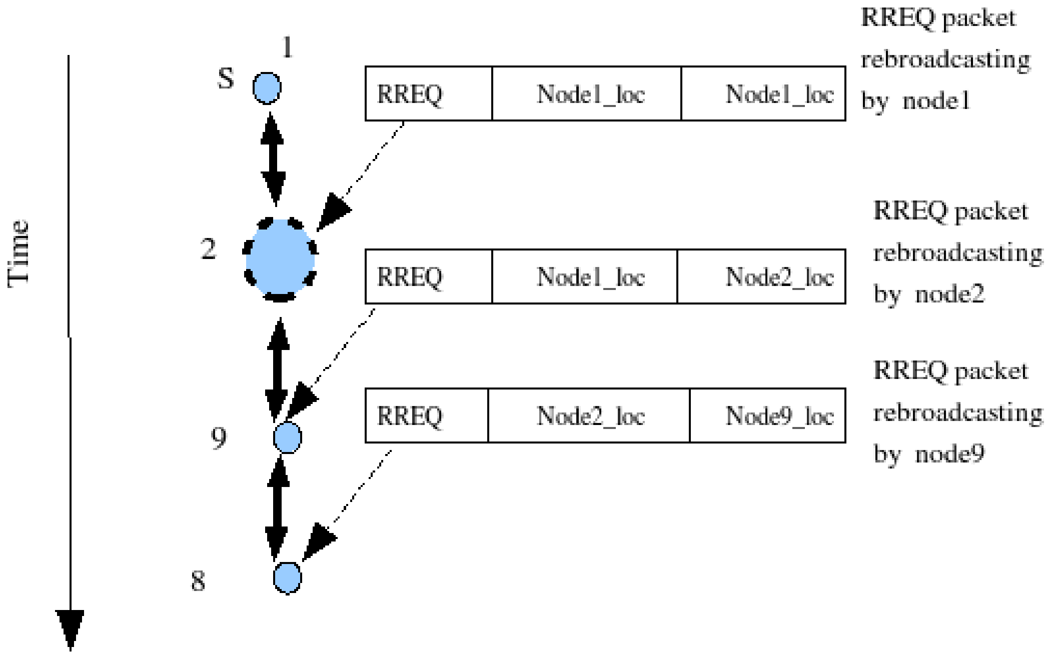


Figure 5.6: RREQ packet traversing

3. The node compares its transmission range to the distance calculated in step 1:

```
if (Distance > Transmission_Range_CurrNode)
        link is unidirectional
else
        link is bidirectional
```

To fix the unidirectional link problem, each node caches information about each visited RREQ packet. Instead of dropping all RREQ packets of the same flood ID and source ID, the node caches the information in RREQ packets to detect and resolve unidirectionality during the flooding of the same RREQ packet. This information is stored in a table called “seen_data_table”, which is similar to the seenTable in AODV which is used to avoid duplication of the same RREQ packet (where it keeps the ID of source and flood number of the

source id	**flood id**	**forwarding node address**	**B_last_loc**	**last_loc**	**isUnidirLink**

Figure 5.7: Seen_Data_Table formate

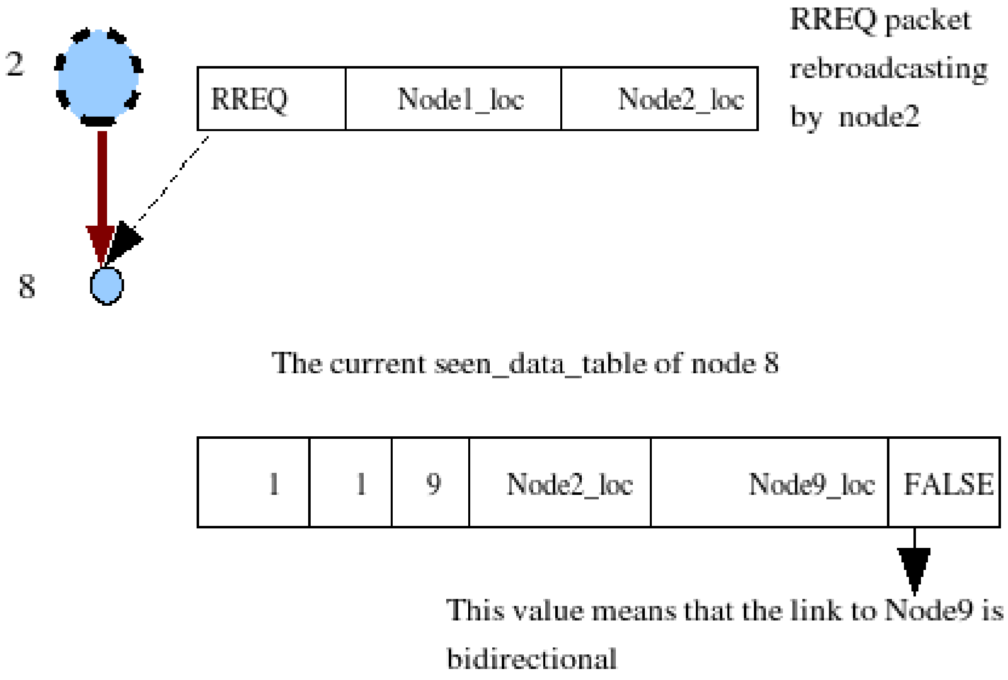


Figure 5.8: Incoming RREQ packet through unidirectional link

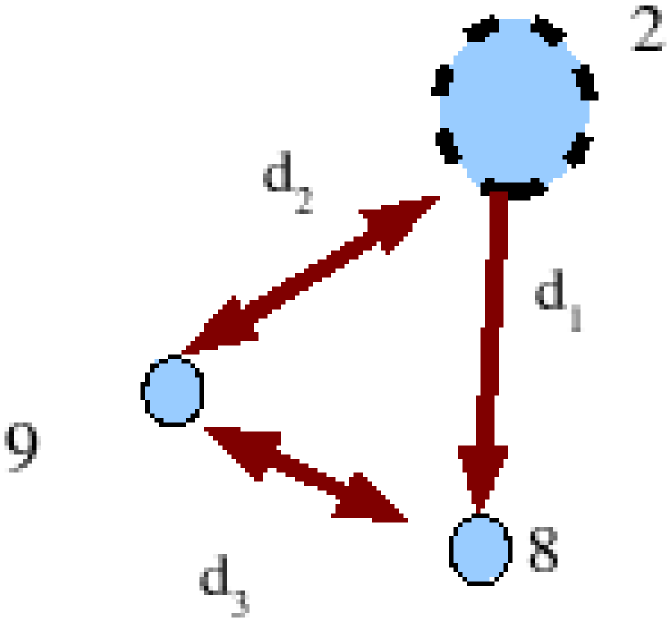


Figure 5.9: The triangle inequality in distance between nodes

first incoming RREQ packet). The format of this table is shown in Figure 5.7. In the table, source ID and flood ID are the identification of each received RREQ packet. The third filed is the address of the node ,which forwards the RREQ packet. B_last_loc and last_loc are the location of 2-hop and 1-hop forwarding nodes of this packet. Last filed in the table is a boolean value to represent the link type between the received node and the forwarding node e.g. true means the link is unidirectional otherwise it is bidirectional.

Each node receives the RREQ packet and detects the type of the link. Each type of link is processed differently as follows:

Unidirectional Link:

If the link is unidirectional (see Figure 5.8) then node searches the seen_data_table for a record, which resolves the problem where:

1. Source ID and flooding number are the same as the current received RREQ packet. This guarantees the freshness of nodes location information and updates the unidirectionality situation in a timely fashion within neighbouring nodes.

2. The value of isUnidiLink is false, which means the forwarded node has a bidirectional link to the current node.

3. The location value of B_last_loc field of the record is same as the location of Last_Node in the received RREQ packet. In Figure 5.8, node 8 looks in its seen_data_table for a node that can reach the forwarding node of the current RREQ packet.

4. To avoid long paths and to replace unidirectional links with only 2-hop links, a node is selected based on its location to form a triangle inequality with current and forwarding node . In other words, the situation where the length of unidirectional link is less than the sum of lengths of other 2 links is preferred as shown in Figure 5.9 where $d_1 < d_2 + d_3$ and d_i is the distance between the pair of nodes.

If a record is found that satisfies all of the above conditions, then the “forwarding node address” in the seen_data_table is used as the next hop to the current forwarding node of the current received RREQ packet. Otherwise, information about the RREQ packet and unidirectionality are inserted in the seen_data_table. Also if the received RREQ packet has not been processed yet, then the packet will be processed after the unidirectional link is fixed where node 9 will be the source of the packet. To conserve node memory, each record that has been used to solve unidirectionality in seen_data_table is deleted. Therefore, the record about node 9 in seen_data_table is deleted because it has already been used to solve the unidirectional link between node 8 and node 2. Consequently, as this problem has been solved,

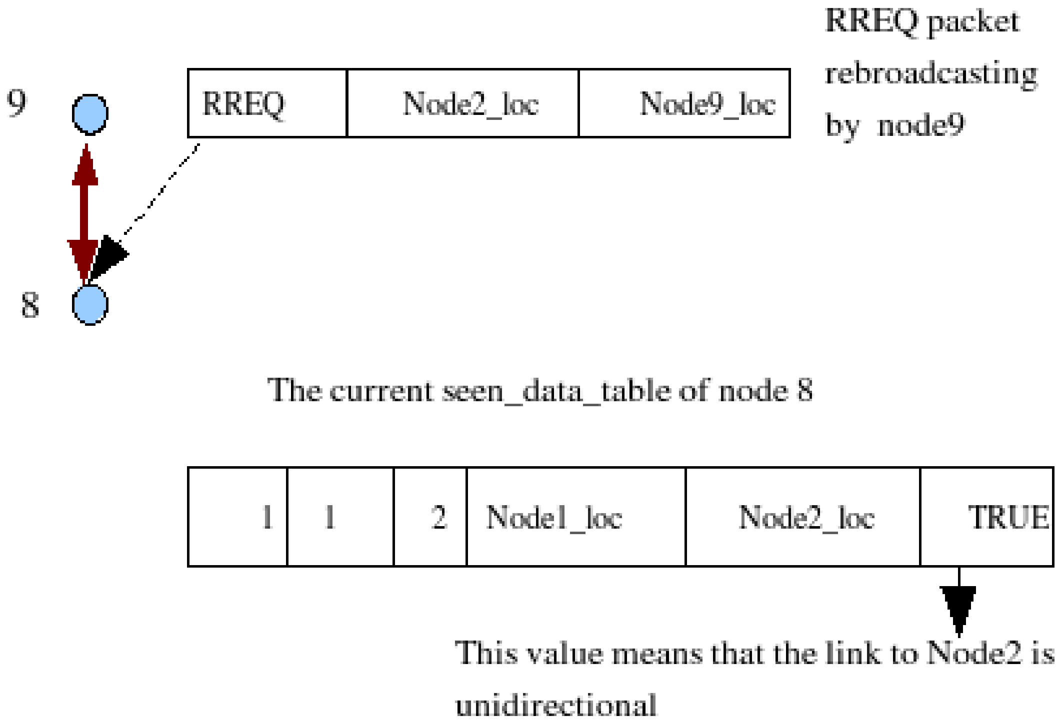


Figure 5.10: Incoming RREQ packet through bidirectional link

it is inefficient and unnecessary, to insert information about node 2 in seen_data_table.

<u>Bidirectional Link:</u>

If the link to/from the forwarding node of the current received RREQ packet is bidirectional (see Figure 5.10) then information from this packet is used to solve any unidirectional link in seen_data_table if:

1. Conditions 1 and 4 are satisfied as described above;
2. The value of isUnidiLink is true, which means the forwarding node has a unidirectional link to the current node; and

3. The location value of last_loc of the record is same as the location of B_Last_Node in the received RREQ packet. In Figure 5.10, node 8 looks for a node where the forwarding node of the current RREQ packet can reach it while node 8 can't.

If a record is found that satisfies all of above conditions then the address of current forwarding node is used as the next hop to the forwarding node of the recorded packet. In Figure 5.10, node 9 will be the next hop to node 2. Otherwise, information about the RREQ packet and bidirectionality are inserted in seen_data_table to be used to solve any incoming unidirectional link. To conserve node memory, each record of unidirectionality that has been solved seen_data_table is deleted. Therefore, the record about node 2 in seen_data_table is deleted. Each node which receives a second flood of the same RREQ packet will delete all records about the first flood in the seen_data_table.

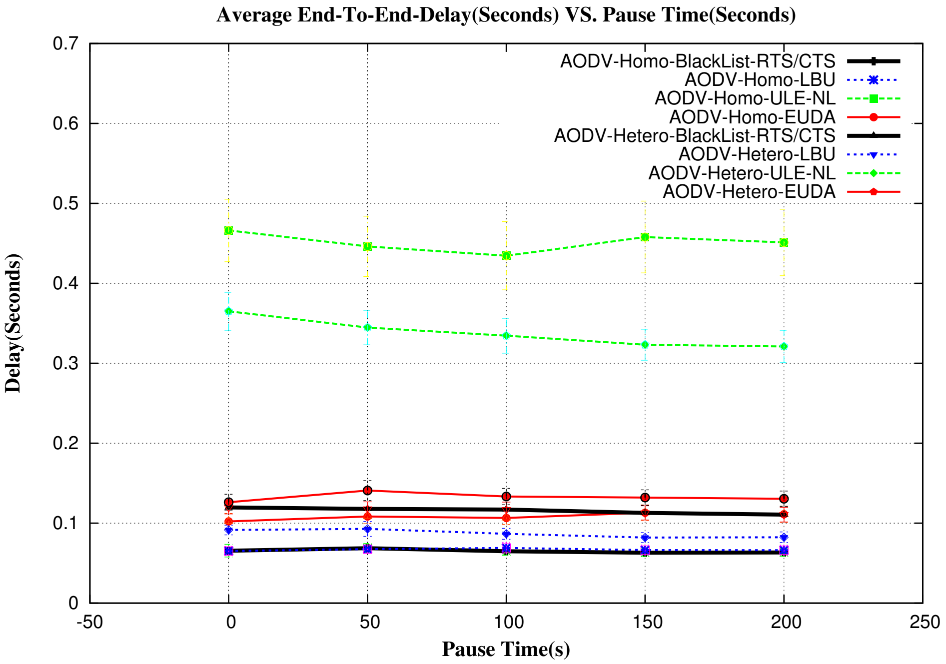
5.3.2 Simulation Models

The performance of LBU for unidirectional links is compared to ULE_NL,BlackList and the standard RTS/CTS strategy. AODV [1] and OTRP are used as routing protocols. OTRP described in Chapter 3, combines the idea of hop-by-hop routing such as AODV with an efficient route discovery algorithm called Tree-based Optimised Flooding (TOF) to improve the scalability of Ad hoc networks when there is no previous knowledge about the destination. These two protocols have been simulated using QualNet4.5. The simulation parameters are listed in Table 5.2.

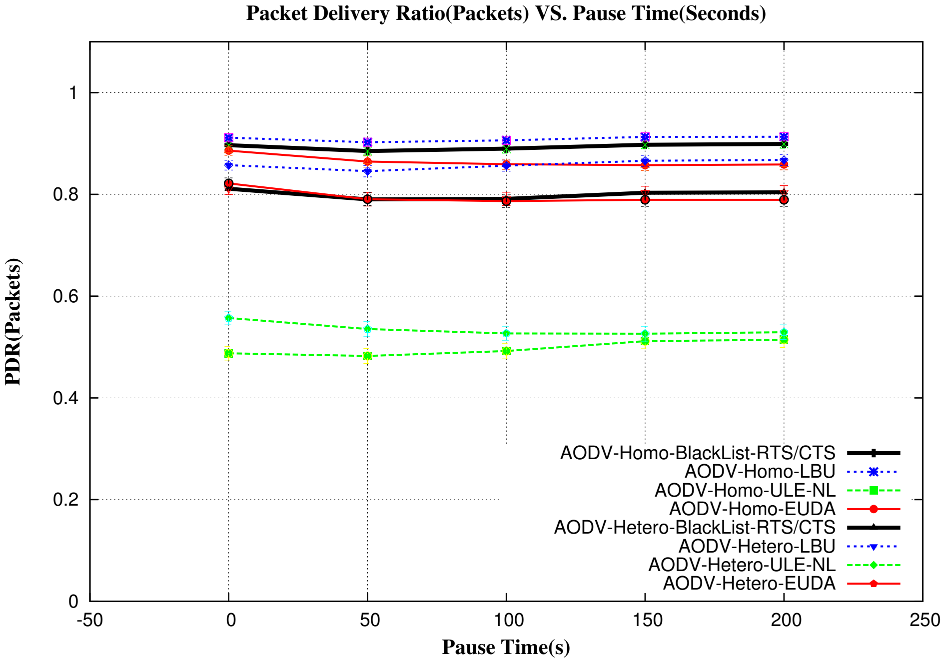
Packet Delivery Ratio (PDR), End-to-End Delay, Normalised Control Overhead (NCO), and Retry Ratio (Ret_Ratio) were used as performance metrics of each protocol. Confidence intervals of 95% are used to present the data.

Simulation Parameter	**Value**
Simulation Time	200s
Number of seeds	100
Number of Nodes	100 randomly distributed
Simulation Area	1500 x 1500 m^2
Node Mobility Model	Random way point
Nodes Speed Range	0-20m/s
Pause Times	0s, 50s, 100s, 150s, and 200s
Number of Traffic Flows	10
Traffic Details	10 flows, Constant Bit Rate (CBR), 4 packets per second, 512 bytes/packet
MAC Protocols	IEEE 802.11b
Transmission Power	15 dBm in homogeneous MANETs, in heterogeneous MANETs: 50% of nodes have 10 dBm and the others have 15 dBm

Table 5.2: Simulation Parameters

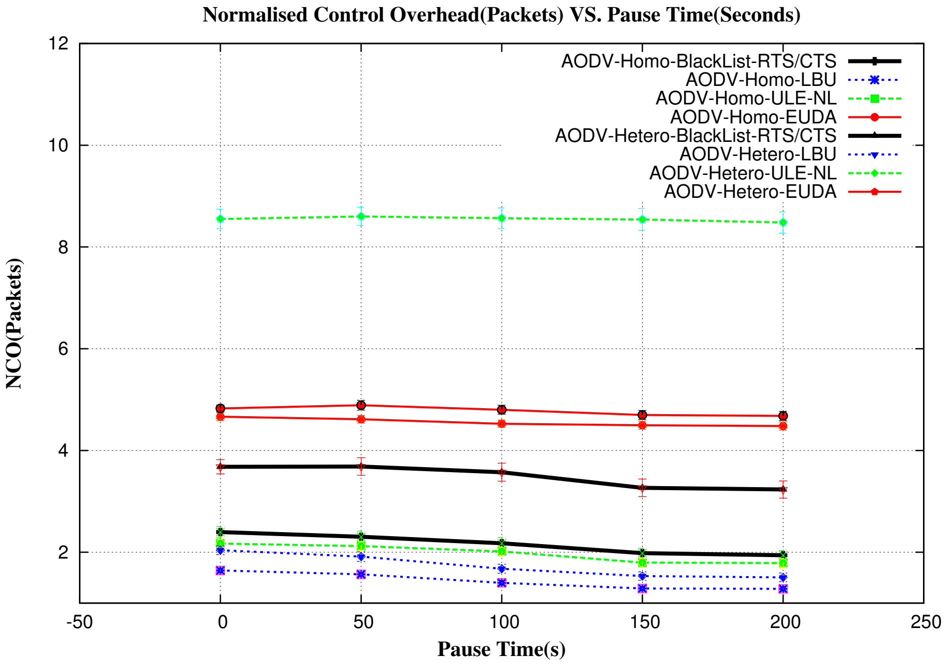


(a) Delay

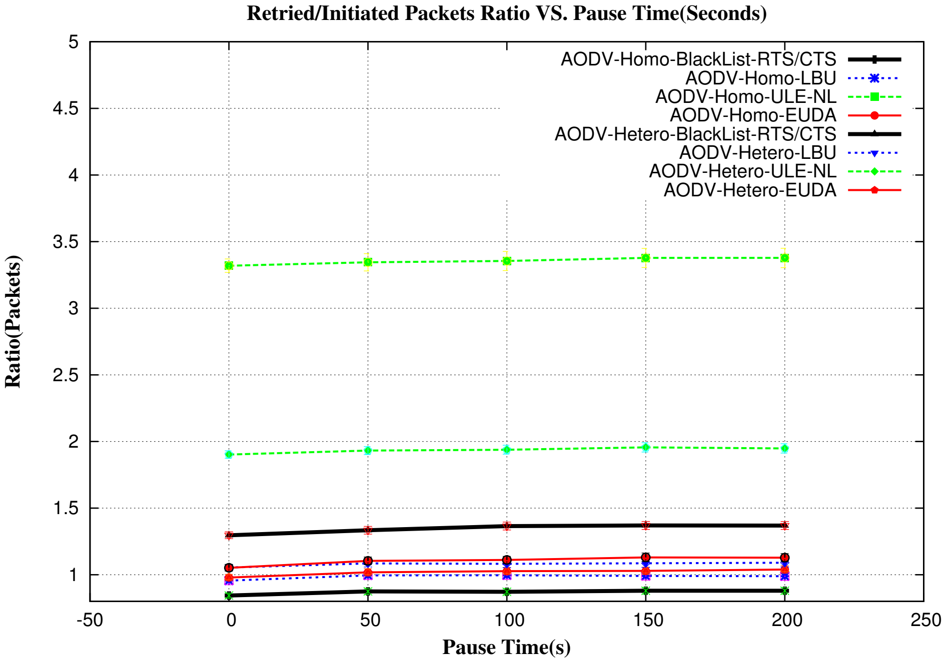


(b) PDR

Figure 5.11: Comparison of LBU with BlackList_CTS/RTS, ULE_NL and EUDA with AODV and 100 nodes in both homogeneous and heterogeneous networks.

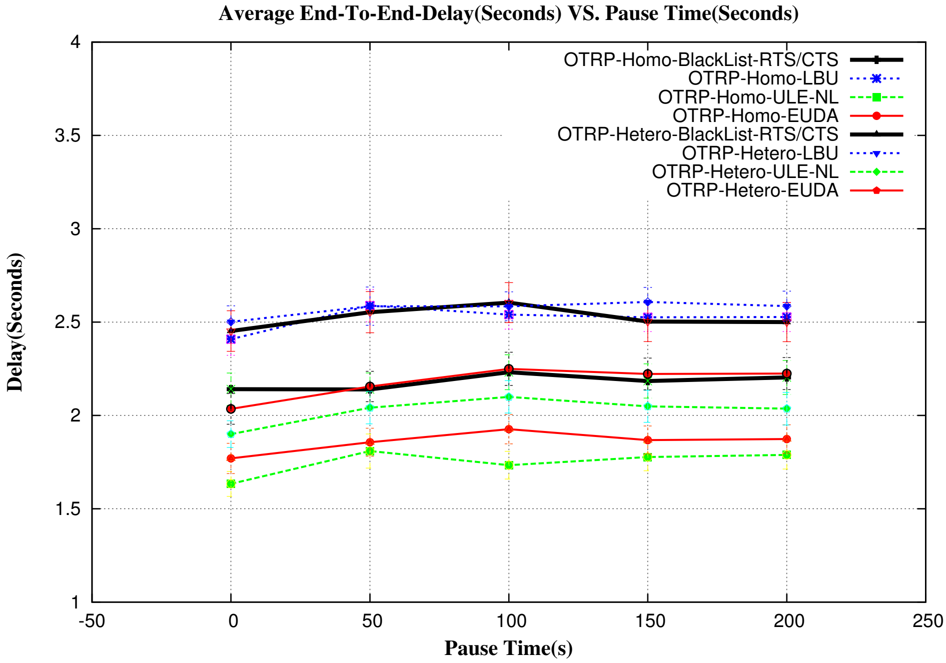


(c) OH

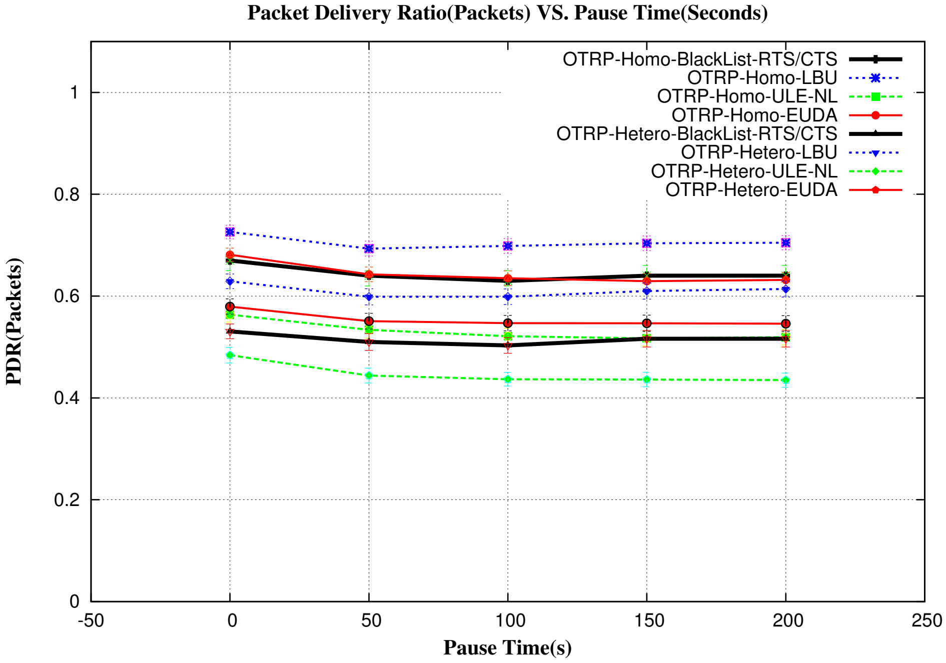


(d) Ret

Figure 5.11: Comparison of LBU with BlackList_CTS/RTS, ULE_NL and EUDA with AODV and 100 nodes in both homogeneous and heterogeneous networks.

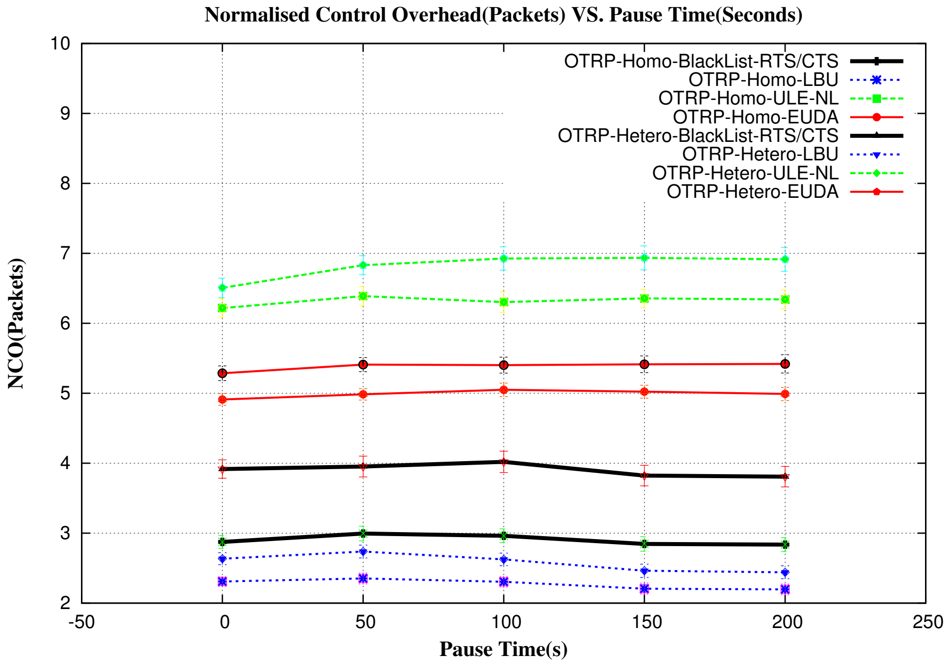


(a) Delay

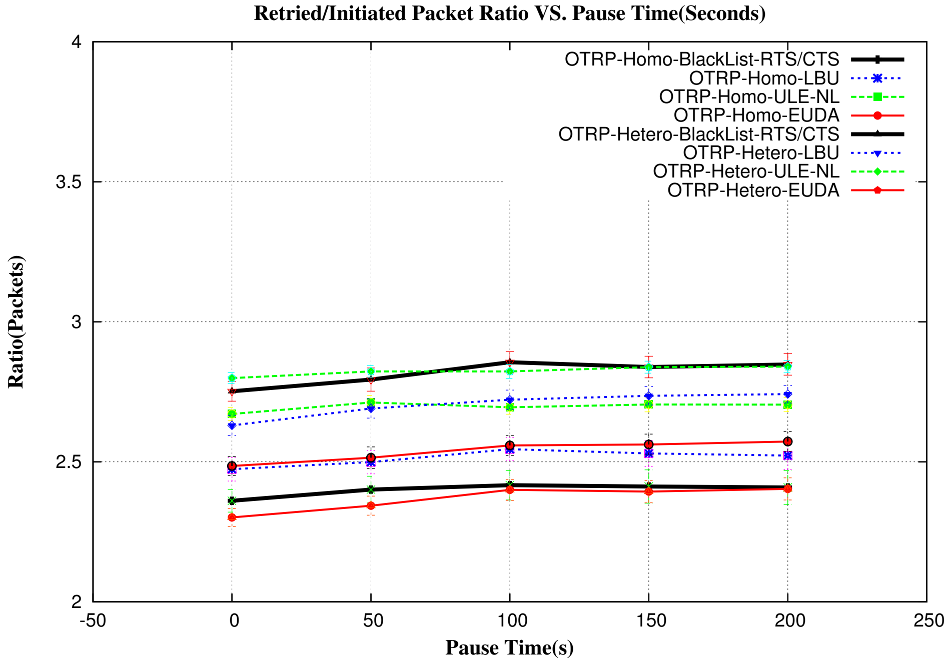


(b) PDR

Figure 5.12: Comparison of LBU with BlackList_CTS/RTS, ULE_NL and EUDA with OTRP and 100 nodes in both homogeneous and heterogeneous networks.



(c) OH



(d) Ret

Figure 5.12: Comparison of LBU with BlackList_CTS/RTS, ULE_NL and EUDA with OTRP and 100 nodes in both homogeneous and heterogeneous networks.

5.3.3 Results

LBU is compared to to Blacklist_CTS/RTS, ULE_NL and EUDA. These strategies are applied on top of AODV and OTRP, see (Figure 5.11- 5.12).

The problem of unidirectionality affects the routing process of on demand routing protocols, since the forwarding node of the RREQ may have unidirectional links to its neighbour nodes. In other words, rebroadcasting nodes store incorrect information about the first hop, which is unreachable because of unidirectionality. Consequently, source nodes do not received RREP packet and hence the route may not found. This will increase the number of route discovery attempts and consequently increases the Ret_Ratio.

Blacklist_RTS/CTS strategy with AODV and OTRP detect unidirectional links after they occur then avoids unidirectional links without solving. This strategy may work with homogeneous MANETs where nodes have similar transmission power and the occurrence of unidirectionality is low. However, LBU outperforms the Blacklist_RTS/CTS strategy in term of PDR and NCO under both unidirectional and bidirectional link scenarios (see Figure 5.11b, 5.11c, 5.12b, and 5.12c). This is because the LBU strategy supports AODV and OTRP by filtering incoming RREQ packets where not all incoming packets are processed. In other words, incorrect information about first hop neighbours is ignored using LBU. Moreover, LBU strategy provides sufficient routing information about 2-hop neighbours by solving unidirectional links.

In a homogeneous MANET where bidirectional links are assumed to exist between any pair of nodes, LBU is more efficient than Blacklist_RTS/CTS. AODV_LBU increases PDR by approximately 2% and (see Figure 5.11b) while OTRP_LBU increases PDR by 10% (see Figure 5.12b). Although the locations of the last two hops are attached to the RREQ packet in LBU, NCO is improved in comparison to Blacklist_RTS/CTS as shown in Figure 5.11c and 5.12c where AODV_LBU and OTRP_LBU reduces NCO by 0.8 packets. However, delay with LBU is higher than Blacklist_RTS/CTS for both protocols where the number of unidirectional link is low under homogeneous network, as shown in Figure 5.11a and 5.12a. This is because if a unidirectional link exists between the forwarding node and its relay, this will reduce the rebroadcasting area, which may increase the Ret_Ratio and consequently increase delay as shown in Figure 5.11d and 5.12d. However, detecting unidirectional links and resolving it immediately can a reliable path to route data, which explains the improvement in PDR and NCO. In heterogeneous MANETs, nodes with different transmission ranges exist. Therefore, a high percentage of unidirectional links occur. In both protocols, LBU resolves this problem without any increase of NCO or delay in comparison to the Blacklist_RTS/CTS strategy or other strategies as shown in Figure 5.11 and 5.12. This is because LBU detects and immediately resolves any unidirectional links that may occur in the first RREQ_RETRIAL (see Figure 5.11d and 5.12d) compared to the Blacklist strategy, where unidirectional links are avoided and some nodes are blocked. Therefore, AODV_Blacklist_RTS/CTS and OTRP_Blacklist_RTS/CTS consume nearly 2 and 3 out of 3 RREQ_RETRIALS respectively to find bidirectional paths to route the data. This will increase delay as shown in Figure 5.12a. Unlike AODV, the number of rebroadcasting nodes is reduced in OTRP, which reduces rebroadcasting area, hence OTRP requires a higher value of RREQ_RETRIAL. Therefore, generally the delay with OTRP is sightly higher than AODV but OTRP_LBU has constant delay. As RTS/CTS is used too, Blacklist_RTS/CTS increases NCO by 1.5 and decreases PDR by at least 6% as shown in Figure 5.11b, 5.11c, 5.12b and 5.12c respectively.

ULE_NL is attached to RREQ packets. If the receiving node is not in list, then it considers that there is a unidirectional link from the forwarding node. Consequently, the packet is dropped. However, the forwarding node may have insufficient knowledge about its neighbours. Therefore, it is inaccurate to predict unidirectionality if the receiving node is not in the list. In the simulation presented in this Chapter, Hello messages are enabled to improve the ULE_NL strategy. However, AODV_ULE_NL has poor performance compared to AODV_LBU. AODV_ULE_NL is 30% worse than AODV_LBU, and delay and NCO are four times higher than AODV_LBU, see (Figure 5.11 and 5.12). Secondly, due to inaccurate predication of unidirectionality, ULE_NL is attached to RREQ packet with an arbitrary size, which can significantly increase network load. This explains the poor result of AODV. In OTRP, rebroadcasting nodes are selected by a forwarding node which depends on the nodes locations. Therefore, inaccurate information regrading unidirectionality doesn't affect the performance of OTRP. However, attaching the neighbour list to RREQ can increase NCO which therefore degrades the other performance metrics such as delay and PDR as shown in (Figure 7.3).

LBU outperforms EUDA for both protocols in heterogeneous and homogeneous networks as shown in Figure 5.11 and 5.12. The significant differences between two strategies in performance are in NCO as shown in Figure 5.11c and 5.12c. This is because EUDA avoids unidirectional links in the routing process and dropps all RREQ packets that are received over this kind of link. Consequently, EUDA needs more control packets to find a route to destination. Although LBU takes more time to resolve the unidirectionality problem, this results in lower delay and higher PDR respectively for both AODV and OTRP.

5.4 Conclusion

In Mobile Ad hoc Networks (MANETs), mobility, traffic and node density are main network conditions that significantly affect the performance of the network. In addition, most current routing protocols assume homogeneous network conditions where all nodes have the same capabilities and resources. In this Chapter, different simulations have been carried out to compare the performance of different routing protocols in homogenous and heterogeneous networks. All simulated protocols misbehave in heterogeneous networks. They suffer from high delays and achieve very low PDR. Current MANETs routing protocols suffer from the unidirectional link problem and problems with increasing node density. Therefore, the current routing protocols for MANETs are inadaptable for heterogeneous networking. LBU is proposed to resolve unidirectional links in MANETs. Instead of dropping duplicated RREQ packet, each incoming RREQ packet is used to filter routing information of neighbours subject to unidirectionality. LBU, Blacklist_CTS/RTS, ULE_NL and EUDA are applied on top of AODV and OTRP. LBU outperforms the other strategies in homogeneous and heterogeneous MANETs in term of PDR and NCO, without increasing delay.

More work needs to be carried out to investigate the problems that arise with routing protocols in heterogeneous networks. For example, it is necessary to develop a rule-based algorithm to adjust nodes dynamically and control their routing behaviour based on their resources and the environment around them. This is the objective of Chapter 6.

Chapter 6

Optimising Route Discovery for Multi-Interface and Power-Aware nodes in Heterogeneous MANETs

6.1 Introduction

On-demand routing protocols have the potential to achieve high levels of scalability in Homogeneous MANETs (HMANET). However, in the previous Chapter it was found that current routing protocols behave inefficiently and unexpectedly in heterogeneous networks. Moreover, the study of scalability and connectivity of HMANET routing protocols is limited. Few papers have considered multi-interface heterogeneity and issues of routing and scalability in HMANETs [69]. OLSR has been enhanced to Hierarchical OLSR (HOLSR) in [69] to work with three types of nodes equiped with different numbers of interfaces; with assumption the network is fully connected. Each type of node forms a cluster to exchange network topology information independently . HOLSR is observed to limits the propagation of the topology information but incurs more overhead since hierarchical messages are periodically propagated between the cluster heads to keep them aware of the membership information of their peers.

Most of the proposed protocols and methods that are related to the work in this Chapter are designed for Wireless Mesh Network (WMN) where there are only two types of nodes: Mesh-Routers which are static and capable of multi radio and multi channel communications and Mesh-Clients which are mobile and have only a single radio and single channel [70, 71, 72, 73]. In most cases, the network is assumed to be fully connected. Moreover, the issue of power consumption is not considered. In [70], AODV has been extended to work with Multi-Radios (AODV-MR) in a hybrid WMN. AODV-MR maintains an interface number of the next hop to destination in its routing table and RREQ packets are rebroadcasted to all interfaces. Although simulation results show the superiority of AODV-MR when compared to AODV with single radio under high mobility and traffic load conditions, AODV-MR has higher overheads as the number of interfaces increases. AODV-MR has been extended to utilise the heterogeneity and reduce overheads via the use of node-type awareness, link quality estimation, and optimal selection. Although simulation results show the benefits of the extended AODV-MR protocol, the scalability issue has not been considered. Moreover, the proposed protocol is designed to work with Mesh-Routers and Mesh-Clients only where they have common interfaces and channels to communicate.

In summary, the problems with current routing strategies for HMANET are as follows:

- Most of the proposed protocols and methods are designed for WMN with two types of nodes only;
- There is no real model for MANETs with multi-interfaces heterogeneity that includes issues related to routing and scalability; and
- Using the hop count metric with HMANETs can degrade the performance of MANET routing protocols. This is because the minimal hop count only considers the shortest

path with minimum number of hops to route data, regardless of nodes heterogeneity and links quality.

Therefore, the focus of this Chapter is on utilising the heterogeneity of resources to reduce overheads and simultaneously ensure the connectivity between different types of nodes by proposing:

1. A network model for heterogeneous MANET which considers nodes with different capabilities and resources: multiple interfaces (multi interfaces, single interface), variable power schemes (battery and continuous power), and different transmission ranges. See Section 6.2;
2. A new routing discovery process that works in HMANET (see Section 6.4). The proposed strategy is implemented on top of the OTRP protocol, such that it is aware of:
    - Heterogeneous multi-interfaces;
    - The existence of different power schemes; and
    - Connectivity among nodes in HMANET.
3. A new routing metric for heterogeneous MANETs which replace the traditional hop count metric. This is metric is described in Chapter 7.

6.2 Modeling Nodes Heterogeneity in MANET

In Chapter 5, the first architecture of node heterogeneity is described. This Chapter, focuses on the second form, where nodes have different resources as shown in Figure 6.1. Different scenarios are applied using this kind of heterogeneity in real life scenarios, such as battlefields (see Figure 6.2). Node heterogeneity in MANETs has only been simulated based on

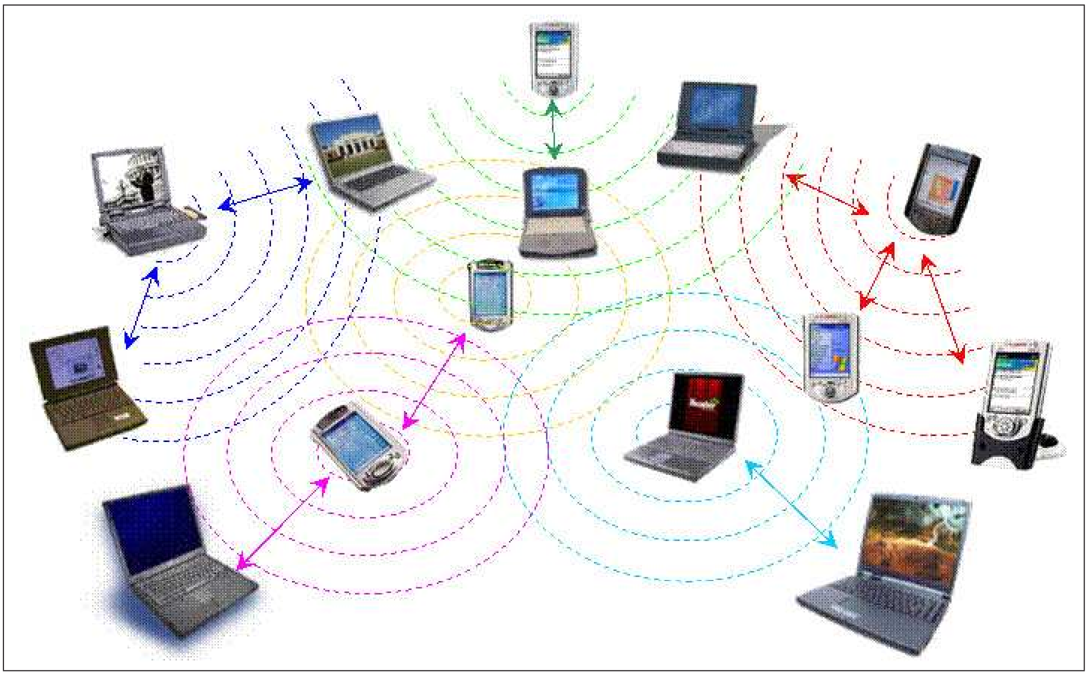


Figure 6.1: The second architecture of heterogenous MANETs

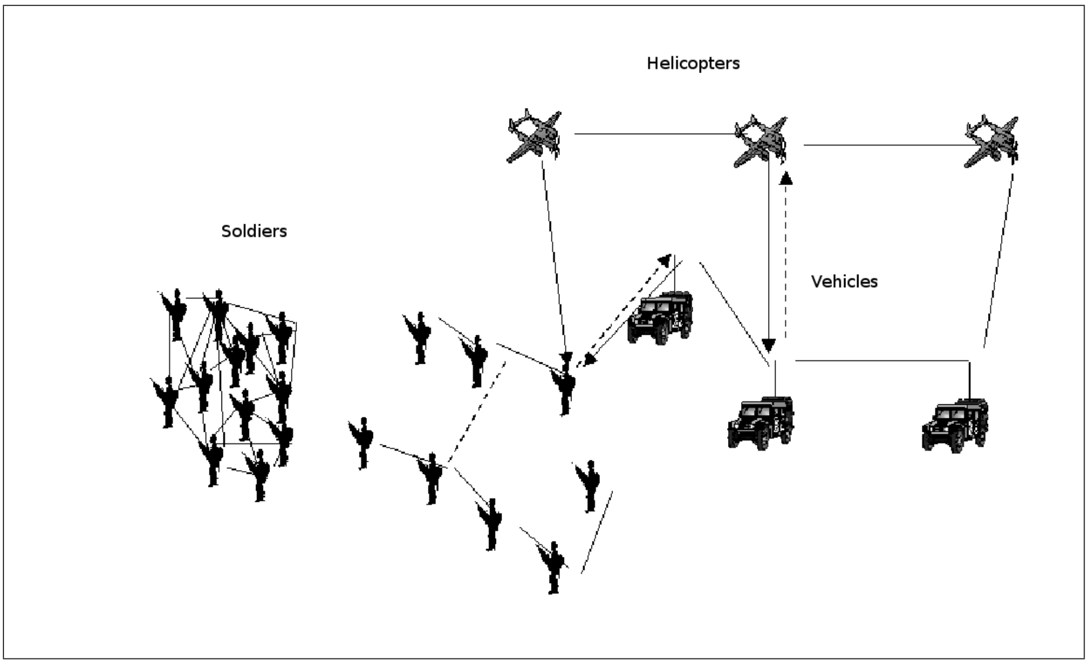


Figure 6.2: Battlefield network scenario

the first architecture in most previous studies, which is an unrealistic approach for some practical scenarios [64, 51, 52]. Given this limitation in existing studies, there is a need for a more realistic approach to model node heterogeneity in MANETs. Such an approach is expected to help better understand the effects of node heterogeneity in various routing protocols.

In this section, a model for node heterogeneity on MANETs is proposed to exploit the heterogeneity of resources to reduce the overheads introduced due to having multiple interfaces and to simultaneously ensure connectivity between different types of nodes. Node heterogeneity in MANETs can be modeled using graph theory as follows. Consider a set of nodes of size n as V= $V_1, V_2, ..., V_n$. These nodes may differ in their communication capacities, mobility, level of transmission power and buffering capacity. Since each node may have different transmission power, each node may have a different transmission range r_i. Lets E be a set of edges that represents links between each pair of nodes as such as E = $\{(V_i, V_j) : \left\| V_i\ V_j \right\| \leq \min(r_i, r_j) \}$ where $\left\| V_i\ V_j \right\|$ is the Euclidean distance between node V_i and node V_j. The link between node V_i and node V_j can be unidirectional or bidirectional. The link is unidirectional from V_i to V_j if $V_j \in N_{Vi}$ where N_{Vi} is neighbor set of node V_i. Bidirectionals link can exist between V_i and V_j if $V_j \in N_{Vi}$ and $V_i \in N_{Vj}$.

According to this graph theory concept and the second architecture of node heterogeneity, as described previously, nodes in this model are identified by: the number of radio interfaces, the types of interfaces, and the types of power that provides energy for nodes. There is no guarantee of direct connectivity between two different types of nodes with different interfaces.

Assume that the network consists of a set of nodes V of size N such that $V = \{V_1, V_2, ..., V_n\}$, and the nodes have the following features:

Node Type	**Number of Radio Interfaces**	**Types of Interfaces**	**Number of Channels**	**Types of Powers**
Type1	2	IEEE 802.11 a/b	1	External Power
Type2	1	IEEE 802.11 a	1	External Power
Type3	1	IEEE 802.11 b	1	External Power
Type4	1	IEEE 802.11 b	1	Battery Power

Table 6.1: Types of nodes that are used in our model

1. Multiple Interfaces: Each node type has a different number of interfaces. Let us assume we have a set I of different H interface types in the network, then $I = \{I_1, I_2, ..., I_H\}$.

2. Different Transmission Ranges: As there are H different interfaces, then each interface has a different transmission range, where $TR = \{TR_1, TR_2, ..., TR_H\}$.

3. Different Power Sources: The power source of a node can be external P_U or battery P_B. After time T, node V_j can not transmit or receive where its energy level $P_{level_j} \approx 0$, and $V_j \in P_B$, .

This work will be based on four types of nodes with specific communications of the above features (See Table 6.1). According to Table 6.1, nodes differ in resources such as: transmission range, number of interfaces, and available energy. Based on these resources, nodes are classified into four types. Type1 nodes are the most powerful nodes in the network, which have the greatest transmission range, two different interfaces and a external power source. On the other hands, Type4 nodes have limited resources. This heterogeneity of resources can reduce control overheads and delay if they are utilised efficiently in the routing process. The gain of each of these resources are described as follows:

6.2.1 Transmission range

Nodes with greater transmission range can reduce the required number of rebroadcasting nodes, which consequently reduces control overheads. To show this, in Chapter3 it was found that the number of rebroadcasting nodes are reduced by 50% of the total number of nodes with OTRP when nodes are uniformly distributed in a network of size W x L, the distance between each pair of nodes is $T/2$, and the total number of nodes is N ($N = \frac{W}{T/2} \cdot \frac{L}{T/2}$). Then, the number of rebroadcasting nodes is NB_T:

$$NB_T = \frac{1}{2}\left(\frac{W}{T/2} \cdot \frac{L}{T/2}\right)$$

$$NB_T = \frac{1}{2}N = \frac{4}{8}N \tag{6.1}$$

where T is the transmission range of all nodes.

If the transmission range is increased to $2T$, replacing T by $2T$:

$$\begin{aligned} NB_{2T} &= \frac{1}{2}\left(\frac{W}{T} \cdot \frac{L}{T}\right) \\ &= \frac{1}{8}\left(\frac{W}{T/2} \cdot \frac{L}{T/2}\right) \end{aligned}$$

Then,

$$NB_{2T} = \frac{1}{8}N \tag{6.2}$$

When Equation (6.2) is compared to equation (6.1), it is observed that nodes with higher transmission range can reduce the number of rebroadcasting nodes by more than 75%. Therefore, selecting powerful nodes with high transmission range to rebroadcast can greatly reduce redundant routing packets.

6.2.1.1 Multiple-Interfaces

Nodes with multiple-interfaces may provide more connectivity and increased bandwidth. As two interfaces will participate in broadcasting, each rebroadcasting node with multi-interfaces will be considered as two nodes. Then the number of rebroadcasting nodes with transmission range equals to 2T is given by:

$$NB_{2T} = 2 \cdot \frac{1}{8}\left(\frac{W}{T/2} \cdot \frac{L}{T/2}\right)$$

Then,

$$NB_{2T} = \frac{1}{4}N \tag{6.3}$$

By comparing equation (6.3) to equation (6.2) it may be seen that the number of rebroadcasting nodes is higher with 2 interfaces. However, network load is divided between two interfaces. This will balance the load and increase connectivity. In addition to reducing overhead, preferentially choosing nodes with multiple interfaces to rebroadcast can provide links with good quality between each pair of nodes. Moreover, nodes can transmit and receive on different channels simultaneously which decreases delay.

In addition to reducing overhead and delay, and increasing reliability, multi-interface nodes can interconnect different types of nodes in the network. Therefore, connectivity is a critical issue to be considered in the heterogeneous environment. Based on the proposed heterogeneity model, node x can communicate with node y directly if all following conditions are satisfied:

1. Similar interface: $I_x \cap I_y \neq \emptyset$
2. Bidirectional Link: $Dist(x, y) \leq Min(TR_{Ix}, TR_{Iy})$ to have bidirectional link or $Min(TR_{Ix}, TR_{Iy}) \leq Dist(x, y) \leq Max(TR_{Ix}, TR_{Iy})$ to have unidirectional link.
3. Sufficient power resources (long lifetime): $P_{level_x} > \alpha$ and $P_{level_y} > \alpha$ if $x \in P_B$ and $y \in P_B$ where α is critical level of battery energy.

If the first condition fails, where x and y have diffeent interfaces, then x can communicate with y using relay nodes like z which have multiple-interfaces and links between x and z, and z and y which satisfy the above conditions. Therefore, externally powered multiple interfaces nodes are preferred and battery-powered single-interface nodes are avoided in rebroadcasting.

6.3 Problem Formulation

The main idea of OTRP is to minimise the number of rebroadcasting nodes when previous knowledge about destination is not available. The main criteria to select the rebroadcasting nodes was based on the node location, where the nodes should be located in one of four regions of the transmission area of the source node or three regions of the relays to ensure that routing packets reach most of the nodes in the network. OTRP does not perform well with the above model as it selects rebroadcast nodes according its location only. Table 6.2 outlines the expected problems with current routing protocols in HMANET. In a scenario where Type 2 node need to find path to a Type 3 node, it searches for 4 of its 1-hop neighbours according to their locations. Then, relay nodes will do the same procedure to find

Characteristic of Heterogeneity on MANET	**Expected problem with current routing protocols**
Different transmission range	Unidirectional links
Different power energy(battery and external power)	Unreliable links
Multiple-Interfaces	Routing data only through similar interfaces

Table 6.2: Expected problems with MANET routing protocols in HMANETs

the next hop relays. If all rebroadcasting nodes are from the same type as the source node, then a destination that is from a different type can not be reached unless all nodes are rebroadcasting. This means that OTRP behaves like AODV with higher overheads and delay where all nodes will rebroadcast in the last trial to find a route. Therefore, the solution to the problem here is based on answering the following questions:

1. How to utilise heterogeneity of resources to reduce delay and overheads while achieving scalability as the number of nodes increases.

2. How to find a path efficiently with OTRP from a node with interface a to a node with interface b where $a \neq b$ and there is an existence of nodes with multiple-interfaces a/b.

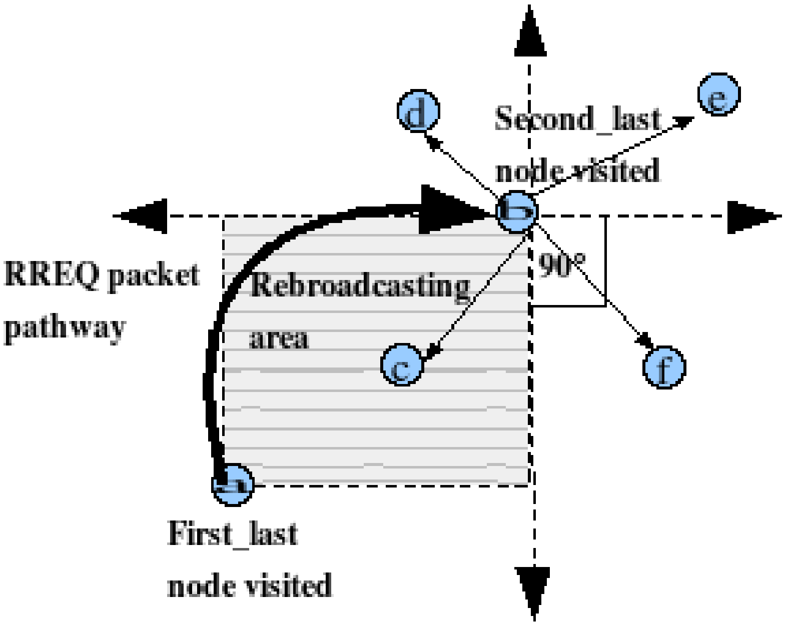


Figure 6.3: Location and local density of rebroadcasting nodes

6.4 Description of OTRP_HA

This section presents a new routing discovery strategy for heterogeneous MANETs. This proposed route discovery algorithm is implemented on the top of OTRP and hence it is called OTRP Heterogeneity-Aware (OTRP_HA). OTRP_HA utilises node heterogeneity and optimises route discovery to reduce overheads and ensure connectivities between different types of nodes with different interfaces.

In OTRP_HA, the source node does not select rebroadcasting nodes, however the decision to rebroadcast is left to relay nodes. A relay node also decides its own type according to the available resources as shown in Table 6.1. Algorithm 3 presents the OTRP_HA algorithm and outlines the conditions for forwarding when a RREQ packet is received. The decision to rebroadcast depends on:

1. Trial Number: this is the number of trials that the source node uses to try to find a route to the destination. As the trial number increases, more nodes can rebroadcast.

2. Available Node Resources: the nodes that have more resources (like multi-interfaces, continuous power, and high transmission range) have the priority to rebroadcast. Battery-powered single-interface nodes are avoided in the first 3 RREQ trials. These nodes are called limited nodes. C2 and C1 represent powerful nodes and limited nodes, respectively in Algorithm 3.

3. Local density: Relay nodes must have at least three 1-hop neighbours that are located in three regions of their transmission range. This is to ensure that RREQ packets will be rebroadcasted in all directions within network area. The routing table is used to extract this information. The condition of local density is clear by C4 in Algorithm 3. This condition is shown in Figure 6.3, where node b will rebroadcast since it has more than 3 neighbours in different directions.

4. Location: The relay nodes must not be located between two rebroadcasting nodes. In other words, a relay node must not be active in an area that have been already covered. This is dictated by comparing the location to the location of the first and the second nodes visited by the RREQ packets. These locations are attached to RREQ packet. C5 shows this point in Algorithm 3. Figure 6.3 shows this condition, where node c can not relay the packet as it is located between two rebroadcasting nodes.

5. The availability knowledge about the type of destination node in the received node of the RREQ packet: This information helps to select the proper type of nodes to rebroadcast. This condition is presented in Algorithm 3 in C3 and C6.

Trial_No	Source_Node _Type	Location_1st_Prev _Node	Location_2nd_Prev _Node	Original RREQ Packet

Figure 6.4: The format of RREQ packets with OTRP_HA

The format of RREQ packet is shown in Figure 6.4. With OTRP_HA, the route discovery process goes through 4 RREQ retries (trials) to find the destination. In each trial, a number of conditions must be satisfied in order to relay RREQ packet. Algorithm 3 illustrates the selection relay algorithm. If no route is found in trial 1, then the source node retries again with more rebroadcasting nodes. If there are unreachable nodes or no route was found through three trials, then all nodes will rebroadcast the RREQ packets. All Type1 nodes rebroadcast in all trials regardless of their locations, local density, and destination node type. These nodes are the most powerful nodes, with multiple interfaces, high transmission range, and the ability to link between different and unconnected nodes of Type2, Type3 and Type4. Nodes of Type4 are avoided in the first 3 trials because they are limited in their resources.

Nodes of Type4 broadcast in last trial in final attempt to find unreachable nodes which may lead to the destination. If a node receives a RREQ packet, it then checks if it satisfies the rebroadcasting conditions for the current RREQ retry. If it does, then it forwards the packets, otherwise the packet dropped. Forwarding nodes update the RREQ packet before rebroadcasting it by copying the value of Location_2nd_Prev_Node to Location_1st_Prev_Node then copying its current location into the Location_2nd_Prev_Node field. It also maintains node type information in the TypeTable. OTRP_HA maintains a TypeTable that stores information including: ID, node type and the state of battery if it is a battery powered node. The format of TypeTable is shown in Figure 6.5. TypeTable gets node ID and node type from the

Algorithm 3 The relay self-selection algorithm for OTRP_HA

Input: Received RREQ Packet.
Output: Action to received RREQ packet (rebroadcast it or ignore it).

```
for $i \leftarrow 1, 7$ do //Initialization
    //C is a boolean set to represent conditions to be a relay node
    $C_i \leftarrow FALSE$
end for
$C_1 \leftarrow NodeType = Type4$
$C_2 \leftarrow NodeType = Type1$
$C_3 \leftarrow NodeType = DestinationType$
$C_4 \leftarrow Have3Neigh(Node\_loc, RT)$
    //Have3Neigh function checks if node has at least 3 neighbours in different 90 degree angle
$C_5 \leftarrow Node\_reb(Node\_loc, RREQ\_Location\_2nd\_Prev\_Node,$

$RREQ\_Location\_1st\_Prev\_Node)$
    //Node_reb function checks the node is not located in between two rebroadcasting nodes
$C_6 \leftarrow DestinationType \neq null$
    //ckech if destination node type is known
$C_7 \leftarrow NodeType = RREQ\_SourceType$
if $(RREQ\_Trial\_No == 4)$ then
    $All\_Nodes\_Rebroadcasting$
else if $(Not(C_1))$ then
    if $(C_2)$ then
        $Rebroadcasting$
    else if $(C_6)$ then
        if $((RREQ\_Trial\_No == 1) \& C_3 \& C_4 \& C_5)$ then
            $Rebroadcasting$
        else if $((RREQ\_Trial\_No == 2) \& C_3 \& C_5)$ then
            $Rebroadcasting$
        else if $((RREQ\_Trial\_No == 3) \& C_3$ then
            $Rebroadcasting$
        end if
    else
        if $((RREQ\_Trial\_No == 1) \& C_2)$ then
            $Rebroadcasting$
        else if $((RREQ\_Trial\_No == 2) \& C_7 \& C_4 \& C_5)$ then
            $Rebroadcasting$
        else if $((RREQ\_Trial\_No == 3) \& C_4 \& C_5$ then
            $Rebroadcasting$
        end if
    end if
end if
```

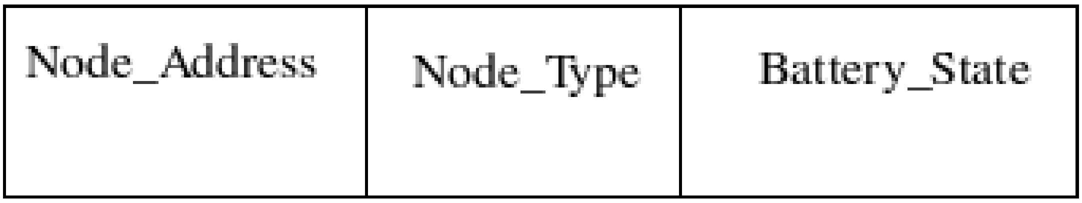
RREQ and RREP packets. Battery state has two values: 0 and 1. A value of 1 means that the node is function, 0 indicates that the battery is exhausted. The battery state of externally powered nodes is always 1. State 0 for battery node is determined by the routing processes of other nodes, which observes that this battery powered node no longer responds to route requests. In other words, it is assumed that if the destination node is a battery powered and no route has been found in all RREQ trials, then this node is considered as exhausted node and its state battery is set to 0. The battery state value helps to avoid initiating any traffic or route request to dead nodes, which reduces overheads. The TypeTable information at the source node is used to identify the destination type and which types of nodes can be selected to discover route most efficiently. The decision to rebroadcast depends on the availability of the destination node type information for the received node. If the destination node type is known then the relay nodes type must be the same as the destination (see Algorithm 3). In this case, these nodes will rebroadcast if they satisfy the conditions of:

1. Local density and location in the first trial;
2. Location only in second trial; and
3. All nodes that have the same type as the destination node rebroadcast in the third trial.

If the destination type is unknown, then:

1. In the first trial, powerful nodes are the only nodes which can rebroadcast;
2. In the second trial, nodes which have the same type as the source node type and satisfy the conditions of local density and location can rebroadcast; and
3. In the third trial, all nodes that satisfy the location and local density conditions can rebroadcast.

The route maintenance process is the same as a OTRP. The location of one-hop neighbours of the parent nodes are valid as long as the links are active between two nodes. Since



Node_Address	Node_Type	Battery_State

Figure 6.5: The format of TypeTable with OTRP_HA

the node mobility would affect the validity of stored information regarding node locations, then the locations of neighbours can be updated using the control packets (i.e. RREQ, RREP, and RERR) which include the location of the last node that has been visited. When a node receives any control packet, it copies the location of the neighbour that forwarded the packet to its routing table. Then it replaces the location values in the control packet with its own location information.

6.5 Simulation and Results

The performance of OTRP_HA is compared to AODV and OTRP using simulations performed in QualNet4.5. In the route discovery phase of AODV [1], the source node initiates a blind flood of RREQ packets throughout the network regardless of nodes resources and types. By contrast, in OTRP, rebroadcasting nodes are selected ,to relay RREQ packets, according their positions regardless of nodes resources and types. LBU is applied on top of these protocols to enhance the routing and resolve any unidirectional links.

The simulations parameters are listed in Table 6.3. To represent the heterogeneity in term of interfaces, two different types of radio interfaces are used in the simulation. These are 802.11a and 802.11b. They are different in the radio transmission and the maximum data rate that can transmit. In other words, 802.11a transmits at 5 GHz and can send up to 54

Simulation Parameter	**Value**
Simulation Time	200s
Number of seeds	10
Number of Nodes	400 randomly distributed
Simulation Area	1000 x 1000 m^2
Node Mobility Model	Random way point
Nodes Speed Range	0-20m/s
Pause Times	0s, 50s, 100s, 150s, and 200s
Number of Traffic Flows	30
Traffic Details	30 flows, Constant Bit Rate (CBR), 4 packets per second, 512 bytes/packet
MAC Protocols	IEEE 802.11a and IEEE 802.11b
Transmission Power	IEEE 802.11a: 6 Mbps, 20 dBm and IEEE 802.11b: 2 Mbps, 15 dBm

Table 6.3: Simulation Parameters

Total Number of Nodes	**IEEE 802.11a**	**IEEE 802.11b**	**IEEE 802.11a/b**
out of 200	95	95	10
out of 400	190	190	20

Table 6.4: Nodes distribution among interfaces

Mbps whereas 802.11b transmits at 2.4 GHz and sends up to 11 Mbps. There were 400 nodes, see Table 6.4 for nodes distribution among interfaces. 50 nodes out of the total number of nodes with IEEE 802.11b interface only are battery-constrained nodes. The purpose of this simulation is to evaluate the performance of OTRP_HA under heterogeneity environment which has been suggested in Section 6.2. Therefore for simplicity, Constant Bit Rate (CBR) is used instead of Variable Bit Rate (VBR).

Protocols were evaluated according to: average of end-to-end delay, Packet Delivery Ratio (PDR), Normalised Control Overhead (NCOH), average energy consumed by all nodes (in mJ) for transmit and receive modes.

Figure 6.6 shows the results of simulation. Delay, PDR and NCOH have been used to evaluate protocols with different node mobility (pause times) as node movements affect the performance of all protocols.

OTRP has the highest delay for 200 and 400 nodes (Figure 6.6a). This is because OTRP does not consider node heterogeneity and the sender selects at most 3 nodes according to their location to rebroadcast. In some cases, there are no nodes similar to the sender at the required location. Hence, the source node has to go through all four trials to find a path to the destination. On the other hand, with AODV all nodes rebroadcast, which speeds up the process of finding paths to destination. However, when the number of nodes increases then the load per node increase as all nodes are rebroadcasting, which increases the rate of collisions due to contention. Therefore, this will delay delivery of data packets and increase data loss rate. Figure 6.6a shows that OTRP_HA outperforms the other two protocols. OTRP has the lowest PDR with 200 nodes (Figure 6.6b). However, it is more scalable than AODV as the number of nodes increases, since OTRP delivers more than 65% of data packets with 400 nodes while AODV drops more than 60% of the data packets. The behaviour of OTRP can be explained as follows. As the number of nodes increases, the chance of potential finding rebroadcasting nodes increases simultaneously, which means that there are more paths to deliver data with less overhead. However, OTRP_HA outperforms both protocols as it delivers more than 85% of the data packet with 400 nodes. This is because OTRP_HA utilises node heterogeneity and at the same time reduces the NCOH.

OTRP has the highest NCOH in the 400 node scenario, which is the cost of good PDR as shown in Figure 6.6c. This is because OTRP has the largest RREQ packets. Therefore, this affect the performance of the protocol as the number of nodes and traffic volume increase. However, AODV still suffers from high NCOH as the number of nodes increases as shown in Figure 6.6c. This is because all the nodes are rebroadcasting, which increases the rate of collisions and the number of route recalculation. In addition, neither protocols takes node heterogeneity into account, OTRP selects rebroadcasting nodes according to their locations while in AODV all nodes are rebroadcasting. Although OTRP_HA does not select a finite number of nodes to rebroadcast, it has the lowest NCOH and consequently the highest PDR and lowest delay. The consistency of NCOH of OTRP_HA for both 200 and 400 nodes can be explained as follows:

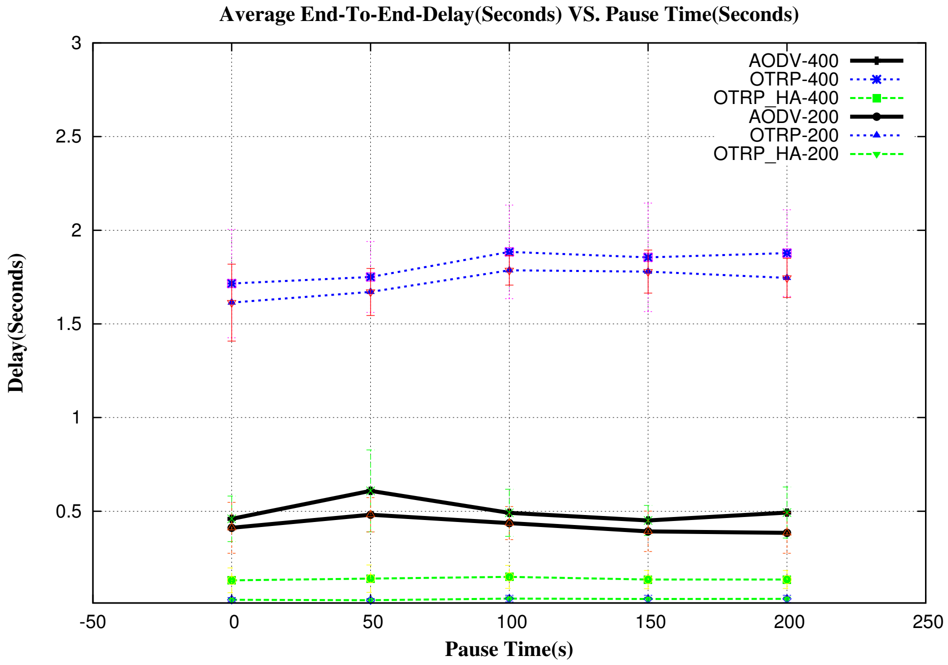
1. Powerful nodes with multiple-interfaces have the highest priority in rebroadcasting, which results in a reduction in the number of rebroadcasting nodes;
2. Using node type information, the search area for destination and the number of rebroadcasting nodes can be controlled;

3. Avoiding battery-powered nodes in the route discovery process decreases link failures and route recalculations;
4. Awareness of battery-powered node lifespan avoids initiating traffic to flow over battery-powered nodes, which intend to reduce overheads; and
5. Each node incorporates a self-selection mechanism to decide whether to select itself as a rebroadcasting node. This eliminates the dependence on location information alone, which the relay nodes must receive to rebroadcast as is the case in OTRP. At the same time, it reduces the size of RREQs packet which include four addresses of rebroadcasting nodes in OTRP.

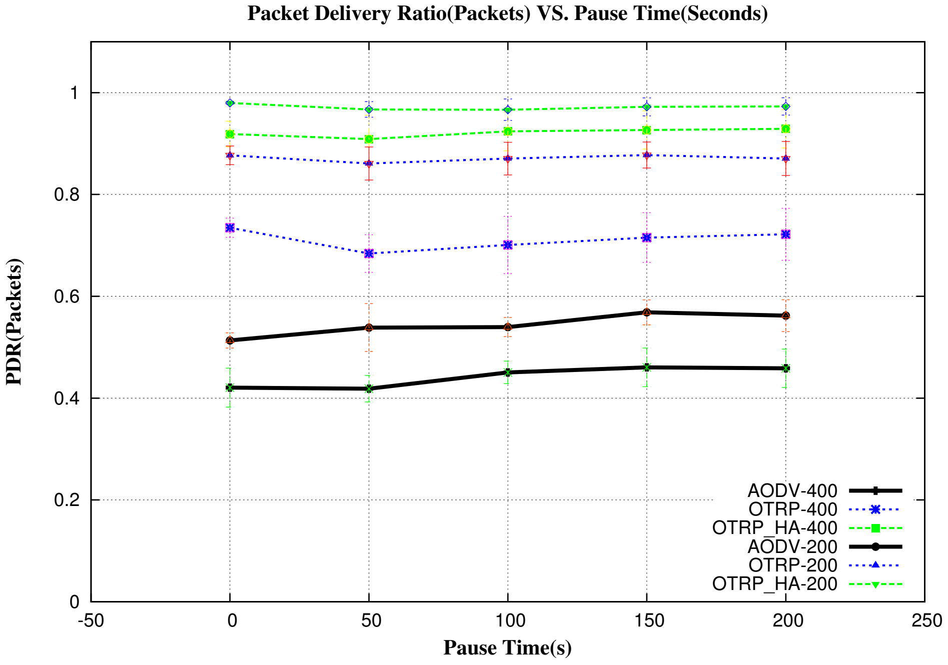
In order to investigate the energy efficiency of the three protocols, the energy consumed by transmitting and receiving has measured during 5 intervals of simulation time (0 s, 50 s, 100 s, 150 s, 200 s), with pause time =100 s. In all protocols, nearly the same amount of energy was consumed as shown in Figure 6.6d. However, in AODV more energy is consumed in the 400 node scenario. This is because more nodes are rebroadcasting. In OTRP and OTRP_HA, a similar amount of energy is consumed with a slight increase with OTRP for 400 nodes. This can be attributed to the fact that OTRP creates more overhead than OTRP_HA as explained previously. Therefore, OTRP_HA is an efficient power-aware protocol.

6.6 Conclusion

In this Chapter, a new routing discovery strategy for heterogeneous MANETs is proposed to reduce routing overheads and adapt to node heterogeneity. Rebroadcasting nodes are selected according to their resources and locations. Powerful nodes with multiple-interfaces are preferentially used to link between two different types of nodes. The performance of

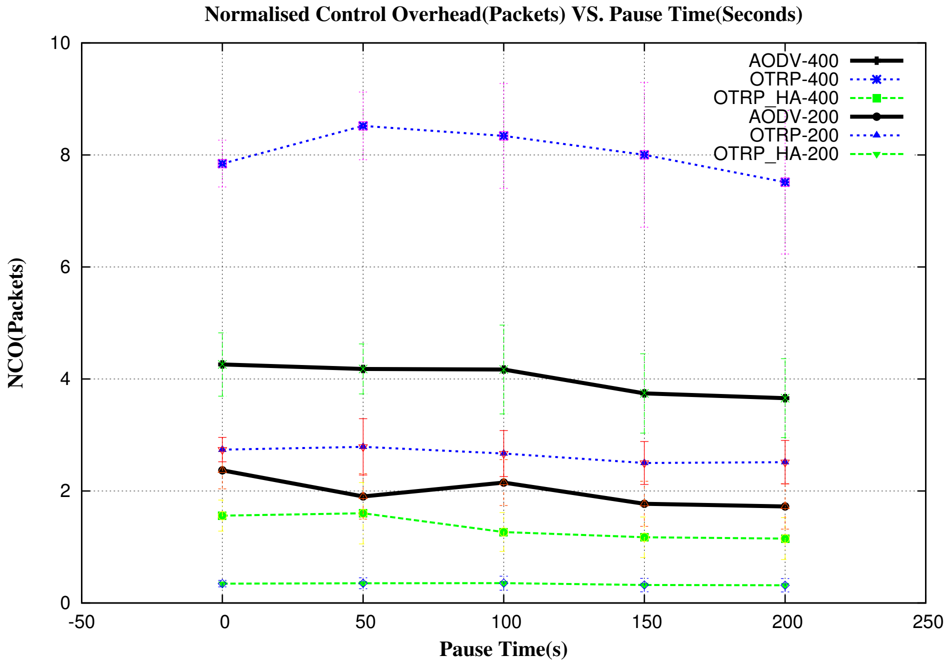


(a) Delay

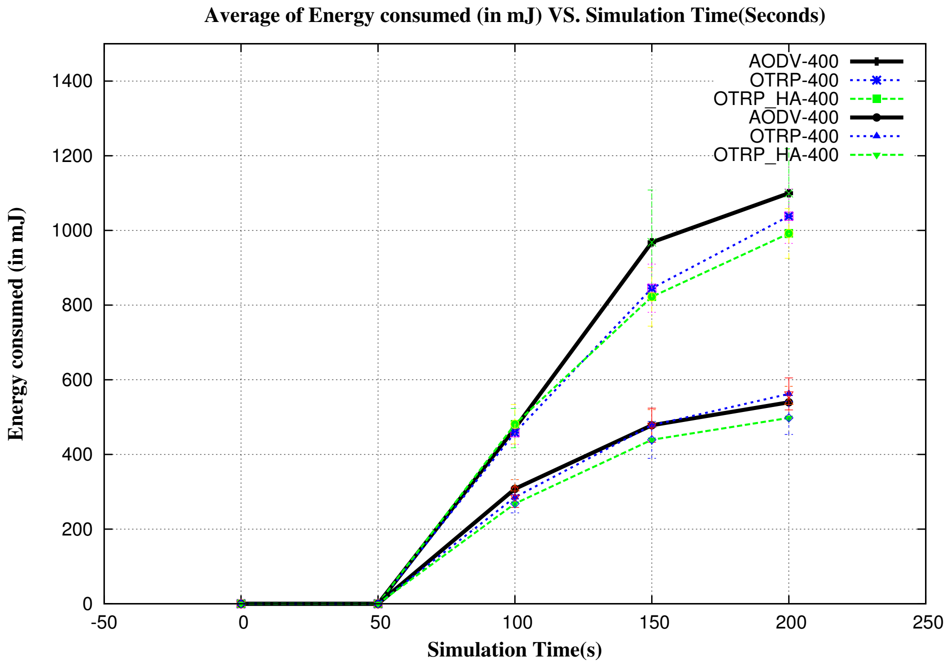


(b) PDR

Figure 6.6: Compare OTRP_HA to AODV and OTRP with 200 and 400 nodes and 30 Traffic Flows.



(c) NCO



(d) Energy consumed

Figure 6.6: Compare OTRP_HA to AODV and OTRP with 200 and 400 nodes and 30 Traffic Flows.

OTRP_HA, OTRP, and AODV were compared under a variety of network conditions including various degrees of mobility and node density. Simulation results show that OTRP_HA significantly reduces routing overheads and achieves higher levels of data delivery than the other protocols. Moreover, the simulation results show that OTRP_HA is a power efficient and a battery-aware protocol.

Chapter 7

Routing Metric for Multi-Interface and Power-Aware nodes in Heterogeneous MANETs

7.1 Introduction

The focus of this Chapter is to select a path according to the heterogeneity ratio of the intermediate hop nodes along the path. Most previous work ignore using the hop count and focuses on the quality of the links used to deliver data in HMANETs. The Expected number of transmissions (ETX) has been heavily used in WMN and HMANETs to measure the link quality [71, 74]. However, ETX uses only probe packets to estimate the loss rate, which may not reflect the loss rate for actual data packets [73]. Beside ETX, Received Signal Strength Indicator (RSSI) is another common routing metric which is used to consider the issue of link heterogeneity. This metric is used in [70], where HELLO packets are used to detect connectivity and update information about RSSI. Although RSSI provides stable and longer routes, it introduces high overheads in high mobility conditions because its use of HELLO packets. Other approaches evaluate the path to the destination according to the number of powerful nodes that are involved in the path. For example, in [72], the authors have developed a route discovery process for AODV in WMN to route data through Mesh-Routers by choosing the path with the maximum number of Mesh-Routers. However, mobility has not been considered in evaluating this metric. Combining different routing metrics is another approach to evaluating routes with node heterogeneity. In [75], the authors combined hop count, traffic load and energy cost to adapt to node heterogeneity in multi-hop wireless networks. The weight of each of these costs is varied according to nodes resources and other concerns. Intermediate nodes can rebroadcast duplicated RREQ packets which increases routing overheads.

In this Chapter, a new routing metric to route data in HMANETs is proposed. The route quality is estimated according to the ratio of the number of powerful nodes to the hop count. This ratio is called Heterogeneity Ratio (HR) . The term “powerful nodes” here refers to nodes that have more resources than the current node and will be precisely defined in Section 7.2. Node heterogeneity for this metric is modeled as in Section 6.2. The HR metric is implemented on top of the OTRP_HA protocol (see Section 7.3).

7.2 Description of Heterogeneity Ratio Metric

OTRP_HA selects nodes with more resources to rebroadcast. However, shortest paths with minimal hop count are normally preferred to route data regardless of links heterogeneity. Selecting paths according to minimal hop count may lead to poor performance in HMANET where there are different types of nodes offering a path with better performance despite a higher number of hops. On the other hand, routing data to nearby nodes with good links and a lower hop count is better than using a path with higher hop count and more powerful nodes which may delay delivery of data. Therefore, the work in this Chapter is based on answering the following questions:

Type	**Number of Radio Interfaces**	**Types of Interfaces**	**Types of Powers**	**Associated**	i	w_i
Type1	2	IEEE 802.11 a/b	External Power	2	1	4
Type2	1	IEEE 802.11 a	External Power	3	2	3
Type3	1	IEEE 802.11 b	External Power	5	3	2
Type4	1	IEEE 802.11 b	Battery Power	7	4	1

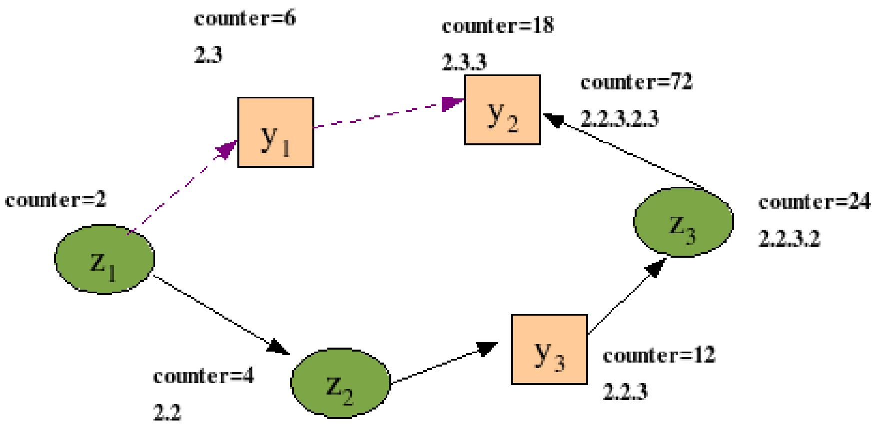
Table 7.1: Types of nodes and their features

- Which is the best path to use in HMANET with different types of nodes: a path with high nodes heterogeneity or path with less hop count?
- How can we balance between the nodes heterogeneity and hop count metrics to achieve good performance?

In this Section, OTRP_HA is extended to select a path according to the heterogeneity ratio of hop nodes along the path. Heterogeneity Ratio (HR) is the ratio of the number of powerful nodes to hop count which is used to select the best path to destination. HR depends on the number of nodes of each type on the path and the hop count and is defined as:

$$HR = \frac{\sum_{i=1}^{4}(w_i.t_i)}{HopCount}$$

where $w_4 \leq w_i \leq w_1$, $\sum_{i=1}^{4} t_i = HopCount$, and t_i represents the total number of nodes of type i and w_i refers to the node type weight as shown in Table 7.1. The node type with more



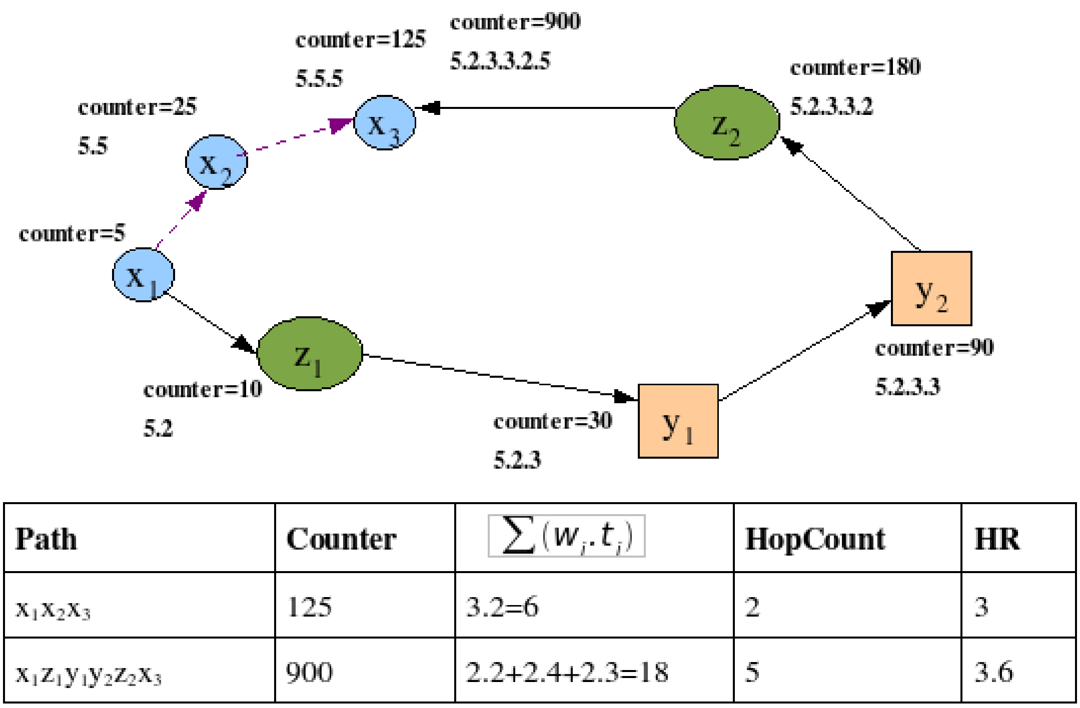
Path	**Counter**	$\sum(w_i.t_i)$	**HopCount**	**HR**
$z_1y_1y_2$	18	1.4+2.3=10	2	5
$z_1z_2y_3z_3y_2$	72	3.4+2.3=18	4	4.5

Figure 7.1: The path with minimal hop count is selected.

resources has a higher weight value. The value of t_i is calculated as following. A counter is appended to the RREQ and RREP packets to calculate the number of nodes of each type that the packet has visited. To avoid creating a counter for each type, which increases the size of control packets as the number of node types increases (consequently increasing overhead) the Unique Factorisation Theorem is used to create only one counter for all types [76]. This is done by assigning a different prime number for each node type (see Table 7.1). Then, the value of the counter is the product of prime numbers of node types that the packet has visited. Therefore, based on Table 7.1 the counter value must be in the form of:

$$counter = 2^{\alpha_1}3^{\alpha_2}5^{\alpha_3}7^{\alpha_4}$$

where α_i is an integer, i is the node type number, and $\alpha_i \geq 0$. The value of α_i represents the number of node in each type.



Path	**Counter**	$\sum(w_i.t_i)$	**HopCount**	**HR**
$x_1x_2x_3$	125	3.2=6	2	3
$x_1z_1y_1y_2z_2x_3$	900	2.2+2.4+2.3=18	5	3.6

Figure 7.2: The path with higher number of powerful nodes is selected.

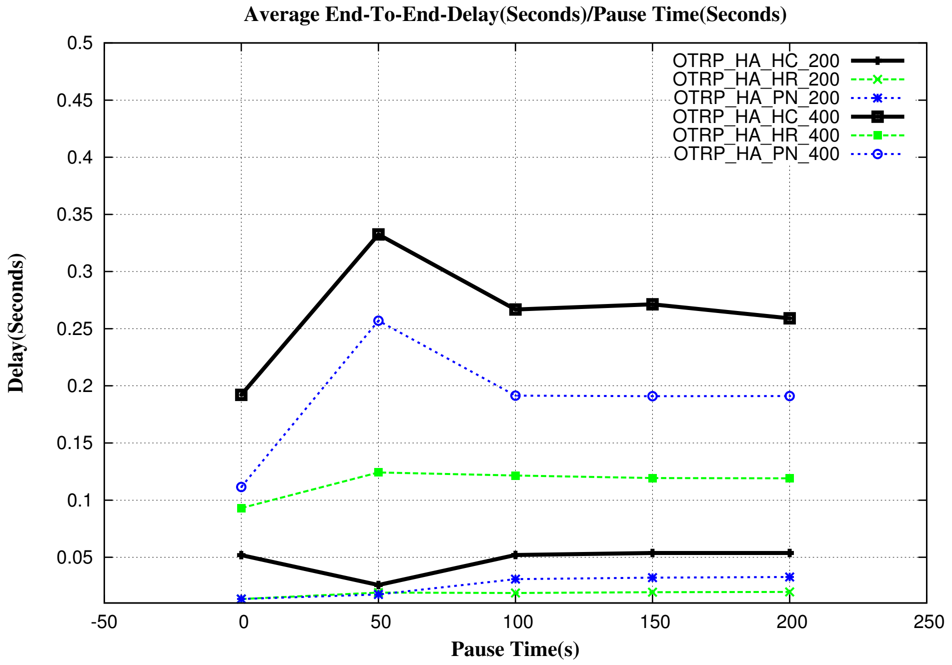
The source node initially sets the counter in the RREQ packet to the prime number of its type. Each rebroadcast node updates the counter by multiplying it by the prime number corresponding to its own type. Each node receives the control packet, adds the counter to the route entry for the source/destination in routing table. The route to a destination in the routing table can be replaced by the new path, if the new path has higher HR than the route that is in the the routing table. The number of nodes of each type that are included in the path is calculated by decomposing the counter value to its prime factors and then counting the frequencies of each prime number. Figure 7.1 and 7.2 are exapmles of using HR. In Figure 7.1 and 7.2, $z_i \in Type1$, $y_i \in Type2$,and $x_i \in Type3$. In Figure 7.1, there are two paths from z_1 to y_2. Node z_1 chooses $z_1y_1y_2$ as a path to destination y_2 with higher HR where this path has a sufficient number ratio of powerful nodes to the number of hops compared to the path $z_1z_2y_3z_3y_2$. This is because both paths may have similar packet delivery ratio, but $z_1y_1y_2$ has less delay. In Figure 7.2, node x_1 chooses the longest path $x_1z_1y_1y_2z_2x_3$ when it is considered worth while to use a long path with more powerful nodes.

7.3 Simulation and Results

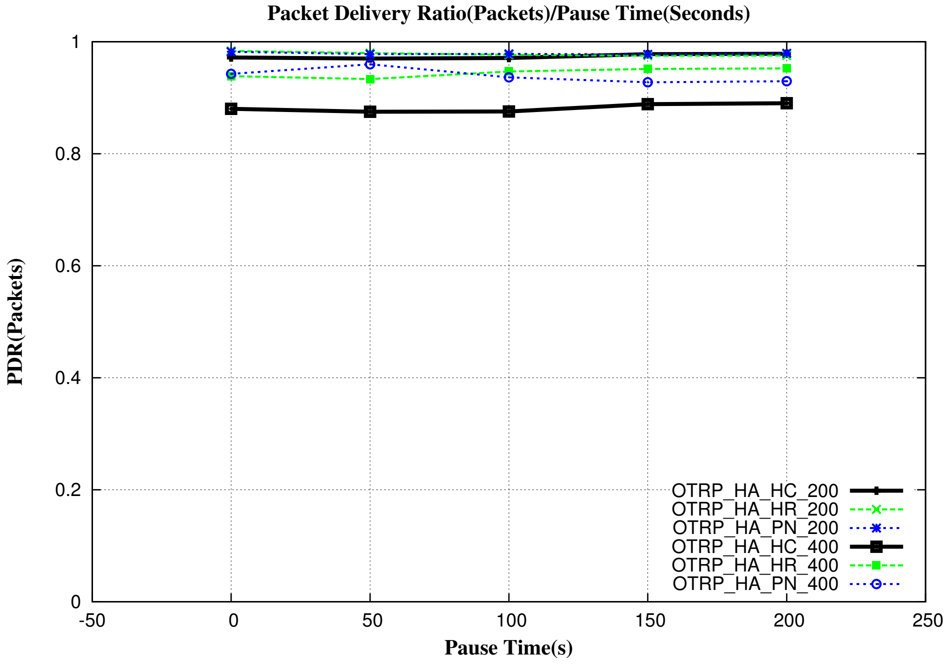
The performance of OTRP_HA has been compared with three different routing metrics that are used to select the path to a destination: minimal Hop Count (HC) , maximal Heterogeneity Ratio (HR), and maximal number of Powerful Nodes (PN) . The performance is evaluated using QualNet4.5, and the simulation parameters are the same as in Section 6.5. The performance of the protocol with three metrics is evaluated according to: average of end-to-end delay, Packet Delivery Ratio (PDR), Normalised Control Overhead (NCOH), average of consumed energy by all nodes (in mJ) for transmit and receive modes, and residual battery capacity (in mAhr) of battery nodes. The energy model and battery model from QualNet4.5 are used to obtain the amount of energy consumed.

Figure 7.3 compares the performance of OTRP_HA based on the different routing metrics with 200 and 400 nodes and 30 traffic flows. OTRP_HA with hop count metric is observed to have the highest delay within 200 and 400 nodes respectively (Figure 7.3a). This is because HC metric which ignores the types of nodes that are involved in the path. Selecting a path according to PN reduces the delay compared to the hop count, but it is not the best. Using HR significantly decreases the delay with 200 and 400 nodes compared to HC and PN. This is because it balances the advantages of using the shortest path with having the powerful nodes, which accordingly provides links with high quality to deliver data.

The PDR of OTRP_HA are similar with 200 nodes using the different metrics with slight increase in HR, (see Figure 7.3b). With 400 nodes, PDR with HC metric is no more than 90% since using HC metric may result in a path with low performance links that affect the PDR. Routing data with high PN metric can provide links with high quality, but it may re-

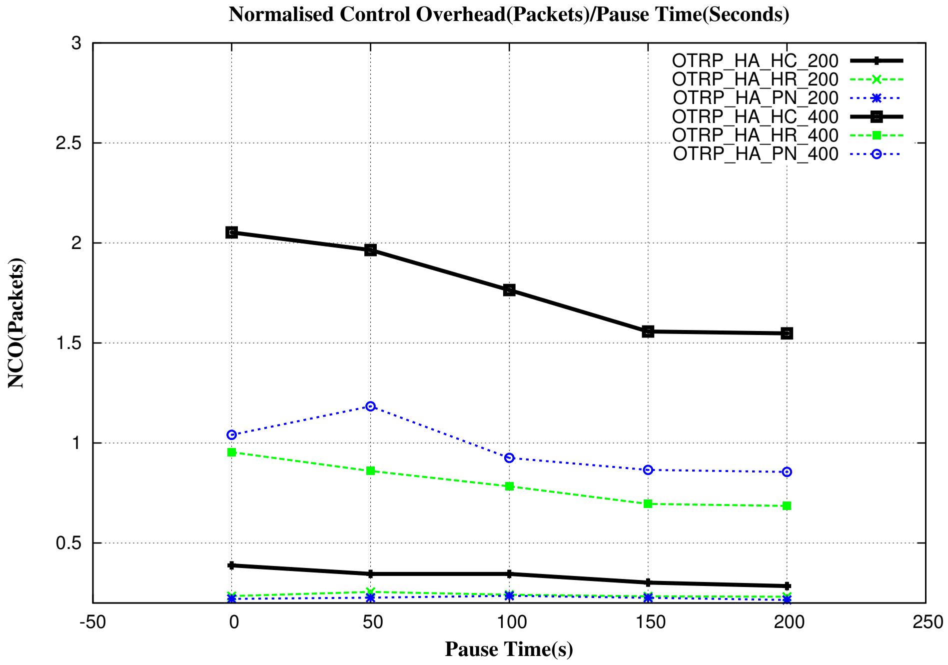


(a) Delay

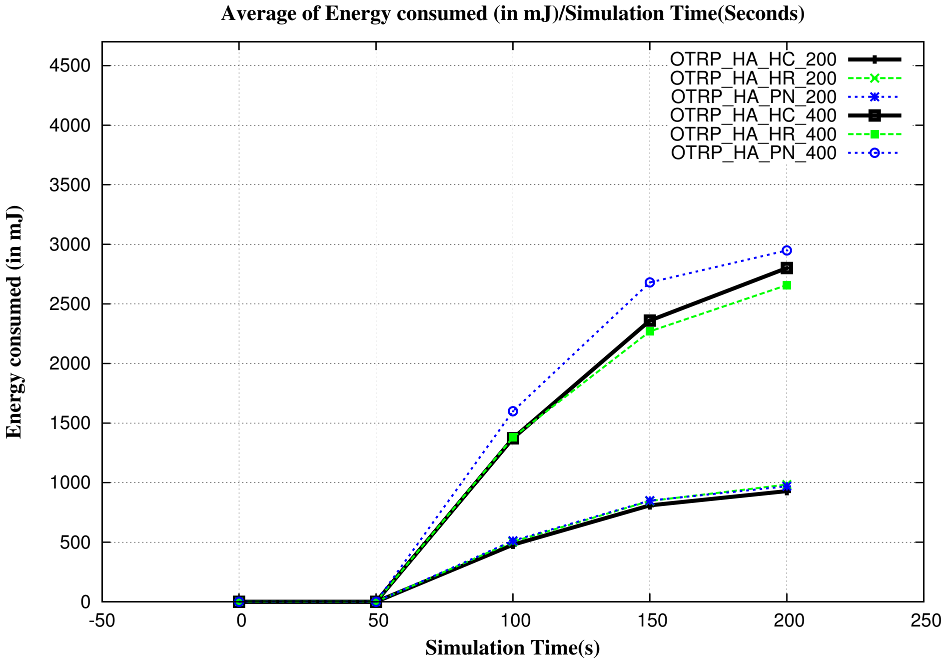


(b) PDR

Figure 7.3: Comparison of the performance of different routing metrics with OTRP_HA with 200 and 400 nodes and 30 traffic flows.



(c) NCO



(d) Energy consumed

Figure 7.3: Comparison of the performance of different routing metrics with OTRP_HA with 200 and 400 nodes and 30 traffic flows.

sult in long paths that may delay the delivery of data. However, OTRP_HA with HR has the highest PDR. It delivers more than 92% of the data, where the long paths are avoided and good quality links are preferred.

Since the main aim of OTRP_HA in HMANET is to improve scalability and reduce COH, then HR is clearly the best option since it can maximise the efficiency of this protocol as it highly eliminates COH as shown in Figure 7.3c. Using HC to select a path in HMANET reduces the performance of OTRP_HA. Similarly, focusing only on a high number of powerful nodes that may have more than one interface can increase COH. The HR metric outperforms the both HC and PN metrics in term of COH. Moreover, using only one counter to count all types of hop nodes improves the performance of OTRP_HA and reduce COH.

To test the energy efficiency of the three metrics, the energy consumed when transmitting and receiving modes during 5 intervals of simulation time (0 s, 50 s, 100 s, 150 s, 200 s) with pause time =100 s. In all metrics, nearly the same amount of energy is consumed in the 200 nodes scenario as shown in Figure 7.3d. However, using the PN metric, more energy is consumed as time increases with the 400 nodes scenario. This is because more powerful nodes are used, which may have more than one interface, and more power is consumed in receiving and sending. By using HC and HR, similar amount of energy are consumed with a slight increase with HC for the 400 node scenario. This is can be attributed to the fact that HC creates more overhead than HR as explained before. Therefore, HR is an efficient power-aware metric.

7.4 Conclusion

In this Chapter, the heterogeneity ratio is proposed as a new routing metric for heterogeneous MANETs in order to utilise node heterogeneity and route data efficiently. The heterogeneity ratio balances the use of the shortest path based on the minimal hop count metric and paths with the best quality that have a high number of powerful nodes. This metric is implemented on top of the OTRP_HA protocol where rebroadcasting nodes are selected according to their resources and locations. The performance of OTRP_HA with three metrics, heterogeneity ratio, hop count, and number of powerful nodes were compared under a variety of network conditions include mobility and node density. Simulation results show that OTRP_HA with heterogeneity ratio significantly reduces routing overheads and achieves higher levels of data delivery than the other routing metrics.

Chapter 8

Conclusions and Future Work

8.1 Overview

The Mobile Ad hoc NETwork (MANET) architecture has enriched wireless networks with new technologies and mechanisms to facilitate communications between people and devices. However, existing literatures has outlined many problems associated with MANETs. This thesis has addressed an essential issue in MANETs; the scalability of MANET routing protocols in homogeneous and heterogeneous environments. This has been achieved by reducing control overhead during the route discovery process and utilising nodes characteristics including locations, resource availability and heterogeneity. In this Chapter, the main ideas and findings of the previous chapters are summarized, and present the main conclusion of this dissertation. Finally, potential future work in this area is discussed.

8.2 Significant Results

This section present a summary of the main concepts explored in this thesis.

The investigation of scalability in MANETs routing protocols begins by reviewing and studying related literatures discussing the scalability problem in current routing protocols. This includes studying existing strategies for the route discovery process in heterogeneous MANETs. The literature identifies the needs for new mechanisms to reduce control overhead during the routing processes. In addition, it demonstrate a deficiency in existing in models for the nodes heterogeneity which must be addressed in order to give a better understanding of the scalability problem in Heterogeneous MANETs (HMANETs). Consequently the need for new routing protocols that can resolve scalability and heterogeneity issues in HMANETs is demonstrated.

In Chapter 3, a new on-demand routing protocol called On-demand Tree based Routing Protocol (OTRP) has been proposed to improve the scalability of MANETs. This is achieved by an efficient route discovery algorithm called Tree-based Optimised Flooding (TOF) which reduces the routing overhead of on-demand routing protocols when previous knowledge of destination is not available. Particular nodes (branching-nodes) are selected to forward RREQ packets. The relay selection process depends on the location of the node in relation to the location of the source node. Theoretical study has shown that OTRP can reduce the number of rebroadcasting nodes by 50% in a grid based node distribution. Overheads will correspondingly reduce by the same fraction. The performance of OTRP was compared with two reactive protocols (AODV and DYMO) and one proactive routing protocol (OLSR) with varying degrees of node density and mobility in QualNet simulation. Results show that OTRP significantly reduces routing overheads and achieves higher levels of data delivery than the other protocols. However, selection of branching-nodes in OTRP is affected by different factors which consequently affect the performance of the protocol. These factors, namely the number of branch nodes, the location of the branching nodes and number of RREQ retries, have been theoretically analysed and evaluated in Chapter 4. It has been found that increasing the number of branching nodes with a low number of RREQ retries maximises the performance of OTRP. Moreover, the strategy of choosing branching nodes in OTRP is more efficient than selecting nodes that are located at the boundary of the parent node or very close to it.

Most of the current routing protocols assume homogeneous network conditions where all nodes have the same capabilities and resources. In Chapter 5, the issue of node heterogeneity in MANET routing protocols is discussed. Simulations have been carried out to compare the performance of different routing protocols in homogeneous and heterogeneous networks. However, all simulated protocols without knowledge of heterogeneity are observed to misbehave in heterogeneous networks, suffering from high delays and achieving very low PDR. It has also been found that current MANET routing protocols suffer from the presence of unidirectional links. Therefore, the Location-Based Utilisation (LBU) strategy is proposed to resolve unidirectional links in MANET. Instead of dropping duplicated RREQ packets, each incoming RREQ packet is used to filter routing information of neighbours under unidirectionality. LBU, Blacklist_CTS/RTS, ULE_NL and EUDA are applied on top of AODV and OTRP. LBU outperforms the other strategies under homogeneous and heterogeneous MANET in terms of packet delivery and control overheads without increasing delay.

In Chapter 6, a network model for heterogeneous MANET is proposed to consider nodes with different resources and capabilities, such as: multiple interfaces, variable power schemes (battery and external power), and different transmission ranges. This model considers scalability and connectivity in the existence of heterogeneous multiple-interfaces nodes with different power schemes. Using this model, a new route discovery strategy for heterogeneous MANETs is proposed to adjust nodes dynamically and control their routing behaviour based on their resources and the environment around them. Rebroadcasting nodes are selected according to their resources and locations. Powerful nodes with multiple-interfaces have been used to link between two different types of nodes. The performance of OTRP_HA, OTRP, and AODV were compared under a variety of mobility and node density scenarios. Simulation results show that OTRP_HA significantly reduces routing overheads and achieves higher levels of data delivery than the other protocols. Moreover, the simulation results show that OTRP_HA is a power efficient.

However, selecting paths according to minimal hop count may lead to poor performance in HMANETs where there are different types of nodes with the potential to provide a path with better performance despite a higher number of hops. Hence, in order to utilise node heterogeneity and route data efficiently, the heterogeneity ratio has been proposed in Chapter 7 as a new routing metric for heterogeneous MANETs. The heterogeneity ratio balances the use of the shortest path based on the minimal hop count metric and paths with better overall link quality due to having a high number of powerful nodes. This metric is implemented on the top of OTRP_HA where rebroadcasting nodes are selected according to their resources and locations. The performance of OTRP_HA when the heterogeneity ratio, hop count, and number of powerful nodes are used as routing metric were compared under a variety mobility and node density scenarios. Simulation results showed that OTRP_HA with heterogeneity ratio significantly reduces routing overhead and achieves higher levels of data delivery than the other routing metrics.

8.3 Future Work

The work within this thesis can be extended for further research in the following:

- OTRP suffers from high delay because of fixed number of rebroadcasting nodes. There are different enhancements which can be added to this protocol as follows:

   1. A new strategy to dynamically detect the node density and then accordingly adjust the number of rebroadcasting nodes;
   2. OTRP uses nodes locations within 2-D network. In real life, network is 3-D. There is a need enhance OTRP to work within a 3-D environment; and
   3. Improve OTRP to work as face routing protocol. The advantage of a face routing protocol is guarantees packet delivery without flooding the network or imposing stringent memory requirements.

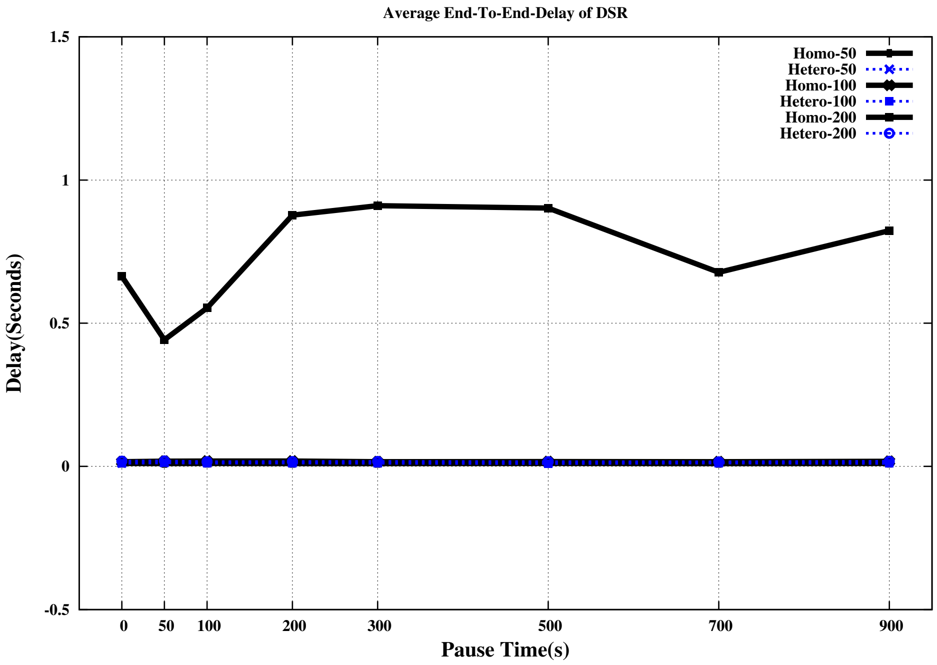
- In HMANETs, the links between any two nodes can be different in their capability and quality. The quality of the path in HMANET can be enhanced to increase the reliability of the HMANET network. This can be based on:

   1. Mutihoming to create multiple connections in one path using the features of powerful nodes in HAMENT;
   2. Exchanging information regarding destination nodes in a cooperative manner to facilities route discovery in a heterogeneous environment.

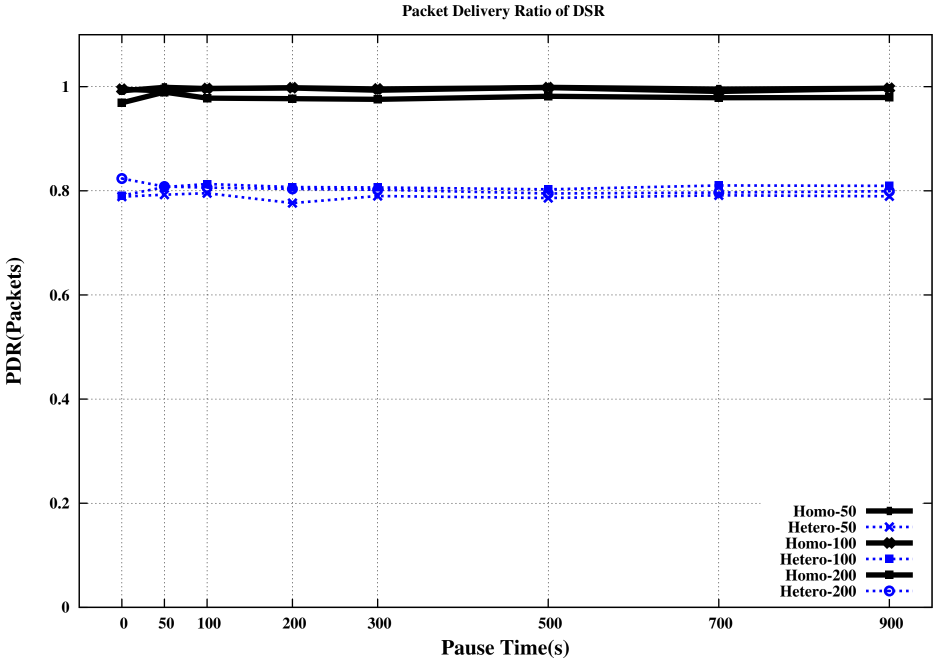
Appendix A

Nodes Heterogeneity and MANET Routing Protocols

A.1 Performance of MANET Routing Protocols in Homogeneous and Heterogeneous Environments

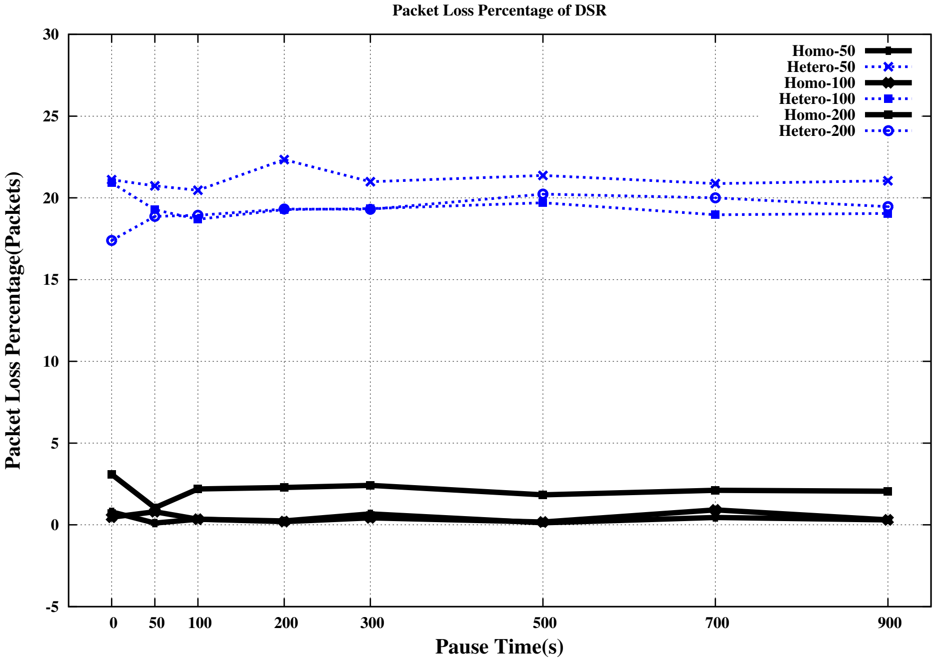


(a) Delay

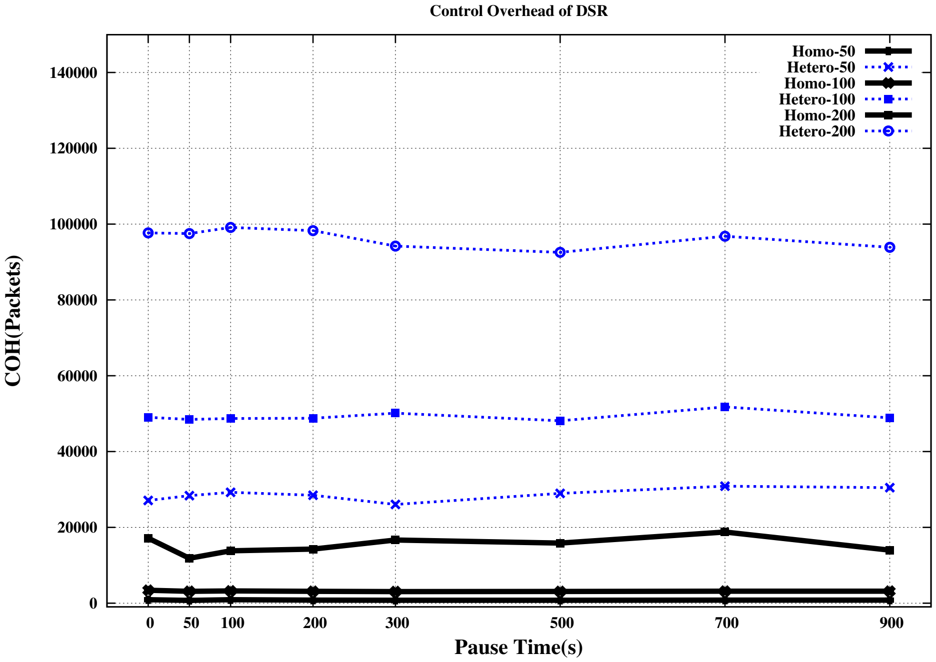


(b) PDR

Figure A.1: The performance of DSR for 50, 100, and 200 nodes in both homogenous and heterogeneous networks.

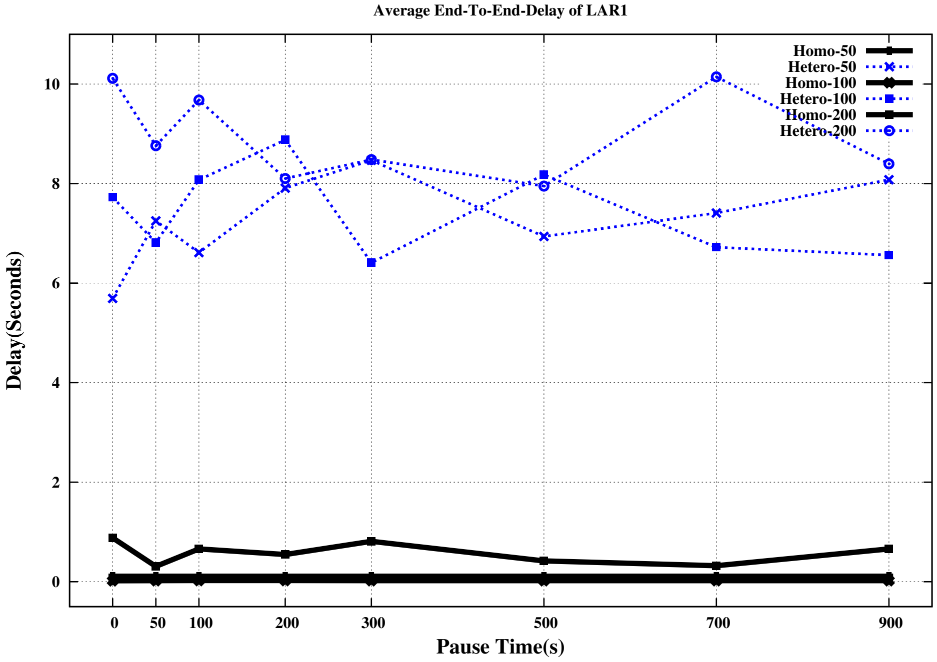


(c) Packet Loss

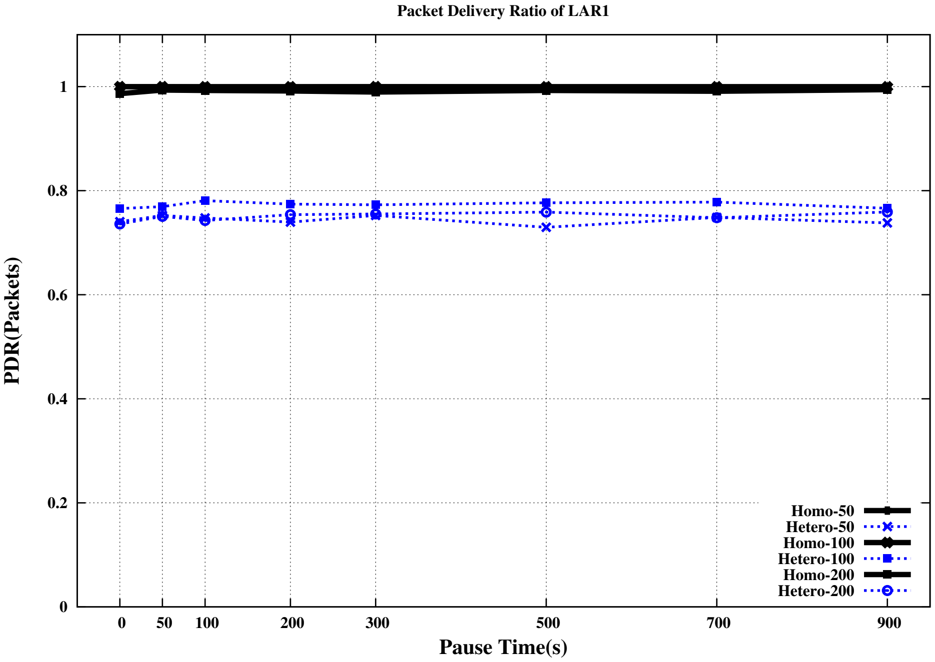


(d) OH

Figure A.1: The performance of DSR for 50, 100, and 200 nodes in both homogenous and heterogeneous networks.

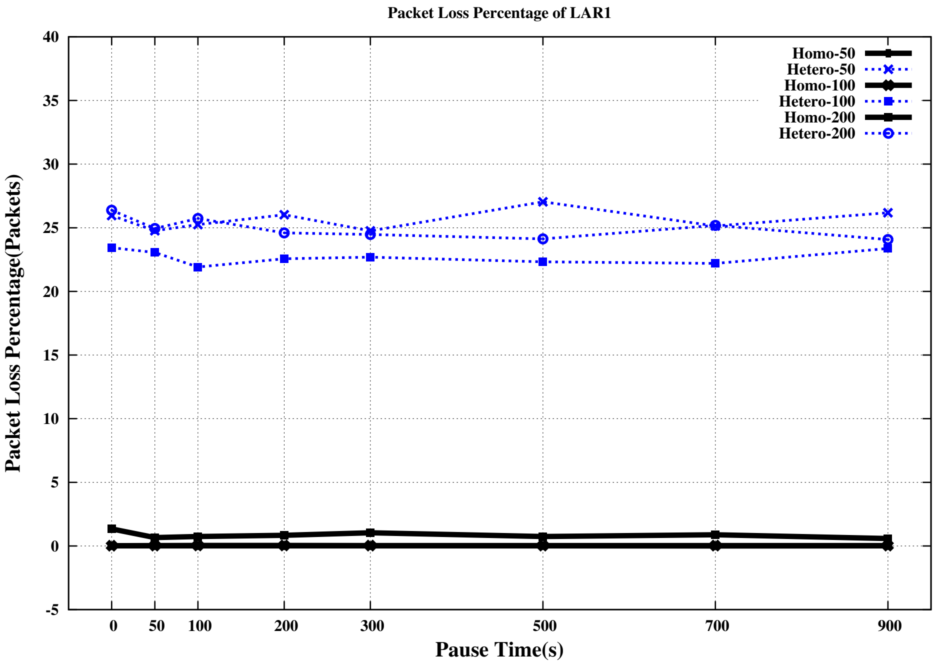


(a) Delay

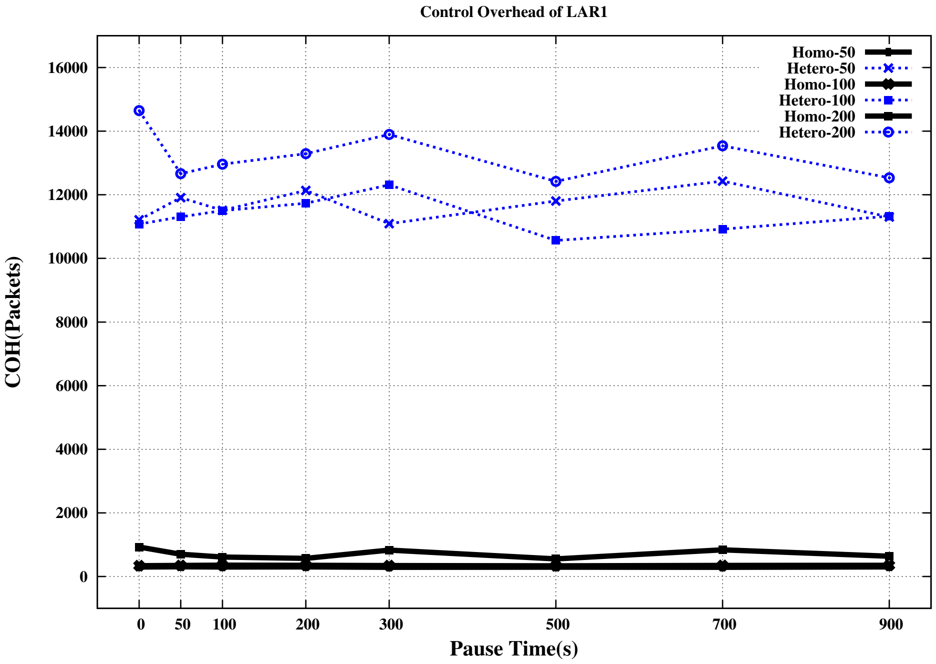


(b) PDR

Figure A.2: The performance of LAR1 for 50, 100, and 200 nodes in both homogenous and heterogeneous networks.

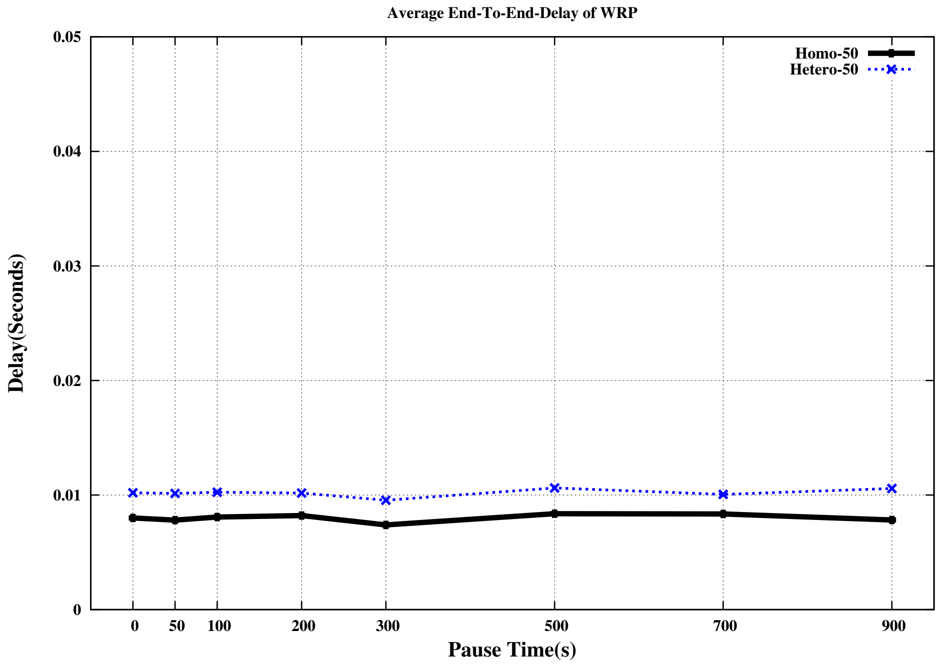


(c) Packet Loss

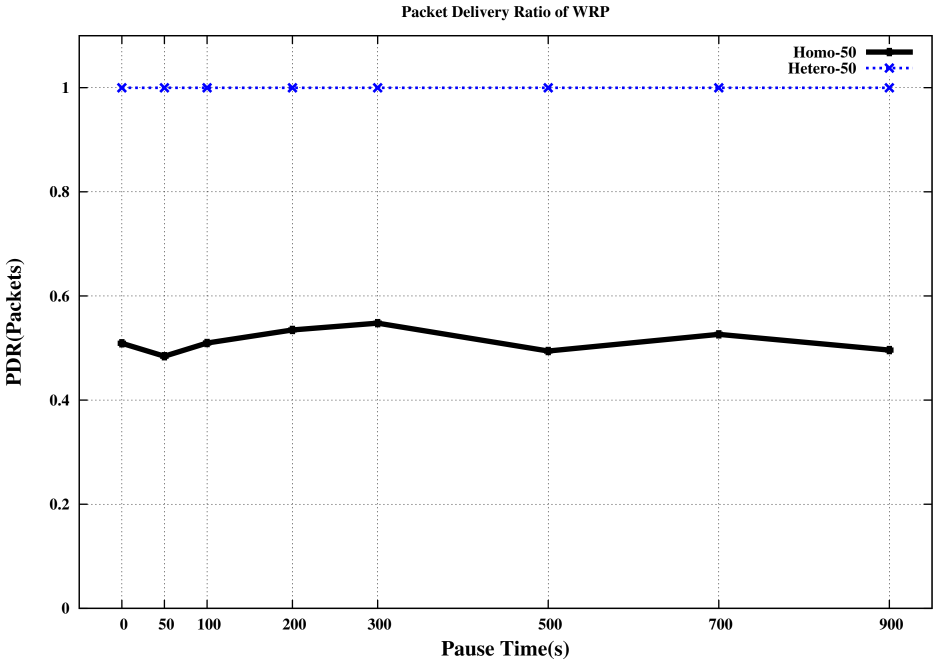


(d) OH

Figure A.2: The performance of LAR1 for 50, 100, and 200 nodes in both homogenous and heterogeneous networks.

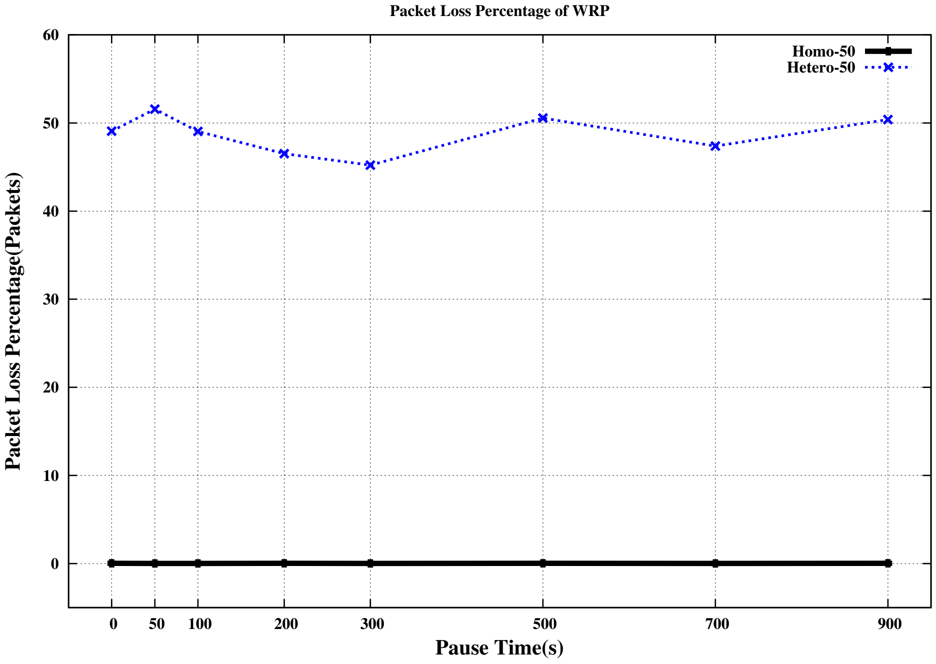


(a) Delay

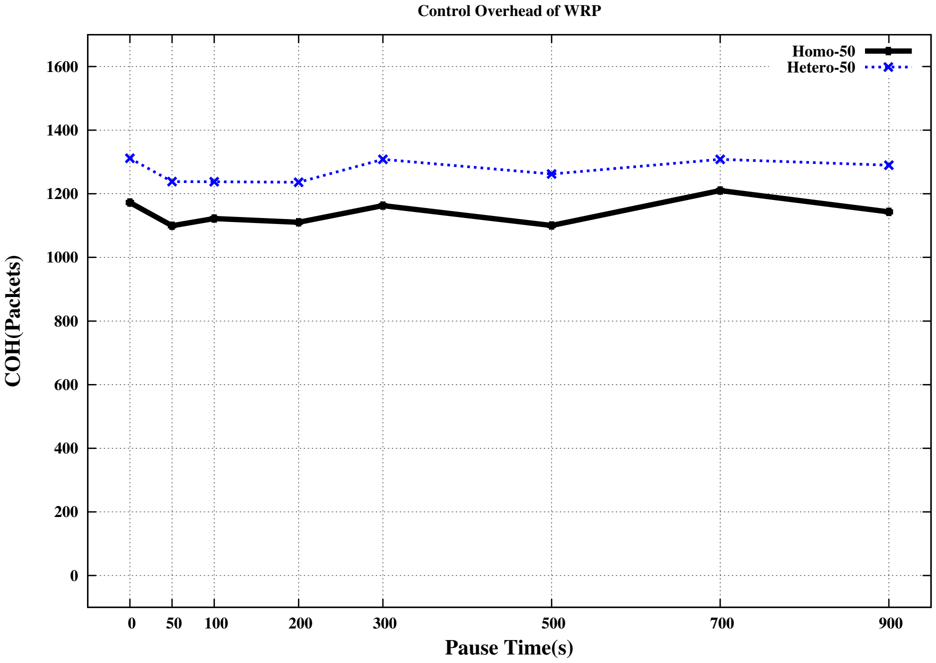


(b) PDR

Figure A.3: The performance of WRP for 50, 100, and 200 nodes in both homogenous and heterogeneous networks.



(c) Packet Loss



(d) OH

Figure A.3: The performance of WRP for 50, 100, and 200 nodes in both homogenous and heterogeneous networks.

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