Route Discovery Schemes in Mobile Ad hoc Networks with Variable-Range Transmission Power

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Abstract

Broadcasting in MANETs is important for route discovery but consumes significant amounts of power that is difficult to renew for devices that rely heavily on batteries. Most existing routing protocols make use of a broadcast scheme known as simple flooding. In such an on-demand routing protocol (e.g. AODV) the source node originates a Route Request (RREQ) packet that is blindly rebroadcast via neighbouring nodes to all nodes in the network. Simple flooding leads to serious redundancy, together with contention, and collisions, which is often called the *broadcast storm problem*. This thesis proposes two improvement strategies: topology control (adjusting transmission power) and reduced retransmissions (reducing redundant rebroadcasts) to reduce energy consumption. For energy efficient route discovery the main idea is to reduce the energy consumed per broadcast during route discovery.

An Energy Efficient Adaptive Forwarding Algorithm (called EEAFA) is proposed to reduce the impact of RREQ packet flooding in on-demand routing protocols. The algorithm operates in two phases: 1) Topology construction phase, which establishes a more scalable and energy efficient network structure where nodes can adjust their transmission power range dynamically, based on their local density. 2) A Forwarding Node Determination phase, that utilises network information provided by the constructed topology, where nodes independently decide to forward a RREQ packet or not without relying on GPS or any distance calculations.

A further Enhanced EEAFA (called E-EEAFA) algorithm is also proposed, which combines two techniques: graph colouring and sectoring techniques. Graph colouring increases awareness at network nodes to improve the determination of a forwarding node, while the sectoring technique divides neighbours into different forwarding sectors. This helps to reduce overlap between forwarding nodes and select suitable nodes in each sector to forward RREQ packets. These techniques are employed in a distributed manner and collaborate to reduce the number of forwarding nodes, which thus reduces the volume of RREQ packets populating the network. These algorithms have been validated as effective by NS2 simulation studies that are detailed in the thesis.

Dedication

To my Mother and Father

To my Wife

To my daughters Elan and Lamar, and my sons Ali and Ammar

Acknowledgements

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Glossary

AODV	Ad hoc On Demand Distance Vector
AOMDV	Ad hoc On-demand Multipath Distance Vector
CBR	Constant Bit Rate
CDS	Connected Dominating Set
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTS	Clear To Send
GPS	Global Positioning System
MAC	Medium Access Control
MANET	Mobile Ad hoc Network
MPR	Multipoint Relay
OLSR	Optimized Link State Routing
OSI	Open Systems Interconnection
RAD	Random Assessment Delay
RERR	Route Error
RNG	Relative Neighbourhood Graph
RREP	Route Reply
RREQ	Route Request
RSS	Received Signal Strength
RTS	Request To Send
TCL	Tool Command Language
TPC	Transmission Power Control
TTL	Time To Live
VANET	Vehicular Ad hoc network

Publications

Publications of this research:

- Alghamdi Atif A., Robert J. Pooley, Peter JB King and Ibrahim Idris S. Improving the Power Efficiency of a High-Density Cluster in MANETs. In PGNET Proceedings of the 15th Annual Postgraduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting, pages 8-12, Liverpool, UK, 2014 (It proposes the idea of improving the power efficiency Cluster in MANETs)

- Alghamdi Atif A., Robert J. Pooley, and Peter JB King, Energy-Efficient Adaptive Forwarding Scheme for MANETs. In Wireless Days (WD), pages 160-166, Toulouse, France, 2016. (It proposes Chapter 4, which combines two different approaches collaborate to reduce energy consumed per broadcast).

- Alghamdi, Atif A., Peter JB King, and Nawaf S. Mirza, Colour-Based Forwarding Scheme with Variable-Range Transmission Power in AODV. In Wireless Days (WD), pages 248-251, Porto, Portugal, 2017. (It proposes the colouring algorithm in Section 5.2 in Chapter 5, which operates over the topology structure constructed).

Publications of other research:

- Mirza N.S., King P.J., Romdhani I., Abdelshafy M.A. and Alghamdi A.A., Reliable Multipath Multi-Channel Route Migration over Multi Link-Failure in Wireless Ad Hoc Networks. In Wireless and Mobile Computing, Networking and Communications (WiMob), pages 123-130, Rome, Italy, 2017.

- Mirza N.S., Hamish Taylor, Abdelshafy M.A., King P.J., Romdhaniy I. and Alghamdi A. Cross-Layer Multipath Multichannel MAC Protocol for MANETs. In International Symposium on Networks, Computers and Communications (ISNCC), pages 1-8, Rome, Italy, 2018.

Chapter 1

Introduction

"An ad hoc network is a self-configuring network composed of a set of devices with wireless capabilities that can communicate between them without any infrastructure" [1]. These networks, are self-organised, have a heterogeneity of devices and dynamic unpredictable behaviour that may make them difficult to implement. Limiting factors are in changing topology, limited transmission range, and battery life plus partitioning of the network.

MANETs is short for Mobile Ad hoc Networks in which a network is created by a group of mobile devices. The special characteristics of MANETs mean that they play a significant role in wireless communications research. MANETs are deployed for a variety of applications, including emergency rescue missions, military operations and personal area networks. However, there are many challenges to bear in mind when designing MANETs which include scalability, quality of service and energy efficiency.

Energy efficiency in MANETs has attracted many researchers' attention in recent years [2]. In these networks collaboration among devices is vital for relaying packets or performing as a router to support the network. Therefore, how to reduce the energy consumed in each transmission is a critical question and has thus been extensively studied. In [3] it is reported that wireless communication is responsible for approximately 50% of the total power consumed by a device. Consequently, developing a joint approach in which the number of packets retransmitted is reduced while transmission power ranges are varied promises to lead to large energy savings.

1.1 Characteristics of MANETs

A number of MANETs' characteristics that make their design challenging are addressed below:

- ***Decentralised operation:*** As MANETs comprise infra-structureless networks, individual nodes are able to run algorithms locally and all decisions are taken by the nodes without any centralised administration. Each node acts as an independent router in addition to generate and forward messages to other nodes that may be beyond its existing transmission range [4].

- ***Dynamic topology:*** Nodes in a MANET can roam freely in or out of its geographical coverage area in an unpredictable manner causing frequent changes to the network topology. Thus, an ongoing communication session is prone to suffering frequent path breaks. As a result, broadcasting and routing protocols for MANETs must handle mobility management efficiently [5].

- ***Multi-hop communication:*** MANETs often exploit multiple hops in relaying data due to their node's limited transmission ranges. In MANETs a packet must be relayed by intermediate nodes in multi-hop communication to forward the packet to its final destination.

- ***Energy constrained:*** Nodes in MANETs are usually devices that use batteries as their source of power. Due to the limited life of a battery, the availability of power is a major concern. There are different approaches for improving the effectiveness and rate of energy use of a mobile node: these include reducing the transmission power range, scheduling the mobile devices into other power saving modes, reducing the number of unnecessary retransmissions, etc. [6]. In addition, nodes will use up more energy in transmitting, receiving and processing messages. A great deal of energy is wasted from the following [7]:

  - Overhearing: in the shared medium of wireless communication, when a packet is transmitted by the sender node to the next hop, this packet is received by all one-hop neighbours within the sender's transmission range even if only one of them is the intended recipient.

  - Interference: from the perspective of interference, all nodes situated within the transmitter's range and the range of interference are affected unintentionally, where they receive an interfered packets and cannot decode it.
  - Collision: collisions cause more energy consumption by corrupting otherwise good packets [8], where the energy is dissipated in the transmission and reception of colliding packets.

- ***Computational Power:*** The components of mobile devices are not designed to have high capacity or processing power. Therefore, for communication protocols, only algorithms that have modest computational requirements should be employed [9].

- ***Bandwidth constrained:*** Similarly to the computational capacity, the available bandwidths of the wireless channel in MANETs are significantly smaller than those available to wired counterparts [10]. Nodes within the same transmission range share the same wireless channel. Thus the bandwidth available for each wireless channel is dependent upon the total number of nodes present and the traffic injected into the network by each element. This means that each node utilises only a small proportion of the available bandwidth. This bandwidth limitation causes problems in the regular maintenance of topological information through routing and broadcasting protocols.

- ***Radio interference:*** Two main forms of interference may impede transmission over the wireless communication medium: these are adjacent channel and co-channel interference [6, 11]. Co-channel interference resulting from other nearby communication systems using the same transmission frequency is one of the most serious problems in MANETs [9]. The MAC layer of the IEEE 802.11 standard [10, 12] is designed to minimise interference within a channel through dynamical coordinating access to the wireless channel among mobile nodes. These barriers generally restrict the data rate, reliability and range of wireless transmission. Therefore, any communication protocol for MANETs should contend with these issues. One of the more technical approaches to reducing interference is to monitor and control transmission power [12]. Through adjusting the transmission power, a node can limit its interference with other transmissions [13].

1.2 Protocols Layers of MANETs

The layers of the Open System Interconnection (OSI) reference model [14] for MANETs are presented, and the function of each layer is described. As illustrated in Figure 1.1, the protocol layers of MANETs include: the application, transport, network, data link, and physical layers.

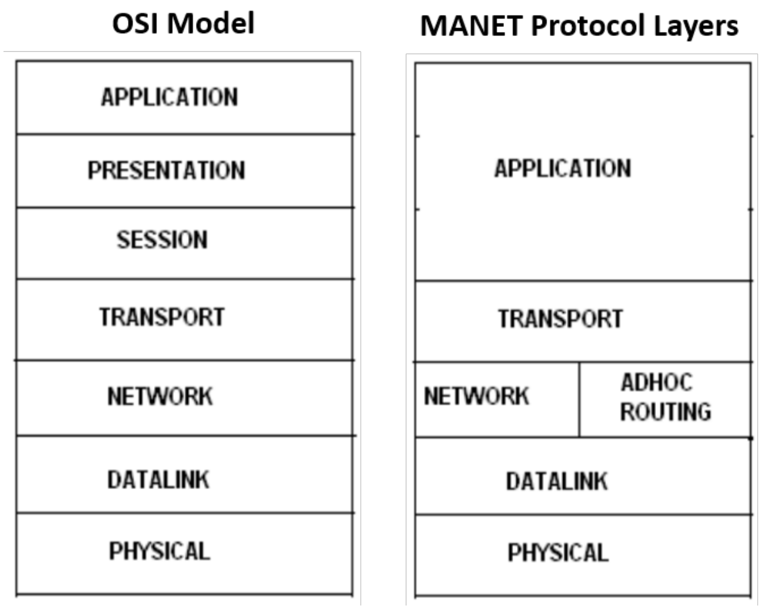


Figure 1.1: OSI reference model and MANET protocol layers.

- **Application Layer:** In this layer, data packets are generated and passed to the network layer to be delivered. The network layer is the layer that ensures the delivery of packets across the network.

- **Transport Layer:** This layer provides the end-to-end connection between source nodes and the destination nodes and ensures its reliability. It performs some of the important tasks such as congestion and flow control as well as supporting data packet's integrity [14]. Two key protocols are employed in this layer: these are the Transmission Control Protocol (TCP) [15] and the User Datagram Protocol (UDP) [16]. By using acknowledgement and retransmission methods, TCP ensures reliable data delivery to a destination node. In contrast, UDP is a connectionless protocol and thus is not reliable nor able to provide a guarantee of delivery.

- **Network Layer:** This layer performs all operations to discover and establish routes from source to destination nodes. These operations include, forwarding data packets and routing them through intermediate nodes, as well as repairing and maintaining links [17].

- **Data Link Layer:** This layer consists of two sub-layers [14]. The first of these is the Logical Link Control (LLC) layer; its responsibilities include maintaining links, controlling the flow and the synchronisation of the frame and detecting errors. The second layer is the Medium Access Control (MAC) layer, which controls access to the shared wireless channels between nodes and is thus, crucial to prevent collisions and contention among the nodes [18].

- **Physical Layer:** This layer is responsible for transmitting signals over a physical link connecting devices together [19, 20]. The physical layer consists of two sub-layers: the Physical Layer Convergence Procedure (PLCP) and the Physical Medium Dependent (PMD) sublayer [21]. The PLCP ensures that when a frame is passed up from the MAC layer, it is then transformed into a suitable format to be retransmitted by the PMD, that is, the frame is translated into radio signals so that it can be transmitted.

In MANETs the lower levels of the protocol layers are used for communication between nodes, while higher level (e.g. Application layer) communications are only associated with the source and destination nodes. Ad hoc On Demand Distance Vector (AODV) is a network layer protocol which ensures packets are transmitted across the network, via intermediate nodes, in order to travel to their destination.

Packets are sent to the network by the application layer which does not see them again until they reach their destination. This procedure is shown in Figure 1.2.

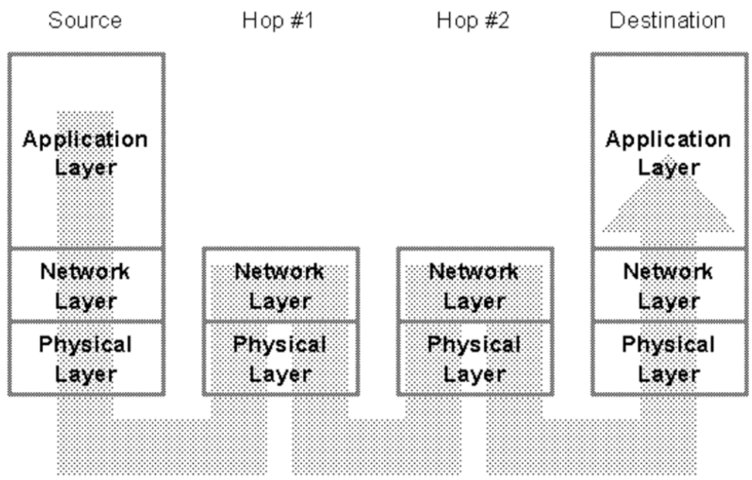


Figure 1.2: Packet flow through the network layers.

1.3 Motivation

Broadcasting provides an essential network service for routing protocols in MANETs. As a key step of the route discovery process in such protocols, broadcasting is to propagate the Route Request (RREQ) packets throughout the network. The simplest mechanism to do this is flooding: in this procedure, every node in the network forwards each unique packet it receives just a single time. Although simple flooding makes sure that each particular packet reaches every node in the network, it also means that a great number of redundant transmissions are generated throughout the network [13, 22]. Thus, in a dense network, this would lead to more redundant transmissions leading to significant contention and collisions among the transmissions. This phenomenon is known as a *broadcast storm* [22], which can result in the collapse of the whole network.

A simple flooding approach not only results in congestion throughout the network but, in addition, greedily consumes the battery power of mobile devices so this approach is not advisable. In [23], the authors show that a failure discovering the destination in routing causes fewer problems than the inherent overhead generated by simple flooding. Moreover, in sparse networks, where the loss rates are high, the coverage obtained is low, even when a flooding approach is employed [24]. Thus, there is a need for more efficient broadcasting algorithms to address these challenges and conserve energy.

For on-demand route discovery, good network performance and scalability is a key requirement. To enable nodes to find routes to their destinations, the core problem in broadcasting needs to be addressed. This involves finding a way to minimise the number of nodes rebroadcasting RREQ packets, while achieving the desired level of reachability (i.e. maintaining the percentage RREQ packets reaching the intended nodes).

Efficient broadcasting in MANETs poses a challenge due to the unique characteristics of this type of environment, in terms of a rapidly changing network topology caused by node mobility and network partitioning. A broadcast storm may occur in an ad hoc network with high node density and many rebroadcasting nodes. The direct impact of the broadcast storm problem on network performance is long end-to-end delay, high power consumption and wastage of bandwidth. Therefore, it is crucial to design efficient broadcasting schemes that can limit the redundancy while maintaining network performance and saving energy.

Topology-based broadcasting schemes use network topology information to perform packet forwarding. Most existing topology-based broadcasting schemes rely on using fixed high range transmission power in exchanging *hello messages* or *beacon* among nodes. However, the drawback of using a fixed high range is high energy consumption with the possibility of decreasing the capacity of the network. Ideally, the transmission power range should be dynamically adjusted so that both high energy saving and a good level of connectivity are possible when there are frequent changes in the network topology. Transmission power should also be adjusted to a high range for nodes that are located in sparse areas to maintain connectivity and should be adjusted relatively lower for the nodes located in dense areas to reduce radio interference among nodes present in the network, and hence conserve their power.

1.4 Contributions

In view of the challenges associated with mobile ad hoc networks discussed previously, it is clear that specific characteristics have to be considered when designing broadcasting algorithms. It is essential to design decentralised algorithms which can take decisions locally, and enable nodes to collaborate in the process of routing packets. It is also important for protocols to be able to adapt to the changes in topology caused by the movement of nodes and by the unstable nature of MANETs. These algorithms need to include mobility support, adaptability and be able to react to frequent changes. It is also essential to know the time taken for the protocol to respond to a change. As energy is often limited and may be difficult to renew in a wireless network, algorithms running on these networks need to conserve energy. Specifically, a node needs to decide whether to participate in retransmitting a broadcast packet or not and also to decide on which transmission power range is suitable for that transmission.

Any valid solution should be scalable, decentralised, localised, and able to adapt itself to topology changes. It all requires limited complexities: storage complexity which is the storage size every node needs to maintain necessary information; control packet size which may be different for different protocols; time complexity which is the number of steps needed to perform a protocol operation; and communication complexity which is the number of control messages needed to perform a protocol operation [25, 26, 27].

In MANETs, the distribution patterns of mobile nodes are frequently arbitrary or random over a given topology area. Thus dense and sparse regions of the network need to be identified so that each node can be assigned the appropriate transmission power range in these regions with different densities. To minimise the level of interference in a dense network, the transmission power range should be reduced. In a sparse network, however, the transmission power range should be increased, to improve the network connectivity.

To achieve this, as a first contribution a cross-layer technique has been designed where the algorithm adjusts the transmission power range at each node into different levels in a dynamical response, according to its local density (number of neighbours). This technique constructs a dynamic self-organised topology structure that uses lightweight variable-range beacons to form and maintain this topology structure. In this thesis, the local density around a node is calculated by counting the number of one-hop neighbours it has, obtained by monitoring the number of *hello messages* which are periodically exchanged between neighbouring nodes. As a result, the nodes in the network are classified into different groups based on their transmission power levels.

A second contribution is a new Energy Efficient Adaptive Forwarding Algorithm (named EEAFA) that has been designed to work over the constructed topology structure mentioned above, and uses one-hop local information provided by this topology for making rebroadcast decisions. It is a receiver-based (source independent) algorithm system where nodes can estimate their location and determine their forwarding decisions earlier without relying on GPS or any distance measurement. Moreover, nodes need not wait for a random assessment delay time, but each one can immediately make a decision whether to forward/rebroadcast the RREQ packet (the decision is pre-defined). This collaboration between the variable-range topology structure and the EEAFA algorithm can reduce redundant retransmissions of the RREQ broadcast packets and reduce transmission power usage, thus conserving the overall energy consumed per broadcast.

Despite the fact that the proposed route discovery algorithm is able to make a significant reduction in the routing control overhead without affecting the overall throughput of the network, it faces two drawbacks: how to determine the forwarding nodes between different groups with the same transmission power level; and how to minimise overlaps between forwarding nodes in the same region. As the forwarding node is determined only by the power level information received in the neighbouring table, the node could be located between different groups of nodes with the same transmission power level, thus no node declares itself as a forwarding node. As a result, the RREQ broadcast packet will be retransmitted by all one-hop nodes to avoid the early die-out of the RREQ broadcast packets and to avoid any collapse. In these parts of the network, a large volume of RREQ packets will be broadcasted, causing a high level of redundant retransmissions, together with a great deal of channel contention, leading to many packet collisions and more energy consumption especially in highly dense regions in the network. A second challenge is reducing the overlap between forwarding nodes in the same region. This may lead to high number of redundant rebroadcasts especially in the absence of a coordination function among forwarding nodes. This causes contention, collision and eventually results in high power consumption.

As a third contribution in this thesis, an optimisation of the proposed route discovery algorithm in Chapter 4 has been introduced. An Enhanced EEAFA algorithm (named E-EEAFA) was designed to tackle the previous drawbacks. The new algorithm uses two new techniques: colouring and sectoring to improve the determination of the forwarding node and to help optimise the RREQ forwarding decision and thus conserving energy. The proposed colouring algorithm aims to increase the awareness at nodes to improve the determination of the forwarding node. This is achieved by assigning a unique colour for each group of nodes. This one-hop colouring technique utilises the existing *hello message* in its operation in order to avoid any extra overhead. A group-colour field is included in the *hello message* and exchanged between neighbours, which assists in increasing the awareness of the nodes that are located between different groups which have similar levels of transmission power. On the other hand, a sectoring algorithm aims to improve the effectiveness with which RREQ packets are disseminated and to shrink the size of the relaying (forwarding) area at each group. This is achieved by dividing the forwarding area in each group into different sectors. The sectoring algorithm assigns a weight value for each node according to the distance from different adjacent groups. This distance can be estimated using the neighbour table. The node that has the highest weight in each sector is considered to be the most suitable forwarding node to participate in the forwarding of the RREQ broadcast packet. This technique can significantly reduce the overlap between the forwarding nodes located in the same region. Both techniques reduce the number of forwarding nodes and ultimately the amount of RREQ packets in the network.

As a fourth contribution in this thesis, a comparison of the effectiveness of the proposed route discovery algorithm EEEAFA-AODV (in Chapter 5) is made against that in the Optimized Link State Routing (OLSR) protocol. OLSR was chosen for comparison as it is classified as a neighbour knowledge approach that uses neighbours' information to decide whether to rebroadcast the message or not. It uses two-hop topology information to calculate relaying nodes (forwarding nodes) by exchanging *hello messages* periodically to maintain topology information. Their performance is compared based on varying network conditions: varied density, mobility and offered load (source-destination connections). The comparison aims to demonstrate the efficiency of relying on one-hop information to calculate forwarding nodes (the case of EEEAFA-AODV) as opposed to other techniques that use two-hop information (the case of OLSR) in terms of routing overhead and how algorithms react rapidly to frequent topology changes.

1.5 Thesis Organisation

The structure of the thesis is as follows and the thesis road map presented in a flow chart form as shown in Figure 1.3:

- **Chapter 1 has described the context and the state of the problem to be addressed in this study**, along with the motivation behind conducting this study. It also specifies the main intellectual contributions of this thesis and how this thesis is organised.
- **Chapter 2 reviews representative Ad hoc based broadcasting algorithms related to the research presented in this thesis.** The literature review provides a classification of energy efficient techniques. It then addresses both fixed-range and variable-range transmission power based broadcasting algorithms. The chapter presents an overview of the broadcast algorithms and discusses an existing classification of these broadcasting schemes and algo-

rithm systems. This chapter also assesses the limitations of existing fixed-range transmission power based broadcasting algorithms and provides a discussion of the current issues of Ad hoc based broadcasting algorithms.

- **Chapter 3 describes the methodology used for this study.** It presents the chosen routing protocol and provides a brief description of its components. It also describes the cross layer design and approach. It lists its system modelling techniques and discusses them in relation to its approach to simulation. The energy consumption model, studies' assumptions and the metrics employed to gauge the performance of the proposed algorithms are presented in this chapter. A justification of the approach is also provided.

- **Chapter 4 presents and evaluates a new energy-efficient route discovery scheme.** It combines two different approaches which collaborate to lower the overhead and reduce energy consumed per broadcast. In addition, a novel broadcasting algorithm is introduced, which makes use of an underlying power control based topology for broadcasting the RREQ packets.

- **Chapter 5 proposes and evaluates an enhanced version of the energy efficient route discovery scheme introduced in Chapter 4.** This chapter proposes an improved scheme that optimises the route discovery process by combining two new distributed algorithms: a Colouring and a Sectoring Algorithms that collaborate to reduce the number of forwarding nodes required and, in turn, the number of RREQ packets travelling through the network.

- **Chapter 6 draws a comparison between the proposed EEEAFA-AODV algorithm in Chapter 5 and the OLSR routing protocol.** This comparison is used to demonstrate the efficiency of a technique using one-hop information as opposed to other techniques that use two-hop information.

- **Chapter 7 draws conclusions from the work of this thesis and provides recommendations and suggestions for further research.**

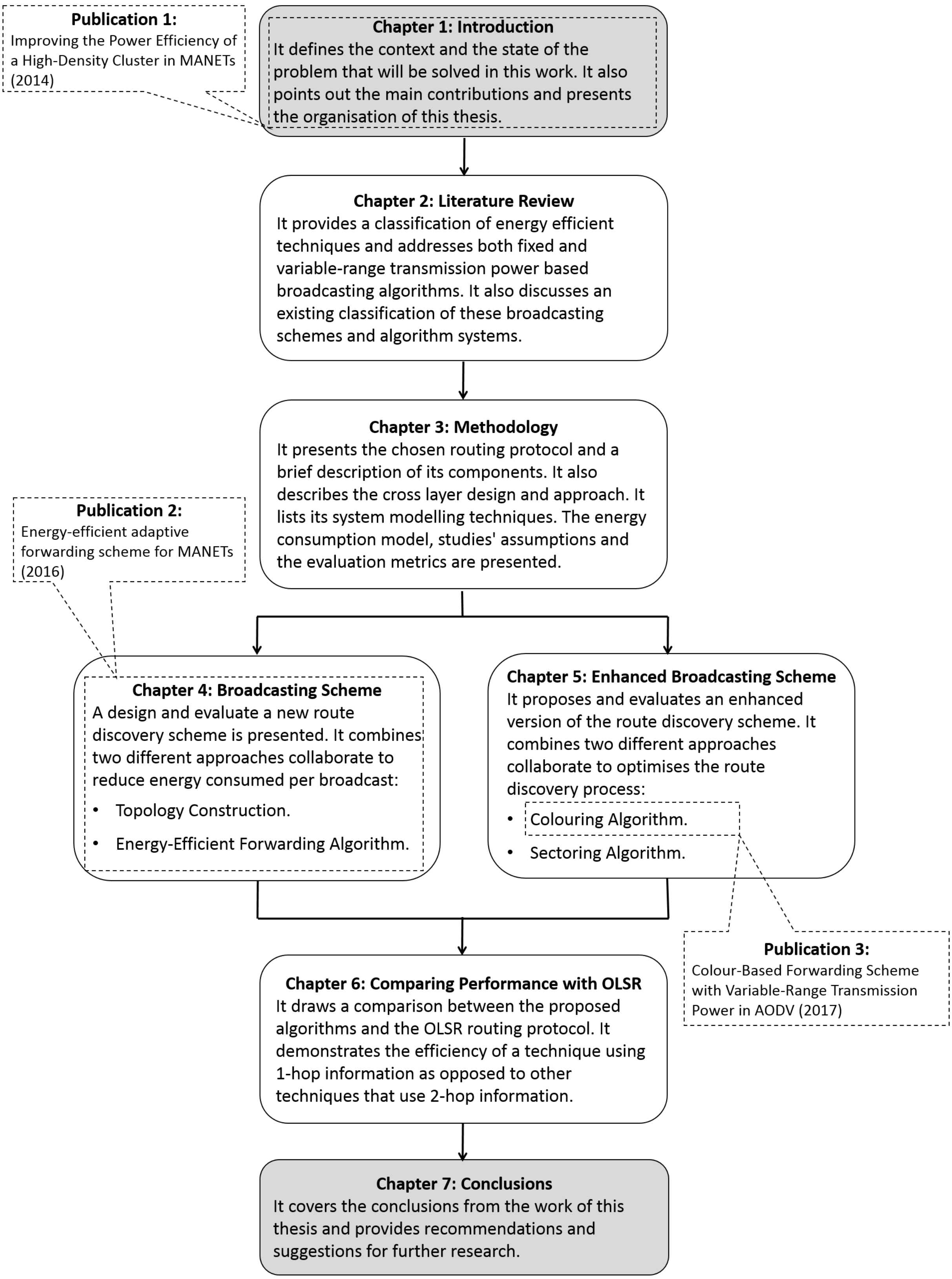


Figure 1.3: Thesis Road-Map.

Chapter 2

Literature Review

2.1 Introduction

Unlike wired networks, broadcasting in MANETs does not guarantee full coverage, for many reasons including: network partitioning, the shared medium, the mobility of nodes, etc. Additionally, as nodes are energy constrained, energy efficient protocols are required. It is estimated that wireless communication is likely to account for approximately 50% of the energy consumed by a MANET device [3]. Thus, a key aim in the design of energy efficient broadcasting algorithms is the reduction of the transmission power range so that both high energy saving and a good level of connectivity are possible, and reduce redundant retransmissions of the broadcast packets, thus conserving the overall energy consumed per broadcast.

This chapter reviews representative ad hoc based broadcasting algorithms related to the research presented in this thesis. The literature review addresses broadcasting algorithms which are based on both fixed- and variable-range transmission power. Section 2.2, reviews and discusses the classification of current energy efficient techniques and strategies. Section 2.3, discusses topology control approaches. In Section 2.4, an overview of broadcasting schemes and their classification is provided. Section 2.5 explains the main characteristics that differentiate the broadcast algorithms and discusses broadcasting algorithms that use fixed-range and variable-range transmission power for broadcasting. It also assesses the limitations of existing fixed-range transmission power based broadcasting algorithms. Section 2.6 addresses the current issues of ad hoc based broadcasting algorithms in relation to this study's proposed broadcasting schemes. Conclusions are drawn in section 2.7.

2.2 Classification of Energy Efficient Techniques

Due to the largely energy-constrained nature of mobile ad hoc networks, reducing power consumption is one of the chief aims of all the proposed energy-efficient protocols. It can classify the energy efficient techniques into four strategies [28] which are detailed in the following four subsections:

2.2.1 Energy Efficient Routing

This strategy, aims to conserve the power used in the end-to-end transmission of broadcast packets. This is achieved by avoiding nodes with low remaining power to preempt unsuccessful transmissions, as described in [29, 30, 31].

2.2.2 Node Activity Scheduling

Scheduling node activity involves alternating node states that vary between sleep and active states, to conserve power while maintaining the network performance and functionality of applications, as explained in previous studies [32, 33, 34]. However, scheduling node activity in MANETs is a particular challenge, for two reasons [35]:

(1) A node can be both a data source and a router that forwards data for other nodes. Additionally, the roles of a particular node may change over time.

(2) In a decentralised network, there is no access point to control and maintain the power mode of each node in the network (e.g., buffer data, and wake up sleeping nodes).

Therefore, power control in ad hoc networks must be done in a distributed and cooperative fashion.

2.2.3 Topology Control by Adapting the Transmit Power

Topology Control (TC) is a key technique used in wireless ad hoc networks to conserve energy [36]. This strategy finds the optimum node transmission power that minimises the energy being consumed while maintaining the connectivity of the network. The protocols e.g. in [37, 38, 39, 40] manage energy consumption by adjusting transmission power ranges. This technique reduces the level of interference in the network. Thus, it reduces the likelihood of collisions, which enhances network utilisation, reducing both latency times and the risks of hidden and exposed terminals [41]. This will be further discussed in relation to this research in Section 2.3.

2.2.4 Limiting the Number of Retransmissions

This strategy consists in optimising the broadcast of messages throughout the network, which leads to the prevention of unnecessary rebroadcasting by a node. It reduces overhearing by other nodes and aids energy conserving in transmission, reception and overhearing nodes. This will be further discussed in relation to this research in Section 2.4.

2.3 Topology Control by Adjusting the Transmit Power

Considering that nodes can change their transmission power, topology control (TC) is a power control technique, which involves deciding the appropriate transmission power range that provides the network with a required function, such as connectivity [42]. Conserving and thus controlling power is an overriding priority in mobile ad hoc networks [43]. Some key concepts relating to the usage of power in the operation of ad hoc networks are reported in the literature [44, 45].

Definition *Transmission power.*

"the output power of the signal transmitted by the transceiver of a sender" [46].

Definition *Received power.*

"the strength of the signal received at the receiver. The received power is typically smaller than the transmitted power due to signal attenuation between the sender and the receiver" [46].

Definition *Transmission range.*

"the distance from a sender within which a node can receive and decode packets correctly. This is a function of the transmit power and the signal attenuation between the sender and receiver, and the signal noise around the receiver" [46].

Definition *Carrier sense range.*

"the distance from a sender within which a node can sense the transmission, i.e., the signal can be received, but the packet may not be decoded correctly. The carrier sense range is typically larger than the transmission range" [46].

It is possible to alter the transmission range alongside the carrier sense range. This can be done by varying either the transmission power of the sender, or the sensitivity level of the receiving node (known as the carrier sense threshold) [47]. Reducing the transmission range enables energy to be saved by the sender, whereas reducing the sensitivity of the receiver has no effect on the output power of the sender. However, energy use can still be reduced if the carrier threshold is lowered, as this limits the amount of unnecessary overhearing (receiving and then discarding packets addressed to other nodes) [48] resulting in an increase in throughput in the network.

2.3.1 Transmission Power Control (TPC)

Transmission power control (TPC) is a cross-layer design issue that affects all the layers of the Open Systems Interconnect (OSI) [49] model from the Physical layer to Transport layer [50], and it can be performed with the help of topology control in a MANET [51]. TPC allows many improvements to the operation of such networks, including enabling links with higher reliability to be established, communication with a low cost of energy, and useful reuse of the medium [52]. TPC also has a key role in certain network performance measures, which include throughput, delay, and energy consumption [53].

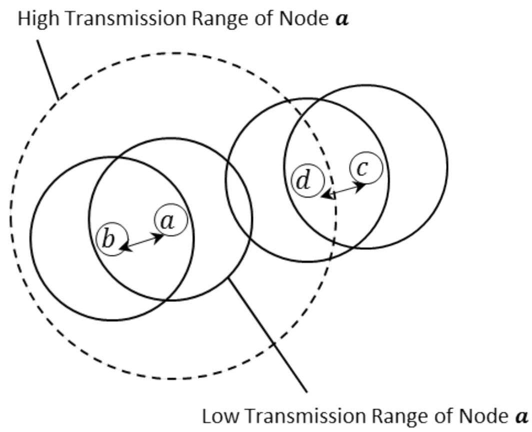


Figure 2.1: The need for power control.

TPC is important for MANETs for the following reasons [54]: its impact on battery life, and also its possible effect on the traffic carrying capacity of the network. In terms of prolonging battery life, it can be seen in Figure 2.1 that there is no need for Node a to use high transmission power in sending a packet to the neighbouring, Node b since Node b is situated inside the low transmission range of Node a meaning it can conserve battery power. In terms of carrying capacity, let us assume that Node c, in the same figure, also requires to send a packet at the same time to Node d using low transmission power. If Node a sends using low transmission power to Node b, then both transmissions can be successfully received simultaneously, since Node b is not in the range of its interferer Node c (for its reception from Node a) and Node d is not in the range of its potential interferer Node a. However, if Node a broadcasts with high transmission power, then that risks interfering with Node d's reception from Node c, and so only one packet might be successfully transmitted from Node a to Node b. This illustrates how a MANET's traffic carrying capacity can be enhanced by applying transmission power control.

It is generally acknowledged that adjusting transmission power levels might be used to achieve more economical use of energy in wireless ad hoc networks [55]. However, this technique depends on the network topology to enable the source node to reduce its transmission power when trying to reach the nearest node. It also risks increasing the number of hops required to relay a packet to its final destination [56]. This may lead to a correspondingly longer end-to-end delivery time. Moreover, it potentially offloads some of one node's power consumption onto others which raises the issue of free riding and might erode the basis of cooperation among nodes in carrying packets for each other.

2.3.2 Effects on the Bidirectional Links

Many routing protocols are based on the assumption that all links are bi-directional [56], where route reversals have been employed, e.g., Route Reply (RREP) packets in AODV [57] and DSR [58] routing protocols reverse the route followed by the Route Request (RREQ) packets. However, changing transmission power levels can create unidirectional links between the nodes in the network. This may occur when a nodes' power level is sufficiently high for another node to hear it but it cannot itself hear the other node' transmissions, thus giving rise to the *Asymmetric Link Problem* [59].

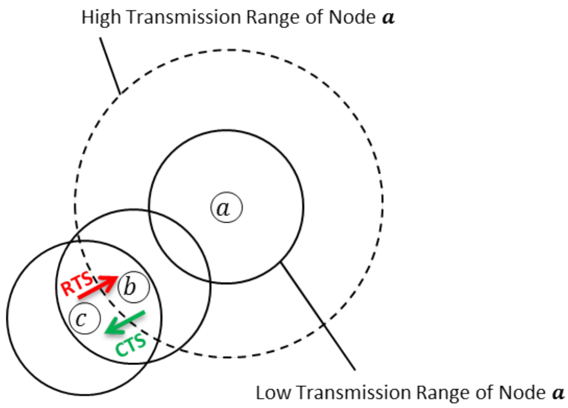


Figure 2.2: Asymmetric Link Problem

The IEEE Standard 802.11 [19] specifies the Distributed Coordination Function (DCF) mode of MAC (for ad hoc networks). The DCF in IEEE 802.11 is based on carrier sense multiple access with collision avoidance (CSMA/CA) [35]. The protocol relies on bidirectionality assumptions. According to this standard, Request-to-Send (RTS) and Clear-to-Send (CTS) control packets are to be used for unicasting data transmissions between neighbouring nodes. The node intending to transmit data initially broadcasts a brief RTS control packet to the intended recipient, which then sends a CTS packet in response. When this is received, the source node then transmits the data packet and an Acknowledgement (ACK) is then sent by the recipient node, to confirm that the data packet has been received. In regard to the MAC layer protocol, common levels of transmission power are used to ensure that two nodes that are situated within the same transmission range are able to hear each other. However, utilising variable transmission power can lead to further problems, as both nodes may not be setting within the same transmission range [4]. Therefore, as seen in Figure 2.2 the CTS from *b* only silences the nodes which are able to hear *b*, whereas other nodes may be in range, that have higher power and could be heard by *b* (e.g. Node *a* with high transmission range).

2.3.3 Benefits of the Transmission Power Control

The use of TPC in MANETs offers considerable scope for improving throughput and simultaneously decreasing energy consumption [60]. However, the selection of the transmission power level can have a fundamental impact on many aspects of network operation [56]:

- **Power control affects the physical layer**, as the level of transmitting power determines quality of the signal which arrives at the receiver.
- **Power control determines the range of the signal** which affects the network connectivity (see [61] and [62]), and thus, whether it can successfully deliver a packet to its intended destination (a lower power level means a shorter transmission range).
- **Power control determines the magnitude of the interference at receivers in the network.** This is because as transmission power level is reduced, this decreases the level of interference and thus increases capacity.
- **Power control improves spatial reuse** and mitigates MAC-level medium contention.

A survey on saving power by employing controlling transmission power was conducted by [40].

2.4 Limiting the Number of Retransmissions: Broadcasting Schemes

Conventionally, broadcasting in ad hoc networks has been carried out based on the concept of flooding. One of the earliest schemes used for disseminating a message in ad hoc networks, was *Simple flooding* [63]. Many of the routing protocols proposed for ad hoc networking in their early stages were based on flooding algorithms [64, 65, 66, 67, 68]. In a simple flooding mechanism, packets are broadcast by a source node to all its one-hop neighbours. Each one of the receiving nodes would then rebroadcast the packets to all their one-hop neighbours. This process finishes when all the nodes have received the packets or until the expiry of the packets' time-to-live (TTL).

A flooding approach is a simple broadcasting scheme and guarantees high reachability in certain scenarios. In low density network environments, flooding has the advantage of achieving better reachability than other existing schemes [22, 69] but impacts network efficiency and capacity. On the other hand, in dense networks, a simple (or blind) flooding approach remains expensive and inefficient in terms of bandwidth and consumption of energy and has a critical effect in limiting the lifetime of the network [70]. Therefore, in resource-constrained networks, a simple flooding approach is not advisable especially in high density network environments as it not only wastes the battery life of nodes, but also adversely impacts on usage of network resources in other three ways:

- **Redundancy:** a node's rebroadcast messages may already have reached all its one-hop neighbours [13, 22, 63]. As illustrated in Figure 2.3(a), the edges between nodes indicate that they are within the transmission range of each other. It is noticed (i.e. we can see it in the figure) that when node A sends a broadcast message, both node B and node C will receive and rebroadcast it. However, as node B rebroadcast the same message to A and C this information is redundant, as both node A and node C now have the same version of the broadcast message.

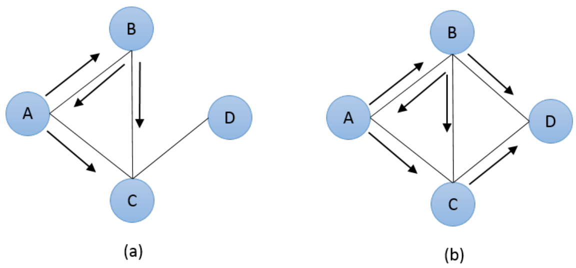


Figure 2.3: Illustration of redundancy, contention and collision.

- **Contention:** more than one node attempts to retransmit the same packet simultaneously. These contend for space in the shared communication channel, thus delaying the dissemination of data packets. As illustrated in Figure 2.3(a), both node B and node C compete to rebroadcast the message. When node B is the faster and rebroadcasts the message first, node C is aware that it has to wait until the channel is less busy.

- **Collision:** when using a flooding approach to send a broadcast message, neither channel reservation nor acknowledgement mechanisms employ at MAC layer [19]. There is a high chance that simultaneous transmissions will lead to collisions, and as mechanisms allowing reservation and acknowledgements may be too costly in terms of increased transmission time; thus flooding-based protocols can benefit from not employing such functions. However, packets are dropped by the receiver when it detects collisions. The sender then never knows that the packet is lost especially with the absence of the acknowledgement mechanism. As illustrated in Figure 2.3(b), both node B and C rebroadcast the message as soon as they receive it from node A. In this case, the transmissions from B and C will collide leading to the message which is intended to be received by node D being dropped. This shows the major problem presented by collision, as it means the broadcast message is never actually forwarded and the data is simply lost.

Multiple different approaches have been published to address these problems and bring about a reduction in the number of redundant retransmissions. They achieve this by selecting a subset of nodes in the network to act as relaying nodes [70, 71, 72, 73, 74].

2.4.1 Classification of Broadcasting Schemes

Several classifications of ad hoc based broadcasting schemes have been considered in the literature [63, 65, 69, 71, 75]. Some existing classifications that give a global view of the related work are briefly reviewed here. Two classifications proposed by Ni *et al.* [63] and Williams *et al.* [69], respectively, have been widely adopted. Ni *et al.* [63] classify existing ad hoc based broadcasting schemes into five different categories: **Counter-based**, **Location-based**, **Distance-based**, **Probabilistic-based** and **Cluster-based**.

2.4.1.1 Counter-Based Broadcasting Scheme

In this scheme a node determines whether a packet is to be rebroadcasted or not, based on the number of copies of the message previously received. Every node keeps track of the same copies received during a random time interval. Where the number of duplicate packets is above a predetermined threshold, the packet is dropped. Otherwise, the node rebroadcasts the packet [63].

2.4.1.2 Location-Based Broadcasting Scheme

In this scheme a node can decide whether to broadcast or not, based on the percentage of additional coverage area achieved when a packet is rebroadcasted. This is done by calculating the additional coverage which can be gained by broadcasting nodes using the location information on nodes. In this case location information such as GPS data is needed. However, like all measurement tools, a GPS receiver can be affected by different sources of error, which include hardware malfunctioning or environmental or atmospheric effects which can reduce its accuracy [76]. Additionally, GPS is also not desirable, when the GPS signal is too weak (e.g., indoors), when it is jammed, or when a GPS receiver has to be avoided for cost or integration reasons [77].

2.4.1.3 Distance-Based Broadcasting Scheme

In this scheme the nodes use an alternative approach to a location-based broadcasting scheme. Instead of relying on positional information as in location-based schemes; the relative distance between the receiving node and the source node is used, and the relaying node decides whether to rebroadcast the packet or not accordingly. The relative distance can be estimated from the Received Signal Strength (RSS) [22, 64, 77, 78, 79] between the sender and the relaying node. Upon expiry of the waiting time, every relaying node checks whether the distance between itself and the sender is equal to or above a threshold; if yes the relaying node will rebroadcast, otherwise it will drop the packet.

2.4.1.4 Probabilistic-Based Broadcasting Schemes

In this scheme a decision to forward is taken based on a probability, where every node retransmits with a fixed probability p [80]. However, this probability can be set in terms of the behaviour of the node or devices around. Simple (or blind) flooding can be viewed as a specific case of this family, in which the forwarding probability is set to $p = 1$ [81].

2.4.1.5 Cluster-Based Broadcasting Schemes

This scheme divides the nodes in the ad hoc network into groups called clusters, which each comprise a cluster head, cluster members and several gateways. The cluster head is representative of the cluster; it is responsible for managing and acts as its central controller. Each cluster head rebroadcasts a packet received from one of its members, and the cluster is organised so that this rebroadcast can reach all its nodes. Furthermore, every cluster head selects a subset of its members to act as gateways for communication with other clusters. Broadcast tactics depend on the types of nodes. Thus, only gateways are allowed to communicate with members of other clusters, and they are responsible for propagating broadcast packets across the network.

Williams and Camp [69], classify broadcasting algorithms into simple flooding, probability based methods, area based methods and neighbour knowledge methods. In simple flooding, the dissemination process is instigated by a source node and each node then rebroadcasts the message only once. In this method, here is no scheme for limiting the number of forwarding nodes, and no requirement for network information. Probability-based schemes are either probabilistic or counter-based schemes. Area based broadcasting schemes include both distance-based and location-based broadcasting schemes. Neighbour knowledge methods rely on a node using information it has about its neighbours when making a decision as to whether or not a message should be rebroadcasted. The node obtains knowledge about its one-hop neighbours by exchanging *hello messages* or *beacons* periodically so that neighbours are aware of the presence of each other.

A *hello message* can include various kinds of information making it possible to react to different situations. It can include node *id*, its compass degree, and its coordination information [82]. More specific knowledge can be obtained if this message includes some information, such as the list of its own neighbours; in that way each node can gather information about neighbours at a two-hop distance. While regular exchange of information among nodes about their network knowledge may seem useful, short intervals between *beacon* messages will result in collision and contention, while longer intervals will result in inaccurate and outdated neighbourhood information due to node movement.

Yi *et al.* [83], propose a different classification between heuristic based protocols and topology based protocols. The former group includes the first four categories of Williams and Camp [69]: probabilistic, counter-based, distance-based and location-based algorithms. In topology-based protocols the network connectivity information acquired mainly from the exchange of *hello messages* between nodes is exploited. Topology-based methods are differentiated into the following types:

- **Neighbour knowledge based protocols:** in these protocols, forwarding decisions are made based on the one-hop or two-hop neighbourhood information;

- **Tree based protocols:** in such protocols a tree is constructed, rooted at the source node, and node forwards broadcast packets according to its status within the tree;

- **Cluster based protocols:** in this method nodes are grouped into clusters and the nodes elect a representative or cluster-head. Their broadcast strategy is generally based on the role of the nodes in their cluster.

2.5 Broadcast Algorithms

Broadcast is the process in the wireless medium through which messages are sent to all neighbouring nodes in the transmission range [84]. In wireless networks, broadcasting techniques need to address the risk of causing *broadcast storms* [22]. The different existing methods developed to solve this problem are known as broadcast algorithms.

Classical flooding in wireless ad hoc networks result in a great many redundant transmissions. Much work has been carried out to optimise network flooding by reducing the amount of the retransmissions so that the total energy consumption is minimised. Two main approaches can be identified in the literature to reduce the energy expended when flooding a message throughout the network [71]:

(1) Trying to reduce the number of rebroadcasts (reduction of redundancy or unnecessary retransmission).

(2) Limiting the transmission range (control of transmission power used by transceiver). An overview of the proposed broadcast taxonomy is illustrated in Figure 2.4.

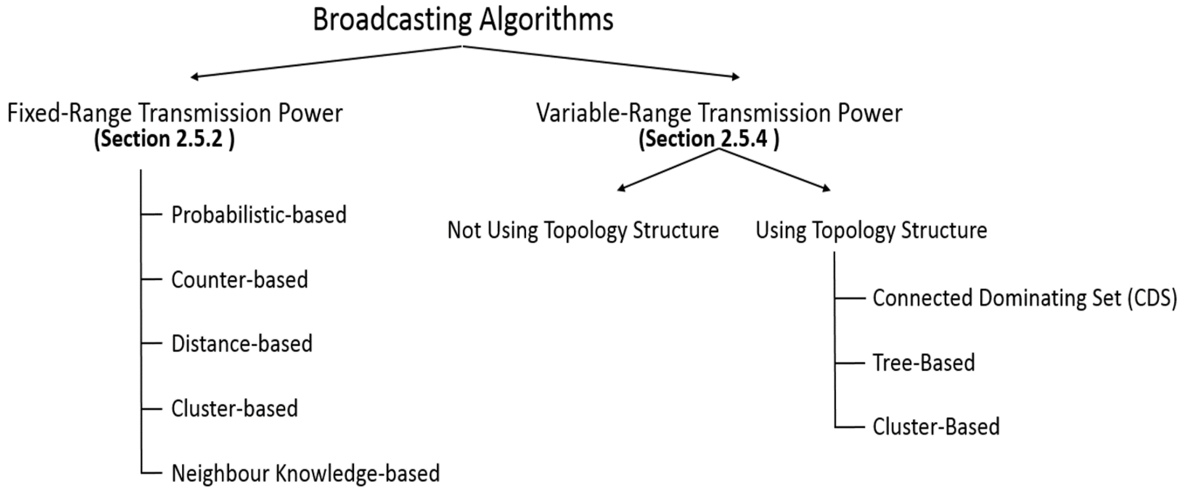


Figure 2.4: Taxonomy of the energy efficient broadcasting algorithms.

2.5.1 Classification of Algorithm Systems

Prior to the review of the existing literature, some distinguishing features of the algorithms will be explained. Recently, Ruiz and Bouvry [71] have classified broadcast algorithms based on their systems' characteristics:

2.5.1.1 Centralised and Decentralised

In a centralised system, a central node is responsible for managing the whole system. The central node can make a decision based on its information or information obtained from different nodes in the system. However, central system based schemes suffer from overhead and delay due to significant coordination among nodes. Moreover, this type of system is subject to the single point of failure problem if the central node should fail. It also introduces significant delay while the cluster elects a new cluster head. On the other hand, in a decentralised system, nodes can make decisions based on their local information and can also change their behaviour without having to defer to central units.

2.5.1.2 Global or Local Knowledge

In global or local knowledge based systems, if a node's decision to rebroadcast a packet requires information about the whole network (e.g., location information on all nodes in the network); then this scheme is considered as a global knowledge based system. Conversely, if a node's decision to rebroadcast a packet relies on locally obtained data; then this scheme is considered as a local knowledge based system. However, local knowledge-based systems not only rely on information regarding the node itself, but may additionally require information from its neighbouring nodes, which they can obtain by exchanging *beacons*, from messages received from these nodes, or simply by eavesdropping.

2.5.1.3 Deterministic and Stochastic Processes

In terms of the predictability of the algorithms there are two different features: deterministic and stochastic process features. In the former, the broadcast process includes no non-deterministic decisions, i.e. a given particular input always generates the same result. In stochastic schemes, however, there are random inputs to some choices and the execution of the same procedure several times under identical conditions can result in different outcomes.

A drawback of deterministic schemes is the large overhead incurred because the transmitting node pre-determines the identity of the forwarding nodes before the broadcast. This involves the building and maintenance of a fixed backbone, consisting of the set of forwarding nodes, which requires more time and greater complexity of the messages, particularly in mobile situations or if one or more nodes should fail. In comparison, stochastic schemes demonstrate more agility to adjust to mobile environments [85]. This is because they are more likely to rebuild a backbone from the beginning in the source of each broadcast [71, 68]. This incurs a smaller overhead than for deterministic schemes, although it generally leads to a trade-off of sacrificing reachability.

2.5.1.4 Source Dependent and Source Independent

In source-dependent techniques, the broadcasting scheme relies on the source node to select the subsequent forwarding nodes from its direct one-hop neighbours. In source independent (or receiver-based) techniques, the receiving node decides the next forwarding node.

2.5.2 Fixed-Range Transmission Power Protocols

The majority of the current broadcasting approaches described in the literature [2, 71] focus on power consumption. The algorithms which only consider nodes that use fixed-range transmission power, aim to decrease the overall amount of energy consumed in a dissemination operation through a reduction in the number of rebroadcasts required to flood the network during a route discovery phase. The following sections present the most relevant algorithms that attempt to make effective use of the network resources for broadcasting using fixed-range transmission power.

In a MANET, nodes obtain a certain amount of information about the present situation (this is known as being context aware) or gain knowledge concerning their neighbours and the strategies they employ (neighbour knowledge) to make a forwarding decision [72]. In contrast, there are also what are known as context-oblivious approaches [72] in which modes only engage in forwarding decision-making based on probability. According to [63], there are three types of forwarding schemes: (1) a probabilistic-based scheme when each node rebroadcasts a message based on a specific probability P, (2) a counter-based scheme, where the node has an ongoing awareness of the network traffic, and (3) an area-based scheme in which the nodes are aware of the network density. An outline of some of the stochastic schemes is given below.

2.5.2.1 Probabilistic-based Broadcasting Schemes

Probabilistic-based broadcast schemes for MANETs were initially put forward by [80, 86, 87] and further developed by [88, 89, 90]. In the probabilistic approach, forwarding probability for each intermediate node to rebroadcast received packets is entirely predetermined. In all schemes under this category, nodes forward incoming broadcast packets based on a probability value p, and all the nodes are permitted to take part in the broadcasting process [70]. The probability value can be fixed or adjusted by node density or by a counter value or its distance/location to the sender [91]. Figure 2.5 summarises the algorithm of this scheme for each node.

A probability-based flooding approach in ad hoc networks using an AODV rout-

Algorithm: Probabilistic-Based Broadcasting Scheme

For a node X
On reception of a broadcast message m for the first time
- Initialise the probability p
- Generate a random number RN over [0, 1]

For every message m received
- If $(RN \leq p)$
  Rebroadcast the message m
- Otherwise,
  Drop the message m

End

Figure 2.5: Algorithm of the probabilistic-based broadcasting scheme.

ing protocol implementation has been put forward by Haas *et al.* [86]. This algorithm alleviates the problems arising from simple flooding mainly by basing the decision regarding a message will be rebroadcasted on a fixed probability p. Thus, in the case where the probability value is 1, the scheme is reduced to blind flooding. Simple or blind flooding is defined as a way to improve reliability when broadcasting. However, the high number of collisions associated with this approach could decrease reliability, especially in dense networks.

Jamal-deen *et al.* [92] proposed a dynamic probability function where the independent variable is the number of one-hop neighbours and the dependent variable is the forwarding probability. The number of neighbours is compared to n_{avg} according to the topology deployed; where n_{avg} can be estimated by employing Equation 2.1 [93]:

$$n_{avg} = (N-1)\frac{\pi R^2}{A} \tag{2.1}$$

where:

N : number of mobile nodes which are deployed in the network.

R : signal transmission range.

A : area of the network.

In [94] the same authors propose an adjusted probabilistic route discovery scheme. This scheme proposes two probabilistic methods aiming to reduce the amount of RREQ packets in the network using a predetermined fixed-value forwarding probability. Unlike other similar algorithms, the proposed mechanism does not use GPS based devices. This work mainly relies on basic topology information obtained by using *hello message*. The first probabilistic route discovery scheme is called the *2P-Scheme* in which the nodes are categorised into two groups based on their neighbourhood information. If the node is situated in a sparse region, it gets assigned to Sparse-Group and if in a dense region, it is assigned to Dense-Group. Nodes in Sparse-Group are allocated a higher forwarding probability than those in Dense-Group. In the second scheme, *3P-Scheme*, the nodes are classified into three groups (Sparse group for sparse regions, Dense group for dense regions and Medium group for medium dense regions). For this scheme, the forwarding probabilities are assigned in non-decreasing order.

An adjusted probabilistic flooding scheme has been proposed by Bani-Yassein *et al.* [88] which combines fixed probability and knowledge-based approaches. They proposed two values for the probability of rebroadcasting. These are dynamically adjusted according to the local density at each mobile node (node's degree). The rebroadcast probability is set high or low depending whether the node is in a sparsely populated area of the network or a dense one. They found that a greater reduction in rebroadcast packets was achieved with the fixed probability scheme. However, the forwarding probability expression used is dependent on global density, which is represented by the total number of nodes in the network. In real life scenarios, it may not be feasible for the nodes to collect such global information.

In [95, 96] the same authors propose a smart scheme, the probability of forwarding is determined based on three defined threshold values. In this scheme, each of the three regions of the network (i.e. dense, moderate and sparse) is assigned a different rebroadcast probability p value : nodes located in a dense region are assigned the lowest probability value, while a high probability value is assigned to those located in a sparse region. However, as with the previous scheme, the use of global density measures like (n_{avg}, n_{avgmin} or n_{avgmax}) means that, in real life scenarios, it may be unfeasible for nodes to collect this type of global information. A more realistic way to adapt the forwarding probability might be the use of the nodes' local parameters such as local density.

2.5.2.2 Counter-based Broadcasting Schemes

In a counter-based approach [63] the number of copies c of a given broadcast packet received is used by nodes as a key metric to establish the state of the broadcast process in their regions. When the node receives a broadcast message for the first time, it starts waiting for a random time interval referred to as the *Random Assessment Delay* (RAD) before rebroadcasting. If a node receives multiple copies of the same packet during the random time interval and the number of duplicated packets received is greater than the threshold (Cth), it will discard the packet to avoid collisions. Figure 2.6 summarises the algorithm of this scheme for each node.

Algorithm: Counter-Based Broadcasting Scheme

```
For a node X
On reception of a broadcast message m for the first time
    - Initialise the counter c to 1
    - Set random assessment delay (RAD) [0, Tmax] and wait for it to expire
    - While waiting:
          For every duplicate message m received, increment c by 1
    - When the delay RAD expires
          - If (c < Cth)
                Rebroadcast the message m
          - Otherwise,
                Drop the message m
End
```

Figure 2.6: Algorithm of the counter-based broadcasting scheme.

In a counter-based scheme the forwarding probability can be adjusted by combining many factors. Such adaptive counter-based schemes are based on density and can be further classified into different types, including purely counter-based, node degree, density threshold, and colour-based systems [70]. In purely counter-based schemes the forwarding probability is determined solely by the number of received copies. The colour-based scheme is similar, but a colour-field is used as the main parameter to adjust the forwarding probability. In node degree-based schemes, the number of copies received is combined with the number of neighbours. Similarly, density thresholds are also defined according to the number of neighbours and the number of copies received.

The approach proposed by Tseng *et al.* [13] is an adaptive and probabilistic counter-based scheme, in which the threshold (i.e. the maximum number of duplicate copies permitted) depends on the neighbourhood's status. A low threshold value can greatly reduce the number of nodes participating in retransmission; however, the performance of the system in terms of reachability greatly degrades in sparse networks. In contrast, a high threshold value can guarantee high reachability but entails large number of retransmitting nodes. To tackle the above problem, the algorithm takes into consideration the number of neighbouring nodes, i.e. the value of the counter threshold varies depending on the number of neighbouring nodes surrounding each source node. Each node periodically exchanges *hello* packets as a simple way to calculate the number of neighbours.

Keshavarz-Haddad *et al.* [68] introduce a variant of the counter-based scheme called the colour-based broadcast scheme, in which a colour is assigned to each broadcast packet, in a colour-field. The condition which has to be satisfied at expiration time is similar to that in the original counter-based scheme; thus the number of colours presents in the broadcast packets must be below a threshold. In the case where this condition is met, the packet is rebroadcasted with a new colour assigned to its colour-field. Their study, aimed to prove that nodes can utilise neighbourhood information in order to adapt the threshold value autonomously and dynamically. Despite appearing to be a promising scheme, the colour-based broadcasting approach has some limitations. These are summarised as follows:

- As in the case of the fixed counter-based approach, high efficiency scores are achieved only when it is used with homogeneous density networks, for example, n can range from 3 when the network is sparse, and to only 2 when it is dense.
- Although the authors claim that reachability increases when n is increased, they also acknowledge that, in reality, no threshold value can ensure complete reachability for any arbitrarily connected network.

Chen *et al.* [97] combine the concept of a distance-based scheme with a counter-based scheme. They propose a scheme called DIS RAD which assigns shorter waiting time to relay nodes located at the transmission range boundary. Specifically, relaying nodes nearer to the boundary of the source node have a higher probability of rebroadcasting than those at only a small distance from the source node. The further the relaying node from the source node the shorter the RAD time that is assigned to that node. However, it is not specified how relaying nodes can estimate the distance to the source node.

Al-Humoud *et al.* [98] propose an adaptive approach which employs two different threshold values based on local node density. This is based on the assumption that where a node has a higher local density, its forwarding probability should be lower, in order to avoid packet collisions. It compares the number of current active one-hop neighbours to the average (the authors do not specify how the average number of neighbours in networks can be calculated). The network is considered to be sparse If the average is lower than a threshold, otherwise it is considered dense. A random delay and a counter threshold value are set accordingly.

An Adaptive Probability-based (ProbA) scheme is proposed by Liarokapis and Shahrabi [99]. In this scheme, the decision regarding the density volume of the network is undertaken locally and the probability threshold is adjusted in line with this. This is achieved by a random delay being set by the node receiving a message. During this waiting period, the number of repeated copies received is counted, allowing the node to set the forwarding probability based on the number of copies.

Bani-Yassein *et al.* [100] introduced an Adjusted Fixed-Density Counter Broadcast Scheme (AF-DCBS), in which the density thresholds are set according to the number of copies received and the number of neighbours, as in [88]. Thus, three different density counter thresholds are used to control the broadcast decisions at each node. The node is assigned a large or small value depending on whether it is situated in a sparsely populated area or in a dense area. Through this simple adjustment, the amount of rebroadcasting can be reduced in a dense area, while at the same time the level of reachability in a sparse area can be enhanced.

In a counter based scheme, the forwarding probability is adjusted through the use of density metrics, with the help of an assessment of the delay time [70]. However, a rebroadcasting delay caused by interface queues in adjacent nodes can negatively affect the assessment of time efficiency. Besides, counter-based broadcasting is inherently slow in terms of reaction time; this is because of the necessity to wait for timer expiration before rebroadcasting any messages.

2.5.2.3 Distance-based Broadcasting Schemes

Distance-based approaches rely on the distances among nodes to adjust the forwarding probability. The distance between sender and receiver can be calculated using the Global Positioning System (GPS) or Received Signal Strength (RSS). The system is based on the notion that the nodes which are more distant from the sender are given a higher retransmission probability, since they are more likely to avoid redundant retransmissions.

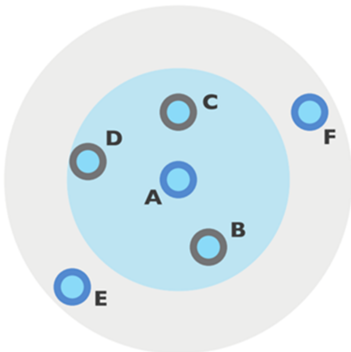


Figure 2.7: Distance Based Approach

Figure 2.7, shows the distance-based approach mechanism. In this system, the message will be retransmitted only by nodes that are further away than a predefined distance (i.e. those located in the forwarding area, represented by the grey zone). In this figure, nodes that rebroadcast the message received from Node A are Node E and Node F.

Distance-based schemes can be grouped further into two categories in terms of the relative distance between nodes [70]. The first type are Area-based schemes, in which the main idea is to adjust the forwarding probability, according to the relative distance between two nodes, which does not require global information regarding the other nodes in the network. In the second type, the Location-based approach, the additional coverage of rebroadcasting is used to determine the forwarding probability, where nodes exchange positioning data in order to construct a map of the network. In this case, GPS information is usually needed. Both approaches make a node start after a random delay time. In the course of this waiting period, if the node receives a packet and the distance d between the sender and receiver is less than some threshold Dth, the retransmission is cancelled. Otherwise, the node keeps waiting until the timer expires. Nevertheless, such a scheme adds extra delay, due to the random waiting time used. Figure 2.8 summarises the algorithm of this scheme for each node.

Algorithm: Distance-Based Broadcasting Scheme

```
For a node X
On reception of a broadcast message m for the first time
        - Get the sender distance d
        - Set random assessment delay (RAD) [0, Tmax] and wait for it to expire
        - While waiting:
        - When the delay RAD expires
                - If (d > Dth)
                        Rebroadcast the message m
                - Otherwise,
                        Drop the message m
End
```

Figure 2.8: Algorithm of the distance-based broadcasting scheme.

Chen *et al.* [70] propose two adaptive versions of the distance-based scheme to improve the efficiency of broadcasting in a MANET. Every node maintains both neighbourhood size and signals information in a neighbour table, where nodes are sorted based on the strength of their received signal. Neighbourhood information is collected by periodical exchanges of *hello messages*. The main idea of this work is to utilise both neighbourhood density information and the relative distances among the source node and its neighbouring nodes to select the nodes to forward to. The reason behind maintaining the distance information is to select the outermost neighbouring nodes as forwarding nodes. In the first proposed DAD-NUM, only a predefined number of forwarding nodes is specified. However, in the subsequent version, DAD-PER a percentage of nodes that will rebroadcast the message is also specified.

Sun and Lai [101] propose a distance-based defer time (timeout) scheme, to select forwarding nodes efficiently. The basic idea of the proposed work is that rather than selecting forwarding nodes randomly, it is more useful to select forwarding nodes which cover more new areas, and these nodes are usually those located at a greater distance from the source node and closer to its transmission boundary. Additionally, an angle-based scheme is proposed to eliminate redundant retransmissions. In this scheme when a node receives multiple retransmissions of the same packet during a random waiting period, it then calculates the area covered by each node based on a coverage angle. After that, the scheme will retransmit the packets only in uncovered directions given that the other areas are already covered by other nodes.

Cartigny and Simplot [102] combine the benefits of distance-based and probability-based schemes to achieve better reachability. The broadcasting probability is adjusted depending on the local density of the network and the distance to the source node. In the proposed algorithm, each node maintains one-hop neighbour information which is obtained by exchanging *hello message* periodically. Furthermore, the protocol does not need a positioning system, because probabilistic information is deduced by comparing the neighbour lists. However, this involves including the list of the senders' one-hop neighbours in the broadcast packet's header, which could increase the packet size overhead, especially in a high dense network by increasing the list of neighbours. Additionally, a neighbour elimination scheme is used, in which the node ignores the retransmission in the case it does not expected that any new neighbours will be covered.

Liarokapis *et al.* [103] combine distance-based and counter-based schemes to develop an adaptive distance-based scheme (DibA). The distance threshold is adapted according to the number of retransmissions of a particular packet which have been heard. In the proposed scheme, each node locally estimates network density without relying on GPS or *hello* packets. Nodes within one-hop rebroadcast according to how far they are from the source. The retransmission probability of nodes which are N hops away is determined according to the distance (hops) and density of the network.

Kasamatsu *et al.* [104] propose a distance-based broadcasting scheme which considers the energy level of nodes. Their proposed scheme assigns weightings that are inversely proportional to the distance between two nodes and the remaining energy level of potential forwarding nodes. The underlying idea is that nodes with higher energy and further away from the source node set a shorter delay. However, this scheme relies on GPS positioning information to calculate the distance, which is not always available in ad hoc network environments.

Leng *et al.* [105] combine location-based and distance-based schemes to propose a relative position-based scheme called RPBR. In this proposal, each node maintains location information on neighbouring nodes through exchanging *hello messages* periodically among nodes (using GPS). Moreover, the proposed RPBR also uses forward angle information to select forwarding nodes. The main idea is to select forwarding nodes from circular areas at the transmission boundary of the nodes. There are three dedicated symmetric areas that have been identified, and each of them is located at 120 degrees away from each other. To select outermost nodes from each symmetric area, they propose using delay time; this means that even nodes which are at a greater distance from the source node can be selected as forwarding nodes. However, techniques which use angle information require the nodes be equipped with directional antenna or an antenna array to measure the angle at which a signal arrives [106]. These antenna arrays are expensive to implement and maintain. Moreover, angle calculations are quite susceptible to errors regarding the range. At greater distances from the source, accuracy of the position is reduced [107].

Kim *et al.* [108] propose a dynamic probabilistic broadcasting approach, combining probabilistic-based and area-based schemes. In this work, rebroadcast probabilities are assigned to nodes according to how far they are from the sender. In this approach the basic idea is to divide the transmission coverage area of nodes into inner and outer areas. The distances among nodes can be calculated using either GPS or received signal strength. Nodes located in the outer areas are assigned higher rebroadcast probabilities than nodes located in inner areas. It recognises that nodes located in outer areas of nodes can reach additional coverage areas and therefore cover more new nodes. Moreover, to prevent early die out of rebroadcasting, a neighbour confirmation scheme is applied. The idea is that, after a given waiting time, a node verifies if the previous rebroadcast packet has been received by all its one-hop neighbours. If not, the node rebroadcasts the packet. As seen in Figure 2.9(b), $n1$ waits a given amount of time t and checks if all the neighbours have received the broadcast packet. If $n2$ did not receive the packet, $n1$ rebroadcasts it. This scheme uses the transmission range of the node in the expression to calculate the coverage area of the node. However, the real value of the transmission range of the node may be affected by external factors, such as external noise and interference [70].

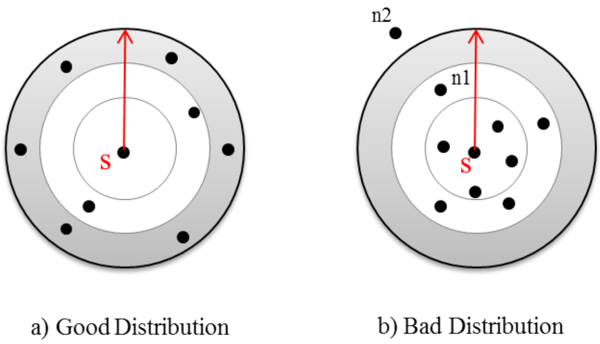


Figure 2.9: The distribution of mobile nodes in MANET

Many broadcasting schemes which have been proposed to address broadcast storm issues in the ad hoc network utilise directional antennas [109, 110]. Directional antennas have the ability to radiate their energy as a beam in a particular direction. Figure 2.10 shows a comparison between Omni-directional broadcasting and Directional broadcasting.

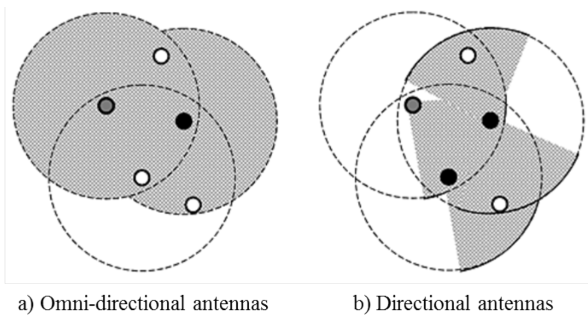


Figure 2.10: Omni-Directional vs. Directional broadcast

Hu *et al.* [109] propose three schemes to mitigate broadcast storm issues in ad hoc networks. In this work, authors assume that each node is installed with four beam directional antennas.

- In the first scheme (on/off the directional broadcast), the first time a node receives a broadcast packet, it forwards the packet in three different directions to the direction from which the packet was received. This is done by switching off the directional antenna beams towards the direction from which the packet was received.

- In the second scheme (relay node based directional broadcast); each forwarding node can have only one relaying node in each direction, i.e. four relaying nodes per forwarding node. This scheme is based on one-hop neighbour information which is collected by periodical exchange of *hello messages*. Each forwarding node selects the farthest node in each direction where the distance is estimated using received signal strength.

- In the third scheme (Location-Based Directional Broadcast); unlike the second scheme in which the nodes are assigned uniform waiting time, in this third scheme, each node is assigned a different waiting time. The waiting is proportional to the extra coverage area the node can reach (GPS used), i.e. the greater the new coverage area, the shorter waiting time is assigned to the node. However, this scheme requires some mathematical calculations to calculate the new coverage area. Thus, the calculations have to be precise for the scheme to function properly.

Da Li *et al.* [111] propose a distance-based directional broadcast for VANETs employing directional antenna. In this work, only the furthest receiver has the responsibility for forwarding the packet, which is sent in the opposite direction to that from which the packet was received. In addition, there are repeaters located at intersections to assist in dissemination of the data. The work also proposes a probabilistic approach.

In general, the approaches discussed above, including those that are counter-based, area-based, or RAD-based, involve setting thresholds in order to make decisions. However, it is argued [71] that the task of establishing appropriate values for use in rapidly evolving MANETs is complex and has a major impact on the protocols' subsequent performance.

2.5.2.4 Cluster-based Broadcasting Schemes

"Clustering in mobile ad hoc network can be defined as the virtual partitioning of the dynamic nodes into various groups" [112]. The main goal of the clustering is grouping nodes according to certain common characteristics or shared properties. In cluster-based broadcast schemes, the network is partitioned into several groups called clusters which form a simple backbone structure. Each cluster comprises a single cluster head (CH), cluster members and several gateways. Nodes belonging to two or more overlapping clusters declare themselves to be gateways [113]. Using this information, only CHs and gateways are permitted to rebroadcast messages (see Figure 2.11).

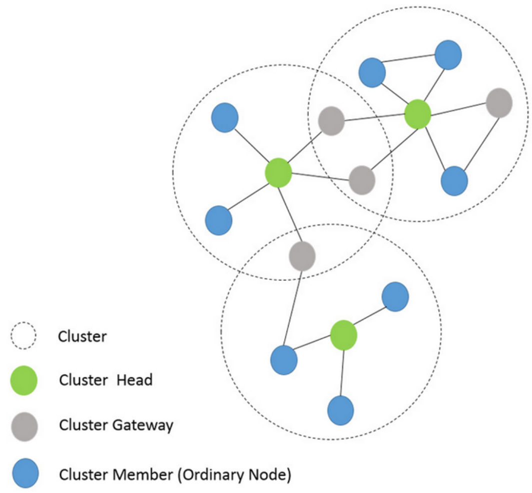


Figure 2.11: Illustration of adjacent clusters with gateways

Clustering schemes in mobile ad hoc network (MANET) are classified into five different categories [114, 115, 116]: Identifier Neighbour-based, Topology-based, Mobility-based, Energy-based and Weight-based clustering scheme (see Figure 2.12).

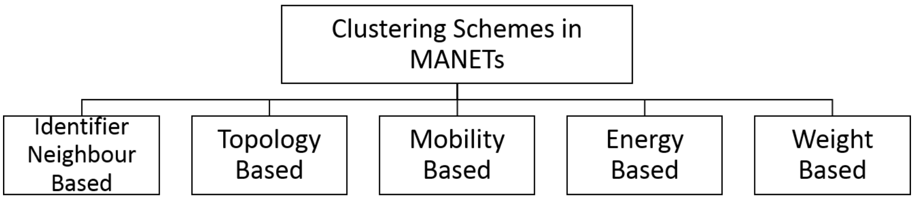


Figure 2.12: Clustering Schemes Classifications.

In identifier neighbour based clustering, a unique ID is assigned to each node. Each node in the network can obtain the ID of its neighbours by exchanging *hello massages* or *beacons*. Then the Cluster-head (CH) is selected based on criteria involving these IDs such as the lowest or highest node ID. In the topology based clustering, the CH is chosen based on a metric computed from the network topology like node connectivity. The idea of mobility based clustering is to choose nodes with low mobility (speed) as CH because they provide more stability of the cluster. Energy based scheme is also used to maintain stable clusters by preventing nodes with low residual energy from being elected as a CH. The weight-based clustering is the most commonly used approach for CH election. It uses combined weight criteria, such as node degree, residual energy, transmission power, and node mobility [116], and achieves several goals of clustering: decreasing the number of clusters, increasing the lifespan of mobile nodes in the network, decreasing the total overhead, minimising the CH change, decreasing the number of re-affiliation, improving the stability of the cluster structure, and ensuring good resource management as it saves energy and communication bandwidth [115].

Clustering can involve two main approaches: Active clustering and Passive clustering [83]. In the former, nodes cooperate to elect the CH through periodically sharing information. On the other hand, in passive clustering, the election of the CH initiates the ongoing traffic. In this approach, information is included within the packets and is simply gathered by eavesdropping, which does not incur any overhead or require setting up.

Low Energy Adaptive Clustering Hierarchy (LEACH) [117] is a classical clustering algorithm, and it periodically chooses cluster heads. The algorithm aims to conserve energy and improve the network lifetime by distributing energy consumption among all the sensor nodes in the network. However, there are some drawbacks to the algorithm which may lead to it consuming more energy as follows:

- It does not guarantee an even distribution of cluster heads throughout the network.
- It may result in clusters that are too big and too small in the network at the

same time.

- Cluster head selection is not optimal in heterogeneous networks where nodes have different residual energy.

Many studies, like those of [118, 119] have tackled these issues by finding appropriate cluster heads to form optimum clusters at each round.

Zanjireh *et al.* [118] propose a new distributed clustering algorithm called Avoid Near Cluster Heads (ANCH). This is one of the most recent algorithms algorithm designed for uniform distribution of cluster heads (CHs) throughout the network area. It increases the number of potential CHs across the network using a regression method. Then, it eliminates a number of nominated CHs due to their closeness position to other CHs in order to meet the optimum number of CHs. The ANCH algorithm has considerably greater efficiency than LEACH [117] in terms of network energy consumption and network lifetime.

Ephremides *et al.* [120] present the idea of constructing a virtual backbone using a Lowest-Identifier (LID) clustering algorithm, in which all nodes are white when first deployed. A white node that discovers it has the lowest ID among its one-hop neighbours declares itself to be the cluster head and then turns black. The white neighbours all then join this cluster and promptly turn grey. The process ends at the point where no white nodes remain.

Gerla and Tsai [121] propose a Highest Degree algorithm (HD), which first takes into account the node degree in clustering decisions. In this protocol, the node which has the largest number of neighbours is selected as CH. If two or more nodes have the same degree, the node with the lowest ID becomes the CH. This algorithm generates only a limited number of clusters. However, in a high movement scenario, re-elections of CHs become more frequent, due to the frequent changes in their degree. Surveys of different clustering techniques were conducted by [122, 123, 124]. Some of the most relevant broadcasting algorithms based on cluster approaches are now presented.

In [125] the use of passive clustering is proposed for on-demand routing in ad hoc networks. In this approach, nodes employ predefined thresholds to decide whether to become CHs, ordinary nodes or gateways. Both the CH and gateways rebroadcast messages.

Li *et al.* [126] propose vote-based clustering, in which nodes which combine a high degree with a high battery power level are considered to be preferred candidates for becoming CHs. Location information is also considered in this work. However, this has the disadvantage of a frequently changing cluster topology.

Andronache *et al.* [127] introduce a weighted-based clustering algorithm called (NLWCA). This algorithm involves frequent CH changes and thus, its structure tends to be somewhat unstable. Thus the stability of the link is also considered in this approach, in which both the node state (in terms how much power and signal strength it has left), together with the link stability are used as criteria for electing CHs. Cluster heads disseminate a message within its cluster by broadcasting it, but they also unicast it directly to all neighbouring CHs which are regarded as stable [128].

Wu and Lou [129] propose a clustered network where each CH designates the forwarding nodes within the cluster to form a path to each neighbouring CH. The broadcast message includes information concerning the CHs which will receive the message so that CHs can use a pruning technique to calculate the coverage area. Their paper also introduces the very novel concept of 2.5-hop coverage.

Clustering allows for better performance of the protocol for the *Medium Access Control* (MAC) layer by enhancing spatial reuse, throughput, scalability and power conservation [130]. However, costs are incurred in this approach that cannot be disregarded. These include the overhead entailed by the formation and maintenance of clusters, as forming a cluster requires explicit control messages to be exchanged and assumptions that nodes are stationary [116].

2.5.2.5 Neighbour Knowledge Approaches

Nodes can gain awareness of the neighbours located within their transmission range by exchanging *hello messages.* In addition, they can obtain information about two-hop neighbours by including the *beacon* lists of their one-hop neighbours. Although the two-hop neighbours' knowledge gives more information about topology networks, where there is high mobility present more difficulty in ensuring the information is entirely accurate and up to date. Nevertheless, many studies incorporate the neighbours' knowledge to assist in making efficient forwarding decisions [131, 132, 133, 134, 135].

Wu and Dai [131] propose *Flooding with Self-Pruning* (FSP) which is the simplest flooding scheme based on one-hop neighbour knowledge. FSP is a receiver-based technique that uses direct neighbourhood information. In the usual way, nodes obtain a list of their adjacent one-hop neighbours via broadcasting one-hop *hello messages* periodically. Each broadcast packet includes the list of known neighbours in its header. To make the decision whether to rebroadcast, the receiving node compares its own neighbour list to that of the sender. The receiving node rebroadcasts the packet to the extended list, unless the comparison shows that no additional nodes would be reached by rebroadcasting it.

Peng and Lu [132] introduce a *Scalable Broadcast Algorithm* (SBA) which exploits two-hop neighbours' knowledge, obtained via the periodic exchange of *hello* packets containing the node's address and the list of its known neighbours. Once it has received a *hello* packet from all its neighbours, the node has a bank of two-hop topology information with itself at the centre. Thus by comparing this information with the ID of the node which sent or forwarded the packet, the receiving node can decide whether any additional nodes would be reached by forwarding it.

Lim and Kim [133] propose a source dependent (or sender-based) technique called *Dominant Pruning Scheme*, where the adjacent nodes that will be able to relay its broadcast packet are selected by the sending node. This scheme relies on two-hop neighbour's knowledge. To instruct one-hop neighbours to rebroadcast the packet, the sending node includes its address in the header. The receiving node then checks the header to see if the sender's address appears in its own list. If this is the case, it employs a *Greedy Set Cover* [50] algorithm which identifies the largest set of neighbours which are not yet covered by the original sender's broadcast.

Qayyum *et al.* [134] propose an efficient broadcast scheme referred to as the

Multipoint Relaying (MPR) scheme. In this source-dependent technique, the next forwarding nodes are selected by the source node using one-hop neighbours' information. Two-hop neighbours' knowledge obtained from the *hello messages* is also required. To set up the MPR network, each node is required to select a subset of its one-hop neighbours as MPRs; this is achieved by first identifying the two-hop neighbours which it can only access via one of the one-hop neighbours and selecting them as MPRs. The node then checks the remaining one-hop neighbours and selects those that cover the most two-hop neighbours which are not yet covered. This procedure is repeated until all two-hop neighbours are covered. The process is illustrated graphically in Figure 2.13. It can be seen that MPR nodes are only responsible for re-transmitting the broadcast message transmitted by Node S.

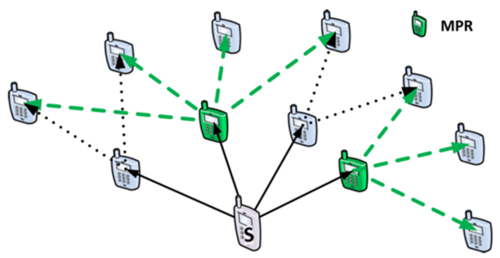


Figure 2.13: Multipoint relay mechanism

The well-known *Optimized Link State Routing* [136] (OLSR) Protocol is based on the MPR. This is explained in further detail in RFC 3626 [137]. There is a comprehensive survey on multipoint relays for broadcasting in [138].

Khabbazian *et al.* [135] present a *Hybrid Broadcast Algorithm* which combines both *neighbours designating scheme* and *self-pruning*. It uses two-hop information, where just one forwarding node is selected by the source node from its set of one-hop neighbours. For any node which is not selected as a relay, at reception, the source node compiles a list of its neighbours then removes from them the neighbours' lists of both the sender and the selected forwarding node. The message is retransmitted, unless the list is empty in which case it is dropped.

Although neighbour knowledge approaches are successful in cutting down the volume of redundant RREQ broadcast packets in the network, the periodic *hello messages* need to include the addresses of all the neighbouring nodes. This takes up the available bandwidth and may increase the overhead in certain cases. Moreover, the high mobility of the nodes means that the two-hop information obtained may not be accurate. In general, deterministic schemes are not as scalable as non-deterministic schemes; this is due to the high overhead involved in the constructing and maintaining of up-to-date topological information, particularly in a high density network.

Table 2.1: Classification of the Fixed-range Transmission Power Approaches

	Neighbour info.	**Hops knowledge**	**GPS**	**Forwarding decision**
Probabilistic flooding [86]	local	-	no	source independent
Dynamic probability [92]	local	1-hop	no	source independent
Adjusted probabilistic flooding [88]	local/global	1-hop	no	receiver-based
Adaptive Counter-based flooding [13]	local	1-hop	no	receiver-based
3P-AODV Scheme [94]	global	1-hop	no	receiver-based
Colour-based broadcast [68] *DIS RAD [97]*	local	-	no	receiver-based
Adaptive approach [98]	local	1-hop	no	receiver-based
ProbA [99]	local	-	no	receiver-based
AF-DCBS [100] *DAD-NUM and DAD-PER [70]*	local	1-hop	no	receiver-based
Distance and Probability based [102]	local	2-hop	no	receiver-based
DibA [103]	local	-	no	receiver-based
Distance-based broadcasting [104]	local	-	yes	receiver-based
RPBR [105]	local	1-hop	yes	sender-based
LEACH [117] *ANCH [118]* *LID [120]* *HD [121]* *NLWCA [127]*	local	1-hop	no	structure
[129]	local/global	2.5-hop	no	structure
FSP [131] *SBA [132]*	local	2-hop	no	receiver-based
Dominant Pruning Scheme [133] *MPR [134]* *Hybrid Broadcast Algorithm [135]*	local	2-hop	no	sender-based

2.5.3 Limitations of the Fixed-Range Transmission Power Schemes

Fixed-range transmission power means that all transmitters have a common, fixed power setting, translating into a fixed communication radius [139]. Most existing fixed-range transmission power based broadcasting schemes for MANETs have the following limitations:

- They are not scalable because of the likelihood of signals overlapping with other signals in a particular geographical area, which induces contention in the MAC layer.
- Algorithms where nodes utilise *hello messages* to exchange and collect information from each other periodically using fixed high range transmission power induce more contention and collision especially in highly dense networks.
- They have a high consumption of restricted network resources such as bandwidth and energy. The main reason behind both bandwidth and energy consumption is due to a large number of redundant retransmissions and fixed use of high range transmission power.
- They suffer from performance degradation in high mobility and high density environments.
- They rely on GPS providing location data accurately in order to function properly i.e. exact positioning information is required.
- They suffer from interference, collision and contention which are caused by simultaneous retransmission of packets (especially in highly dense network regions).
- Several schemes have to wait for a random assessment delay (RAD) time before deciding to retransmission the broadcast message. However, this markedly influences the broadcast time and increases the significant delay in the broadcasting process.

Due to the above limitations, the existing fixed-range transmission power based schemes cannot be effectively deployed with restricted network resources such as bandwidth and energy. Thus, a more efficient scheme that is able to dynamically adjust the transmission power level is required to achieve a balance between connectivity and transmission power used. Furthermore, new schemes must be scalable, able to react fast to any changes (i.e. use only local one-hop neighbour's information), not be rely on intermittent and potentially inaccurate GPS location data and should be able to control their transmission power to minimise the energy consumed in the broadcasting process.

2.5.4 Variable-Range Transmission Power Protocols

As previously mentioned, conserving power is a critical issue, since devices forming mobile ad hoc networks may run out of battery power, which will result in degradation of the network. There are two different approaches which can be used to cut power consumption in ad hoc mobile networks. The first is the fixed common range approach that tries to curb overall energy consumption by reducing the volume of retransmissions. This aspect is the main focus of all the algorithms reviewed in Section 2.5.2. The second method involves adjusting the transmission power range, which deals with conserving energy by employing transmission power control. The second approach will be reviewed next.

In variable-range transmission power schemes, each node can transmit broadcasting packets using different amounts of transmission power, meaning that the number of neighbouring nodes reached by a particular broadcast message will vary depending on the level of transmission power used [60]. Thus, one of the main problems arising from such schemes is to adjust each node's transmission power to ensure the optimal transmission range [140]. This issue has been addressed by the minimum range assignment [140] and the minimum energy broadcast problem [141]. Calamoneri *et al.* [142] explain that addressing the minimum-energy broadcast problem involves assigning a transmission range to each node of an ad hoc wireless network which ensures that each source node can undertake broadcast operations while minimising the overall power consumption over the range assigned.

A common approach to the problem of conserving the energy used when a message is disseminated through the network, involves either creating or assuming the existence of a virtual topology in the network. This information regarding this topology is then employed to forward broadcast messages smartly. The key benefit of a virtual topology is the ability of each node to adjust its transmission power rather than transmitting at constant high power, with the objective of reducing energy consumption while maintaining network connectivity [37]. However, it has been widely argued that the expense involved in the creation and maintenance of this topology is too great, or even that it is not feasible to create such a structure. Thus, two different approaches have evolved: those that employ a topology structure and those that do not [71].

2.5.4.1 Algorithms Not Using Topology Structure

This section presents and reviews the most relevant algorithms using variable-range transmission power in broadcasting without the assumption of the existence of any topology construction in the network.

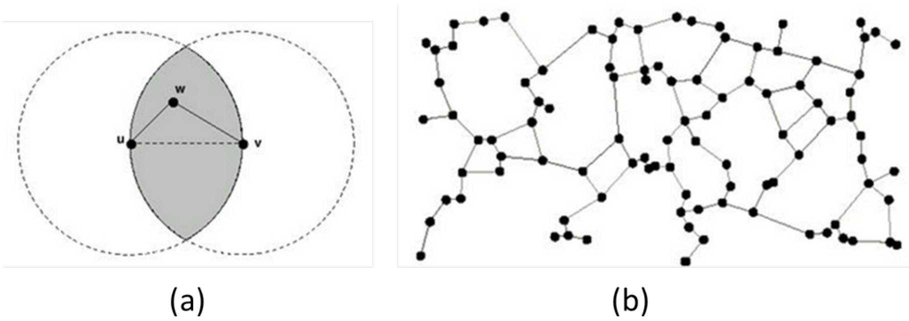


Figure 2.14: a) the edge (u,v) is not in RNG because of w, b) an example of an RNG

Cartigny *et al.* [143] present an RNG Broadcast Oriented Protocol (RBOP) which employs the Relative Neighborhood Graph (RNG), introduced by Toussaint [144]. In RNG a list of relative neighbours is maintained by each node which uses this information to build a broadcast route. In RBOP the authors attempt to reduce power consumption at each node by using the smallest transmission radius needed to retain the continuing connectivity of the broadcast process. Although the proposed algorithm runs locally on each node, the node needs to know the distance to each of its neighbouring nodes and the distances among its neighbouring nodes (distance calculation). Nodes have to send a *hello message* periodically including their coordinates (by using a positioning system like GPS). A one-hop neighbour list is maintained by each node. This includes the neighbours' locations, allowing them to decide whether or not an edge is in RNG, which is an undirected graph in which an edge is added between two points if there is no node closer to both nodes.

This condition is depicted in Figure 2.14(a) where an edge (u, v) is part of the RNG if no node is present in the grey area. When a broadcast message is received from a RNG neighbour, the node retransmits it using the minimum transmission power required in order to reach the most distant RNG neighbour which has not yet received that message. Otherwise, it instigates a timeout and compiles a list of those RNG neighbours which have not yet received it. Only if the list is not empty once the waiting time has expired, does it rebroadcast the message with enough transmission power required to reach the most distant RNG neighbour on the list. An alternative version, is proposed by[145]. In this version the timeout is reset each time a message is received.

Wang *et al.* [146] incorporate the concept of a forbidden set in RNG to enhance the broadcasting process. Using the selection criterion for this set, nodes with low residual energy are excluded from acting as forwarder nodes. Thus, it can avoid the broadcast path being disrupted by energy being depleted at nodes which have low energy threshold values, thus prolonging the lifetime of the broadcast path. The node will also change the relative neighbour when it receives any redundant retransmissions, or will ask to be covered by only one.

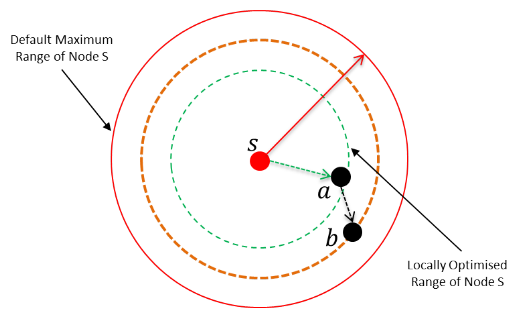


Figure 2.15: Power Adaptive Broadcasting

Faloutsos *et al.* [147] propose a Power Adaptive Broadcasting with LOcal information (PABLO) algorithm. The PABLO algorithm relies on two-hop neighbourhood information to minimise the overall energy consumption for each broadcast. Nodes periodically exchange information using *hello* packets that contains a list of the node's one-hop neighbours and the levels of transmission power required by that node to reach them. The source node then considers whether it is worth excluding the current most distant node from the one-hop neighbourhood and then reducing the transmission range to reach the new furthest neighbour (during the random back-off time). Figure 2.15 shows that node s excludes node b from the one-hop neighbourhood if the sum of the power required by node s to reach node a plus the power node a requires to reach node b is less than the power node s needs to directly communicate with node b.

Chiganmi *et al.* [148] propose the Inside-Out Power Adaptive (INOP) approach. It uses two-hop neighbour knowledge to decide about energy expenditure for covering all direct neighbours. This approach differs from existing methods in that each node initially sorts its neighbours according to the power needed to cover them before calculating the optimal energy saving strategy, beginning with the nearest neighbour to directly or indirectly cover the next neighbour. There are two different ways of selecting the forward nodes. The first is INOP, based on the self-pruning notion [133], where a random timeout from an interval is set for which the range is inversely dependent on the number of non-covered neighbours. Following the delay, if the list of neighbours which were previously not covered is found to be empty, the node will not carry out the rebroadcast. In the second version: INOP with neighbour designation, rather than adding a new forward in order to cover a non-covered neighbour the possibility of increasing the transmission power of a forward node that has already been selected is considered. As the timeout is set randomly, the INOP is really a stochastic approach. However, the main weakness of the approaches discussed so far, is that when they decrease the transmission range they do not set a limit; this could result in a sharp rise in the number of hops that are needed to disseminate a message and with the result that the average end-to-end delay will increase.

Ruiz and Bouvry [149] propose an Enhanced Distance Based (EDB) broadcasting Protocol. The EDB is a receiver-based technique where the receiving node decides whether the received packet should be rebroadcasted or not. The proposed algorithm uses a Cross-layer design and variable transmission range to reduce energy consumption in rebroadcasting messages. Every node sends a *hello* packet (or *beacon*) and the received signal strength (RSS) of the *beacons* is utilised in the Physical-layer in order to estimate how far apart two nodes are.

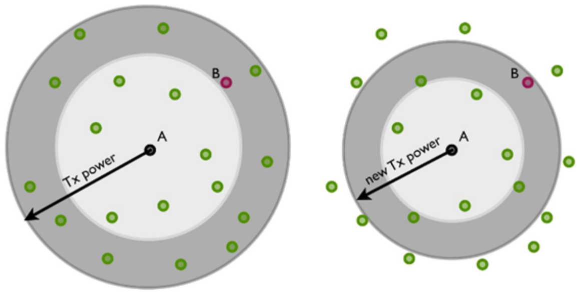


Figure 2.16: The mechanism of AEDB

In [150] the same authors later presented an adaptive version (AEDB) in which nodes are discarded from the one-hop neighbourhood in order to conserve energy in dense networks. In this case, the algorithm attempts to reduce the number of forwarding hops, where the transmission range is reduced to a predefined threshold value called *neighbours_ Threshold*. The main rationale is that, usually, in a highly dense network the connectivity is high. This means that if the Transmission power, Tx, is reduced, the loss of some one-hop neighbours will reduce the power consumed without entailing any negative effect on the performance of the broadcasting process. As can be seen in Figure 2.16 [150], when the number of neighbours in the forwarding area (dark grey zone) rises above a pre-set threshold, the power is adjusted to reach the node that is now most distant, node B (in red).

Park and Yoo [151] introduce an Efficient Reliable One-Hop Broadcasting (EROB) algorithm. In this system, three different channels are determined for transmissions, two of which act as control channels and one which is used to send data packets. This approach involves using a control packet referred to as BIP (Broadcast In Progress) to circumvent the *hidden terminal problem* [152] while broadcasting. It also enables nodes to control their levels of transmission power to reduce energy consumption leading to fewer collisions while enhancing the throughput and extending the lifetime of the network.

2.5.4.2 Algorithms Using Topology Structure

Topology control is a key technique used in wireless ad hoc networks to conserve power, and thus prolong operational time of the network [36]. The main aim of

Table 2.2: Classification of the Variable-range Transmission Power Approaches with no Topology Structure

	Neighbour info.	**Hops knowledge**	**GPS**	**Forwarding decision**
RBOP [143] *RNGFR [146]*	local	2-hop	yes	receiver-based
PABLO [147]	local	2-hop	no	receiver-based
INOP [148]	local	2-hop	no	sender/receiver-based
EDB [149] *AEDB [150]*	local	1-hop	no	receiver-based
EROB [151]	local	1-hop	yes	receiver-based

this technique is to dynamically adjust the nodes' transmission power range so as to optimise network power consumption while maintaining connectivity. Moreover, if the transmission range of each node can by dynamically adjusted, this may reduce the level of interference (which has a positive effect on traffic carrying capacity of the network) among nodes in the network [37, 153].

Topologies in a wireless ad hoc network provide nodes with extra information that helps them to make better forwarding decisions. For this reason, there have been many proposals to either utilise an existing topology structure (already created for other purposes), or create a virtual topology structure in the network and decide upon forwarding accordingly. As earlier mentioned in this chapter (Section 2.4.1), there are three main topology-based structures that have been proposed to solve the broadcast problem [83]: these structures are the connected dominating set (CDS), tree-based topology and cluster-based topology.

Connected Dominating Set (CDS)

CDS is receiver-based or source independent system that constructs a virtual backbone which will cover most of the nodes present in the network. Each node is either part of the backbone or is adjacent to at least one node within it. There is an extensive review of this approach in [154]. Broadcasting algorithms that use a variable-range transmission power based on CDS presence are discussed here.

Wu and Wu [155] propose a transmission range reduction scheme for power-aware broadcasting in which the transmission power of each node can be dynamically reduced in the broadcast process with no detriment to reachability. This reduction in transmission power is based on observing of the maximal distances from each node to all its neighbours together with the dominant set status of each node. Because the nodes in the CDS will consume more power, the same authors propose a technique [156] aimed at scheduling node activities rather than minimising overall energy consumption.

Li *et al.* [157] propose two decentralised approaches to construct the CDS which will minimise the overall power consumption in communication. The aim is to find the CDS which minimises the sum of the transmission power of the CDS nodes.

Tree-Based Topology

Tree-based topology broadcasting algorithms aimed to assist energy conservation in broadcasting are presented here.

Wieselthier *et al.* [158] propose the Broadcast Incremental Power (BIP) algorithm to solve the energy conserved broadcast problem. This algorithm requires global information. The basic idea of BIP is the construction of a Minimum Spanning Tree (MST) in terms of power costs. More specifically, BIP transforms the network graph to a minimum energy broadcasting tree rooted at a given source. Their work also provides a sweep procedure is also to further reduce overall energy consumption.

Bulbul *et al.* [159] introduce a Hop-Constrained Minimum Broadcast Incremental Power (HC-BIP) algorithm, to ensure that any message broadcasted in the network will reach all the nodes in the network in fewer hops. However, this algorithm also requires global information.

Xu and Garcia-Luna-Aceves [160] introduce a *redundant radius* scheme to achieve a trade-off between energy efficiency and coverage. The proposed broadcasting algorithm requires global information on the network. It assumes that the transmission radius is adjustable at each node. Two different ranges of transmission power are utilised in this work. A shorter range is initially considered in constructing the broadcast tree in terms of the neighbourhood, and a longer range is subsequently used for the actual transmission. However, the collection of global information is costly in constrained wireless networks and has significant overheads even in static networks.

According to Ingelrest *et al.* [39] there is an optimal transmission range that reduces the dissipation of energy and at the same time retains a connected topology. They propose two broadcasting algorithms: the Target Radius LMST Broadcast-Oriented Protocol (TR-LBOP) and the Target Radius and Dominating Set-Based Protocol. The TRLBOP first works out which neighbours can be eliminated to create a smaller subset of direct neighbours, and also decreases the radius to retain or even increase connectivity. The second algorithm calculates a CDS to select relay nodes which are as near to the target radius as possible (obtained using GPS).

However, although telecommunication networks have made wide use of a tree-based topology [161], these algorithms usually require a higher degree of network stability than is likely to be the case in MANETs.

Cluster-Based Topology

To alleviate power consumption and radio interference, Cluster-based topology broadcasting algorithms are presented here.

With the aim of increasing the network capacity by improving spatial reuse, Kawadia and Kumar [162] propose a clustering approach to power control, CLUSTERPOW. This approach employs three different levels of transmission power. The clustering of nodes dynamically determines the selection of the power level. Since the power control is applied to both the data and the ready to send (RTS)/clear-to-send (CTS) handshaking packets, this may lead to collisions occurring as a node may not sense the presence of communication while it is attempting a high power transmission.

Oda *et al.* [163] propose an approach to controlling transmission power which can adapt to variations in the node density. In this autonomous cluster scheme, the transmission power of each node is adapted according to how far away the node is from its neighbours in order to obtain a specific number of neighbours (obtained using received signal strength in the Physical layer).

Ni *et al.* [164] introduced an energy efficient clustering scheme. In this scheme the cluster head (CH) is elected according to the residual energy of the node, the neighbourhood topology, and the relative location, and the relative mobility. Moreover, members of cluster have the ability to estimate their distance from the CH and adjust their transmission power range accordingly. A re-clustering operation is triggered if the CH's residual energy falls below a predefined threshold.

Table 2.3: Classification of the Variable-range Transmission Power Approaches using Topology Structure

	Neighbour info.	**Hops knowledge**	**GPS**	**Forwarding decision**
[155] *[157]* *BIP[158]*	local	1-hop	no	structure
HC-BIP[159]	local	-	no	structure
redundant radius[160]	global	-	no	structure
TR-LBOP[39]	local	1-hop	yes	structure
CLUSTERPOW[162] *[163]*	local	1-hop	no	structure
[164]	local	2-hop	no	structure

2.6 Discussion

After reviewing the literature, we have distinguished between 1) Fixed-range transmission power based algorithms and 2) Variable-range transmission power based algorithms. In the following discussion, major issues related to broadcasting approaches, like: localised and distributed, scalability, energy efficiency, minimum delay and reactiveness and adaptability will be discussed in relation to this research proposed topology-based broadcasting algorithms.

- ***Localised and Distributed***

  Among approaches using topology structure for disseminating the message, several broadcasting algorithms exploit topology information to enhance their performance. However, global knowledge is required for many of these, or the assumption that the network nodes are static or have low mobility. In mobile ad hoc networks, there is very little likelihood that a node can obtain complete or updated global information unless it is small and not very mobile. In addition, most of the distributed versions require knowledge of the distance to all neighbouring nodes together with the distances between these nodes. To obtain this information, nodes would need to be fitted with location equipment, such as GPS, and they would be required to notify their position to other nodes present in the network. Moreover, it should be noted that, even if distance information was available, the geographical coordinates do not allow for the possible presence of obstacles in the environment and the possibility of shadowing in the channel. Hence, these uncertainties can result in errors in calculating the transmission power overhead for the link.

For a small network, centralised solutions may lead to an efficient performance. In contrast, they lead to many overheads in extensive wireless ad hoc networks, and such methods are not scalable, as the complexity increases with the number of nodes in a network. Thus, a distributed solution depending on local information is more suited to mobile ad hoc networks. In addition, distributed solutions should be localised, where each node executes algorithms locally and takes all its own decisions independently.

- ***Scalability***

  Most existing broadcast algorithms based on topology use fixed high range transmission power in transmitting *beacon/hello* signals to construct and maintain the topology structure. This can be achieved in very small networks, but at higher density, this mechanism is not scalable and becomes impractical. Less attention is paid to reducing the interference caused by maintaining these structures when broadcasting is performed on top of them (i.e. the extra number of collisions as the network's density grows). Additionally, the use of long range distances for communication is costly, either because too many nodes in the shared medium are silenced, or because of the disruption to ongoing traffic [165]. However, if a topology structure has a lot of interference, then many signals transmitted by nodes are likely to collide with each other, or there may be significant delays in delivering data to some nodes, which in turn may cause increased energy consumption. Therefore, broadcasting protocols need the ability to support wireless networks with large size (i.e. many nodes in the network) or high density (a large number of neighbours per node) [153].

- ***Energy Efficiency***

  Energy consumption is strongly related to scalability, in terms of the overhead incurred and how many nodes are operating in the network. The reason is that higher control packet overheads consume more energy in transmission, reception and overhearing. Thus, designing a more scalable protocol can be beneficial for power conservation in MANETs, where there are mobile nodes [166].

  Regarding the transmission power range level, [54] argues that choosing a high power range level results in excessive interference and reduces the traffic carrying capacity of the network, and also the battery life of the devices. However, where there is a very small power range, this results in lower connectivity and hence network partitioning. This research attempts to achieve a balance between transmission power used and maintaining connectivity. This keeps interference levels at a manageable level and utilise the available bandwidth efficiently.

  In addition, the computational power of a mobile device should not be neglected, particularly the amount of memory, the slower processing times and I/O devices. Such devices generally have low memory capacity and limited processing power. This means that algorithms developed for communication protocols should have low computational complexity.

- ***Minimum Delay***

  The reviewed literature considers variable range transmission power schemes that utilise nodes from the one-hop neighbour set and use a technique in which the source node lowers its transmission power in order to send only to nearby nodes depending on the topology. However, this technique increases the number of hops. It also increases the average end-to-end delay with the number of hops which is undesirable in mobile ad hoc networks, particularly when the topology changes frequently. Under a heavy load, increased MAC contention may induce a latency overhead which may offset the latency gains of using a high power level. It also offloads part of one node's power consumption problems onto other nodes. It attempts to free ride on their use of power for it. Any tactic like this is likely to undermine the basis of cooperation among nodes especially if they are provided by parties with different interests.

In addition, several of the reviewed works incorporate a *random assessment delay* (RAD) time before deciding to retransmit a broadcast message. This technique significantly lowers the collision rate and allows sufficient time to receive multiple copies and to take a wise decision of rebroadcasting. However, the maximum value of the RAD also significantly influences the broadcast time and adds to the delay in the route discovery process. Moreover, broadcasting approaches which depend on RAD will suffer in highly dense MANETs if the value of the RAD is not adapted to the level of network congestion.

- ***Reactiveness and Adaptability***

  It can be seen that most of the approaches that reduce the transmission power range use two-hop topology information. This makes the algorithm react slowly to the frequent changes that occur, because two separate time intervals are required for updating all the neighbours with the changes.

2.7 Conclusion

This chapter has reviewed representative ad hoc based broadcasting algorithms related to the research presented in this thesis. The literature review has addressed both fixed-range and variable-range transmission power based broadcasting algorithms. It has also provided an overview of the existing broadcasting algorithms and discussed the existing classification of these broadcasting schemes and algorithm systems. The chapter has provided an overview of power control approaches and the ad hoc based broadcasting algorithms that uses fixed-range transmission power for broadcasting. It also assesses the limitations of existing fixed-range transmission power based broadcasting algorithms. After that a discussion of ad hoc based broadcasting algorithms that use variable-range transmission power for communication, is provided. The last part addresses the current issues of ad hoc based broadcasting algorithms and discusses them in relation to this work's proposed topology-based broadcasting approach.

Even though, many different approaches of broadcasting algorithms were reviewed, an algorithm that rapidly reacts to changes, and relies on only one-hop topology information is desired in this kind of wireless network. Thus, this research aims to design an energy efficient route discovery protocol that employs a hybrid approach in which the desirable features of both controlling the transmission power and reducing the number of retransmissions are combined, thus conserving the average energy consumed per broadcast. The goal is to construct a more scalable and energy efficient topology structure relying on local one-hop information in which nodes use variable-range *beacons* to exchange and maintain topology information, over which network routs are discovered. In this way, as well as conserving nodes' energy the level of interference and resulting collisions and communication delays is also reduced. In Chapter 4 this approach will be discussed.

Chapter 3

Methodology

3.1 Introduction

This chapter describes and explains the methodology used to conduct the research which formed the basis of this thesis. It presents the chosen routing protocol and provides a brief description of its components. It also describes the cross layer design and approach. It lists its system modelling techniques and discusses them in relation to its approach to simulation. A justification of the approach is also provided. The following section describes and explains the selected MANET routing protocol. In section 3.3 the cross-layer design and approaches are presented. Section 3.4 discusses the system modelling techniques. In Section 3.5, energy consumption model is discussed. Section 3.6 presents the simulation approaches, the studies' assumptions and the performance metrics used to evaluate and compare the performance and the efficiency of the existing and the new proposed broadcast algorithms. A summary of the chapter is provided in Section 3.7.

3.2 Routing Protocols

Routing protocols can mainly be grouped on the basis of whether they are proactive or reactive protocols. In proactive routing, a routing table is established and maintained in which routing information to all the other nodes in the network is included. In contrast, reactive protocols only create a route when it is required, that is, when a source node is about to send data to a destination. Although proactive protocols are suitable if the networks are relatively small and the individual nodes have low mobility, in situations where networks are highly dynamic they incur high overheads. Some hybrid approaches have also been proposed which combine features of both reactive and proactive strategies. A review of routing algorithms was conducted by [167].

3.2.1 Selection Criteria

As explained above, in a reactive protocol source node establishes a route only at the point when it requires to send data to a destination node. To initiate the procedure, the source node transmits Route Request (RREQ) packets throughout the network. In response to this request either the destination node or an intermediate node which has already established a route to the destination, unicasts a reply by sending a route reply packet along the reverse path established during the route discovery process at intermediate nodes. Once a route is established, a route maintenance procedure ensures that it is maintained for as long as it is needed.

In this study, the AODV [57] reactive routing protocol has been chosen as a simple and widely used reactive routing protocol for a MANET. This protocol was developed in 2003 at the Nokia Research Centre, University of California, Santa Barbara and University of Cincinnati and has been widely studied and used.

3.2.2 Ad hoc On-demand Distance Vector (AODV)

AODV [57] is a network layer a reactive routing protocol in which a path to an intended destination is set up on-demand basis; this means a route between source and destination is only established at the point where a node wishes to send data to another node. This behaviour is advantageous in mobile environments such as MANETs since it avoids the massive communication overheads and power consumption that would be required to update and maintain a complete knowledge regarding all routes from every node. The routing mechanism of AODV consists of two phases: a route discovery phase and route maintenance phase.

Route Discovery Phase

In this phase, a node that needs to send data first identifies an available route to the destination, by checking its routing table. If it finds there is no existing valid route, it uses a new sequence number to broadcast a Route Request (RREQ) packet to its one-hop neighbours. When an intermediate node receives a RREQ packet, it discards the packet if it is itself the original source of the request or where it has previously rebroadcast the same version of the RREQ packet. This node then establishes a reverse path back to the source and refreshes its routing table, unless it has a more recently updated packet (i.e. with a higher sequence number). Before rebroadcasting the RREQ packet to its neighbours it first increments the hop count. The intermediate node also records the address of the neighbour from which it received the first copy of the RREQ packet in its routing table [168]. This enables a reverse path to be established, as this neighbour would be the first hop towards the source (see Figure 3.1(a)).

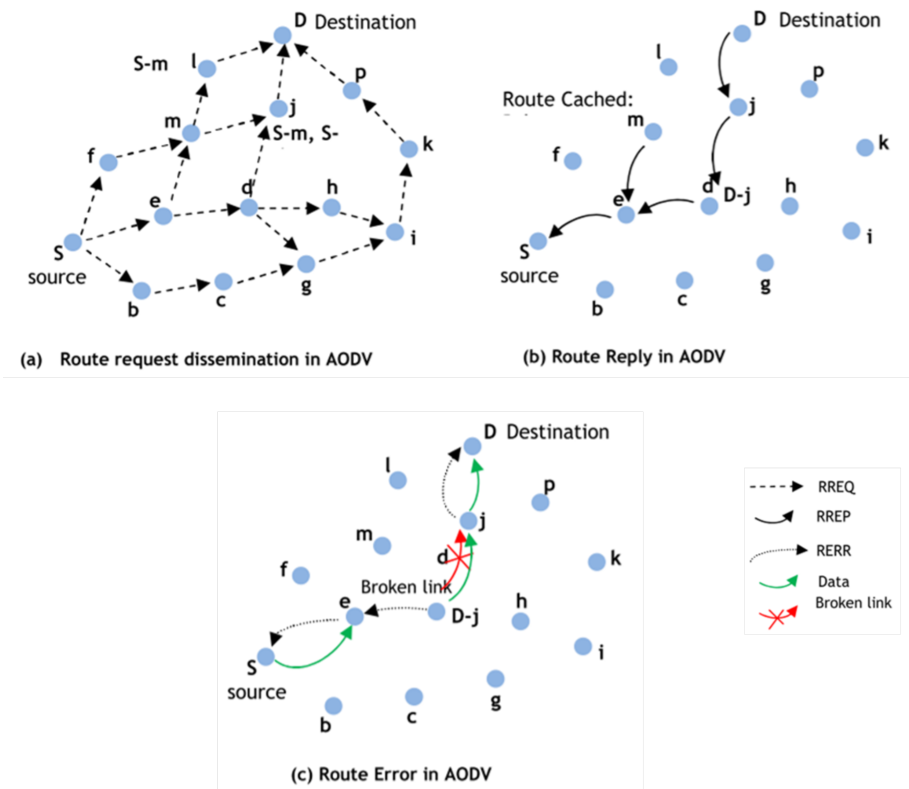


Figure 3.1: Route discovery phases in AODV

As an RREQ packet is forwarded, each intermediate node adds the next hop information to its routing table, and thus establishes a reverse path back to the source node. The reverse route is then used by the destination node or an intermediate node with a valid route to unicast a Route Reply (RREP) packet to the source node to acknowledge receipt of the RREQ packet. To check that a route is valid at the intermediate nodes, the sequence number is compared with that of the destination. By recording the next hop information in the routing table, a forward route to the destination is created as each node that sends the RREP packet back to the source (see Figure 3.1(b)). Each node along the path from the source node to the destination only requires knowledge regarding the next hop nodes leading to the source or destination, but it does not need any knowledge about any other nodes which form the path.

Route Maintenance Phase

Once the route has been discovered and during the period when it is in use, the intermediate nodes undertake a periodic exchange of Hello packets to ensure they have an updated list of their one-hop neighbours. In addition, a timer is activated if the route is no longer considered active, i.e. no data are being sent over it: and the route then lapses once the set time has expired. If the routing agent (i.e. AODV) at a node identifies a broken link in any route that is active, it generates a Route Error (RERR) packet at the point where the link is broken (see Figure 3.1(c)). This is then broadcasted to the appropriate nodes which are actively using the route together with those along the path. This procedure enables the nodes which may be affected to terminate the invalid route. It also means the RERR packet arrives back at the source node, so that it can then begin a new route discovery phase.

3.3 Cross-Layer Designs

Communication systems in wired or wireless networks are divided into layers for reducing complexity in processing and managing information to be transmitted [169]. In wireless networks communication, the characteristics are quite different from wired networks and create new challenges. For example, transmission errors in wired networks only arise when the network is congested. Thus, it is a useful tactic to reduce the bit rate immediately when a transmission error is detected and then to increase it slowly when no more errors occur. However, this is not a valid solution in wireless networks, where interference, collisions, noise and other factors can lead to significant packet loss [42]. Moreover, reduction of the bit rate in response to packet loss might not solve the problem, but only result in a reduction of throughput and take time to recover from.

A Cross-layer design has been successful in wired networks. However, the mobility of the nodes together with wireless transmission could cause interference and raise some inherent issues of mobile ad hoc networks that make cross-layer designs useful to improve the performance of a MANET. The layering design technique is essentially based on cooperation between protocols to adapt their operating mode to data collected from the other layers of the system. By using this technique, each layer is allowed to share and access the information from the different layer. Further details regarding cross-layer design can be found in [170].

3.3.1 Cross Layer Approaches

Approaches to implementing cross-layer interactions are discussed in previous studies [171], which can be classified into three categories:

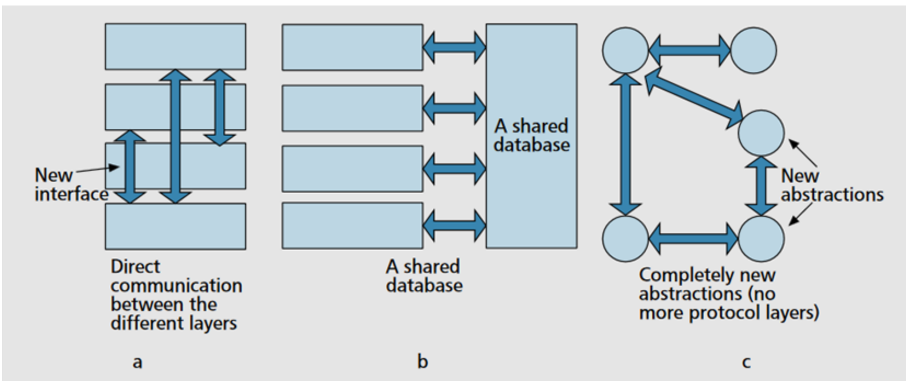


Figure 3.2: Cross-layer approaches.

3.3.1.1 Direct Communication between Layers

A straightforward approach to allow sharing of runtime information between layers to allow them to communicate with each other. Some of the possibilities are illustrated in Figure 3.2(a) [171]. It should be taken into account that such a method is only applicable when there is a need to share runtime information between the layers (for example, in cross-layer designs that require new interfaces or in dynamic vertical calibrations). In other words, direct communication between layers allows the visibility of variables from one layer to another during runtime.

Depending on the direction of information flow, this approach can be further divided into two subcategories [172]:

- **Upward cross-layering** when information from a lower layer is accessed by a layer higher in the stack.
- **Downward cross-layering** when information from a higher layer is accessed by a lower layer.

Direct communication between layers can be achieved either by modifying the layers' interfaces or by using specific fields in the packet headers (downward cross-layering only). Moreover, cases such as cross-layer signalling by using internal packets introduced in [173] provide an efficient mechanism for both upward and downward communication.

3.3.1.2 A Shared Database Across Layers

In this approach to cross-layering, a shared database is made available for access by all the layers, as illustrated in Figure 3.2(b). This shared database is a new layer, and it provides storage/retrieval of information to/from all the layers. This approach is well suited to vertical calibration as mentioned in the earlier section. The main challenge in this category is to design new interactions among the layers and a shared database.

3.3.1.3 New Abstractions

As this approach suggests, this is a new abstraction with no more protocol layers, which we depict schematically in Figure 3.2(c). This approach offers flexibility in design as well as at runtime due to enhanced interactions among protocols.

3.3.2 Selection Criteria

Direct communication between layers is one of the cross-layer design proposals and is reported in the survey by Srivastava and Motani [171]. It is a simple cross-layer design approach that can solve some problems and improve the performance of MANETs. In this work's implementation, the direct communication approach has been used and implemented by using the Downward technique. A specific field in the common packet header designed to share information from the network layer with the physical layer at runtime. By employing this technique, it is possible to adapt nodes' transmission power levels to local conditions. Chapter 4 provides the details of the cross-layer approach used in this study.

3.4 System Modelling

How best to implement MANETs in the real world is still open to debate. Researchers still need to evaluate and validate a variety of algorithms designed for these networks to see which provide the best trade-offs. These approaches will enable system design decisions to be validated in the early stages of the design process. These approaches to testing include creating testbeds and using modelling techniques.

Testbeds are experimental networks that allow experiments to be carried out on real devices. However, they involve many challenges that usually make them difficult for researchers to use. These include the difficulty of monitoring them, the limited mobility of their devices, their lack of reproducibility and their time-consuming nature. Moreover, the scope of this study entails the deployment many mobile nodes, but deploying even a moderately high number of nodes in an experimental testbed would be prohibitively costly.

Modelling techniques use a simple representation of a real system to obtain predictions about how a system will behave without the need to implement it. Various parameters and often some simplifying assumptions can be applied when studying the behaviour of a system. There are two main approaches to modelling: analytical modelling and simulation [174].

An analytical modelling approach describes the system mathematically to provide a general view of the system through the use of numerical methods. Because they are mainly based on mathematical proofs, the validity of analytical results depends mainly on the validity of the conditions, parameters and assumptions underlying them. The use of analytical modelling can be an efficient low cost way of gaining useful insights regarding the effects of various individual parameters and also their interactions [175]. Thus, analytic techniques such as stochastic Petri nets [165] and process algebra have been used to analyse and evaluate the performance of communication systems. However, few analytical studies have been conducted regarding MANETs [176]. This lack of analytical modelling of MANETs arises out of the challenges involved in incorporating the random movement of nodes into these analyses and explains why these studies usually assume that the nodes are not moving. As has already been explained in Chapter 1, the movement of nodes in a mobile ad hoc network is one of its major characteristics and cannot be ignored. This makes analytical modelling unpromising for studying the performance of this kind of network [177].

Due to the previously mentioned drawbacks, most existing studies in the literature have relied on simulations in evaluating and validating MANET routing algorithms. Thus, the accuracy of the simulation is vital if realistic behaviour for the algorithm studied is to be obtained. This means that the level of realism of the simulator selected when conducting the experiments is critical. Fewer simplification assumptions are usually needed to conduct simulation, as it is possible to incorporate in the simulation model almost all of the detailed specifications of the system. Moreover, simulation is generally considered to be an effective tool to study the highly complex environment of networks. They have also been shown to be a useful way to evaluate system performance by examining the proposed model under different scenarios and conditions before designing a real system.

3.4.1 Network Simulators

A large variety of network simulation tools is available, including commercially produced network simulators, e.g. QualNet [178], OPNET [179] and MATLAB [180] and open-source network simulators, e.g. NS2 [181] (and recently NS3) [182], OMNeT++ [183] and J-Sim [184]. Each type of network simulator has particular advantages and limitations. Several factors influence the selection of the most appropriate tool; these include the simulation platform, the type of simulation tool, the sophistication of its modelling constructs, its performance and the user interfaces of the simulation tool [185]. Table 3.1 shows the comparative study [186] of the different simulator (NS2, NS3, OPNET, OMNET++, QUALNET and MATLAB).

Table 3.1: Comparison of Different Simulators [186]

Simulator	Language	Pros	Cons
NS2	C++ OTcl scripts	• Open Source. • Easy to add new protocols. • There are a large number of protocols available. • There are visualisation tools. • Large number of user groups. • Excellent documentation.	• Takes time to learn. • Very limited visual aid.
NS3	C++ Python scripts.	• Open Source. • It is a new simulator; NS-3 is not an extension of NS-2.	• Windows platform are lightly supported as some ns-3 aspects depend on Unix / Linux support. • Limited visual aid.
OPNET	C / C++	• Large number of customers. • Professional support. • Excellent documentation.	• Relatively costly but there is a suitable price for universities. • OPNET seems more suitable for network managers than for research into generic performance.
OMNET++	C++	• Easy to trace and bug. • Simulates power consumption problems.	• Limited routing protocols available. • No compatibility (not portable).
QUALNET	C++	• Easy to use and learn . • Animation capabilities. • There is support for distributed computing and multiprocessor systems.	• Installation problems on Linux. • Slow Java-based UI. • It is costly.
MATLAB	C++	• Excellent graphical support. • Excellent facility for debugging.	• Processing speed is slow. • Exceptional programming skills are required.

Network simulation tools involve time-dependent simulation, in which a simulation clock monitors simulation time events which are ordered chronologically. There are two types of time-dependent simulation, which are time-driven and event-driven simulation [174]. In the former type of simulation, events are executed at each fixed time interval of the selected time units. In contrast, events occurring in the latter type of simulation can be executed at any arbitrary time rather than proceeding according to fixed time intervals. In this procedure, the event on the event list with the smallest time-stamp is retrieved and removed; it is then executed, and the simulation clock advanced to the time-stamp associated with the next event.

3.4.2 Selection Criteria

Network Simulator (Version 2) NS2 [181] is an event-driven simulation tool which can be used to simulate both wired and wireless network functions and protocols. It is extensively employed for network research and has become popular because of its flexibility and modular nature [174]. Thus, to validate the proposed algorithms in this thesis, NS2 is selected as a simulation tool.

3.4.3 NS2 Simulator

Network Simulator (Version 2) [181], generally referred to as NS2, is an object-oriented discrete event simulator which was originally developed by the VINT project at the University of California in 1995. Subsequently it was improved by researchers at the Monarch project at Carnegie Mellon University to enable it to support node mobility. As mentioned above, NS2 is the most commonly used open-source network simulator by networking researchers, as shown in Figure 3.3. As reported on 2016 by Manaseer and Saher in [187], most research in MANET is carried out via NS2 and over half of the papers published regarding simulation-based MANET used NS2 as a simulation tool. As well as supporting simulation of both wired and wireless network services and protocols it can be used to study the behaviours of both existing protocols and new ones that are being developed.

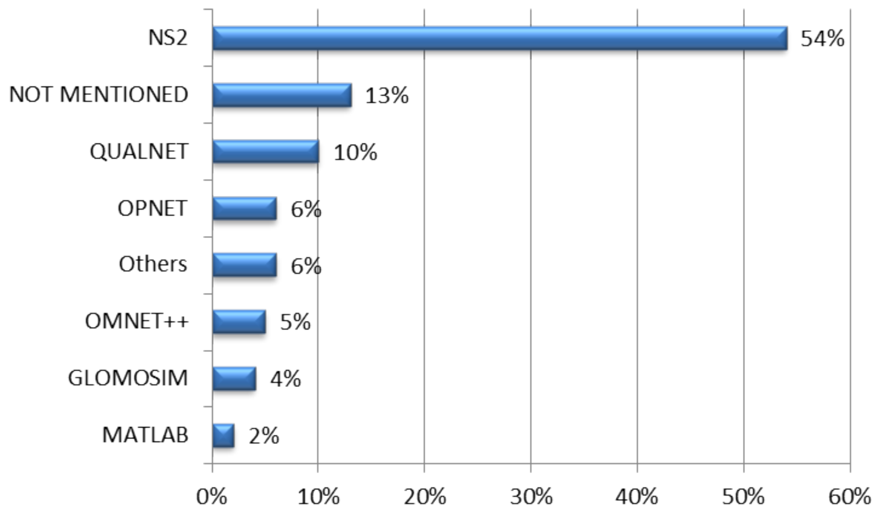


Figure 3.3: Simulator Usage for the MANETs Study.

A key feature of NS2 is the ease with which it can produce multiple randomly constructed scenarios to represent both traffic and mobility patterns in a layered approach. It also includes an Energy Model class which allows the user to calculate the power consumption efficiently. In addition to this, it provides other essential features, including abstraction, visualisation and emulation. It supports a wide range of MANET routing protocols, which include AODV, AOMDV, DSR and DSDV routing protocols.

Two programming languages are employed in NS2, which combines the advantages of both. The simulator is written in C++; this specifies the internal mechanism of the simulation, while a script language known as Object Tool command language (OTcl) is used to construct and configure the network and also functions as a user interface [174]. It is an interpreted programming language, meaning that it is possible to execute any alterations in an OTcl file without compiling them. In the construction of NS2 the advantages of both languages are combined, where the rapid run time of C++, is convenient for running a simulation, while the ability to make changes quickly in OTcl facilitates the process of configuring the network. Thus, C++ code is used to describe the simulation components, together with their behaviour and the network topologies, while the overall simulation behaviour is modelled in OTcl scripts which are employed for binding.

3.4.4 Mobility Model

The patterns of movement of the mobile nodes are captured by the mobility model, by recording changes in their direction and velocity over time. It should be noted that it is vital for the mobility model employed to be as realistic as possible to obtain the most accurate results when evaluating the performance of the protocol. It should be noted that simply assuming nodes are moving in a straight line at consistent high speeds does not represent the behaviour of pedestrian. Similarly, a *random walk* [188] will not be suitable to represent the behaviour and movements of vehicles in vehicular ad hoc networks.

Thus, for a simulation study to be successful, it is crucial to use a credible mobility model, which will only be revealed after taking into consideration an authentic network scenario. This could range from scenarios as varied as a battlefield in a conflict zone to a conference venue in a busy city centre. The simulation environment and its parameters are then designed to mimic that particular scenario. A wide range of mobility models are suitable for simulating ad hoc networks such as *Random Walk*, *Random Waypoint* and *Random Direction* mobility model [189].

The Random Waypoint Mobility Model [190] is the most widely used mobility model in simulation-based studies in MANETs [191], particularly when evaluating the performance of various mobile ad hoc network routing protocols [192]. In [193] it was found that 19 out of 32 (approximately 60%) simulation experiments used this model. In the node movements in this model include pause times between changes in their direction and velocity over the simulation period. One reason for choosing the Random Waypoint mobility model is already built in to NS2 simulators. Specifically, the model was chosen for the simulations in this research because the nodes' movement is unpredictable, which gives us a suitable environment to simulate the proposed algorithms and monitor how they perform and promptly react to unpredictable topology changes.

In this model, a collection of nodes is defined and then randomly placed in a confined simulation space. A random destination within the simulation area is then selected by each node and the node then travels towards this location at a particular speed (s). After reaching the selected destination, the node will then pause for a short time (t), before choosing another random destination and, thus, the process is reiterated. The node speed (s) is specified for each node, based in a uniform distribution, with $s \in (0, V_{max})$, where V_{max} represents the maximum speed. A constant pause time set at (t) seconds. It is worth noting that if the pause time (t) is set to zero second, the node will behave in the same way as described above except it will not stop at any destination. Since this thesis considers broadcasting over topology structure, the pause time is fixed to zero second. This represents continuous node mobility without added stability, which enable to measure the performance of the proposing broadcasting algorithm and how rapidly it reacts to topology changes in high dynamic mobility scenario.

3.4.5 Random Scenario Generation

NS2 supports both deterministic and random mobility. In small networks, the use of deterministic mobility allows the movement of mobile nodes during the simulation to be controlled. However, in an extensive network controlling the nodes' movement while the number of nodes in the network is increasing is a difficult task. This is a challenge in using random mobility: although it offers a wide range of tests, which provide a sound basis for evaluating the behaviour of the network it does not allow the movement of mobile nodes in the network to be reviewed or controlled. To address this, an independent utility is provided in NS2 simulator, known as *setdest* which is generated by CMU. This utility employs the random waypoint algorithm to create movement-related OTcl statements representing an entirely random movement of nodes, which can still be controlled. This representation can be regarded as deterministic mobility, meaning that it is available before the simulation but can be incorporated during the process of the simulation as a Tcl script. This utility can be found in the directory *ns/indep-utils/cmu-scen-gen/setdest.*

Another independent utility provided in NS2 is *cbrgen.tcl*, which is written in Tcl to create traffic-related OTcl statements and, despite its title, has the ability to simulate both TCP and CBR traffic. As it is written in NS script, it is necessary to add this utility to the simulation script before commencing the experiment. This utility can be found in the directory *ns/indep-utils/cmu-scen-gen/cbrgen.tcl.*

A Constant Bit Rate (CBR) traffic generator is employed to generate traffic for data communication. The traffic is transported at a fixed bit rate, which entails an inherent dependence on synchronising the time between the traffic source and destination. This traffic generator is often used for any data for which the end-systems require predictable response times and bandwidths. The CBR data packet traffic has been used in this research to evaluate the broadcast algorithms discussed to ensures that the amount of data being injected into the network is constant, which in turn means that any change recorded in the number of RREQ broadcast packets genuinely results from the proposed broadcast algorithm being used and thus could not have been influenced by the status of the traffic sources.

3.5 Energy Consumption Model

The basic energy Consumption model used in this study is extremely straightforward and is defined by the class Energy Model in which there is only one class of variable energy, denoting the nodes' energy level at any given time. The constructor Energy Model requires the initial Energy (E_{init}) to be passed along as a parameter [194]. The other class methods are employed to reduce the energy level of the node for each packet transmitted (P_{tx}) or received (P_{rx}) by the node. P_{tx} and P_{rx} represent respective levels power required by the node's interface or PHY when transmitting and receiving.

At the commencement of the simulation, the energy level is set to Initial Energy, E_{init} , and then decreased by a set decrement as each packet is transmitted or/and received at the node. Once the node's energy level falls to zero, the node cannot receive or transmit any further packets. Equation 3.1 represents the Energy Model employed in NS2 to calculate the energy consumption on each node [194].

$$\mathrm{E}_{total} = E_{init} - (Duration_{tx} * P_{tx} + Duration_{rx} * P_{rx}) \tag{3.1}$$

where:

E_{total} is the energy level of a node at any time,

E_{init} is the initial energy level of the node,

P_{tx} is the power consumed by a node in transmitting a packet,

$Duration_{tx}$ is the length of time required to transmit a packet,

P_{rx} is the power consumed be a node when it receives a packet,

$Duration_{rx}$ is the time taken for a packet to be received.

3.5.1 Measurement of Energy Consumption

There are four possible states for a wireless node: Transmit, Receive, Idle, Sleep or Overhear [166] (see Figure 3.4).

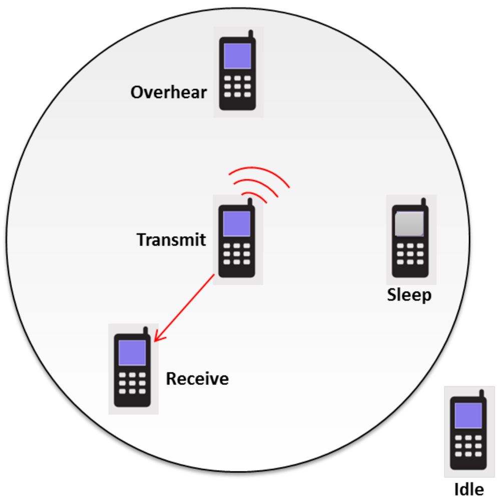


Figure 3.4: Energy consumption states in a wireless network.

- **Transmit:** this is when the node is transmitting a frame with transmission power $P_{transmit}$;
- **Receive:** this is when the node is receiving a frame with reception power $P_{receive}$. The node may or may not decode this frame, which it may or may not be intended for it;

- **Idle (listening):** this is a state where, even though there are no messages being transmitted over the medium, the nodes remain idle and continue to listen to the medium with P_{idle};
- **Sleep:** this is when no communication is possible as the radio is off. As it cannot detect signals the node uses P_{sleep}, which is generally lower than that in any other state, so that there is minimum energy consumption;
- **Overhear:** this occurs when the node is the sender's one-hop neighbour but is not the destination. This node is receiving a frame from the sender with reception power $P_{receive}$ [166].

Table 3.2: Power Value in Each Radio State.

State	Power value ($Watt$)
Transmit	$P_{transmit} = 1.3\ W$
Receive	$P_{receive} = 0.9\ W$
Idle	$P_{idle} = 0.74\ W$
Sleep	$P_{sleep} = 0.047\ W$

Table 3.2 shows the different power values corresponding to each state, which are obtained using a Lucent Sliver Wavelan PC Card for a wireless interface [195]. These power values are adopted in the simulation in this study. The energy consumed in transmitting (E_{trans}) one packet can now be determined by:

$$E_{trans} = P_{tx} * Duration_{tx} \tag{3.2}$$

and energy consumed in receiving (E_{recv}) one packet by:

$$E_{recv} = P_{rx} * Duration_{rx} \tag{3.3}$$

However, due to the shared nature of the wireless medium, when a packet is transmitted to a node's next hop neighbours, all its neighbours receive this packet, even if only one of them was the intended destination, which is known as overhearing. Moreover, although each node which is located between transmitter range and interference range will receive this packet they are unable to decode it. Hence, the receive nodes can be in one of three modes [7]:

- Receive: when a reception node is the packet's intended destination,
- Overhear: when a reception node is within the transmission range of the sender but is not the intended destination,
- Interference: this occurs when a reception node is beyond the transmission range of the sender and although it has still received a packet, this is with only low reception power, which means it cannot decode the signal. This type of reception is regarded as interference and is alleviated by reducing the transmission power range, and thus the level of interference in the network will decrease;

Energy is lost due to interference and overhearing [7]. These problems have been taken into account by various protocols, some of which consider both of them, while others have considered only one. In this thesis, the energy dissipated by each transmission by the sender, i, is calculated thus [196]:

$$\text{Cost}_{transmission}(i) = E_{trans} + n * E_{recv} \tag{3.4}$$

where n is the number of one-hop neighbours of transmitter i.

Thus, the energy cost of a broadcast packet in this thesis works will be of the form

$$\text{Cost}_{broadcast} = \sum_{i \in Sender_{broadcast}} \text{Cost}_{transmission}(i) \tag{3.5}$$

where i is a sender or a forwarder of a broadcast packet.

3.6 Simulation Approaches

In this study, the NS2 simulator [181] is used to simulate the behaviour of the proposed route discovery protocol, and the performance analysis were conducted using AWK script [197]. Experiments have previously been conducted on a *bwlf* server cluster of 32 machines running under a Linux CentOS 6.7 operating system (see Table 3.3). The reason for such a large number of machines was to accommodate a very large number of simulations. Thus these scenarios were distributed among the machines in the cluster to minimise the simulation time and to overcome storage constraints resulting from the huge file sizes for each of the scenarios implemented. NS2 works independently of the machine specifications it is not necessary to focus much on the length of time taken to implement a scenario.

Table 3.3: Machine Specification Used for Experiments.

Machine Specification					
Machine	Number of cores	CPU's Speed	Memory Size	Hard Drive Size	Operating System
32 machines	8 Intel processors	2.0 GHz	12 GB RAM	1 TB	Linux CentOS 6.7

All the experiments reported in this thesis were conducted using simulation to compare the behaviour of the proposed and existing protocols. The results were obtained from simulations of five different mobility scenarios and five different traffic scenarios; thus, each metric value represents the mean of the 25 runs (see Table 3.4).

For simulation purposes, the time set for the commencement of sending data to establish a connection varied randomly between 5 and 150 seconds of the simulation time. The focus of this study is solely on the effect of the CBR traffic. Experiments were also run for increasing numbers of nodes, in a series of experiments to assess the effects of node density. The Random Waypoint method was used to model node mobility. The experiments were run with gradually increasing maximum speeds for the nodes with a simulation area of 1000 m^2 to assess the effects of node mobility (see Table 3.5). These simulation parameters are widely used in the literature [21, 94, 198].

Table 3.4: Simulation Experiments.

Number of Protocol (P)	Network Density (D)	Node Mobility (M)	Number of Connection (C)	Number of Scenario Iterations (I)
AODV TB-AODV EEAFA-AODV EEEAFA-AODV OLSR	25, 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, 300 *nodes*	1, 5, 10, 15, 20, 25, 30 m/sec	5, 10, 15, 20, 25, 30, 35, 40 *connections*	5 different mobility scenarios * 5 different traffic scenarios
5	12	7	8	25
No of experiments with different network density $(P * D * I)$			5 * 12 * 25 = 1500 Runs	
No of experiments with different node mobility $(P * M * I)$			5 * 7 * 25 = 875 Runs	
No of experiments with different connections $(P * C * I)$			5 * 8 * 25 = 1000 Runs	
The total number of all experiments = 1500 + 875 + 1000 = **3375 Runs**				

Table 3.5: General Simulation Parameters

Configuration	
Simulator	NS2 version (2.35)
Topology size	1000 m^2
Number of nodes	25, 50, 75,100 ... and 300
Simulation time	300 sec
MAC type	IEEE 802.11 DCF
Bandwidth	2 $Mbps$
Antenna type	OmniAntenna
Propagation model	Two-ray ground
Number of trials	25 $iterations$
Mobility	
Mobility model	Random way point
Maximum speed	1, 5, 10, 15 ... and 30 m/sec
Pause time	0 sec
Traffic	
Traffic model	CBR
Packet size	512 $bytes$
Packet rate	4 $packets/sec$
Number of connections	5, 10, 15, 20 ... and 40
Energy	
Initial energy of node	100 $Joules$
$P_{transmit}$	1.3 $Watt$
$P_{receive}$	0.9 $Watt$

3.6.1 Assumptions

Extensive simulations were carried out for performance evaluation of the proposed route discovery approaches in MANETs, which will be reported in later chapters. Throughout this study, certain assumptions were adopted which have also been widely used in previous studies reported in the literature. These are as follows:

- Real nodes in real MANETs may exhaust their battery power or turn themselves off to conserve power. However, in the scenarios simulated in this study, it is assumed that each node has enough power to function during the whole period of the simulation and is switched on. This is to enable direct and fair comparisons to be made among the proposed and existing algorithms without losing nodes.

- The number of mobile nodes present in a specific topology does not change for the entire period of the simulation. However, it should be noted that it is still possible that network partitioning may occur and therefore the network connection may not be continuous during the simulation.

- All mobile nodes can adjust their transmission power level at different ranges.

- Each node is fully participating in the routing protocol of the network. Particularly, it is also assumed that each of these participating nodes will be willing to forward packets to other nodes in the network.

- It is possible for a path discovery process to be instigated by any source node with a data packet which requires to be transmitted.

3.6.2 Performance Metrics

Various metrics are used to evaluate the performance of an ad hoc network in terms of its efficiency and superiority. Specifically, this research aims at recording the number of redundant forwarding (or rebroadcasting) of Route Request (RREQ) packets during a path discovery operation. However, simply recording the number of redundant packets is not sufficient as a measure of the efficiency of the scheme, as the aim of initially sending the packet is that it should arrive at its destination. Therefore, it is essential to measure the proportion of successfully transmitted packets, for which metrics for reachability or throughput are required.

A further goal of the proposed scheme is that nodes can use variable-range transmission power levels to save energy and enhance the network's capacity. In addition, using variable-range transmission power will lead to a lower level of interference in the network, resulting in fewer collisions. Packet collision rate is a key measure of the efficiency of any routing protocol or broadcast scheme. Fewer collisions are an indication of more effective use of the bandwidth which is available, assuming that data packets are arriving quickly and safely at their intended destinations.

The broadcast efficiency metrics such as reachability and redundancy can be used to compare broadcast schemes purely in terms of their effectiveness as dissemination techniques [70]. These metrics are particularly useful in situations when warning messages are required to be disseminated through broadcast schemes. However, considering that broadcasting is also used as a fundamental element of the discovery phase of routing protocols, this study incorporates the new route discovery broadcasting scheme into currently available routing protocols. The following widely used performance metrics are then used to evaluate their effectiveness in mobile ad hoc networks:

- **Routing Overhead:** this measures the total number of Route Request (RREQ) packets which are generated and transmitted throughout the simulation period. Where the packets are sent over multiple hops, each single hop transmission is counted as one transmission. When several protocols are being compared, the routing packets' size (in Kbytes), is used as a measure to consider the effects of different sized routing packets when using these protocols.

- **Collisions Rate:** this represents the total number of dropped RREQ packets due to collisions in the MAC layer per unit of simulation time.

- **Normalised Throughput:** this is measured as the ratio of the number of data packets which are successfully received at destinations per unit of simulation time divided by the theoretical throughput (i.e. the number of data packets generated per second). Throughput measures the effectiveness of the network in delivery of data packets, i.e., how efficiently the network is delivering packets from the source to the destination.

- **End-to-End Delay:** this is the average length of time incurred in transmitting data packets from their sources to their destinations. This delay includes all the possible types of delay, which might be due to buffering during route discovery process, queuing at the interface and lags in retransmission at the MAC, as well as propagation and transmission times.

- **Route Discovery Delay:** the average of the time taken between the times when Route Request (RREQ) packets are sent from a source to the time when the first corresponding route reply (RREP) packet is received.

- **Normalised Routing Load:** the ratio of the total packet size of control packets sent to the total packet size of data packets delivered to the destinations. Where control packets are sent over multiple hops, each transmission over one hop is counted as a single transmission. To maintain fairness, the size of the control packets is measured, rather than the number of packets when comparing two or more different routing protocols. This metric is used to measure the usage of available bandwidth.

- **Energy Consumption:** the energy consumed by the broadcast process is measured by calculating the sum of the total energy consumed by each node in sending, retransmitting and receiving the RREQ packet.

3.7 Conclusion

In this chapter, the methodology used for this research has been presented and justified. It has described and explained the routing protocol (AODV) employed to implement the route discovery techniques presented in this study, together with the existing cross-layer approaches and the approach selected in this work. It listed the system modelling techniques and discussed them in relation to its simulation approach. After that, the energy consumption model used in this work was explained and discussed. The NS2 simulator employed to carry out the performance evaluation of the designed broadcasting algorithm has also been briefly described, together with the reasons for the selection of simulation as the performance evaluation tool for the routing protocols in this research. Finally, certain assumptions that apply throughout the work were listed, together with the metrics used to compare the performance of the proposed algorithms with the existing ones.

Chapter 4

Broadcasting Over a Power Control Based Topology Structure

4.1 Introduction

Broadcasting is a fundamental and effective mechanism used for important applications in Mobile Ad hoc Networks (MANETs) such as route discovery, disseminating warning messages and other network services [199]. In on-demand routing protocols, e.g. AODV [57] Route Request (RREQ) packets are propagated by broadcasting them throughout the network seeking a destination in an approach to route discovery referred to as *simple flooding* [22]. Thus, in this process, an RREQ packet each is rebroadcasted (or forwarded) once by each receiving node it arrives at until it reaches its destination node. Although this method of propagation is simple to implement and guarantee high reachability, it can lead to redundant retransmissions of RREQ packets throughout the network, which causes contention, packet collisions and ultimately wastes limited bandwidth and energy.

Energy efficiency has attracted much attention in recent years. In MANETs every node acts as both a router and host and this dual function is vital for network performance. However, it increases the energy expenditure of nodes and this has led to many studies aimed to reduce it. Many approaches have proposed improving flooding performance by using schemes that reduce the number of redundant messages. However, little work has so far been done to determine the merits of a hybrid approach that combines the desirable features of both controlling the transmission power and reducing the number of retransmissions.

In this chapter, an energy-efficient route discovery broadcasting scheme is proposed using two different approaches that collaborate to reduce overhead and conserve energy consumed per broadcast. 1) The first approach uses a cross-layer technique that controls transmission power dynamically based on local node density information. This technique constructs a self-organised topology structure that uses lightweight variable-range beacons to form and maintain this structure. 2) The second approach utilises local one-hop information that is provided by this topology structure and enables a node to estimate its location for making a smart forwarding decision without relying on a GPS positioning system or distance measurements. Both approaches adaptively adjust the transmission power level and reduce the overall number of retransmissions. This, in turn, reduces the overall energy consumed in the broadcast during the route discovery process.

Using an NS2 simulation, it has been shown that a reduction in the transmission power does not result in any deterioration in the connectivity of the network, but it can and improves the broadcasting efficiency during the route discovery process, and eventually improves the overall network performance. The next section explains the construction of the topology. In Section 4.3, a new energy efficient adaptive forwarding algorithm is proposed, which is evaluated in Section 4.4. Finally, Section 4.5 summarises and concludes the chapter.

4.2 Topology Construction

One classic way to enable a service to be provided on mobile ad hoc networks is to establish a topology management structure [42] To maintain this structure during the network's lifecycle, beacon packets (Hello) are exchanged and small amounts of information are stored on the nodes. This builds a bank of information regarding the topology structure, which can be exploited and used as a reference by the higher level services such as routing.

Topology construction, the initial step of topology control, is an important means to ensure the energy efficiency of a wireless ad hoc network. It involves deciding the transmission power level that supports a desired property (e.g. connectivity) by exploiting the ability of nodes to adjust their transmission power. The aim of controlling topology in ad hoc networks is to reduce the energy consumed by each node by conserving transmission power and by curbing the likelihood of interference, collisions and thus, redundant retransmissions [200].

Typically, in a MANET network mobile nodes are randomly distributed meaning the density of the nodes varies in different regions. In higher densities less transmission power is needed to communicate. Therefore, nodes in a dense zone should use a low transmission power range to decrease the level of radio interference amongst nodes in the network, and hence conserve energy. In contrast, to maintain connectivity, nodes in a sparse zone should use a relatively high transmission power range. To adapt the transmission power of the node, and immediately react to topology changes, there are two questions that need to be addressed:

- *How to determine node density as either sparse or dense?*
- *How should a node obtain its topology information?*

4.2.1 Node Density

The number of nodes in a region of an ad hoc network is often referred to as its density and has been defined as the number of neighbours located within the transmission range of a node, or the total number of nodes within that area [201]. Density is one of the key parameters in the context of ad hoc networks together with node speed, pause time, network size, and the number of traffic sources [202]. The behaviour of such a network can be influenced in two ways by its density: if there is a high population of nodes in an area this can lead to bandwidth becoming congested and collisions among the packets. Conversely, if an area is sparsely populated, with few nodes, this tends to lead to poor coverage [22]. Moreover, an increase in the density also results in higher overall power consumption and reduces the efficiency of the network [202].

Network node density for the whole network may be considered in terms of either physical density or connectivity density [45]. It is clear that network physical density relates to the number of nodes within a particular area, and how close they are to one another. On the other hand, the connectivity of the network, in terms of the communication range of nodes within its scope also has to be considered [21, 44]. Therefore, it can be said that density of a network is determined not only by how many nodes are present in a specific area, but also their connectivity. Even where there is quite a small number of nodes, a small area may have a high communication range among them which may make them effectively dense. Thus, the node density could be considered as sparse regardless of whether the transmission range is high or low. Thus there have been extensive studies and discussions [203, 204] on the problem of connectivity density, to determine how the connectivity of network is related to the density among neighbouring nodes. Therefore, density can be defined according to the transmission range of the nodes.

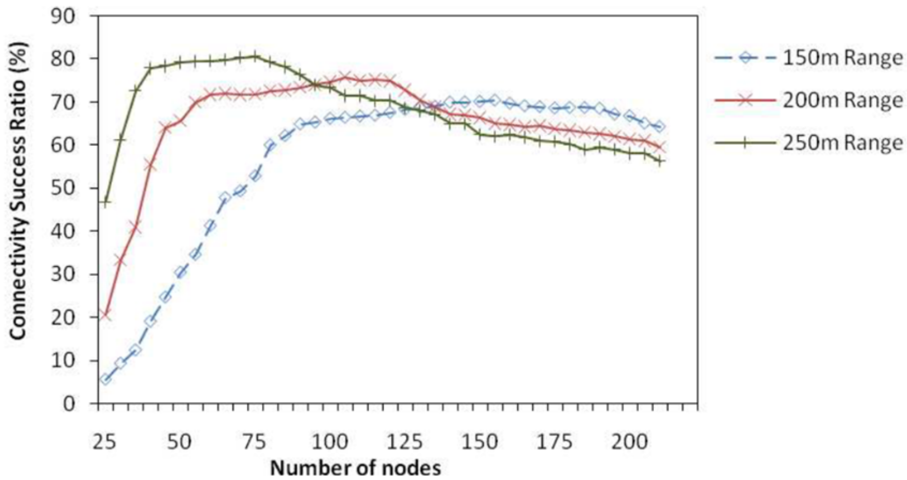


Figure 4.1: Connectivity success ratio vs. network density.

Concerning the first question in Section 4.2 on how to determine node density, a probability-based broadcast algorithm for the route discovery process has been proposed in [92], which simply adapts the forwarding probability value P at each node based on the node density, which ensures that nodes in a sparse density region forward with a higher probability. Figure 4.1 [92] illustrates the relationship between connectivity success and network density for a conventional AODV routing protocol, when the number of nodes located in a fixed area of 1000 m^2 is varied, for different transmission power ranges. It can be seen in Figure 4.1 that the most successful maximum connectivity is achieved when there are 70, 115 and 195 nodes for transmission power ranges of 250m, 200m and 150m, respectively. The average number of neighbouring nodes ($N_{neighbour}$) at each maximum connectivity for all scenarios is theoretically expressed by Equation 4.1 [93]. Thus, on average, a node is considered to be located in a dense network when its number of neighbours is equal or greater than 14 and in a sparse network when there are fewer than 14 neighbours.

$$N_{neighbour} = (N - 1)\frac{\pi R^2}{A} \tag{4.1}$$

where:

N is the number of mobile nodes deployed in the network,

R is the range of transmission power of each node,

A is the area of the network topology.

In another study [21], the author proposes a dynamic counter-based broadcast algorithm. It uses the same Equation 4.1 to determine node neighbour density and alter the counter threshold value (Cth) accordingly. Two different scenarios are examined, both of which share some common parameters, which include: the same network area A (1000 m^2), a traffic generation pattern of 10 $packets/sec$ transmitted by each node during the entire simulation period and a maximum speed for each node of 8 m/sec. In the first scenario, the transmission range R is set at 250m and it is set as 150m for the second one. This study found that the average number of neighbours of each node was around 7 in both the studied cases (a 93-node network topology with transmission range of 150m and a 35-node network topology with a transmission range of 250m). Thus, on average, a node is regarded as being in a sparse network when its number of reachable neighbours is ($n <= 7$) and otherwise it is considered to be in a dense network.

In [45, 205] the authors suggest a power control scheme called (DP-AODV) that attempts to reduce the level of interference and improve throughput and so decrease energy consumption in AODV. It dynamically adjusts the transmission power range at a node based on its neighbour density. Three levels of node density are considered: Low (when the number of neighbours is less than or equal to 7), Medium (when the number of neighbours is more than 7, and less than 15) and High (when the number of neighbours is more than or equal to 15). A degree of context awareness is inherent in it, as it requires knowledge of the count of its neighbour and distance calculation (by using GPS). However, GPS consumes a significant amount of battery power which undermines the goal of power conservation. Moreover, the authors do not specify how to calculate the neighbour density, and there are no restrictions on RREQ packet rebroadcasting in DP-AODV. This means that unnecessary broadcasting can occur, which in turn would lead to higher overheads and more power consumption.

In the implementation of this study, the findings of the two previously mentioned studies [92, 21] were used to determine the node density and adjust the transmission power accordingly. Thus, if there are seven neighbours or fewer, then the density is considered Low, and if there are 14 or more, the density is considered High. Additionally, this work considers node density to be Medium when the number of neighbours is more than 7, and less than 14. Three levels of transmission power are proposed for different densities (see Table 4.1). The idea behind selecting these three levels of transmission power is to adapt the transmission range to a certain extent, which involves maintaining a balance between the number of hops (number of relay nodes situated between the source and destination node) and the transmission power used, while maintaining connectivity.

Table 4.1: Transmission Power Levels

$PowerLevel$	$Range$	$NeighbourDensity(n)$
High	250m	$n <= 7$
Medium	200m	$7 < n < 14$
Low	150m	$n >= 14$

4.2.2 Obtaining the Neighbouring Information

To tackle the second question in Section 4.2 on how should a node obtain its topology information, the strategy involved implementing a simple decentralised mechanism by which enables a node to sense the density of its neighbourhood. Specifically, the nodes initiate a neighbourhood discovery phase as soon as they are deployed. The goal of this phase is to let each node construct a list of its one-hop neighbours. This is achieved by broadcasting a Hello message every *hello_ interval* second. This Hello message contains a time-to-live (TTL) value of 1, which means it cannot be rebroadcasted outside the neighbourhood of the node and prevents it from generating excess overhead in the network. Although AODV is fundamentally a reactive protocol, it employs Hello messages to check that a link is still valid. To do this, two parameters are used: *allowed_ hello_ loss* and *hello_ interval*. Hello messages are transmitted at a periodic interval of one second, allowing a maximum latency of 2 seconds for each message; this has been established as the optimal value for the *allowed_ hello_ loss* parameter [206].

The neighbour information regarding neighbour density is acquired by a neighbour count function in the AODV protocol, which increases the neighbour count for each received Hello message from every unique node *id*. The number of Hello messages received from different neighbours at a node determines if the node is in a High, Medium or Low density region, and the node adjusts the transmission power accordingly.

4.2.3 Hello Message Format

The Hello message is an example of a popular control message, that reveals the existence of its neighbours and provides basic control information required for network operation. In this work, Hello messages are employed not only for neighbour sensing and neighbour information exchange, but also for determining the region's density level based on knowledge of the transmission power level used. In this work's implementation, reserved fields in the Hello message format in the AODV protocol have been utilised and modified to include Transmission Power Level (Pt_{Level}) and node Status (*Status*) fields. The Pt_{Level} field records the node's transmission power level (High, Medium or Low), and the *Status* field records the flag of node's Status (a forward or non-forward node) as shown in Figure 4.2. Further explanation of the benefits of these two fields will be provided at a later stage in this chapter in Section 4.3.

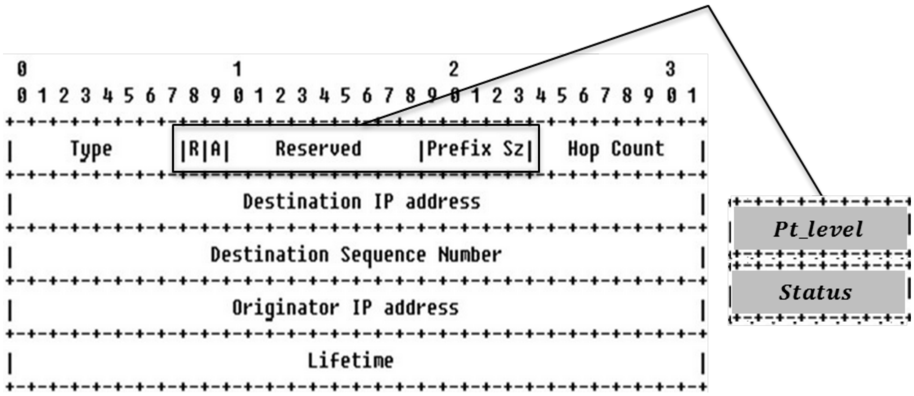


Figure 4.2: The modified form of the HELLO message format in AODV

4.2.4 A Cross-layer Approach in Power Control

A key issue in designing and constructing the proposed topology is to ensure effective transmission power control. If nodes in the network have the ability to adaptively adjust their transmission power, they can exploit network capacity more efficiently, and more energy saving during a broadcast can be achieved [147]. In this work's implementation, a cross-layer design technique is used to allow the lower layer (e.g. Physical-layer) to access data from the higher layer (e.g. Routing-layer). The routing layer is modified so that the neighbour count parameter in the routing layer can be accessed from the lower layer as shown in Figure 4.3.

In NS2 the *common/packet.h* file includes a packet header's size and this is a common header which can be invoked from anywhere in the layer protocols. Each packet in NS2 use this header to exchange information among objects in the simulation (see Figure 4.4). The (*num_ of_ nbrs*) field in the *common/packet.h* file is added to record the number of neighbours calculated by the neighbour count function in the AODV protocol. After the *num_ of_ nbrs* parameter is calculated in the

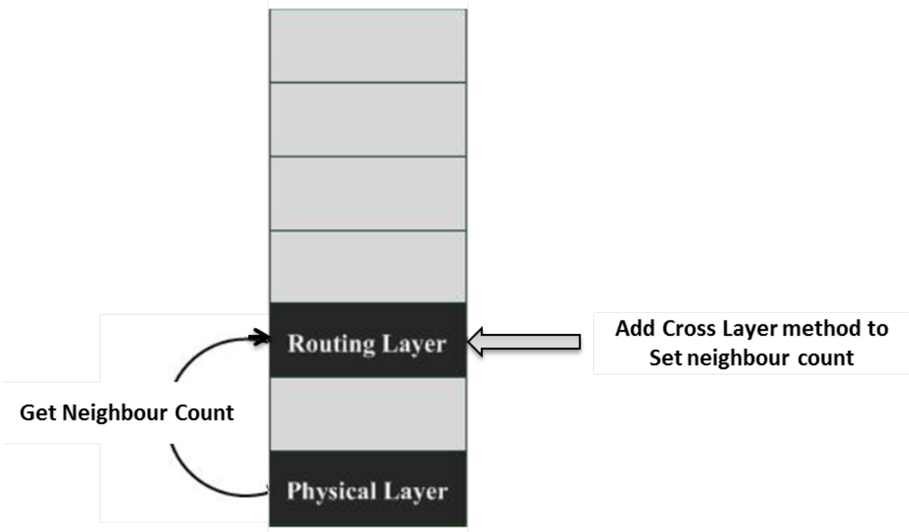


Figure 4.3: Cross layer approach to access neighbour density parameter.

aodv/aodv.cc file, the Hello packet's *common header* will be constructed to set the *num_ of_ nbrs* parameter value at the Network-layer. After that, when the Hello packet is received at the Physical-layer, the *common header* will be constructed again in the *mac/wireless-phy.cc* file to get the *num_ of_ nbrs* parameter value and the transmission power adjusted accordingly. It is important to note that the default value of the *num_ of_ nbrs* field is 0, which means that packets with 0 value will be sent using the default (High level) transmission power range (the case of Data packets).

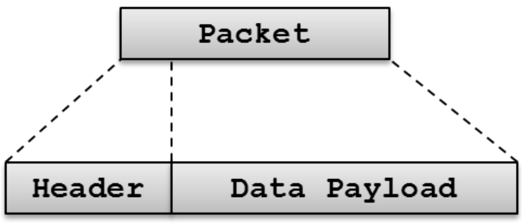


Figure 4.4: Packet format in NS2.

The next source code will be directly imported from a *ns/mac/wireless-phy.cc* file:

```
void
WirelessPhy::sendDown(Packet *p){
.
   // assigning transmission power according to neighbours count
   struct hdr_cmn *ch = HDR_CMN(p); // access packet's header
   int num_of_nbrs = ch->num_of_nbrs; // number of neighbours
   {
      if(num_of_nbrs <= 7)
         Pt_ = 0.2818; // transmit range of 250m (High Level)
      if(num_of_nbrs > 7 && num_of_nbrs < 14)
         Pt_ = 0.2417; // transmit range of 200m (Medium Level)
      if((num_of_nbrs >= 14)
         Pt_ = 0.2019; // transmit range of 150m (Low Level)
   }
.
p->txinfo_.stamp((MobileNode*)node(), ant_->copy(), Pt_, lambda_);
channel_->recv(p, this);
}
```

It should be noted that the transmit power ($Pt\_$) values in the *wireless-phy.cc* file denote the maximum transmitter-receiver separation such that a packet will be decoded correctly.

4.2.5 Variable Range Beacons

In much of the reviewed literature, the algorithms that require the neighbourhood information for any rebroadcast decision nodes exchange periodic Hello messages using a fixed high transmission power range. As a result, all of these beacon signals have the same fixed transmission radius [207]. However, this approach is not scalable and induces considerable contention and collision especially in high density networks.

Maintaining updated information of the network topology is an essential requirement in any network management system [208]. This is a relatively straightforward in fixed wired networks, where changes in topology occur only infrequently (mainly due to the failure of a node or link, or when a node is added or removed) [209]. In a wireless mobile ad hoc network, it is essential that the management system can monitor and react to the frequent topology changes resulting from the movements of nodes. However, exchanging of topology information regularly can result in a considerable signalling overhead, as well as leading to congestion in wireless links with low bandwidth, and reducing further the nodes' limited battery life. Consequently, it is critical to select the most appropriate mechanism to collect or manage topology information.

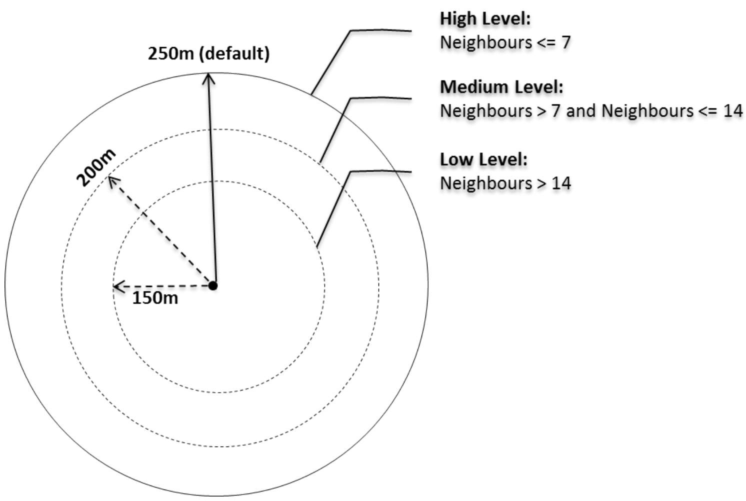


Figure 4.5: Levels of *hello message*'s transmission range

In the implementation in this work, each node in the network transmits a Hello message periodically using variable-range power based on the local neighbourhood density (see Figure 4.5). The main objective of this stage is to group the network's nodes into different groups based on their power levels. As a result, a new topology formation will be created where nodes are categorised into different groups of power level based on their region densities (see Figure 4.6).

Variable range transmission power has been proposed in a manner to limit adverse effects of high transmission power while maintaining connectivity. Therefore, the effectiveness of control over the transmission power of Hello packets is a significant feature in designing the proposed topology structure. Additionally, when nodes

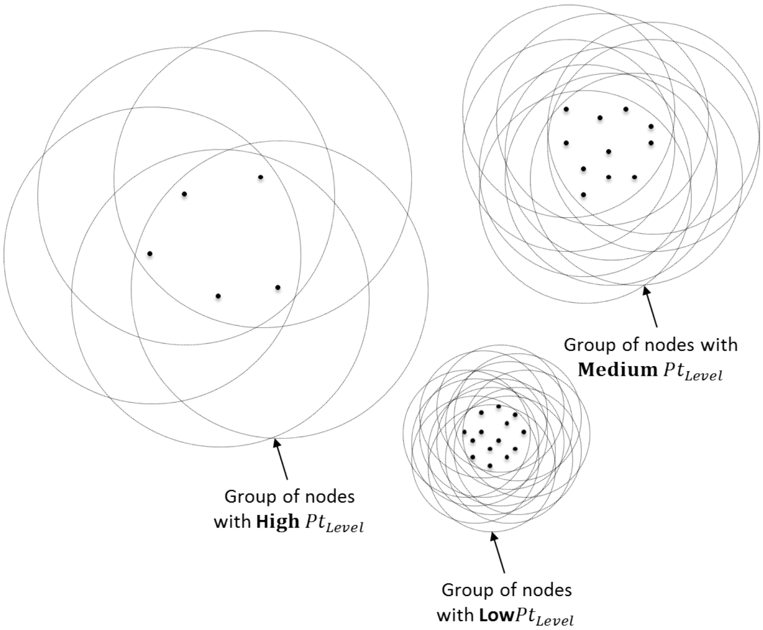


Figure 4.6: Group the nodes into different power level.

in the network can dynamically adjust their transmission power levels (Pt_{Levels}), it helps to reduce duplication of packet reception and to reduce the power consumption when packets arrive at receiving nodes [147]. Moreover, limiting the number of nodes that can hear a broadcast reduces contention among nodes in the medium, increases the utilisation of the medium, and reduces the likelihood of packets colliding [91]. Therefore, avoiding collisions will result in a bandwidth and energy gain. For a functionality testing and to ensure that the physical layer adjusts the transmission power for each packet, a modification code has been implemented in the *trace/cmu-trace.cc* file in NS2. Therefore, we can show the power level of each transmission at the trace file (the code can be found in Appendix A).

Once an energy-efficient topology structure is discovered, it can be maintained at a low cost (low interference and collision, thus low energy consumption). It can deal with high mobility and could rapidly react to topology changes (relying only on local one-hop information). The next section will discuss a new route discovery broadcasting algorithm that works over the constructed topology.

4.3 An Energy Efficient Adaptive Forwarding Algorithm (EEAFA)

EEAFA is a new route discovery forwarding scheme based on the AODV routing protocol. It is designed for a high density and high mobility network environment, and it works over the constructed topology structure proposed in Section 4.2. The main objective is to design a new RREQ forwarding scheme that achieves connectivity using local one-hop information provided by the constructed topology structure and make smarter forwarding decisions.

As mentioned in Chapter 2, one classification of broadcasting systems distinguishes source-dependent and source-independent techniques. In a source-dependent (referred to as sender based) technique, it is the other node that determines whether to forward a message or not. This other node can be the previous relay node, or a cluster head. In this work's implementation, the broadcasting system used in EEAFA is a local decision based (referred to as receiver based), where the decision making of each node is on its own. This decision is whether to rebroadcast (or forward) a particular RREQ message or not.

4.3.1 A Forward Node Determination

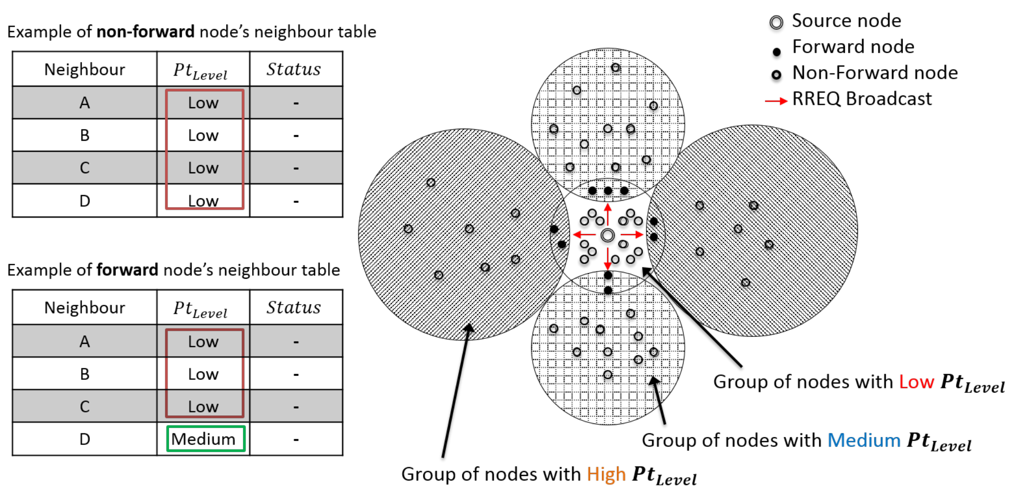


Figure 4.7: The proposed RREQ forward node determination.

The choice of the forwarding node is a critical element in the design of the proposed algorithm. In the proposed EEAFA, the forward node determination process is considered as a receiver-based system, where each host autonomously determines whether or not it should forward an RREQ broadcast packet. In this work's implementation, the algorithm classifies mobile nodes in the network as having a forward or non-forward node status based on the Pt_{Level} information in the Hello message that the node receives from neighbours. It is important to note that if nodes have different values of Pt_{Level} from those in their neighbour table, they are more likely to forward (or rebroadcast) RREQ packets, whereas nodes which have a similar value of Pt_{Level} to those of their neighbouring nodes (see Figure 4.7) are likely to be non-forwarding nodes. Therefore, any rebroadcast by the non-forward node needs to be excluded, to prevent early redundant rebroadcasting and lower the overhead incurred by RREQ routing packets on the entire network. Thus, the selection of which node is a forward node and which is not is determined at an early stage, on the basis of node *Status* which is obtained from (*Algorithm* 4.1).

Algorithm 4.1 Getting Status

Input:

t - transmission level of the node receiving RREQ message.

Pt_Level - transmission level of neighbour.

Output:

Status - node status (forward/non-forward).

```
function GetStatus(t)
i = 0;
while Neighbour list is not empty do
    if Neighbour[i].Pt_Level ≠ t then
        return forward;
    end
    i++;
end
return non-forward;
end function
```

A node that can receive Hello packet from nodes with a different level of its Pt_{Level}, is most likely to be located between groups of different power levels and is thus classified as a **forward**; otherwise it is classified as a **non-forward** node. The idea is to restrict the number of retransmissions to a small set of neighbouring nodes, rather than deploying all the nodes in the neighbourhood. To keep this set as small as possible, the nodes are selected (in terms of one-hop radio range) which will cover most of the network region. The nodes in this set are required to forward the RREQ packet, thus bridging groups of nodes which have different Pt_{Level}. It is intuitive that a node that has a similar Pt_{Level} to its neighbours will probably be situated within the same power level group. This means that there is a high probability that all its neighbours may have received an RREQ broadcast packet. In contrast, a node which is able to receive Hello packets from a different Pt_{Level} will be most likely situated at a considerable distance from its group centre, and is likely to exist between groups of different power levels (in the border of its group's transmission range). However, to maintain the connectivity of the network, the restriction on RREQ forwarding does not apply to a node that is located in a highly-sparse region (e.g. all nodes have 7 neighbours or fewer). The proposed RREQ forwarding process will be presented in detail in the next section.

4.3.2 RREQ Forwarding Process

The route discovery process operates over all nodes, including the source, intermediate and destination nodes. The operating procedure of the route discovery process of the proposed EEAFA scheme is as follows:

The same Source node process is employed as that used in the AODV protocol [57]. When the source node does not have a fresh path, to the desired destination, it promptly starts up the route discovery process by broadcasting a Route Request (RREQ) packet.

Upon an Intermediate node in the sender transmission range receiving the RREQ packet, it inspects the received packet with the proposed mechanism shown in the flowchart in Figure 4.9 (Phase 2), and behaves as follows:

- If the packet has been received more than once, the packet is discarded. This is done by checking the *id* of the received packet against a log of recently received packet *ids*.
- If the time-to-live (TTL) of the received RREQ packet is equal to zero, the packet is discarded.
- If the node receives the RREQ packet for the first time, the node determines its own *Status* whether it is a Forward node or not.
- If the receiver node has neighbours with different values of Pt_{Level}, it decides that it is a Forward node and transmits RREQ packet. Otherwise, it discards it.

However, where all neighbours have a similar Pt_{Level} value to the receiver node, and no neighbour is declared as a forward node in the *Status* field (can be got from *Algorithm* 4.2), the RREQ rebroadcast restriction is ignored to avoid the early die-out of the RREQ broadcast packet and to avoid any collapse.

Algorithm 4.2 Do all neighbours have non-forward status

Input:

Status - status of the neighbour node.

Output:

Flag - all 1-hop neighbours are non-forward (true/false).

function GetFlag(t)

Status: status of the neighbouring node.

$i = 0$;

while *Neighbour list is not empty* **do**

  if *Neighbour[i].Status = forward* **then**

    return false;

  end

  $i{+}{+}$;

end

return true;

end function

In a Destination node where the RREQ packet has arrived at either the desired destination or an intermediate node with a valid path to that destination, a Route Reply (RREP) packet is unicast in response by the receiving node, along the reverse path which was set up at intermediate nodes during the process of route discovery. Algorithm 4.3 shows the pseudocode of the proposed EEAFA.

Algorithm 4.3 EEAFA

Input:

m - incoming RREQ message.

r - node receiving RREQ message.

s - status of the node receiving RREQ message (by *Algorithm 4.1*).

f - flag of the all neighbours are non-forward (true/false) (by *Algorithm 4.2*).

Output:

```
function RREQ_Forwarding(m, r, s, f)
if m is received for the first time then
    update s;
    calculate f;
    if s is a forward node then
        transmit m;
    end
    if f is true then
        transmit m;
    end
    else
        r → drop message m;
    end
end
else
    r → drop message m;
end
end function
```

4.3.3 Power Control of the Reverse Route

Bidirectionalitly of links is assumed in the AODV routing protocol [57], where Route Reply (RREP) packets reverse the route followed by the RREQ packet. However, changing transmission power levels in this work can create unidirectional links between nodes in the network. This can occur when the power level of a node is high enough for another node to hear it, but not vice versa, giving rise to the *Asymmet-*

ric Link Problem [59]. However, since nodes in this work's implementation operate

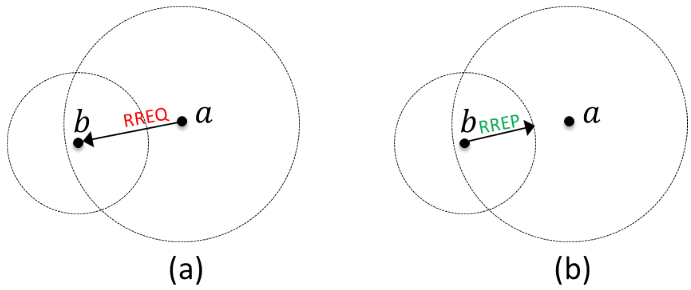


Figure 4.8: Asymmetric links during route discovery.

on variable-range transmission power, asymmetric links can occur regularly. This was observed in simulation studies [210] where an unacceptable proportion of data packets was lost by the routing layer when the proposed EEEFA scheme was implemented on the NS2 simulator. It was negatively affected by the packet delivery ratio. As illustrated in Figure 4.8, node b can hear a Hello message from node a, but node a cannot hear the response from node b. Asymmetric links can result in complete failure of communication between nodes, as node b can receive RREQ packets from node a, but the RREP packets it sends in response may never reach node a. This may result in many data packets being lost, reducing network throughput.

To address this problem, the RREP process is ameliorated to make a high mobility node get connected via a reverse route as much as it can. Specifically, when the destination or an intermediate node has a fresh route to the destination, it unicasts a RREP packet to the next-hop node using the high Pt_{Level} (Default level). This packet travels along the reverse route which was previously established at intermediate nodes during the path discovery process. The source node then begins to send data to the destination through the neighbour node which was the first to respond with a RREP. By selecting a High Pt_{Level} to unicast RREP packets, the algorithm guarantees a high connectivity through data packet transmissions, especially in high mobility network scenarios.

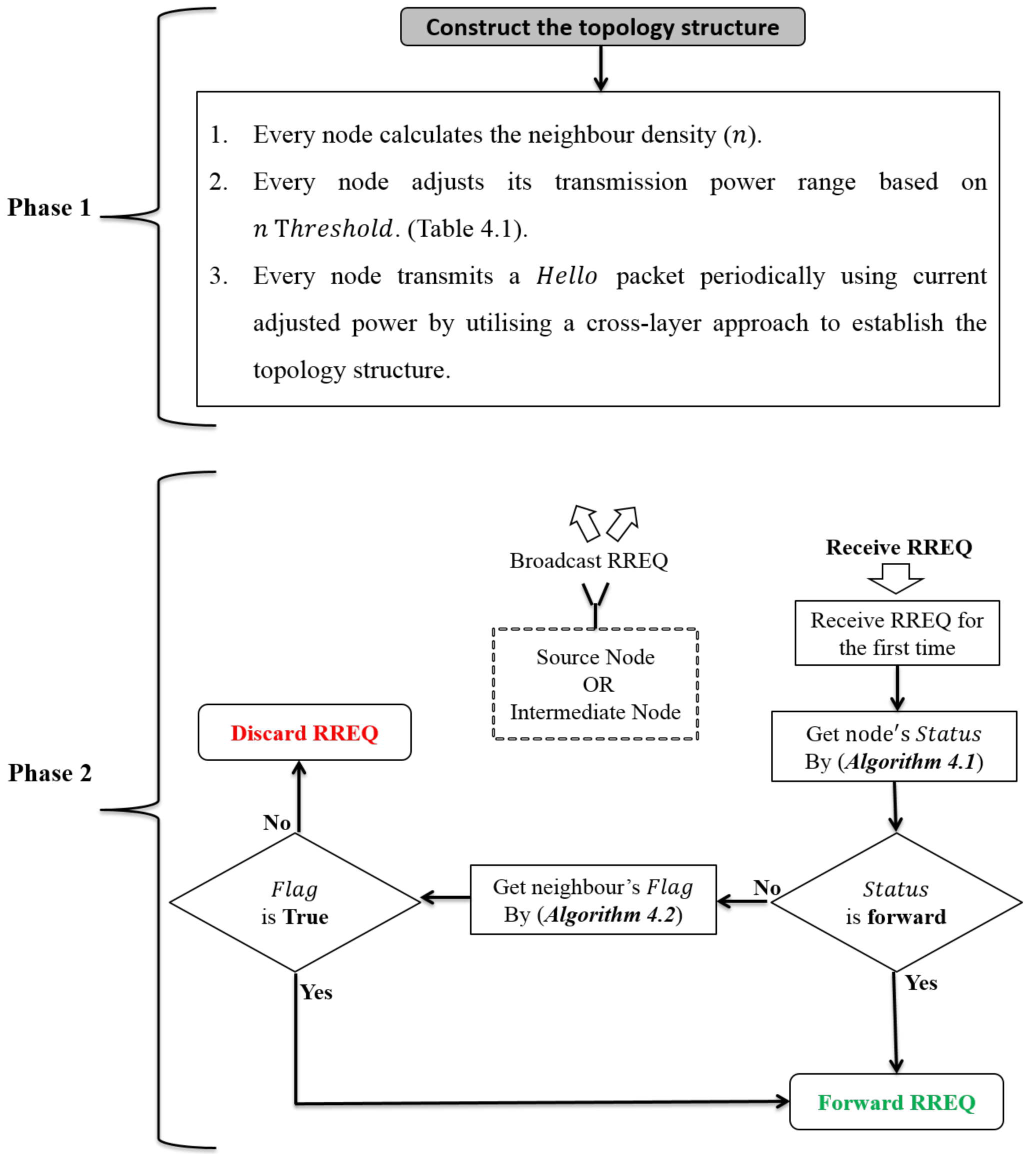


Figure 4.9: Flowchart of the EEAFA Scheme.

When a node employs its knowledge to decide whether or not to participate in forwarding a RREQ or not, two objectives are attained. Firstly, as only specific nodes will participate in rebroadcasting RREQ packets the power resources of the nodes will be conserved. Secondly, this avoids higher control overheads and congestion, which would degrade the performance of the whole network. In the next section, the proposed forwarding algorithm will be evaluated over different conditions (used in a number of studies [18, 21, 44, 45]) using NS2 in order to see how well the algorithm works.

4.4 Performance Evaluation

For performance evaluation of the EEAFA algorithm, a modified version of the conventional AODV routing protocol incorporating the functionality of the EEAFA algorithm was implemented in the NS2 simulator [181]. This modified version of the AODV is referred to as (EEAFA-AODV) from here on.

4.4.1 The Compared Protocols

In this section the simulation results of the previously introduced EEAFA-AODV are compared with those for the following AODV and TB-AODV routing protocols:

AODV: In order to have a performance benchmark, we have performed simulations of the simple flooding protocol AODV [57], which uses the simplest form of broadcasting a packet (every node rebroadcasts fresh packets with probability equal to 1). This method permits each node to retransmit the RREQ control packet to its neighbours only if it has not previously received this copy of the RREQ. Simple flooding has the main benefit that it is always able to find the shortest route between sources and destinations. This is because the topology packets have travelled along every possible route in parallel. The main weakness of this approach is the risk of triggering a large number of packets being forwarded in MANETs, thus degrading network performance. This leads to excessive redundant rebroadcasting (in which some nodes may receive the same packet several times), as well as contention and collision, which increase power consumption. The standard AODV routing protocol was used for the comparison to show to what extent the proposed algorithm can successfully overcome the drawbacks related to simple flooding while maintaining the functionality of AODV.

TB-AODV: Topology-Based AODV (TB-AODV) is a modified version of the conventional AODV which uses a simple flooding approach [22]. In TB-AODV the source code of AODV in NS2 was modified to implement the proposed topology structure [210] constructed in Section 4.2, where *hello messages* and RREQ packets are transmitted with variable range transmission power. In the TB-AODV there is no restriction on RREQ forwarding (simple flooding). TB-AODV was used for the comparison to show the effects of the RREQ forwarding restriction used in the proposed EEAFA-AODV based on the local information provided by the proposed constructed topology structure in this chapter.

4.4.2 Impact of Network Density

The effect of network density on the performance of the three protocols was compared by varying the density in terms of the number of nodes deployed over a 1000 m^2 area in each simulation scenario. Each node moves with a maximum speed of $5m/sec$ with a pause time of 0 *sec* (dynamic network). For each simulation trial, 12 *connections* are randomly selected. The source node generates data packets (CBR 512 bytes) at a rate of 4 packets per second.

4.4.2.1 Routing Overhead

The performance of the three routing protocols was compared in plotting routing overhead versus network density. It can be seen in Figure 4.10 that, in a sparse network with between 25 and 75 nodes), the overhead generated by EEAFA-AODV is much the same as that generated by AODV and TB-AODV. This is because the majority of the mobile nodes in EEAFA-AODV are permitted to rebroadcast RREQ packets they receive when the network density is sparse, in order to improve connectivity. In contrast, EEAFA-AODV performs better than the other protocols in a dense network, reducing the routing overhead by up to 70%.

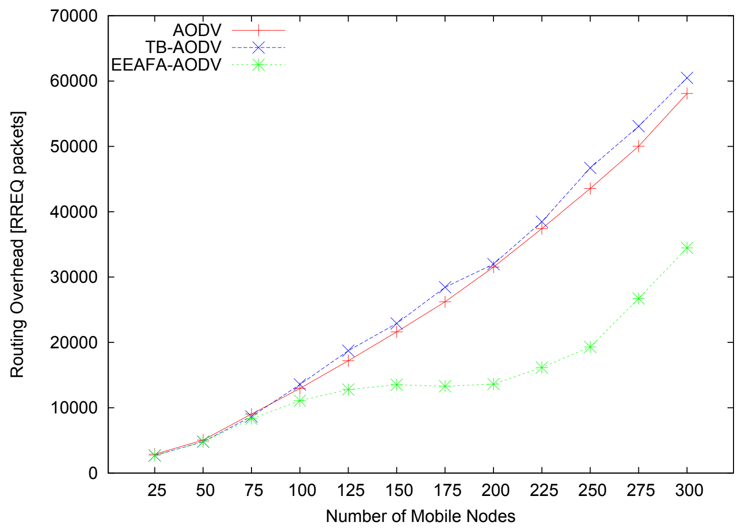


Figure 4.10: Routing overhead vs. network density.

It is also worth mentioning here as shown in Figure 4.10, that TB-AODV generated more overhead compared to the AODV. In AODV there are fewer link breaks for a longer transmission range with a dynamic mobility network, which generate fewer control packets. Whereas, TB-AODV uses a variable range power in RREQ packet dissemination, which increases the number of hops between source and destination node. Therefore, TB-AODV suffers from the mobility of the nodes which cause more breaks and repairs to the links, and hence generate more RREQ packets, especially in the absence of forwarding restrictions.

However, as shown in the figure when the network density is substantially increased (e.g. 250, 275 and 300 nodes) the RREQ overhead generated by EEAFA-AODV increases dramatically. The reason is that forwarding decisions at a node are made according to the existence of a different power level in the neighbour table. Therefore, the probability of a node with a forward *Status* is uncommon in a highly dense network, where all neighbours have the same adjusted transmission power level (e.g. all nodes have more than 14 neighbours). In this case, the RREQ rebroadcast restriction has been temporary ignored to avoid early die-out of the broadcast packet and avoid any collapse (see Figure 4.9).

Since node information is piggybacked on Hello messages, the EEAFA-AODV and TB-AODV protocols utilise reserved fields in the Hello packet in the AODV protocol. Consequently, there is no need to measure the routing overhead in terms of bytes where all the three protocols have the same Hello packets size.

4.4.2.2 Collision Rate

It can be seen in Figure 4.11 that there is a dramatic increase in the collision rate for both AODV and TB-AODV as the network density is increased. The reason this occurs is that when the number of nodes rises, there is a proportional increase in the number of possible forward nodes. Thus, the performance of EEAFA-AODV is clearly superior to that of TB-AODV and AODV in a relatively dense network. Fewer collisions occur and performance remains stable at around 70% which is superior to the performance of the other two protocols. However, in a high density network (e.g. 250, 275 and 300 nodes) the collision rate for EEAFA-AODV dramatically increases which is a reflection of the volume of RREQ packets being rebroadcast to deal with the discarding restriction that was mentioned in Figure 4.10.

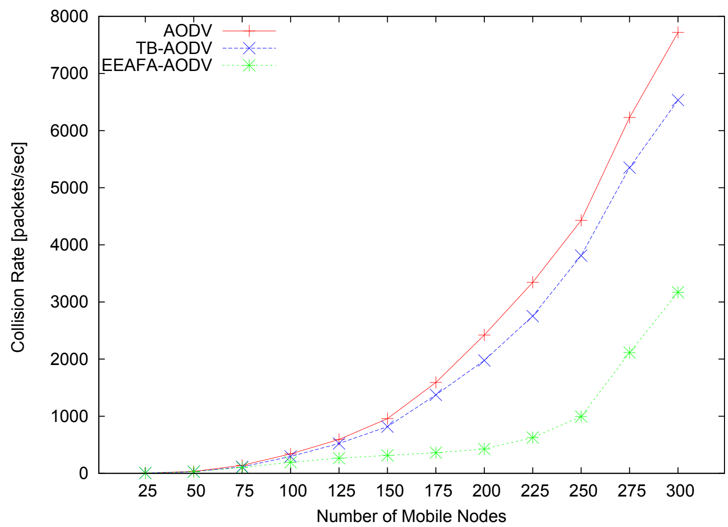


Figure 4.11: Collision rate vs. network density.

As they are broadcast packets, RREQ packets are only transmitted by the node when it has sensed that the communication medium is idle. This means that the transmission of such packets does not accord with the request-to-send (RTS) and clear-to-send (CTS) protocol of the MAC layer [19]. This means that the presence of more nodes, will increase the likelihood two or more nodes may transmit packets simultaneously, with a subsequent increase in collisions.

However, since EEAFA-AODV is designed to work over a power control based topology structure and there is a restriction on the RREQ forwarding, this leads to some of the nodes suppressing broadcasts, thereby leading to fewer of packets travelling in the network. This means, RREQ packets are transmitted using variable range transmission power which inhibits packets from being interfered with across the medium, and reduces the average collision rate.

4.4.2.3 Normalised Throughput

In Figure 4.12 it can be seen that the normalised throughput of the EEAFA-AODV and TB-AODV protocols initially rises as network density rises, but reaches a maximum and then falls with any further increase in the density of the network. This is because, in a sparse network (such as one with only 25 nodes), there is a poor network connectivity, due to network partitions. At a high density, AODV performed worse compared with EEAFA-AODV and TB-AODV. Simple (or blind) flooding in AODV results in excessive redundant retransmissions of RREQ packet triggering broadcast storms which significantly degrade the network throughput, especially when using fixed high range transmission power.

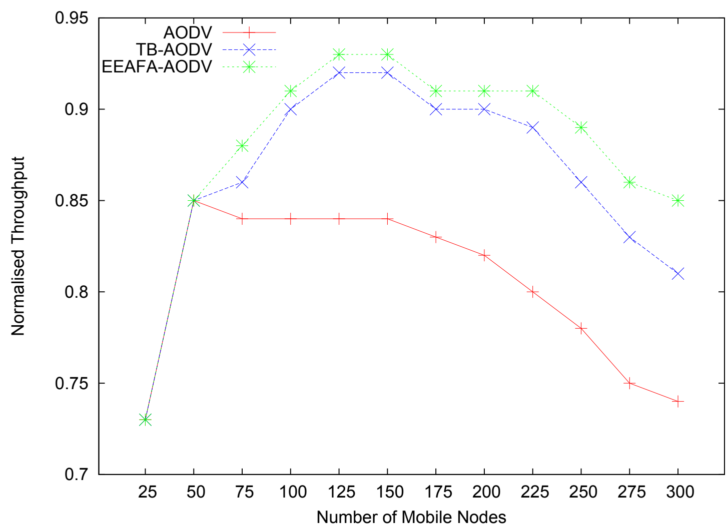


Figure 4.12: Normalised throughput vs. network density.

However, as illustrated in Figure 4.12, when the density of the network increases, the improved performance of EEAFA-AODV over TB-AODV and AODV becomes more marked. Thus, when the network has a high density (300 nodes, for example), the normalised throughput obtained by EEAFA-AODV increases by approximately 7% and 15%, respectively, over the performance achieved by TB-AODV and AODV. This is due to reductions in the number of forwarding nodes together with reduction in the transmission power, which results in lowering the degree of contention and the number of collisions and enables the carrier to be occupied only with the data packets which require to be transmitted. Although TB-AODV applies the same transmission power levels used in EEAFA-AODV, it achieves relatively less throughput compared to EEAFA-AODV. This is because in TB-AODV there is no restriction in RREQ forwarding and all nodes are rebroadcasting received RREQ packets. This generates excessive redundant retransmissions, and contention among neighbours leads to data packets colliding with each other.

4.4.2.4 Delay

It can be seen in Figure 4.13 that, in a relatively dense network, as density increases the end-to-end delays become longer, for all the protocols. This can be explained by the increased likelihood of packets colliding and channel contention as a result of excessive redundant rebroadcasting in a dense network, so that the majority of RREQ packets will not arrive at their destinations. This can increase the time taken for route discovery, and thus the data packets will take longer to travel from the source nodes to their destination.

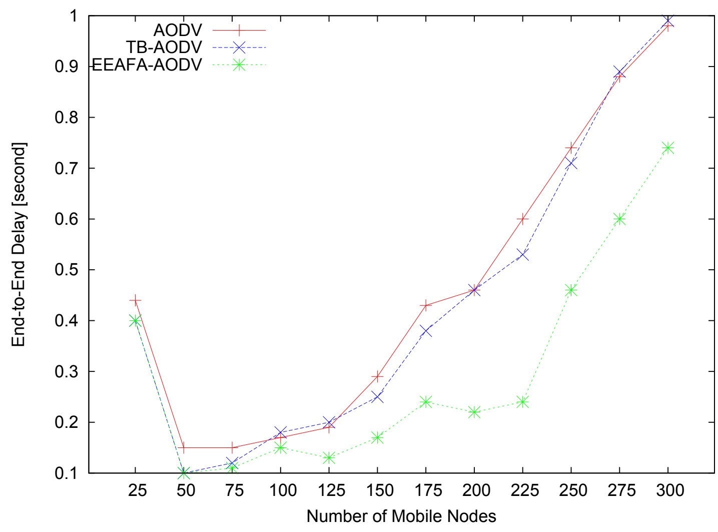


Figure 4.13: End-to-end delay vs. network density.

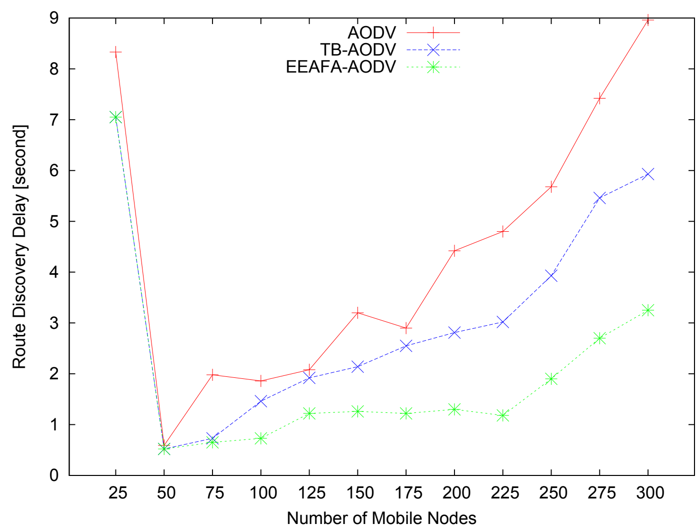


Figure 4.14: Route discovery delay vs. network density.

The graph also reveals that in the scenario where the network is very sparse (e.g. 25 nodes) and poorly connected (i.e. most of the nodes are out of their communication range), there is a prolonged end-to-end delay in each of the protocols, and EEAFA-AODV performs less well than the traditional AODV and TB-AODV protocols. In contrast, at 225 nodes, EEAFA-AODV incurs delays which are around 200% and 150% below those for AODV and TB-AODV respectively. The protocols' performance in terms of delays in route discovery exhibits similar trends, which can be seen in Figure 4.14.

4.4.2.5 Energy Consumption

Figure 4.15 demonstrates the average energy consumption in transmitting and forwarding RREQ packets for all the three protocols. As shown in the figure, as the network density increases, the power consumption for all three protocols also increases. EEAFA-AODV achieves better energy efficiency when compared to the other two protocols. The energy saving of EEAFA-AODV is achieved by the forwarding restriction which adapts the rebroadcasting of RREQ packets to the current status of the node. This helps to reduce unnecessary retransmissions of RREQ packets. Moreover, EEAFA-AODV adjusts the transmission power range of nodes based on the local node's density which helps to reduce transmission power range. This reduces the level of interference, the number of collisions and thus overall power consumed.

We used a column chart type in performance evaluation of energy consumption, to illustrate the comparisons among routing protocols, which is give more observation of the thesis goal.

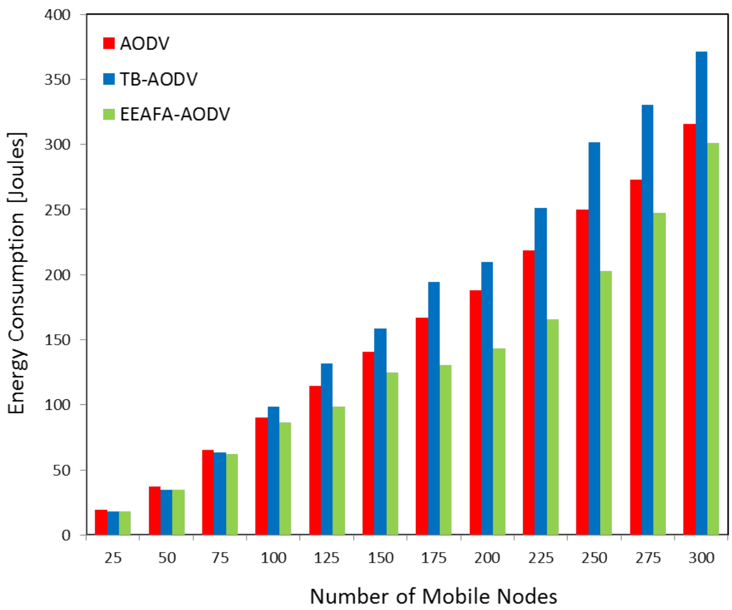


Figure 4.15: Energy consumption vs. network density.

4.4.3 Impact of Node Mobility

In this section, the impact of node mobility on the performance of the three protocols is compared. In order to reduce the impact of node density, the number of nodes in the network is fixed at 100 nodes, which indicates the median value of node density [198]. The aim is to avoid very sparse or dense scenarios and to obtain a general trend for the impact of node mobility on the protocols' performance. A set of simulation experiments was carried out in which the mobility of 100 nodes placed over a 1000 m^2 area was varied by altering the maximum node speed in the network, which was varied from $1m/sec$ to $30m/sec$ with a pause time of 0 *sec* (dynamic network). In addition, to reduce the effect of traffic load, in each simulation scenario the offered load set consisted of only 12 *connections*. Data packets (CBR 512 bytes) were generated by source nodes at 4 packets per second.

4.4.3.1 Routing Overhead

Figure 4.16 shows the effect of the maximum node speed on the routing overhead incurred. It shows that, for each of the studied routing protocols, the routing overhead generated increases along with maximum node speed. This can be attributed to the frequent changes in network topology which occur with higher levels of node mobility. This leads to the generation and dissemination of more RREQ packets because of the need to maintain broken paths or to set up new routes. This extra level of activity increases the total routing overhead. The graph indicates that, across maximum node speed, EEAFA-AODV demonstrates a superior performance to TB-AODV and AODV.

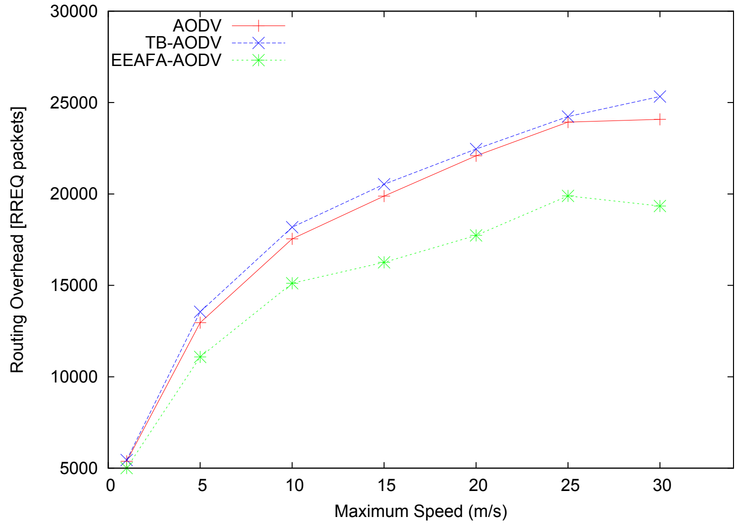


Figure 4.16: Routing overhead vs. node mobility.

4.4.3.2 Collision Rate

Figure 4.17 shows that, for each of the protocols, the average collision rate increases with maximum node speed. This can be accounted for by the increased frequency of broken routes, resulting in more RREQ packets being generated and disseminated. It can also be seen in the figure that there is a significant reduction in the collision rate in EEAFA-AODV when compared with TB-AODV and AODV.

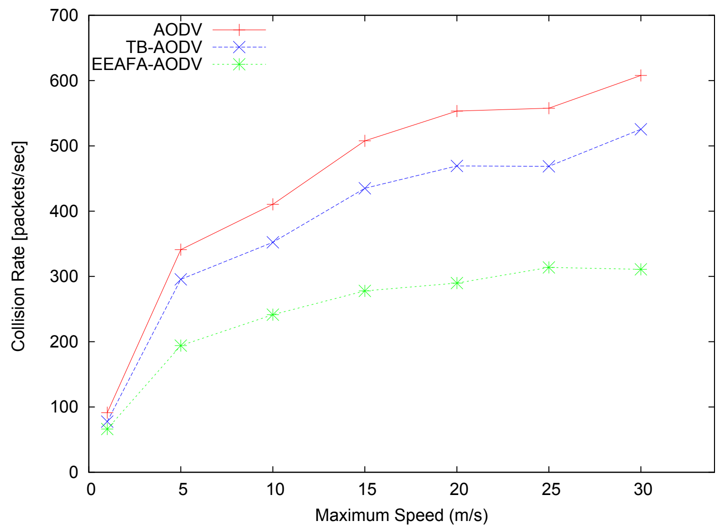


Figure 4.17: Collision rate vs. node mobility.

4.4.3.3 Normalised Throughput

Figure 4.18 shows the normalised network throughput of each of the three routing protocols plotted against maximum node speed. The graph indicates that for each of the protocols, there is a reduction in the normalised network throughput as node mobility increases. There are several reasons that might account for this fall. Firstly, it could be accounted for by more frequent and unpredictable changes that occur in the network topology when node mobility increases, which in turn leads to a higher frequency of broken routes. Moreover, when routes are disrupted due to frequent changes in the topology, this triggers further new route discovery processes and more intensive route maintenance processes, which subsequently leads to an increase in the amount of RREQ broadcast packets generated and disseminated throughout the network. This in turn leads to a higher likelihood of packet collisions.

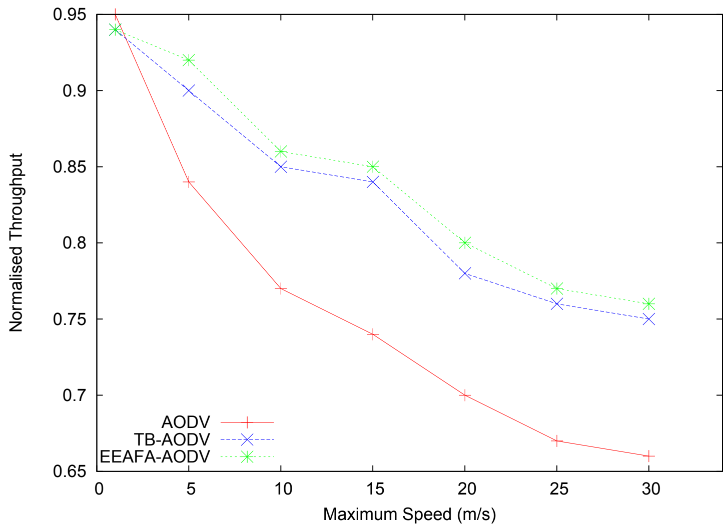


Figure 4.18: Normalised throughput vs. node mobility.

Since the EEAFA-AODV protocol uses a variable range transmission power in RREQ packets dissemination, network capacity increases as the transmission power level is reduced by decreasing the level of interference and unnecessary overhearing by other nodes. Thus, the throughput of the network increases.

4.4.3.4 Delay

The effect of node mobility (measured as maximum node speed) on the average end-to-end time to deliver data packets and on the time taken for the route discovery process in each of the three routing protocols is plotted in Figures 4.19, and 4.20 respectively. In both graphs, it can be seen that, in all three protocols, there is a rise in the average delay incurred in line with the increase in the maximum node speed, which can be attributed to the path breaks which occur more frequently when node mobility increases. In addition, the graphs reveal that in a network with rapidly moving nodes, the average delay experienced in EEAFA-AODV is shorter when compared to that in TB-AODV and AODV.

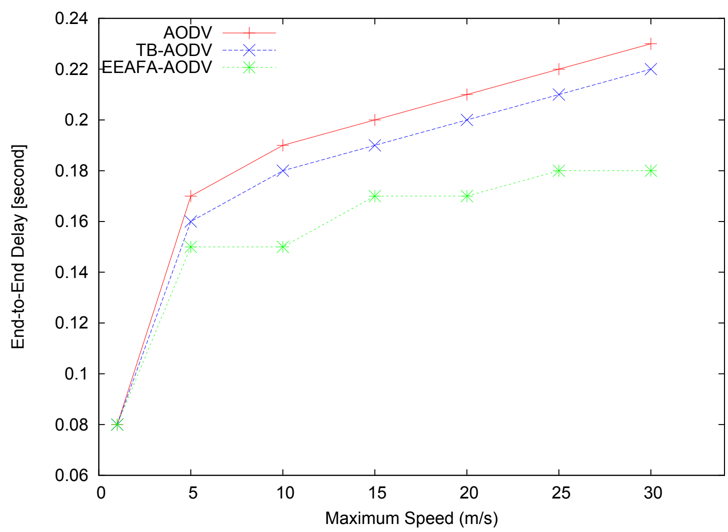


Figure 4.19: End-to-end delay vs. node mobility.

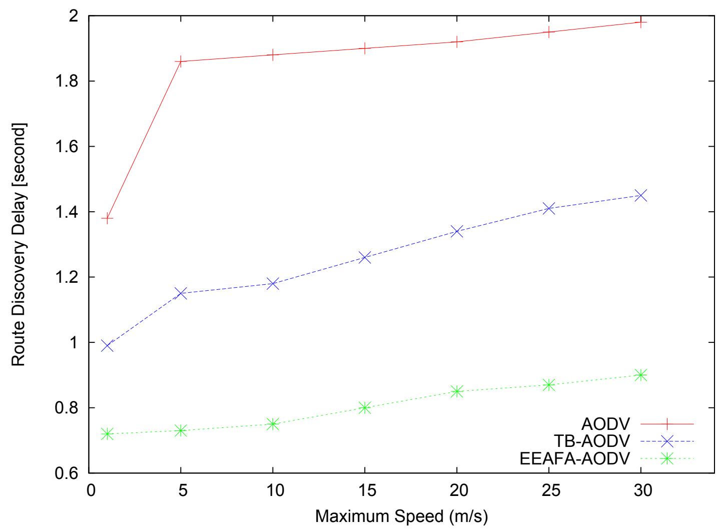


Figure 4.20: Route discovery delay vs. node mobility.

Although both EEAFA-AODV and TB-AODV protocols use variable range transmission power in RREQ packet dissemination which could increase the number of hops, they still perform significantly better than the AODV protocol. Moreover, the superiority of the EEAFA-AODV over the two protocols becomes more noticeable with more rapid node mobility. The reason for this superior result is that the proposed algorithm not only has mobility support (which comes from a robust topology) but also rapidly reacts to frequent changes (relay on only one-hop local information in rebroadcast decisions), which are considered key in MANETs [23].

4.4.3.5 Energy Consumption

Figure 4.21 demonstrates the total energy consumed by the three protocols versus maximum node speed to transmit and rebroadcast RREQ packets. As shown in the figure, the power consumption in each protocols also rises in line with node mobility. This is associated with the increased likelihood of route breakages, which triggers a rise in the number of RREQ packets which are generated and disseminated. EEAFA-AODV achieves a lower energy consumption in comparison with the other two protocols. The explanation behind this lower energy consumption is that nodes in EEAFA-AODV disseminate the route discovery packets in a more energy efficient manner. RREQ packets use both restricted forwarding and variable range transmission power. Thus, the energy expenditure of transmissions is reduced overall in EEAFA-AODV.

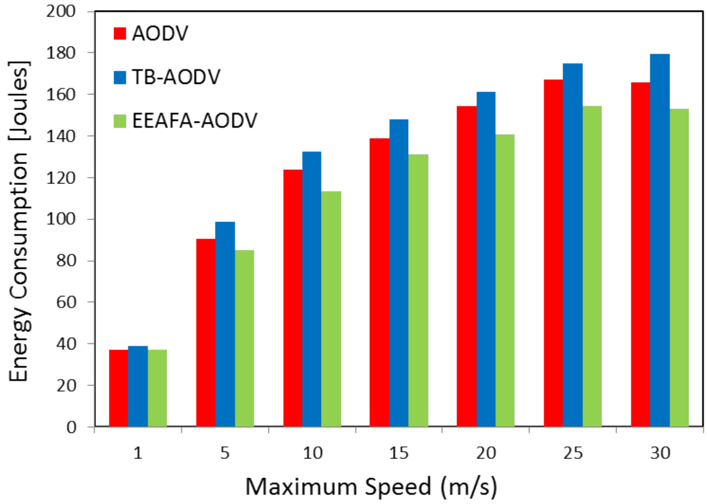


Figure 4.21: Energy consumption vs. node mobility.

4.4.4 Impact of Offered Load

To represent the impact of offered load, varying numbers of source-destination pairs (referred to as connections) were considered. In order to reduce the effect of node density on the performance of the network, the number of nodes in the network is fixed at 100 nodes, which is a median value of network density [198]. The aim is to avoid sparse and dense scenarios and to obtain a general trend for the effect of traffic load on the performance. A dynamic network was considered for this study where the maximum node speed is $5m/sec$ with a pause time of 0 sec (dynamic network) to avoid the effect of high node speed mobility on the network performance. These simulation parameters are widely used in the literature [21, 94, 198]. The offered load was incrementally increased in steps of 5, 10, 15, 20, 25, 30, 35 and 40 *connections*. Data packets (CBR 512 bytes) were generated by the source nodes at a rate of 4 packets per second.

4.4.4.1 Routing Overhead

Figure 4.22 shows that, as the number of connections (i.e. the offered load) increases, a higher routing overhead is incurred for all three routing protocols. The results also

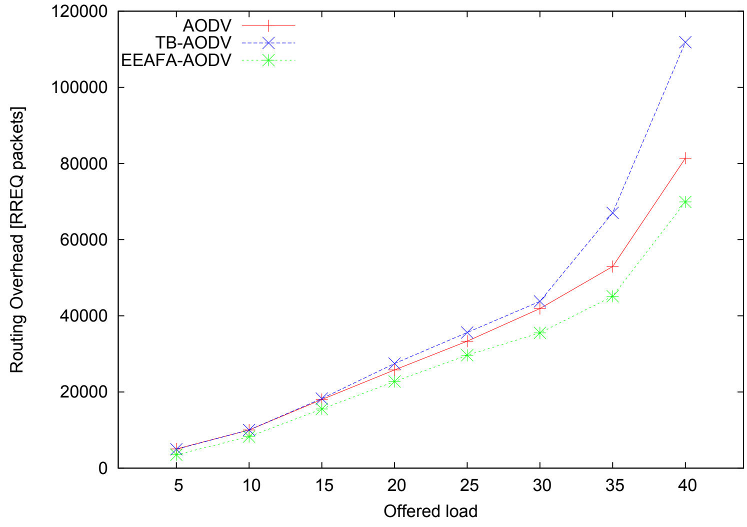


Figure 4.22: Routing overhead vs. offered load (number of connections).

show that the EEAFA-AODV has a performance advantage over the three protocols across all offered loads. This is because the EEAFA-AODV optimises a route discovery process with a relatively fewer forwarding nodes involved in forwarding RREQ packets.

4.4.4.2 Collision Rate

Figure 4.23 plots the collision rate of each routing protocol versus offered load. As with the pattern for the routing overhead (Figure 4.22), it can be seen that the collision rate increases almost linearly in line with the increase in the offered load. The reason for this is that the increase in the offered load is brought about by increasing the number of connections; thus, more RREQ packets are generated and transmitted leading inevitably to more collisions.

Despite the similar performance of TB-AODV and AODV in terms of routing overhead, as shown in Figure 4.22, in terms of collision rate the performance of TB-AODV is better than that of AODV, as shown in Figure 4.23. Although a large amount of the RREQ packets are generated in TB-AODV, they are disseminated by using variable range transmission power thereby reducing the effects of the interference in the network. As a result, collisions occur with lower probability in the channel.

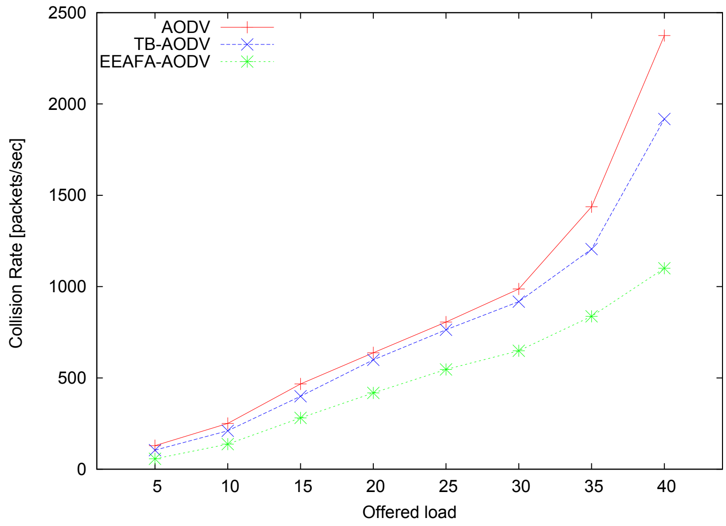


Figure 4.23: Collision rate vs. offered load (number of connections).

4.4.4.3 Normalised Throughput

Figure 4.24 shows the performance of the routing protocols in terms of normalised network throughput when the offered load is varied from 1 to 40 connections. As can be seen in the figure, as the offered load increases, the normalised network throughput falls for all the routing protocols. This is due to the greater number of nodes instigating route discovery operations as there are more connection pairs. This leads to nodes generating and transmitting larger numbers of RREQ packets being, which results in increased channel contention and collisions. This has the effect of degrading the overall network throughput as fewer data packets are delivered to their destinations successfully. The figure reveals that that EEAFA-AODV's superiority over the other two protocols becomes more marked when the offered load increases.

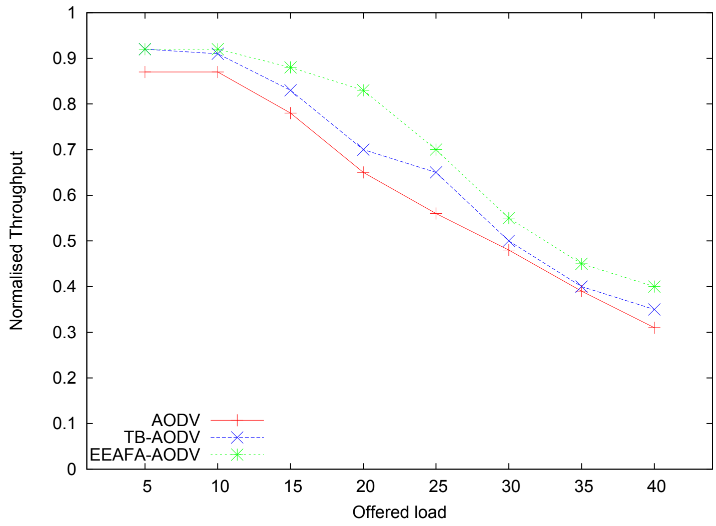


Figure 4.24: Normalised throughput vs. offered load (number of connections).

4.4.4.4 Delay

It can be seen in Figure 4.25 that for all the routing protocols end-to-end delay incurred is prolonged with the increase in offered load. This is due to increased contention as the number of connections (offered load) is increased, leading to a longer queuing time at the transmitter's buffer and a higher rate of packet loss, due to more collisions.

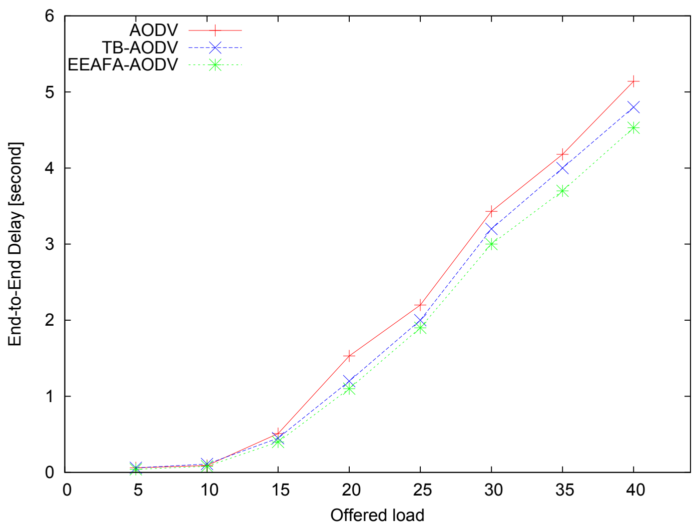


Figure 4.25: End-to-end delay vs. offered load (number of connections).

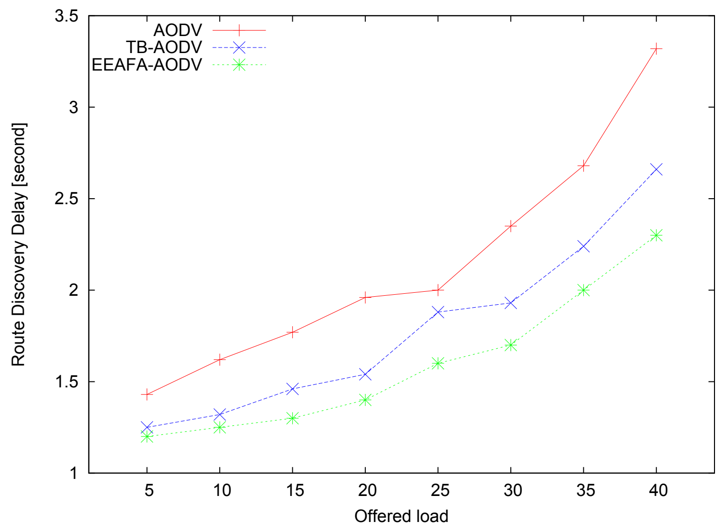


Figure 4.26: Route discovery delay vs. offered load (number of connections).

However, it can be seen in the figure that EEAFA-AODV clearly shows a superior performance to that of the other two protocols with a higher offered load. Similar performance trends for each protocol, in terms of the delay incurred during route discovery, can be seen in Figure 4.26.

4.4.4.5 Energy Consumption

Figure 4.27 compares the total energy consumed by each protocol as the offered load is increased. It can be observed in the graph that the power consumption for all three protocols rises with an increase in the offered load. This is a result of the greater volume of RREQ packets being generated and transmitted. EEAFA-AODV achieved a lower energy consumption compared to the other two protocols. This lower energy consumption is due to nodes in EEAFA-AODV disseminating the route discovery packets in an energy efficient manner by transmitting the RREQ packets using both restriction forwarding and variable range transmission power. Thus, reducing the energy expenditure of overall transmissions.

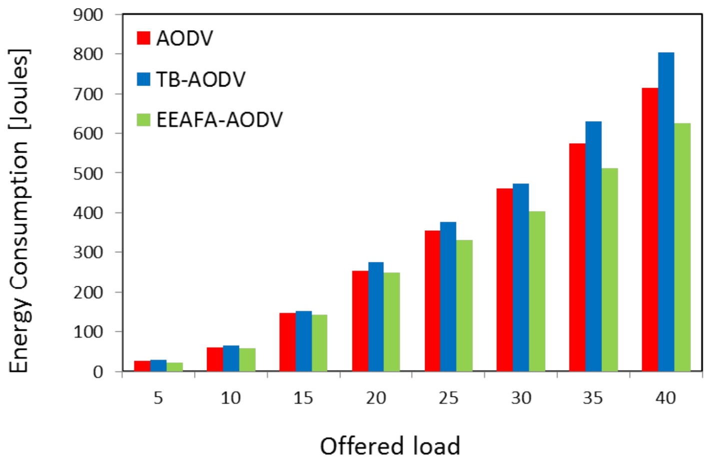


Figure 4.27: Energy consumption vs. offered load (number of connections).

4.5 Conclusions

Simple flooding is the earliest and still most frequently used broadcasting mechanism for route discovery in on-demand routing protocols. A simple flooding technique generates a large number of redundant retransmissions, leading to collisions, contention and a large energy consumption.

In this chapter, two new algorithms are proposed that collaborate to reduce redundant retransmissions of broadcast packets and reduce the transmission power used, thus conserving the average energy consumed per broadcast. The first algorithm uses a cross-layer approach to control power, where transmission range at a node is dynamically adjusted according to its local neighbour density. This mechanism constructs a dynamic self-organised topology structure that uses lightweight variable range beacons to establish and maintain this structure. The goal is to construct a more scalable and energy efficient topology structure in which nodes use beacons with variable-range transmission power to exchange and maintain topology structure. The higher scalability capability comes from the lack of interference levels and collision among neighbouring nodes, where nodes transmit *beacons* (or *hello messages*) with variable range transmission power to exchange and maintain topology structure. Whereas greater energy efficiency comes from the large reduction of power used in exchanging these beacons.

Furthermore, this chapter also aims to design a new receiver-based EEAFA-AODV algorithm that works over the constructed topology structure and uses one-hop local information provided by this topology for making smarter rebroadcasting decisions. This receiver-based broadcast system enables nodes to estimate their positions and assign their forwarding decision earlier without relying on GPS or any distance measurement. Therefore, no additional hardware or calculation is required to operate it. Moreover, there is no random delay period; a node can immediately take a decision to forward (or rebroadcast) the RREQ packet or not.

The proposed approach combines the advantages of reducing redundant retransmissions and reducing the transmission power range, which can lead to a good reduction in the routing overhead and the number of collisions, and thus save energy. However, there are two notable drawbacks with the previous determination process of the forwarding node set in this EEAFA-AODV protocol.

The first drawback is in a worst-case scenario in which the chance of existing two hops topology with same power level is common especially in a highly dense network; thus no node declared itself as a forward node. The reason is the forwarding decision at the node is taken according to the mode of receiving different power levels of beacons. The results of the evaluation presented in Figure 4.10 indicate that when the network density is increased to a high level (250, 275 and 300 nodes), the RREQ overhead generated by the proposed EEAFA-AODV increases dramatically. This is because most of the network nodes' regions have the same density level and thus they have same adjusted transmission power levels. Therefore, the RREQ rebroadcast restriction was ignored in this case to avoid early die-out of the broadcast packet.

The second drawback is that in a highly dense network, adjacent forwarding nodes (situated within each others transmission power range) may have significantly overlapping ranges. This may result in a large number of redundant rebroadcasts especially in the absence of a coordination function among forwarding nodes. This causes contention, collision and eventually results in high power consumption. To overcome these two drawbacks some specific conditions and guidelines are presented in the next chapter.

Chapter 5

Colour-Based Forwarding Scheme for Optimising Route Discovery

5.1 Introduction

In Chapter 4 two new algorithms were proposed that collaborate to reduce redundant retransmissions of RREQ broadcast packets and reduce the transmission power used, thus conserving the average energy consumed per broadcast. A cross-layer approach is employed to control topology, where the transmission power at nodes is dynamically adjusted based on their local densities. The idea is to group mobile nodes in a network into different zones (groups) based on their transmission power level, which forms an energy efficient topology structure that improves the scalability of the network capacity. To minimise route discovery overheads, the network is selectively flooded by means of a limited set of nodes, referred to as forwarding nodes. Forwarding nodes utilise the local information provided by the constructed topology for making smarter forwarding decisions of the RREQ broadcast packets without relying on GPS or any distance calculations.

A *Hello message* has been modified to carry the node's Transmission Power Level (Pt_{level}). The forwarding decision at nodes are determined according to receiving *hello messages* from neighbours of varying levels of transmission power. However, the possibility of finding nodes that have two-hop neighbours with the same power level is high especially in a dense network. Therefore, a node (forwarding node) could belong to different groups of the same adjusted transmission power levels. As a result, there is no node declaring itself as a forwarding node in this area of the network, which means that utilising the Pt_{level} parameter at *hello messages* is not efficient enough to make a wise forwarding decision at nodes. Besides, in a highly dense network, the adjacent forwarding nodes may have significantly overlapping ranges, where nodes are located within the transmission power range of each other. This overlapping may lead to a high number of redundant rebroadcasts, which cause contention, collision and eventually result in high power consumption.

In this chapter, the forwarding node determination process is reviewed and further improved using two distributed algorithms: 1) Colouring Algorithm and 2) Sectoring Algorithm. The proposed colouring algorithm operates over the topology structure that was previously constructed in Chapter 4, and uses one-hop information provided by this structure in its colouring technique. The objective of the colouring technique is to assign colours to each group of nodes in the network. This technique tries to increase the awareness at forwarding nodes and thus improve forwarding decision making at them. On the other hand, the sectoring technique divides the forwarding area at each group into different sectors based on the colour of the adjacent groups. The sectoring algorithm helps to minimise the overlap between forwarding nodes in the same region. The proposed sectoring algorithm also assigns a weight value for each node to select a suitable node in each sector to participate in the forwarding of the RREQ broadcast packet. This reduces the number of forwarding nodes and subsequently the number of RREQ packets in the network.

Using an NS2 simulation, results show that employing the colouring and sectoring techniques improves the broadcast performance during the route discovery process which is significantly superior to that of the previous work reported in Chapter 4, in terms of reducing collisions within the MAC layer and obtaining lower power consumption. The remaining sections of this chapter are organised as follows: Section 5.2 presents the topology colouring schemes. In Section 5.3, a new proposed Enhanced-EEAFA (E-EEAFA) scheme is presented. Section 5.4, discusses its performance evaluation, while the results are summarised and discussed in Section 5.5.

5.2 Topology Colouring

5.2.1 Graph Colouring Overview

In graph theory, colouring constitutes a special form of graph labelling, which involves assigning labels (traditionally referred to as colours) to either edges or vertices of the graph, subject to certain constraints. In edge (or link) colouring [211], colours are assigned to the graph edges, where two edges incident on the same vertex receive different colours, while in vertex (or node) colouring [212, 213], colours are assigned to nodes so that two adjacent vertices do not have the same colour. In both cases, the number of colours used in the graph should be minimised. Both edge colouring and vertex colouring use one-hop colouring. However, in the literature extensions have been proposed to two-hop and three-hop colouring in other schemes [34]. Unlike edge colouring, a vertex colouring scheme enables broadcast communications to be represented. In MANETs, broadcast messages are required to manage the network and build the neighbourhood, so a vertex colouring approach is adopted.

5.2.2 Efficiency of A Distributed Colouring Algorithm

The colouring algorithm required in this study must be distributed, where each node runs this algorithm locally to assign itself a colour, based on its local knowledge. However, global knowledge is costly in wireless networks. In this work, a drawback of the forwarding node determination process employed by the previous EEAFA-AODV algorithm in Chapter 4 is considered. The goal is to improve forwarding decisions of the RREQ message at nodes by increasing the awareness of nodes to their local information. To achieve that, a one-hop colouring algorithm is adopted to introduce more information that enables forwarding nodes to make better forwarding decisions.

In the colouring algorithm, the exchanged of *hello message* in Section 4.2.3 in the previous chapter is utilised to achieve the colouring technique. This means that there is no need to exchange extra packets to obtain and maintain the assignment of colour values. A node periodically broadcast a *hello message* only with its one-hop neighbours and the message is not forwarded any further. This *hello message* is extended to include information necessary to assign colours.

5.2.3 Extended *Hello* Message Format

In this work's implementation, the *hello message* format in the AODV [57] protocol is extended to include three small size fields: *Group Colour*, *Sector id* and *Weight* (see Figure 5.1). The *Group Colour* field records the colour of node's group which is assigned using the proposed colouring algorithm. The *Sector id* field records the sector *id*, which represents the most common colour *id* that node can receive from different adjacent groups. And the *Weight* field records the number of neighbours of a given node that can receive from its sector *id*. More explanation about the benefits of these three fields will be provided later on in this chapter in Section 5.3.

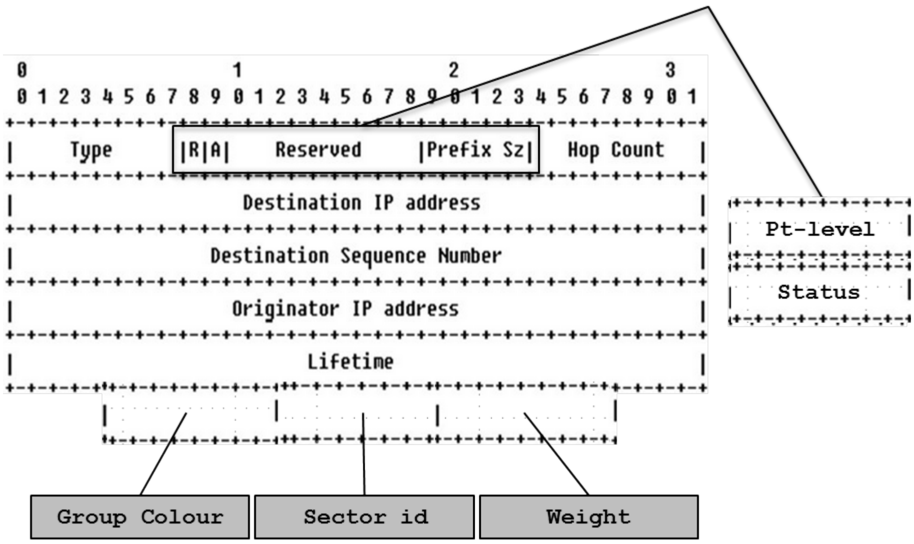


Figure 5.1: The extended form of the HELLO message format in AODV

5.2.4 The Proposed One Hop Colouring Algorithm

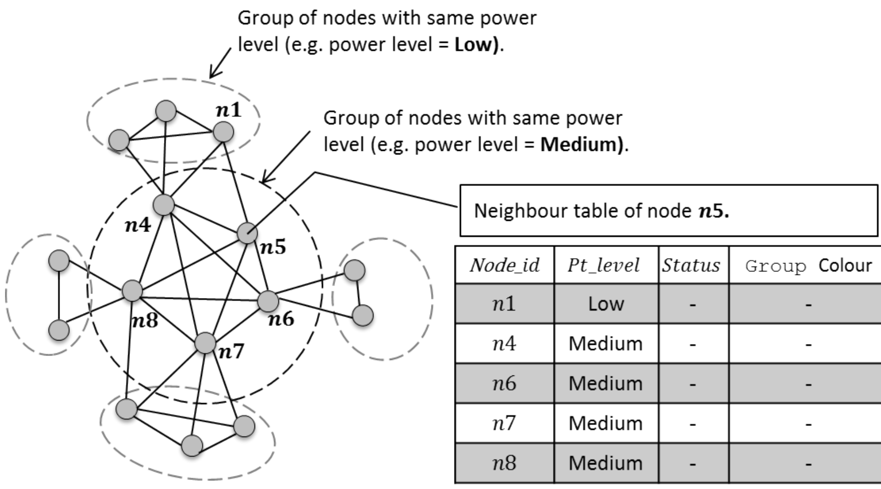
The proposed colouring algorithm operates over the topology structure constructed in Chapter 4, in which nodes dynamically adjust their transmission power level according to their local density. Therefore, nodes in the network are formed into different groups based on their transmission power levels (High/Low/Medium). Below, a summary description of the topology structure is provided and how the proposed colouring algorithm operates over this structure.

- ***topology initiation***

  In the beginning, when the network is first establishing, the nodes do not have neighbours in their neighbour table (no *hello messages* received yet). As the first *hello message* is transmitted using High transmission power level (the default level), nodes will include their ID in the *Node_id* field in the *Hello* packet.

- ***topology control***

  After receiving the first *hello messages* from neighbours, the nodes can then construct their neighbour tables and start adjusting their transmission power level based on their local densities. Figure 5.2 illustrates the neighbour table of $n5$ after receiving the second *hello messages*, where all nodes adjust their transmission power level which form the topology structure proposed in Chapter 4. Then the colouring process will begin as explained next.



Node_id	*Pt_level*	*Status*	Group Colour	Sector id	Weight
$n1$	Low	-	-	-	-
$n4$	Medium	-	-	-	-
$n6$	Medium	-	-	-	-
$n7$	Medium	-	-	-	-
$n8$	Medium	-	-	-	-

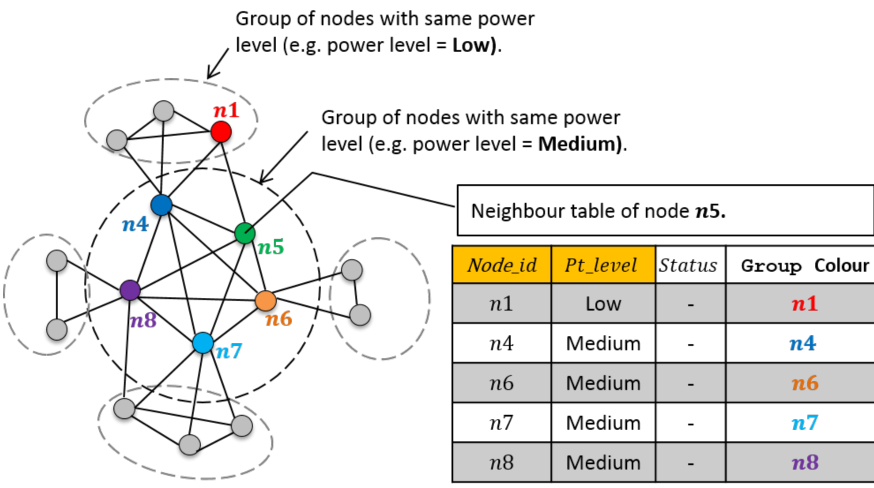
Figure 5.2: The neighbour table of node $n5$.

- ***colour initiation***

  Initially, the Colouring Algorithm makes the assumption that each node in the network carries a unique colour value that is identified by its unique identifier (ID) to avoid any duplication (two nodes having the same colour). The colouring technique utilises one-hop information provided by the previously constructed topology structure for the colouring assignment operation. The main goal is to assign a colour to each group of nodes in the network such that two adjacent groups of nodes have two different colours regardless of their adjusted transmission power level.

- ***colour assignment***

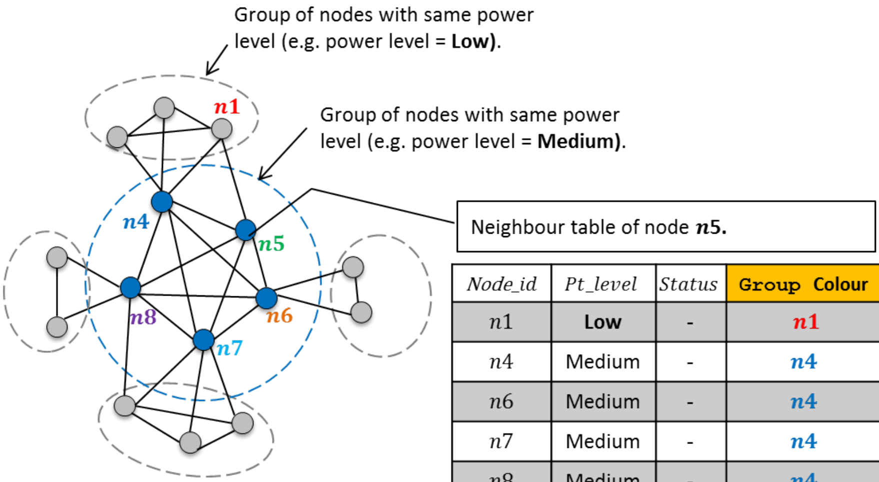
As mentioned above, the node constructs its neighbour table that includes two essential parameters for the colour assignment operation: 1) Node Identifier ($Node\_id$) and 2) Transmission Power Level (Pt_{level}). In this stage, they are utilised in the colouring operation. As seen in Figure 5.3, the table lists the $n5$'s neighbours with the basic information required for the colour assignment process. According to the number of received $Node\_ids$ and their Pt_{levels}, the node ID with the lowest value among neighbours including itself will be adopted as the group colour id among common Pt_{level} neighbours (neighbours with the same transmission power level). For example, Figure 5.3 represents the neighbour table of node $n5$. As shown in the table, $n5$ is using the medium Pt_{level}. Concerning the colour assignment, $n5$ will look for the lowest id within the same Pt_{level}. Then, it will adopt the colour of $n4$ as a group colour. In this case, $n4$ is considered as a Colour-head, where all the group's members adopt the id of Colour-head as a $GroupColour$ value.



Node_id	*Pt_level*	*Status*	Group Colour	Sector id	Weight
$n1$	Low	-	$n1$	-	-
$n4$	Medium	-	$n4$	-	-
$n6$	Medium	-	$n6$	-	-
$n7$	Medium	-	$n7$	-	-
$n8$	Medium	-	$n8$	-	-

Figure 5.3: The information required for colouring assignment.

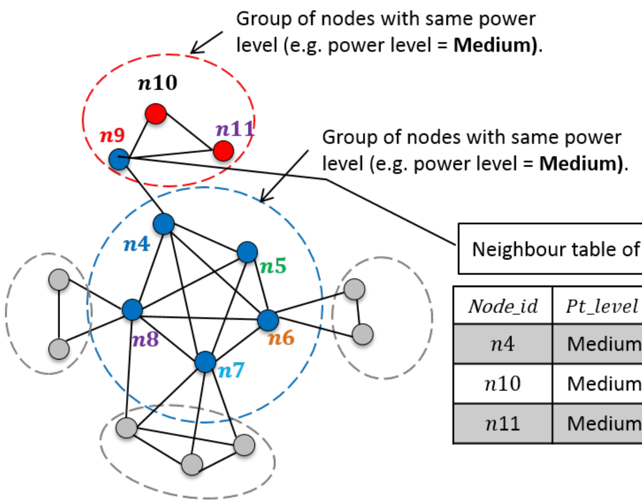
After that, the id of the Colour-head node will be recorded in the $GroupColour$ field and will also be exchanged periodically among neighbour nodes using *hello* *message*. On the other hand, as shown in the graph in Figure 5.4, $n5$ ignored $n1$ although $n1$ has the lowest ID, this is because the two nodes have different Pt_{levels}. This asymmetry condition means that node $n1$ belongs to a different group of nodes. Thus, $n5$ chooses the $n4$'s $Node\_id$ as a colour instead. The node $n4$ is considered the Colour-head in this scenario. The idea is that utilising the available transmission-level parameter in the colour assignment process provides the required infrastructure to determine a forwarding node in each group.



Node_id	*Pt_level*	*Status*	**Group Colour**	Sector id	Weight
$n1$	**Low**	-	**$n1$**	-	-
$n4$	Medium	-	**$n4$**	-	-
$n6$	Medium	-	**$n4$**	-	-
$n7$	Medium	-	**$n4$**	-	-
$n8$	Medium	-	**$n4$**	-	-

Figure 5.4: The group colour assignment.

In case there are two adjacent groups having the same transmission power level, if the node with the lowest ID is actually in a different group, then its colour will be adopted. For example, Figure 5.5 illustrates the neighbour table of node $n9$, as shown in the figure, node $n9$ receives *hello message* from $n4$ which is the lowest ID, but located in the blue colour group. In this case, $n9$ will adopt the colour value of the $n4$ as a group colour, and it will play as a gateway node in forwarding the RREQ message that retransmitted by $n4$ (as a Colour-head).



Neighbour table of node **n9**.

Node_id	Pt_level	Status	Group Colour	Sector id	Weight
n4	Medium	-	**n4**	-	-
n10	Medium	-	**n9**	-	-
n11	Medium	-	**n9**	-	-

Figure 5.5: The other case of group colour assignment.

5.2.5 The Difference with Clustering

A simple clustering distributed algorithm is based on the identifier of the node (ID). By assuming that a unique ID is associated to each node, the node with the lowest ID (in one-hop neighbours) is elected as the cluster-head (CH) [120], and additional overhead usually required for CH election and maintenance. This mechanism introduces extra overhead and consumes more energy. Moreover, most of the traffic processed by the cluster head, and as a consequence, it may become a cluster bottleneck. This problem can be avoided by eliminating the CH role, and adopting a fully distributed clustering approach [214, 215]. With contrast to this, EEEAFA scheme utilises the existing *hello message* to obtain and update the colour values. Moreover, the absence of Colour-head election in EEEAFA make it totally distributed, where there is no need for election mechanism to change the Colour-head. The colouring mechanism in the EEEAFA increases the level of awareness of the forwarding node by assigning a unique colour id which defines a group of nodes in the network. Additionally, the colouring algorithm in EEEAFA enables a node to not only utilise the node's ID but the node's transmission-level parameter as well. This enables a more accurate determination in identifying node's status within the group (a forward node or not), especially when the forwarding node is located among different groups of the same adjusted transmission power level. The colouring process is expressed by *Algorithm* 5.1.

Algorithm 5.1 Group Colour Assignment

Input:

t - transmission level of the node receiving *hello* message.

Pt - transmission level of neighbour.

id - node ID which is the IP address of node.

Nid - neighbour ID which is the IP address of neighbour.

Output:

GroupColour - node's assigned group colour.

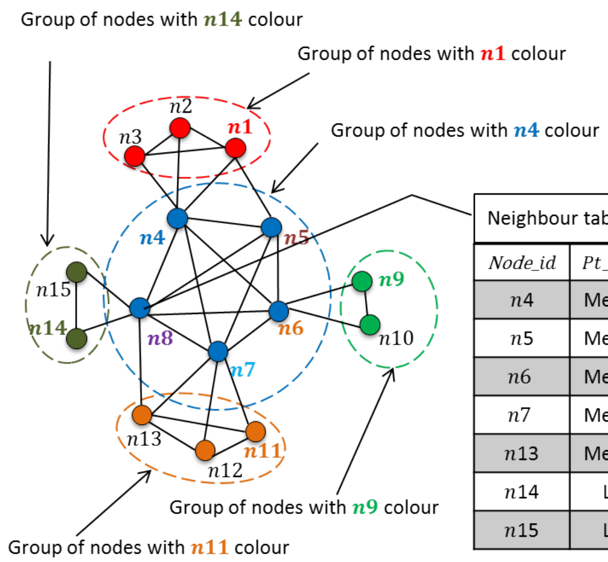
```
function GetGroupColour(t, Pt, id, Nid)
Initial Colour = id; LowestID = id; i = 0;
while Neighbour list is not empty do
    if Neighbour[i].Pt = t And Neighbour[i].Nid < LowestID then
        LowestID = Neighbour[i].Nid;
        Colour = Neighbour[i].Nid;
    end
    i++;
end
return GroupColour;
end function
```

5.2.6 Sectoring Algorithm

Once a set of forwarding nodes is determined in the same region, the risk of collision still exists. The transmission range of some of the forwarding nodes overlaps so that each node almost covers most of the other nodes' transmission range. However, when there is a large number of nodes, this increases the possibility of radio transmissions overlapping, which can lead to a considerable degree of contention and collision in the network. The direct impact of contention and collision is a high number of redundant retransmissions and transmission failures, which also cause higher power consumption.

The proposed group sectoring algorithm is a distributed one, which is implemented at each node independently. The idea is to divide the transmission area of each group into different sectors based on the colours of adjacent groups. From the received *GroupColour ids* in the *hello message*, each node calculates the most frequent *GroupColour id* of the different *GroupColour ids* and then assigns it as a *Sector id*. By this technique, the forwarding area in each group is dynamically partitioned into numbers of sectors where the forwarding nodes of each region cover a different area of groups in the network. This will help in disseminating the RREQ broadcast packet efficiently and thus reducing the route discovery latency.

To simplify the discussion and make the description clearer, node $n8$ in Figure 5.6 is used as an example. First, node $n8$ counts the frequencies of the colours in the *GroupColour* column in its neighbour table, where the *GroupColour* field is different of its own. Node $n8$ then selects the most frequent colour other than its own (e.g. $n14$ in this scenario) to represent the $Sector\_id$ and the number of instances of it to represent the $Weight$ of node $n8$.



Neighbour table of node **n8.**

Node_id	Pt_level	Status	Group Colour	Sector id	Weight
n4	Medium	-	n4	n1	3
n5	Medium	-	n4	n1	1
n6	Medium	-	n4	n9	2
n7	Medium	-	n4	n11	3
n13	Medium	-	n11	n4	2
n14	Low		n14	n4	1
n15	Low		n14	n4	1

Node_id	Pt_level	Status	Group Colour	Sector id	Weight
n8	Medium	F	n4	n14	2

F: a forward node

Figure 5.6: The assigning Sector id and Weight for node $n8$.

The idea is that each sector should have only one forwarding node to relay a broadcast packet to a new area. The weight value coordinates the packet forwarding operation among the set of forwarding nodes that are located in the same sector; in this case, each node uses a weighted value which is piggybacked in the *hello message* to decide whether it has the maximum weight required for rebroadcasting a RREQ packet or not. The proposed sectoring process and weight are expressed by (*Algorithm* 5.2) and (*Algorithm* 5.3) respectively.

Algorithm 5.2 Getting Sector

Input:

A - array of the GroupColour column in the neighbouring table.

s - size of the array A.

c - group colour id of node receiving RREQ message (by *Algorithm 5.1*).

Output:

Sector id - node's sector id.

```
function GetSector(t, Pt, id, Nid)
    maxFrequency = 1;
for i = 0 → s − 1 do
        count = 1;
    for j = i + 1 → s − 1 do
        if A[i]= A[j] AND A[j] ≠ c then
                count++;
        end
        if count > maxFrequency then
                maxFrequency = count;
                frequentColourID = A[j];
        end
    end
end
        return frequentColourID;
    end function
```

Algorithm 5.3 Getting Weight

Input:

S - Sector id of node receiving RREQ message (by *Algorithm 5.2*).

Nc - group colour id of neighbouring node.

Output:

Weight - node's weight.

function GETWEIGHT(S, Nc)

while *Neighbour list is not empty* **do**

  if *Neighbour[i]*$.Nc = S$ **then**

    weight++;

  end

  i++;

end

return *weight*;

end function

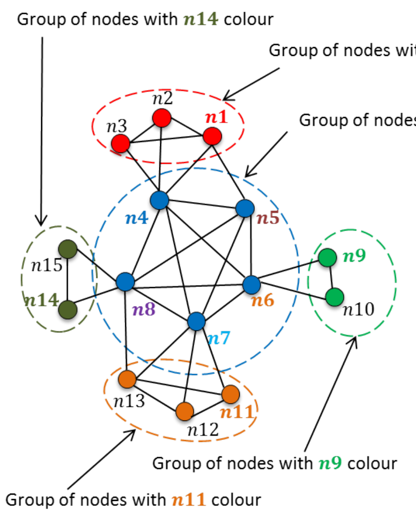
In this section, the proposed colouring and sectoring algorithms were specified. These algorithms are distributed, where each node runs them locally. The colouring algorithm uses one-hop colouring approach. The objective of this algorithm is to assign a colour for each group of nodes in the network, which increases awareness of forwarding nodes and thus improves forwarding decision making.

Sectoring algorithm divides forwarding nodes in each group into different sectors and assigning weight for each of them, which helps to minimise the overlap between forwarding nodes and select suitable forwarding nodes in the same sector to participate in the forwarding of a RREQ packet. This technique considerably reduces the number of retransmissions of RREQ broadcast messages and thus conserving energy. Both techniques can deal with high mobility and rapidly react to topology changes (relying only on local one-hop information). An Enhanced route discovery broadcasting scheme that works over the coloured topology structure is discussed in the following section.

5.3 An Enhanced-EEAFA (E-EEAFA) Scheme

In this section, a new route discovery approach which is referred to as Enhanced Energy Efficient Adaptive Forwarding Algorithm (E-EEAFA, for short) is proposed. In this work's implementation, the broadcasting system used in E-EEAFA is a local decision based (referred to as receiver based), where the decision making of each node is on its own. This decision is whether to rebroadcast (or forward) a particular RREQ message or not. Unlike the previous EEAFA that utilises only the transmission-level of one-hop neighbours (See Chapter 4), the nodes in E-EEAFA dynamically adjust their forwarding decision using colouring and sectoring techniques that collaborate to reduce overheads and conserve energy.

5.3.1 A Forwarding Node Determination



Node_id	Pt_level	Status	Group Colour	Sector id	Weight
n4	Medium	-	n4	-	-
n5	Medium	-	n4	-	-
n6	Medium	-	n4	-	-
n7	Medium	-	n4	-	-
n13	Medium	-	n11	-	-

Example of a **forwarding** node's neighbour table

Node_id	Pt_level	Status	Group Colour	Sector id	Weight
n4	Medium	-	n4	-	-
n5	Medium	-	n4	-	-
n6	Medium	-	n4	-	-
n7	Medium	-	n4	-	-
n13	Medium	-	n4	-	-

Example of a **non-forwarding** node's neighbour table

Figure 5.7: The proposed RREQ forward node determination.

In the process of determining the forwarding node, each host can decide on its own whether to participate in forwarding a RREQ broadcast message. In this phase, the proposed receiver-based scheme classifies the mobile nodes in the network as forwarding and non-forwarding nodes, based on the adjusted group colour of neighbouring nodes. It should be noted that forwarding nodes which have different values of group colour in their neighbour table are more likely to forward RREQ packets. Conversely, non-forwarding nodes are those nodes which have the same value of adjusted group colour as that of their neighbouring nodes (see Figure 5.7). Thus, any retransmission by a non-forwarding node should be exempted to prevent redundant retransmissions which should reduce the overhead of routing packets. Therefore, the decision regarding which node is a forwarding and which is a non-forwarding one is taken by node *Status* (Algorithm 5.4). A node which can receive packets from neighbours with different values of group colour is most likely to be positioned between different groups and is therefore categorised as a forwarding node; the others are non-forwarding.

Algorithm 5.4 Getting Status

Input:

c - group colour id of node receiving RREQ message (by *Algorithm 5.1*).

Nc - group colour id of neighbouring node.

Output:

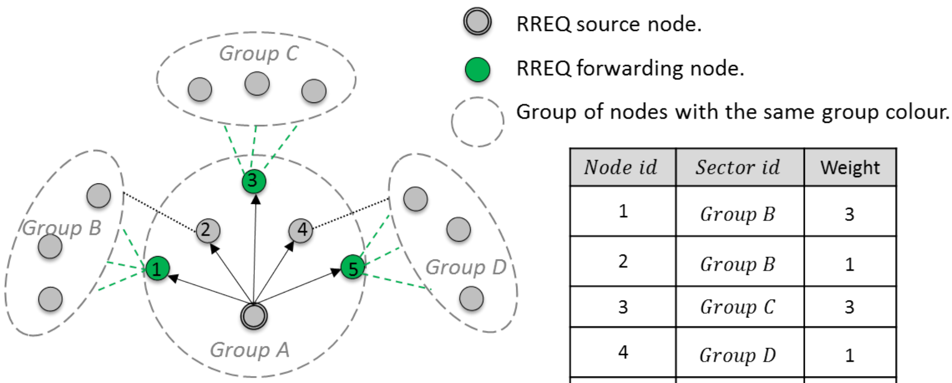
Status - node's status (forward/non-forward).

```
function GetStatus(c, Nc)
i = 0;
while Neighbour list is not empty do
    if Neighbour[i].Nc ≠ c then
        return forward;
    end
    i++;
end
return non-forward;
end function
```

The concept here is that RREQ packets will only be forwarded by those nodes which bridge groups of nodes with a different colour. It appears intuitive that the greater similarity a node's colour shares with all its neighbours, the less need it has to retransmit the packets, thus, it is most likely to be located within the same group, and so all of its neighbours may receive the broadcast packet. Conversely, if the node is able to receive packets from neighbours which have a different colour, it is highly probable that it is located between different groups.

5.3.2 Optimisation of Forwarding Decision

To maintain network functionalities or protocol performance in wireless networks, it is usually necessary to broadcast messages [7]. However, a broadcast based on a simple flooding technique is greedy of network resources. This means that it is important to optimise the number of broadcast messages as this affects network performance. The goal of the forwarding nodes optimisation is to limit the effects of the overall degree of overlap among forwarding nodes in the network. This will further reduce the collision rate.



Node id	*Sector id*	Weight
1	*Group B*	3
2	*Group B*	1
3	*Group C*	3
4	*Group D*	1
5	*Group D*	3

Figure 5.8: The proposed RREQ forwarding decision optimisation.

The sectoring algorithm assigned a *Sector id* and *Weight* value to each node based on the colour of the adjacent group (see Figure 5.8). A weight value of a node is regarded as low if it has a high number of neighbours with the same $GroupColour$, which means it is most likely to be located closer to the centre of its group. In contrast, the weight is considered high if it has more neighbours with a different $GroupColour$, which indicates that it is situated further away from the centre of the group. This means the node is preferred as it is less prone to be affected by radio interference and the risk of collisions. However, although it will limit the number of potential forwarding nodes, this approach will not fully ensure that only one forwarding node will be elected. When there are two or more forwarding nodes in the same sector with the same highest weight value, the algorithm will choose the one with lowest *id* value to avoid using more than one of them. This approach will ensure that a node that is below the maximum weight will eliminate itself from consideration for RREQ rebroadcasting, which will ultimately limit the number of redundant messages that are rebroadcast. The enhanced RREQ forwarding process will be presented in detail in the next section.

5.3.3 An Improved RREQ Forwarding Process

The route discovery process operates over all nodes, i.e. the source node, intermediate nodes and the destination node. The route discovery process of the proposed E-EEAFA scheme operates as follows:

The Source node process is the same as that employed in the AODV protocol [57]. When a source node needs to send data to a destination to which it does not have a fresh path, it initiates the route discovery process by broadcasting a Route Request (RREQ) packet.

When an Intermediate node receives the RREQ packet for the first time, it executes the E-EEAFA algorithm to optimise the rebroadcast process during the route discovery operation. It inspects the received packet with the proposed mechanism shown in the flowchart in Figure 5.9 (Phase 2), and behaves as follows:

- If the packet has been received more than once, the packet is discarded. This is done by checking the *id* of the received packet against a log of recently received packet *ids*.
- If the TTL of the received RREQ packet is equal to zero, the packet is discarded.
- If the node receives the RREQ packet for the first time, the node determines its own *Status* whether it is a Forward node or not.
- If the RREQ receiver node has neighbours with different colour *id*, it decides that it is a Forward node.

- A Forward node then makes its own decision whether it should forward the RREQ message based on the weight of other forwarding nodes in the overlapped area of a sector. If a forward node has the highest weight value within its sector or is the colour head of the group, it forwards the RREQ packet. In the case where there are two or more nodes with identical highest weight values in the sector, then the node with the lowest *id* will participate in forwarding the RREQ packet. Otherwise, it discards it to avoid redundancy.

A Colour-head node as explained in Section 5.2.4 is a node that has the lowest *id* and whose neighbours have adopted as the group colour value. In the RREQ forwarding process, the colour-head should rebroadcast the received RREQ packet to ensure that it reaches all group members regardless of whether it is a forwarding node or not.

In a Destination node which may be the intended destination of the RREQ packet or may be an intermediate node with a valid route to the destination node, it responds by unicasting a Route Reply (RREP) packet along the reverse route which was established at intermediate nodes during the initial route discovery process. The pseudocode of the proposed Enhanced-EEAFA scheme is shown in (*Algorithm* 5.5).

Algorithm 5.5 The Enhanced-EEAFA (E-EEAFA)

Input:

m - the incoming RREQ message.

r - the node receiving RREQ message.

t - sector *id* of the node receiving RREQ message (by *Algorithm 5.2*).

w - weight of the node receiving RREQ message (by *Algorithm 5.3*).

s - status of the node receiving RREQ message (by *Algorithm 5.4*).

Output:

```
function RREQ_FORWARDING(m, r, s, t, w)
if m is received for the first time then
    if s is a forwarding node then
        if w is the highest value in t then
            transmit m;
        end
        else
            r → drop message m;
        end
    end
    else
        r → drop message m;
    end
end
else
    r → drop message m;
end
end function
```

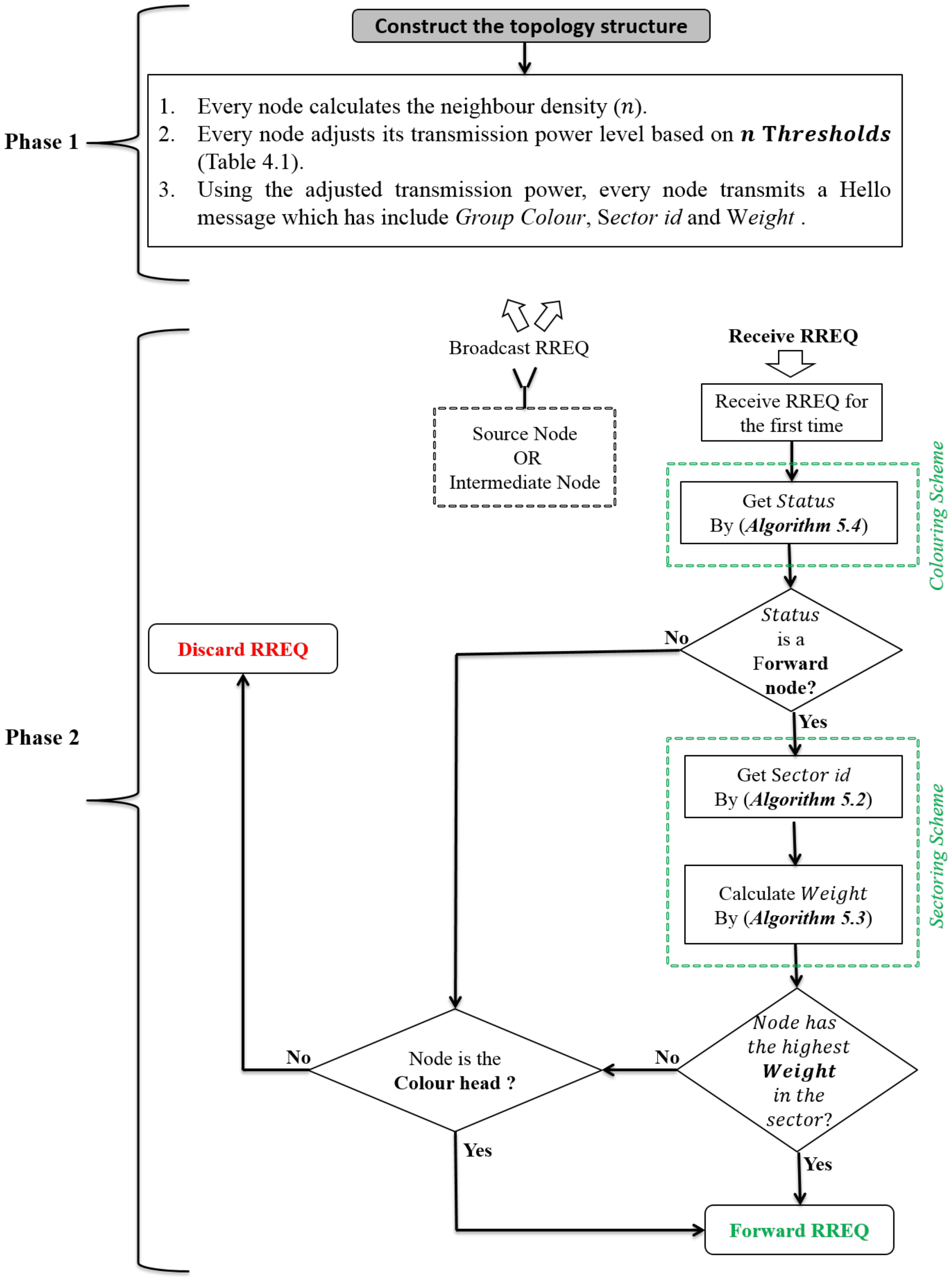


Figure 5.9: Flowchart of E-EEAFA Scheme.

5.4 Performance Evaluation

The performance of the Enhanced-EEAFA algorithm was evaluated by implementing the AODV routing protocol in the NS2 simulator [181] with modifications to incorporate the functionality of the Enhanced-EEAFA algorithm. In the following sections the term EEEAFA-AODV is used to refer to the modified version of the previous EEAFA-AODV. The simulation results of the new EEEAFA-AODV is compared with the previous EEAFA-AODV, TB-AODV and AODV routing protocols.

5.4.1 Impact of Network Density

To compare the performance of the four protocols, the network density was varied by varying the number of mobile nodes being deployed over a 1000 m^2 area in each simulation scenario. Each node was assigned a maximum speed of $5m/sec$ with a pause time of 0 *sec* (dynamic network). In each simulation trial, 12 *connections* are randomly selected. The source node generated data packets (CBR 512 bytes) at a rate of 4 packets per second.

5.4.1.1 Routing Overhead

When the performance of each of the four routing protocols is compared, in Figure 5.10, there are an almost linear increase in the routing overhead incurred by each of them which can be seen in line with the increase in network density. However, it can also be seen that, at each network density, the enhanced EEEAFA-AODV generates a lower routing overhead than that generated by the previous EEAFA-AODV, TB-AODV and AODV. The superior performance of EEEAFA-AODV can be attributed to the significant reduction in the number of redundant retransmissions of RREQ packets when the forwarding decisions at a node are made according to its weighted value among its neighbours in the same sector. This reduction in redundant transmissions, means the overall routing overhead is reduced.

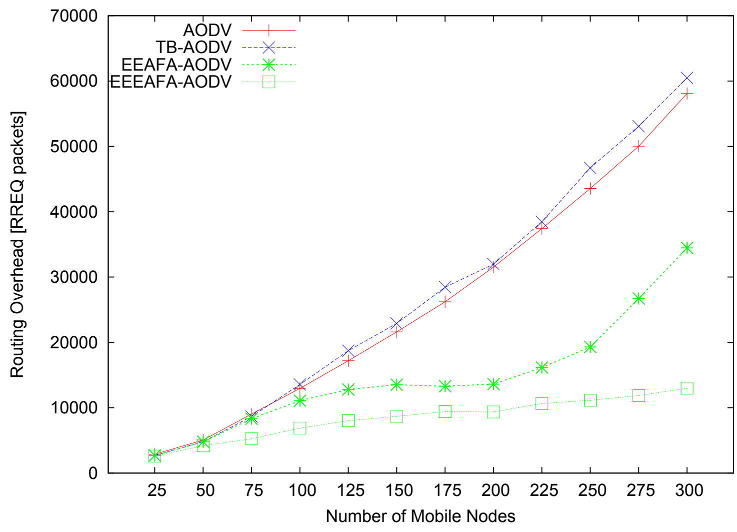


Figure 5.10: Routing overhead vs. network density.

It is also worth mentioning here as shown in Figure 5.10, that when the network density is substantially increased (e.g. 250, 275 and 300 nodes) the RREQ overhead generated by EEEAFA-AODV remains relatively stable compared to the previous EEAFA-AODV which dramatically increases. Unlike the previous EEAFA-AODV, the forwarding decisions at a node are made according to the existence of a different group colour in the neighbour table. Therefore, the colouring scheme can increase awareness at the forwarding nodes. Thus, the RREQ rebroadcast restriction with a colouring scheme has been successful in reducing the number of redundant retransmissions.

It also worth to be mention here that when the network is very high dense (say 1000 nodes) and all neighbours have the same adjusted transmission level (e.g. all nodes have more than 14 neighbours). In this case, the colouring and sectoring algorithms will work to divides the mobile nodes in the network into a different zone and will select the best forwarding nodes to forwarding RREQ messages.

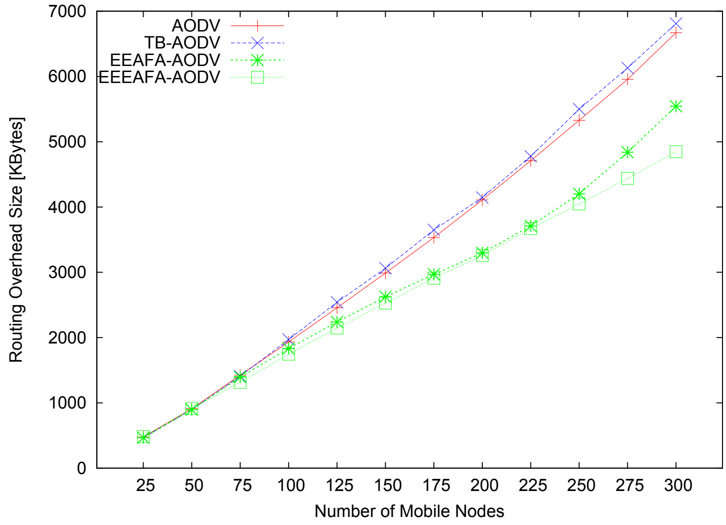


Figure 5.11: Routing overhead vs. network density (in terms of bytes).

As discussed in Section 5.2.3, the *Hello* packet format of EEEAFA-AODV protocol is piggybacked on three new fields. This increases the *Hello* packet size overhead of EEEAFA-AODV in terms of number of bytes. Although Figure 5.10 shows that in terms of number of RREQ packets transmitted, the lowest routing overhead was incurred by EEEAFA-AODV, it can be seen in Figure 5.11 that the advantage of EEEAFA-AODV is relatively small when measured by the number of bytes transmitted. For example, Figure 5.10 shows that at a density of 300 nodes the routing overhead of EEEAFA-AODV is approximately 300% below than that of AODV, in relation to the number of RREQ packets transmitted. However, when the number of bytes transmitted is used as the performance metric, it is only about 50% less than that of AODV.

5.4.1.2 Collision Rate

Figure 5.12 shows the average collision rate at the MAC layer versus the network density. The result in the figure shows that the number of collisions incurred by the four routing protocols increases with number of nodes increases. Since data and control packets share the same physical channel, the collision probability is increased when the dissemination of RREQ packets is not appropriately controlled. It is clear that, for a given network density, enhanced EEEAFA-AODV outperforms the EEAFA-AODV, TB-AODV and AODV. For example, when the network density is substantially increased (e.g. 300 nodes) the collision rate of EEEAFA-AODV is as much as 450% lower than that incurred by the previous EEAFA-AODV.

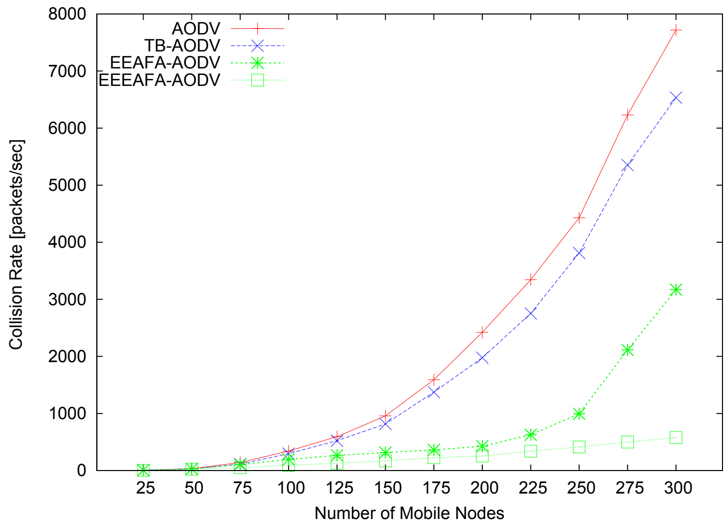


Figure 5.12: Collision rate vs. network density.

A collision occurs when several nodes in the same neighbourhood simultaneously send packets. EEEAFA-AODV divides the forwarding nodes in each group into different sectors. In each sector, the nodes are assigned a weight value, and a forwarding decision takes it into account. This weighted value helps to minimise the overlap between forwarding nodes by selecting suitable forwarding nodes in the same sector area to participate in the forwarding of the RREQ packet. This approach dramatically reduces the overlap between forwarding nodes located in the same sector, which leads to some nodes being obliged to suppress their broadcasts thus reducing the number of RREQ packets being broadcasted throughout the network and hence, the average collision rate.

5.4.1.3 Normalised Throughput

For each of the routing protocols, it is clear from Figure 5.13 that normalised throughput is low when the density of the network is relatively sparse, for example, as few as 25 nodes are operating, which can be attributed to the poorer network connectivity that tends to exist in sparse networks. However, in a dense network where a large number of redundant retransmissions of control packets, such as RREQ packets will predominate, the resulting increase in channel contention and packets colliding will reduce the bandwidth available for data transmissions. This suggests that introducing measures to economise on RREQ packet retransmissions in a dense network, could improve the throughput. It can be observed in Figure 5.13 that in a scenario where the network is relatively dense, EEEAFA-AODV outperforms its rivals. This improved performance can be attributed to significantly fewer redundant retransmissions of RREQ packets afforded by the enhanced EEEAFA-AODV.

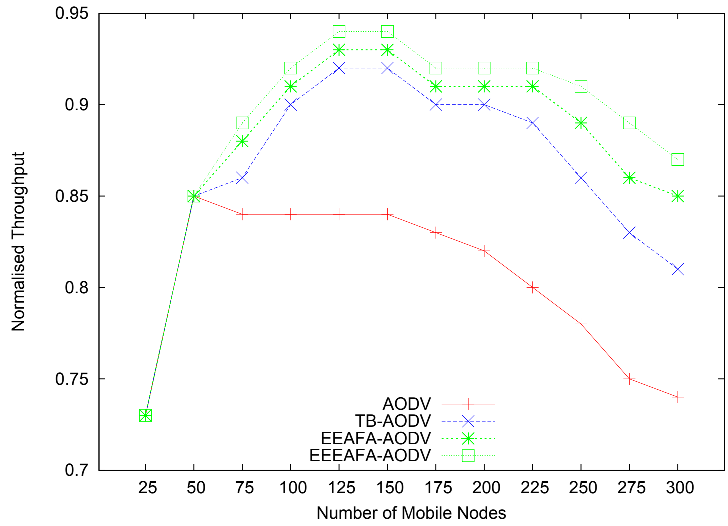


Figure 5.13: Normalised throughput vs. network density.

5.4.1.4 Delay

As might be expected, it can be seen in Figure 5.14 that, in a relatively dense network, there is an increase in end-to-end delay in line with a rise in network density, for all four protocols. As with previous effects, this can be attributed to the increased likelihood of packets colliding and channel contention in a densely populated network, due to a high level of redundant rebroadcasting, which means that the majority of the RREQ packets do not arrive at their destinations. This can lead to an increase in the time taken for route discovery (see Figure 5.15), and hence the length of time taken for data packets to be transmitted from the source to their destination nodes.

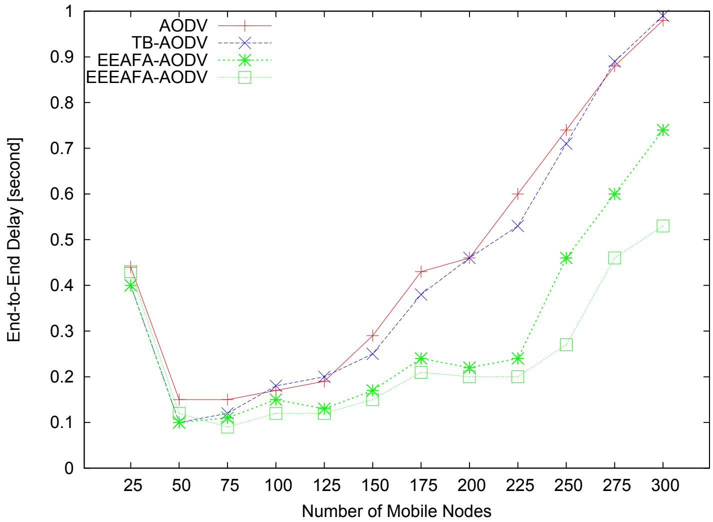


Figure 5.14: End-to-end delay vs. network density.

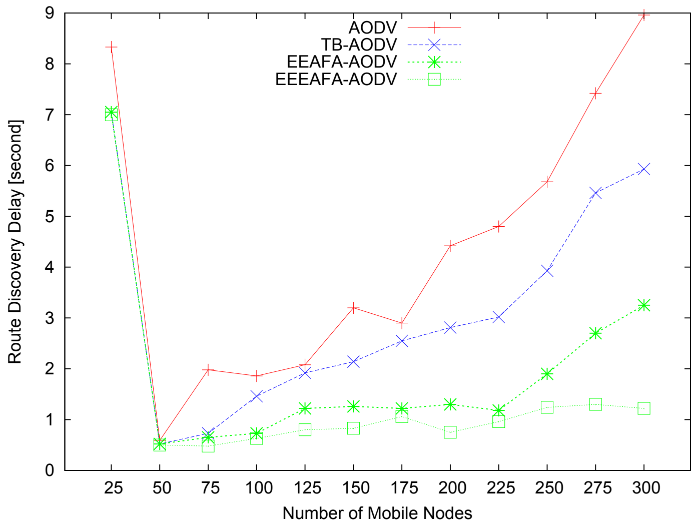


Figure 5.15: Route discovery delay vs. network density.

It can also be observed in Figure 5.14 that the end-to-end delay is prolonged in all the protocols in a very sparse network (e.g. 25 nodes), in which the network is poorly connected (most of the nodes are out of their communication range). However, the enhanced EEEAFA-AODV outperforms the previous EEAFA-AODV in terms of end-to-end delay. For instance, when the network density is substantially increased (e.g. 300 nodes), the delay in route discovery by EEEAFA-AODV is reduced by almost 160% in comparison with the previous EEAFA-AODV as shown in Figure

5.15. This can be attributed to the significantly reduced routing overhead and the collision rate.

5.4.1.5 Energy Consumption

Figure 5.16 demonstrates the total energy consumption by the route discovery broadcasting process for all the four protocols. As shown in the figure, as the network density is increased, the power consumption rises, for all four protocols. It can also be seen that the energy efficiency obtained by EEEAFA-AODV is superior to that achieved in the other three protocols. This additional energy saving of EEEAFA-AODV is achieved as a result of the forwarding restriction which adapts the rebroadcasting of RREQ packets to the weight value of the node in its sector. This reduces the level of interference, the number of collisions and thus overall power consumed. Thus, the energy consumption by EEEAFA-AODV is reduced by around 30%, 40% and 50%, when there are 250, 275 and 300 nodes operating, respectively, when compared with the previous EEAFA-AODV.

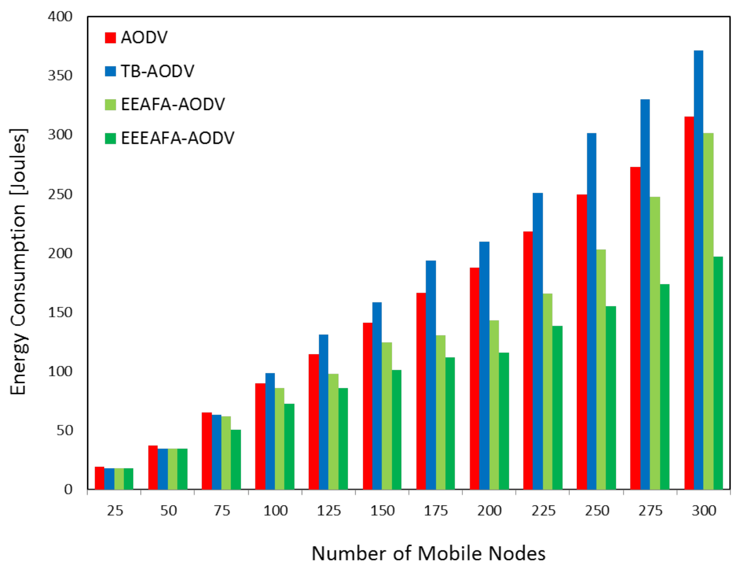


Figure 5.16: Energy consumption vs. network density.

5.4.2 Impact of Node Mobility

In order to reduce the impact of node density on network performance, the number of nodes operating in the network is fixed at 100 nodes, which indicates the median value of node density [198]. The aim is to avoid sparse and dense scenarios and to obtain a general trend for the influence of node mobility on protocol performance. To achieve this aim, a set of simulation experiments was performed, in which the mobility of 100 nodes located over a 1000 m^2 area was altered by varying the maximum node speed in the network, which was increased from $1m/sec$ to $30m/sec$ with a pause time of 0 *sec* (dynamic network). To reduce the effect of traffic load, an offered load of only 12 *connections* was set in each simulation scenario. Data packets (CBR 512 bytes) were generated at a rate of 4 packets per second.

5.4.2.1 Routing Overhead

Figure 5.17 shows that as maximum node speed increases, there is a corresponding increase in the routing overhead incurred by each of the protocols. This can be accounted for by the more frequent changes in network topology when node mobility increases, leading to more RREQ packets being generated and disseminated because of the need to repair breakages or set up new paths. These extra activities increase the overall routing overhead. At maximum node speed the enhanced EEEAFA-AODV shows a superior performance to the previous EEAFA-AODV. Figure 5.18 shows the relationship between the routing overhead size, which is measured in bytes, and node mobility, represented by the maximum node speed.

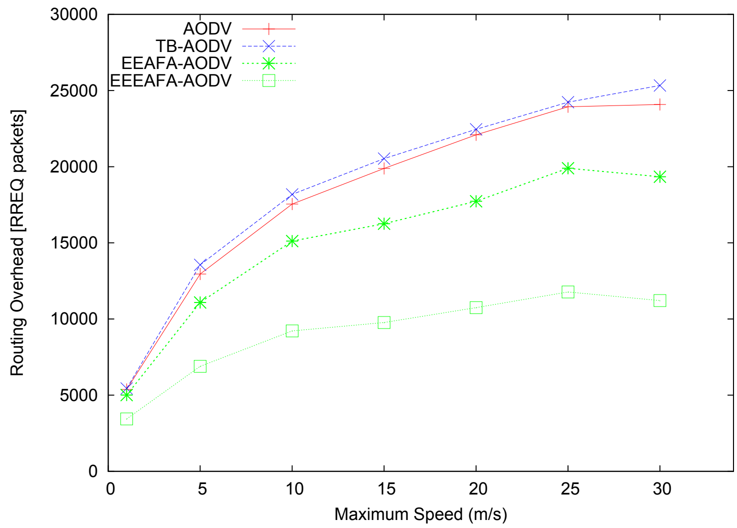


Figure 5.17: Routing overhead vs. node mobility.

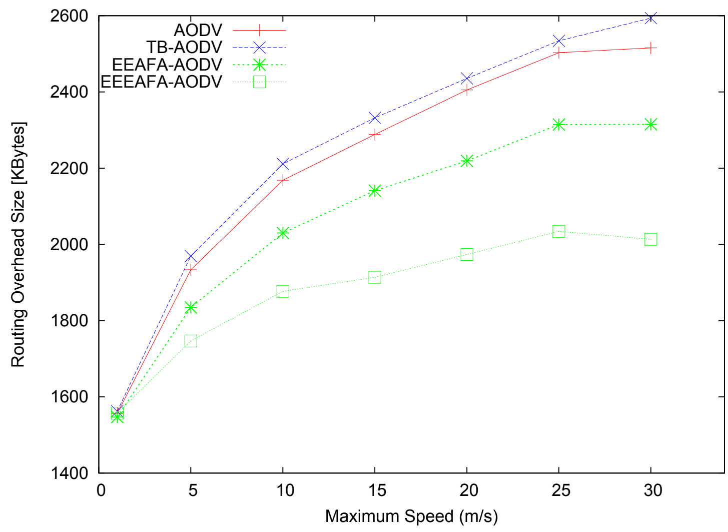


Figure 5.18: Routing overhead vs. node mobility (in terms of bytes).

5.4.2.2 Collision Rate

It can be observed in Figure 5.19 that, for each of the studied protocols there is a rise in the average collision rate as node mobility increases. This can be attributed to the more frequent occurrence of broken routes and a corresponding increase in the number of RREQ packets generated and disseminated. However, the increase in node mobility has only a slight effect on the collision rate of EEEAFA-AODV. Moreover, there is also a significant reduction of almost 130% in comparison with the previous EEAFA-AODV for the collision rate at all speeds.

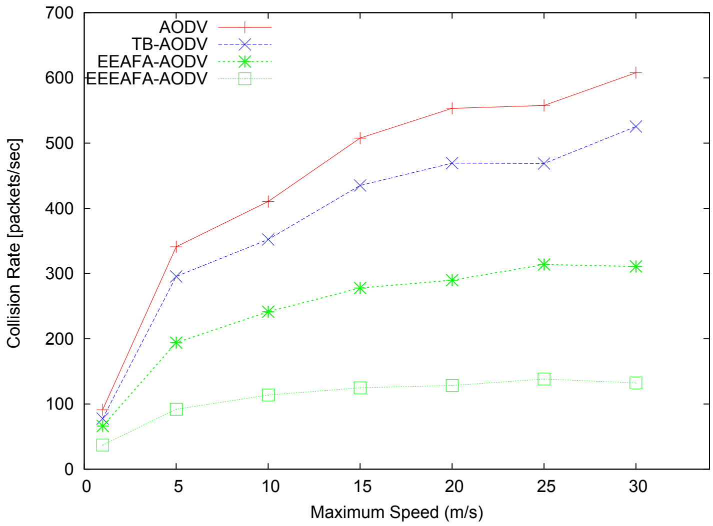


Figure 5.19: Collision rate vs. node mobility.

5.4.2.3 Normalised Throughput

Figure 5.20 compares the performance of the four routing protocols in terms of the normalised network throughput achieved at different maximum node speeds. A degradation of the normalised network throughput as node mobility increases can be seen for each of the protocols. This can be attributed to several factors. These include the more frequent and unpredictable changes in network topology when node mobility increase, and the consequent broken routes. These require further route discovery and route maintenance processes leading to more RREQ broadcast packets being generated and disseminated throughout the network and consequently, a higher likelihood of packets colliding.

Since the EEEAFA-AODV protocol uses a variable range transmission power to disseminate RREQ packets, this increases the network capacity. This is due to the reduction in the transmission power which is brought about by decreasing the level of interference and unnecessary overhearing by other nodes, resulting in improved network throughput.

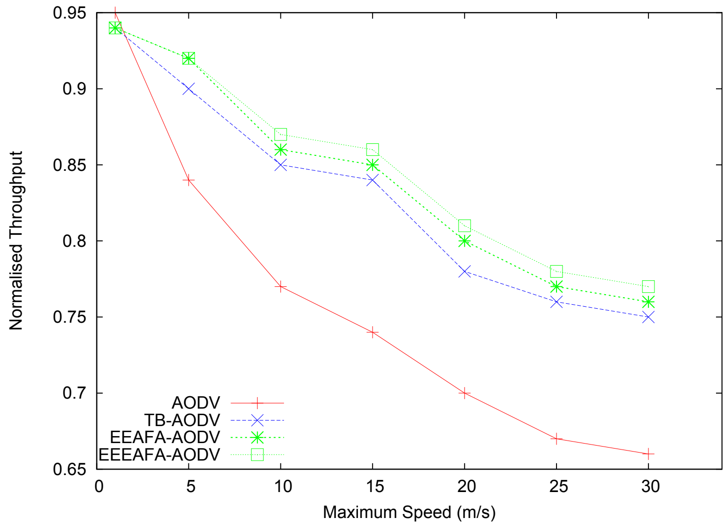


Figure 5.20: Normalised throughput vs. node mobility.

5.4.2.4 Delay

In Figures 5.21 and 5.22 the average end-to-end and route discovery delays suffered by different maximum node speeds. It can be seen that in each of the four protocols the average delay incurred is prolonged as maximum node speed increases. This is accounted for by the higher frequency of path breaks which accompanies increased node mobility. It is clear from the graph that the average delay incurred in EEEAFA-AODV is briefer compared with that incurred in the previous EEAFA-AODV when operating in a network with rapidly moving nodes.

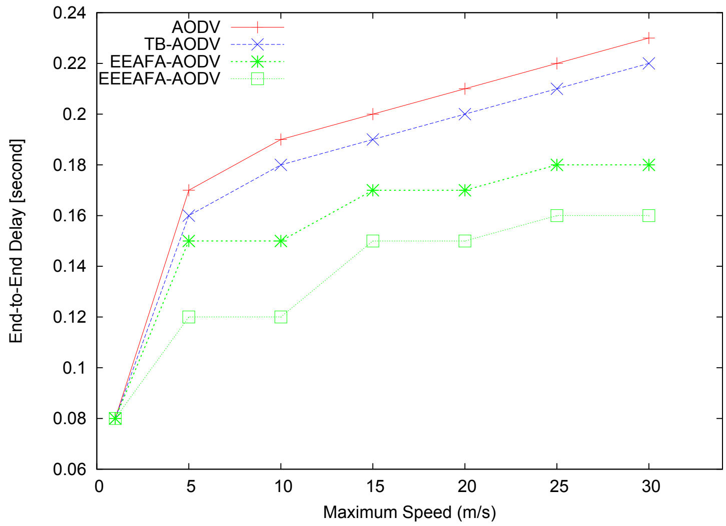


Figure 5.21: End-to-end delay vs. node mobility.

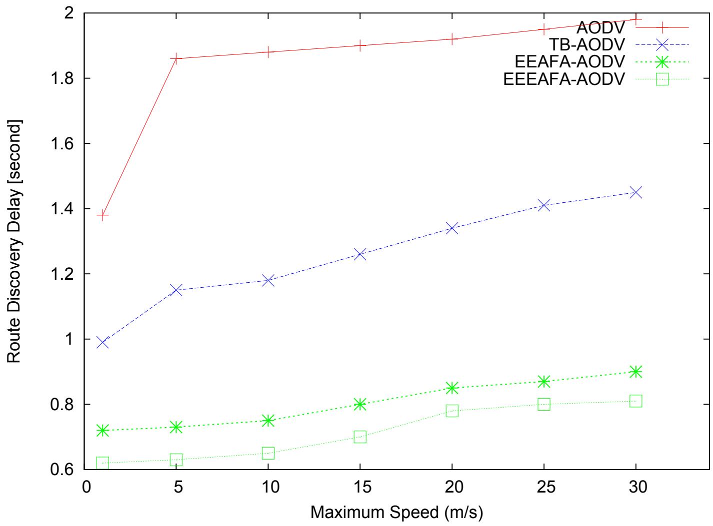


Figure 5.22: Route discovery delay vs. node mobility.

Although both EEEAFA-AODV and the previous EEAFA-AODV protocols use variable range transmission power in RREQ packet dissemination which could increase the number of hops, they still perform significantly better than the AODV protocol. Moreover, at higher node speeds, the superiority of the EEEAFA-AODV over the three protocols becomes more pronounced. The reason for this superior result is that the proposed algorithm not only has mobility support (which comes from a robust topology) but also rapidly reacts to frequent changes (relay on only one-hop local information in rebroadcast decisions), which are considered key in MANETs [23].

5.4.2.5 Energy Consumption

Figure 5.23 shows the total energy consumed by each of the four protocols at varying maximum node speeds. As shown in the chart, increased node mobility is associated with higher power consumption for all four protocols. This can be accounted for by the greater likelihood of route breakage, requiring more RREQ packets to be generated and disseminated. EEEAFA-AODV achieves approximate 20% lower energy consumption compared to the previous EEAFA-AODV. The fact behind this lower energy consumption is that nodes in EEEAFA-AODV disseminate the route discovery packets in a weighted manner. Moreover, RREQ forwarding decision in EEEAFA-AODV use both restricted forwarding and variable range transmission power. Thus, the energy expenditure of transmissions is reduced overall.

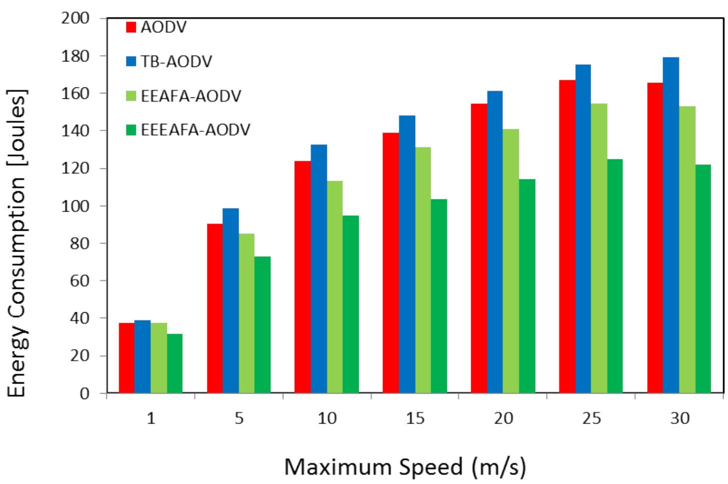


Figure 5.23: Energy consumption vs. node mobility.

5.4.3 Impact of Offered Load

In the next stage of the investigation, the offered load was varied to compare the effects on the performance of the four routing protocols. To do this different numbers of source-destination pairs (referred to as connections) were examined. In order to reduce the influence of node density on the network's performance, the number of operating nodes was fixed at 100, which is a median value of node density [198]. The aim was to avoid sparse and dense scenarios and to obtain a general trend for the impact of traffic load on the performance. A dynamic network was considered for this study where the maximum node speed is $5m/sec$ with a pause time of 0 *sec* (dynamic network) to avoid the effect of high node speed mobility on network performance. These simulation parameters are widely used in the literature [21, 94, 198]. The offered load was incrementally increased in steps of 5, 10, 15, 20, 25, 30, 35 and 40 *connections*. Data packets (CBR 512 bytes) are generated at 4 packets per second by source nodes.

5.4.3.1 Routing Overhead

Figure 5.24 illustrates that increasing the offered load had a clear effect on the routing overhead incurred by the four different protocols, which rose as the number of connections was increased. It is also clear from Figure 5.25 (measured in bytes) that the performance of EEEAFA-AODV is superior to that of the previous EEAFA-AODV, across all offered loads. This can be attributed to the optimised route discovery process in EEEAFA-AODV, in which fewer forwarding nodes participate in forwarding RREQ packets.

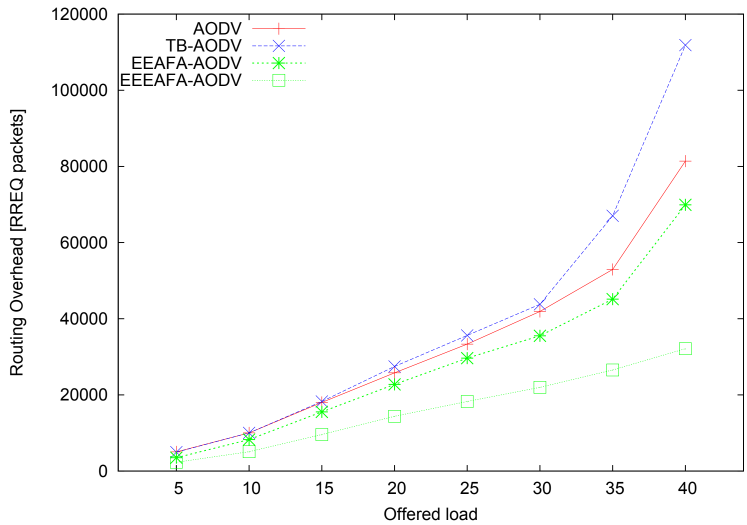


Figure 5.24: Routing overhead vs. offered load (number of connections).

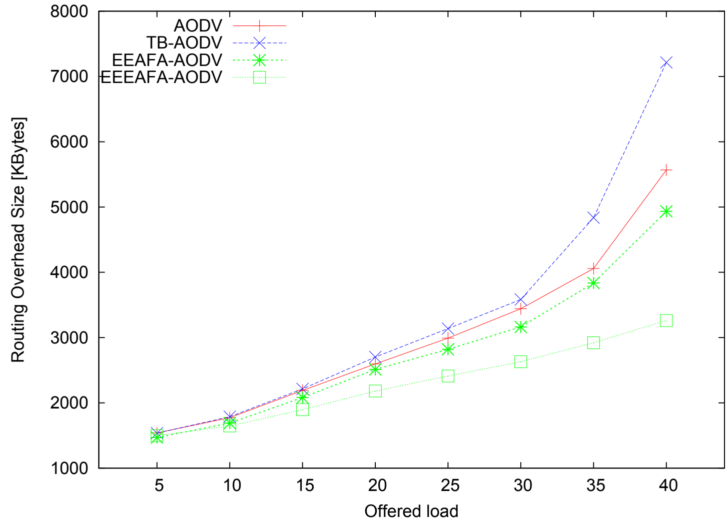


Figure 5.25: Routing overhead vs. offered load (number of connections) (in terms of bytes).

5.4.3.2 Collision Rate

As with the routing overhead incurred (Figure 5.24), it can be seen in Figure 5.26 that the collision rates have an almost linear relationship with the offered load. This is due to the greater number of connections, which is the mechanism for increasing the offered load; hence, more RREQ packets are generated and transmitted. This leads to more packets colliding. However it can be seen that EEEAFA-AODV still outperforms the previous EEAFA-AODV, for all the offered loads.

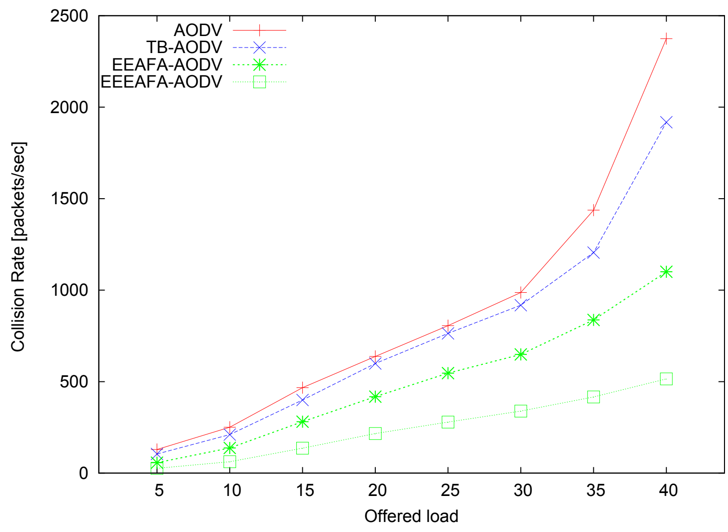


Figure 5.26: Collision rate vs. offered load (number of connections).

5.4.3.3 Normalised Throughput

Similarly to the findings in the previous sections, it is clear from Figure 5.27 that increasing the offered load, which was achieved by varying the number of connections from 5 to 40), lowers the normalised network throughput, for all the routing protocols. This is a result of the increased requirement for the nodes to embark on new route discovery operations to accommodate the higher offered load. Thus more RREQ packets need to be generated and transmitted, with a resulting rise in channel contention and packet collisions. The number of data packets arriving safely at their destinations is thus decreased, resulting in a reduction in overall network throughput. However, the graph reveals EEEAFA-AODV's superior performance over the other three protocols, which becomes more prominent as the offered load increases.

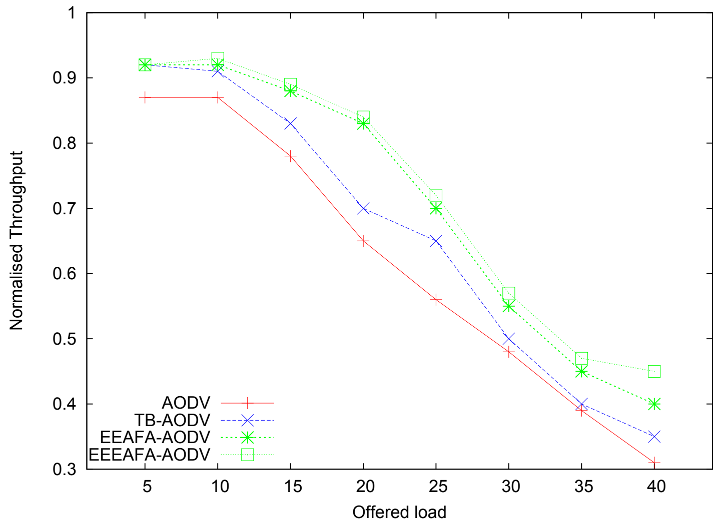


Figure 5.27: Normalised throughput vs. offered load (number of connections).

5.4.3.4 Delay

Figure 5.28 shows that, for all the routing protocols, the end-to-end delay was prolonged when the offered load increased. This can be attributed to the increased contention when there is a greater number of connections (offered load), which results in a longer queuing time at the transmitter's buffers and more collisions, with a consequent increase in the rate of packet loss. However, again the performance of EEEAFA-AODV is somewhat better than that of the other three protocols in accommodating a higher offered load. Similar performance trends for each of the four protocols can be seen in Figure 5.29 in terms of delays in route discovery.

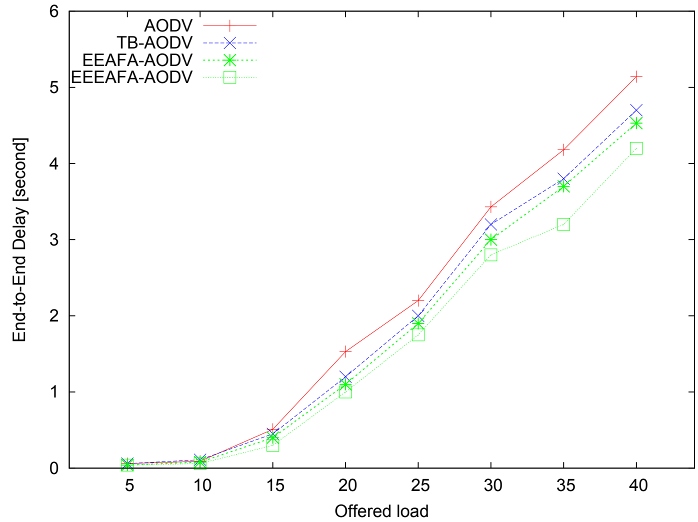


Figure 5.28: End-to-end delay vs. offered load (number of connections).

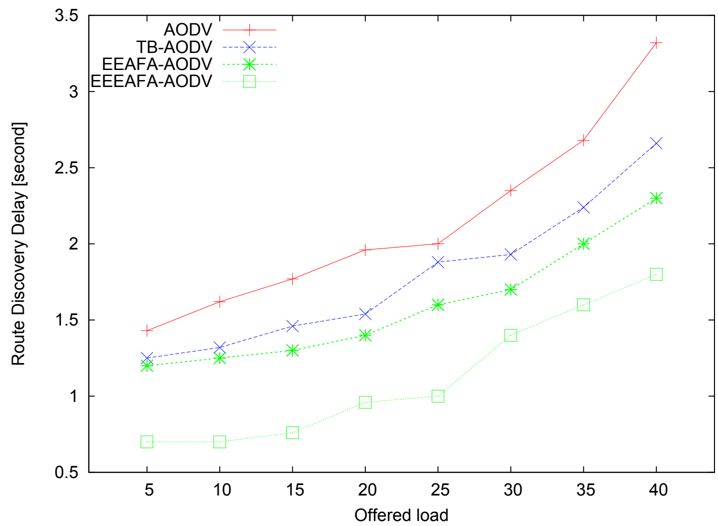


Figure 5.29: Route discovery delay vs. offered load (number of connections).

5.4.3.5 Energy Consumption

In Figure 5.30 the total energy consumption of each protocol is plotted against the offered load. It can be seen that increasing the offered load leads to raised power consumption for all four protocols, due to the larger number of connections, which entails a greater number of RREQ packets being generated and transmitted. Therefore, the total power consumption increases. EEEAFA-AODV achieved a lower energy consumption compared to the other three protocols. This lower energy consumption is due to nodes in EEEAFA-AODV disseminating the route discovery packets (RREQs) in an energy efficient manner by using restriction in the RREQ forwarding. It is also using variable-range transmission power, which reduces the energy cost in overhearing (receiving) nodes. Thus, reducing the energy expenditure of overall transmissions.

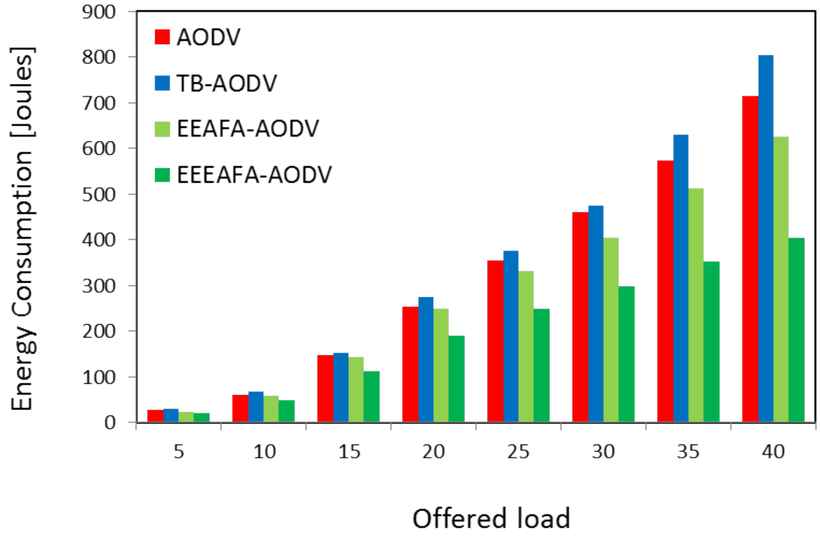


Figure 5.30: Energy consumption vs. offered load (number of connections).

We also compared our EEEAFA-AODV with the *3P-AODV* [94] scheme, where the nodes in *3P-AODV* are classified into three groups based on neighbour density (Sparse, Dense and Medium Group). The general simulation parameters used in our study are almost same with that in *3P-AODV* scheme. This to allow a fare compassion. Both schemes categorised the mobile nodes in the network into three different groups based on their local density. We noticed that the behaviour of both schemes are relatively similar with regard to the routing overhead and the number of collisions in varying number of nodes. This is because both schemes reduce the number of RREQ rebroadcasting in the network which help to minimise the number of collisions and the related retransmission. However, as *3P-AODV* scheme uses global information and a fixed-range transmission power, the amount of energy consumed by this scheme could be more than that of EEEAFA-AODV. This is because, EEEAFA-AODV uses a variable-range transmission power in sending and re-transmitting RREQ message.

5.5 Conclusions

This chapter has presented two new distributed algorithms to enhance the forwarding decision making of a broadcast message in the previous EEAFA scheme in Chapter 4; 1) *Colouring Algorithm* and 2) *Sectoring Algorithm.* The proposed colouring algorithm aims to improve the forwarding node determination process. To achieve this, a unique colour is assigned for each group of nodes. A group-colour field is included in the *hello message* and exchanged between neighbours, which helps to increase the awareness of the nodes which are located between different groups which have similar transmission power levels.

On the other hand, the sectoring algorithm aims to improve the dissemination of the RREQ packets and to shrink the size of the relaying area at each group. This involves dividing the forwarding area in each group into different sectors. The sectoring algorithm assigns a weight value for each node according to its distance from the adjacent group. This distance can be estimated from the number of *hello message* that node can receive from the different members of the group. A node with a highest weight in each sector is selected as a suitable forwarding node to participate in the forwarding of the RREQ broadcast packet. This technique can significantly reduce the overlap between forwarding nodes located in the same region. Both algorithms reduce the number of forwarding nodes and eventually the volume of RREQ packets in the network.

The enhanced EEEAFA (E-EEAFA) scheme in this chapter reduces the effect of unawareness of forwarding nodes by utilising the concept of group colour that is introduced in the one-hop based colouring algorithm in Section 5.2.4. It also reduces the impact of overlapping degree among the forwarding nodes by utilising the concept of sectoring that was presented in Section 5.2.6. This also reduces the overhead induced by E-EEAFA during route discovery, which allows this protocol to be employed even in dense networks with limited bandwidth. In addition, it should be noted that both of the proposed colouring and sectoring algorithms can reduce route discovery time, without degrading the system performance in terms of delivery ratio and overhead. This is due to the fact that the proposed E-EEAFA was originally designed to reduce contentions and collision in the network by reducing the overlap between forwarding nodes and thus conserving energy.

Using NS2 simulation, we compare the performance of the proposed enhanced-EEEAFA (E-EEAFA) algorithm with the previous EEAFA, showing that the superior performance of EEEAFA-AODV can be attributed to the significant reduction in the number of redundant retransmissions of RREQ packets. This reduction in redundant transmissions, means the overall routing overhead is reduced and thus conserve energy. It also shows that when the network density is substantially increased (e.g. 250, 275 and 300 nodes) the RREQ overhead generated by EEEAFA-AODV remains relatively stable compared to the previous EEAFA-AODV which dramatically increases.

Chapter 6

Comparing Performance with OLSR Routing Protocol

6.1 Introduction

This chapter presents a comparison between the proposed EEEAFA-AODV algorithm in Chapter 5 and the Optimised Link State Routing (OLSR) [137] protocol using a particular set of metrics. OLSR was chosen because as it uses a neighbour knowledge approach, where two-hop neighbours' information is required to make forwarding decisions at nodes. The main objective of this chapter is to show how a one-hop based topology information technique (the case of the proposed EEEAFA-AODV) can efficiently react to topology changes compared to a protocol that is based on two-hop information (the case with OLSR). Their performance will be compared based on varying network conditions: different density, mobility and offered load (connections).

In an NS2 simulation, the proposed EEEAFA-AODV outperformed OLSR. The proposed algorithm is scalable, adaptive and more energy efficient than OLSR. In this chapter, first, an overview of OLSR is presented in Section 6.2. The reason for choosing OLSR and the simulation approach is described in section 6.3. Section 6.4 presents the performance evaluation of both routing protocols. Finally, Section 6.5 summarises and draws conclusions from the results in the chapter.

6.2 OLSR: Optimized Link State Routing

6.2.1 Introduction of OLSR

The Optimised Link State Routing (OLSR) protocol, RFC 3626 [137], has been tailored for Mobile Ad hoc Networks (MANETs). OLSR is a proactive routing protocol, designed to ensure that routes are always immediately available when required. In this protocol, nodes periodically exchange information regarding the topology of the region to enable them to establish a path to any destination in the network. OLSR is an optimisation version of classical Link State Routing (LSR) Protocols [216]. Therefore, the topological changes lead to the topological information being flooded to all available hosts in the network. It enables control messages to be flooded efficiently throughout the network by using selected nodes called *MultiPoint Relays* (MPRs) [134]. OLSR uses MPRs to reduce the possible overhead in the network. The idea of a MPR is to optimise flooding/forwarding of broadcasts by reducing broadcasts in some regions in the network (see Figure 6.1).

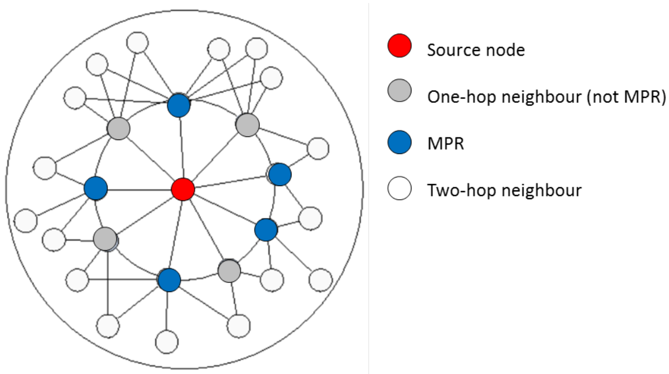


Figure 6.1: An example of flooding by MPR nodes.

6.2.2 OLSR Operation

According to [217] OLSR routing protocol has three main processes:

- *Neighbour/Link Sensing.* Where nodes detect their one-hop and two-hop neighbours by sending *Hello* packets periodically. These nodes then select their own set of MPRs among the one-hop neighbours where each node's MPRs cover all its two-hop neighbours.

- *Efficient control flooding using MPR.* each node maintains a partial topology graph of the network. These nodes use the information received from Topology Control (TC) messages to calculate the shortest paths to destinations. MPR nodes transmit a TC message periodically. These TC messages are disseminated throughout the entire network using other MPR nodes. They contain a MPR selector set of the source of the message which is forwarded by an MPR when it has received the message for the first time from that node and the node is in the MPR set of the previous hop node. This controlled flooding approach can reduce the number of retransmissions.

- *Optimal path calculation.* Dijkstra's algorithm [218] is deployed to compute the shortest path (less number of hops) to any destination node in the routing table.

6.2.3 Multipoint Relays

Multipoint relay (MPR) [134] is a key concept used in OLSR where MPRs nodes forward broadcast packets during the dissemination process. It reduces the message overhead considerably in comparison with a simple flooding approach, in which every node blindly retransmits each incoming message. MPR technique helps in reducing energy consumption at mobile nodes during the broadcasting process. In the OLSR routing protocol, only those nodes which are elected as MPRs will generate link state information. An MPR may choose to report only the links between itself and the nodes which selected it as an MPR. As a result, partial link state information is disseminated in the network which can then be utilised for calculating routes. As OLSR provides the shortest routes in terms of the number of hops, it is particularly suited for scenarios where there are extensive and dense networks, as the technique of MPRs works well in these situations. In previous study of performance evaluations [219] a MANET with OLSR routing has been shown to perform satisfactorily.

6.3 Protocol Selection and Simulation Approach

OLSR routing protocol [137] is used in this chapter because it shares important characteristics with the proposed EEEAFA-AODV protocol. Both protocols are based upon the following.

- optimising flooding algorithms by selecting a subset of nodes to forward a broadcast message through the network.
- being topology based and using *hello messages* to exchange topology information periodically.
- being tailored for MANETs and designed for dense networks.

The NS2 simulator [181] is used to simulate the performance of OLSR and EEEAFA-AODV (proposed in Chapter 5) routing protocols under different network conditions. The parameter settings used are shown in Table 6.1. All results are calculated from the mean of 25 simulation runs.

Table 6.1: Simulation Parameters for Comparing EEEAFA-AODV and OLSR

Simulation time	100 sec
Topology size	1000 m^2
Number of nodes	25, 50, 75, 100, ..., 225
Number of connections	5, 10, 15, 20 ... and 40
Maximum speed	1, 5, 10, 15 ... and 30 m/sec
Pause time	0 sec (dynamic network)
Traffic model	CBR

6.4 Performance Evaluation

To evaluate the performance of the EEEAFA-AODV algorithm against OLSR, the OLSR protocol was patched and installed on the network simulator NS2 because it is not available as part of the NS2 (version 2.35) installation.

6.4.1 Impact of Network Density

To compare the performance of OLSR and EEEAFA-AODV, the network density was varied by changing the number of nodes deployed over a 1000 m^2 area in each simulation scenario. The maximum speed of each node was set at $5m/sec$ with a pause time of 0 *sec* (dynamic network), while 12 *connections* were randomly chosen for each of the simulations. Data packets (CBR 512 bytes) were generated at 4 packets per second.

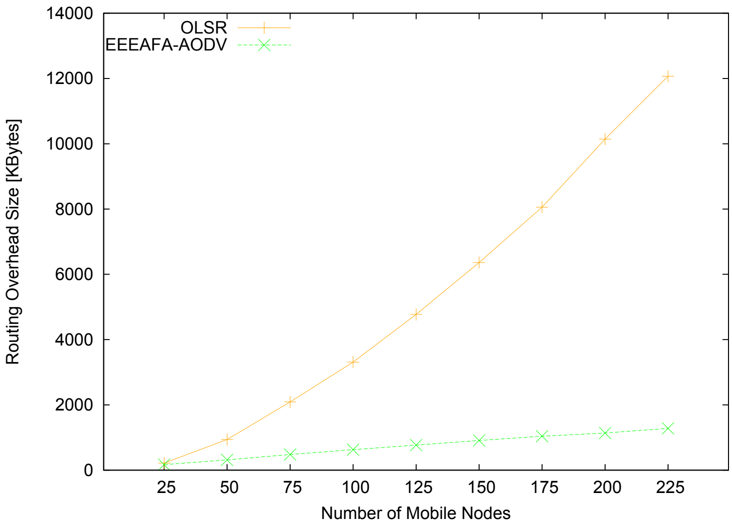


Figure 6.2: Routing overhead vs network density.

6.4.1.1 Routing Overhead

Figure 6.2 shows that EEEAFA-AODV protocol has low overheads that are considerably less than the OLSR protocol. The reason is that the reactive characters of EEEAFA-AODV have a low traffic load in these scenarios. On the other hand, OLSR has a higher overhead for networks with a total of between 50 and 225 nodes. It has bigger overheads compared with EEEAFA-AODV because of its proactive characteristics. It can be seen in the figure that the routing overhead packet size generated by OLSR increases significantly when there is a larger number of mobile nodes. This is because nodes in OLSR exchange lists of neighbours periodically in *hello messages* thus increasing the Hello packet size as the network density increases. Moreover, competition among MPRs in OLSR through TC and *hello messages* result in a high generation rate of routing control packets.

6.4.1.2 Normalised Routing Load

Normalised Routing Load (NRL) is the ratio of the total number of control packets sent to the total number of data packets delivered to the destinations, measured in size. This metric is important in order to determine the performance of a network using different types of routing protocols. This metric is also used in measuring the protocol's scalability, the usage of bandwidth, and its energy efficiency. To conserve bandwidth and energy, MANET routing protocols need to have a low routing load.

Figure 6.3, shows a dramatic increase in the routing load in OLSR as the number of mobile nodes increases. This is because OLSR maintains complete information about the whole network so that whenever a packet arrives, it need not search for a path to the destination. This is done at the cost of bandwidth and it constrains the scalability of OLSR. It is clear that OLSR has greater NRL than EEEAFA-AODV in overall network size, whereas the NRL of EEEAFA-AODV remains constant and is not affected by the network size. The reason is the reactive nature of the EEEAFA-AODV protocol where a path is established whenever it is needed.

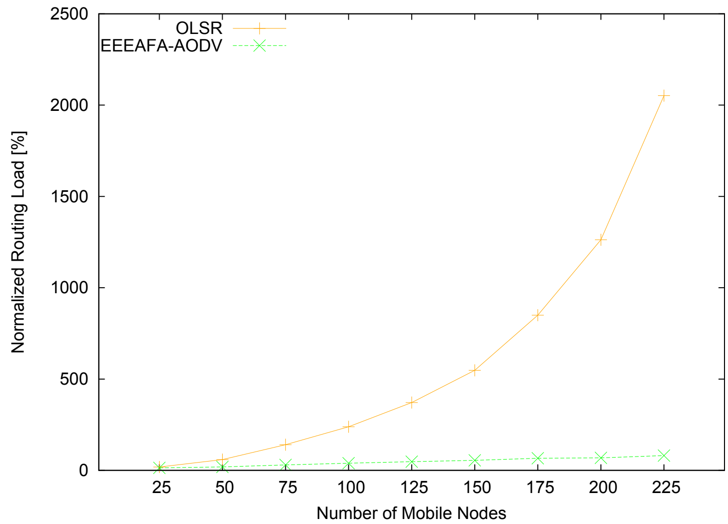


Figure 6.3: Normalised routing load vs. network density.

6.4.1.3 Collision Rate

The average collision rate versus the network density is illustrated in Figure 6.4. The collision rate is related to the routing overhead results. The graph shows that OLSR has a higher collision rate than EEEAFA-AODV. Thus, OLSR may not be suitable for a dense network, while EEEAFA-AODV routing protocol is more efficient in large dense deployed networks. The reason is that the EEEAFA-AODV is designed to work over a power control based topology structure, as a result route discovery packets and the periodically exchanged *hello message* are transmitted using variable range transmission power instead of fixed range (the case with OLSR) which inhibits packets from being interfered with across the medium.

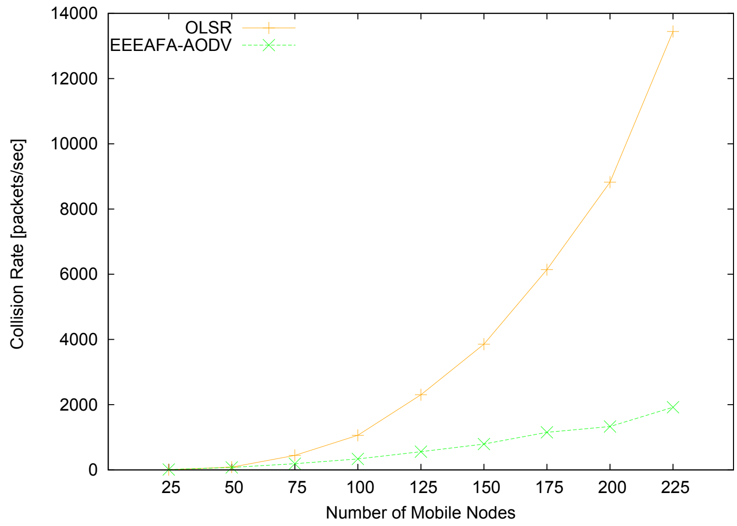


Figure 6.4: Collision rate vs. network density.

6.4.1.4 Normalised Throughput

Figure 6.5 plots the normalised network throughput obtained by both OLSR and EEEAFA-AODV routing protocols against network density. For both routing protocols the normalised throughput is low when the network density is set low (for example, 25 nodes). The reason here results from the poor network connectivity, along with a sparse network. In contrast, in a dense network OLSR performance degraded as the number of mobile nodes increases, while EEEAFA-AODV protocol is clearly constant and is not affected by increasing node density. The reason is that

OLSR has frequent packet collisions and interference due to heavy control overhead traffic, whereas EEEAFA-AODV uses variable range transmission power in order to increase the network's capacity and to reduce the transmission power level by decreasing the unnecessary overhearing by other nodes and the level of interference. This helps to increase the throughput of the network.

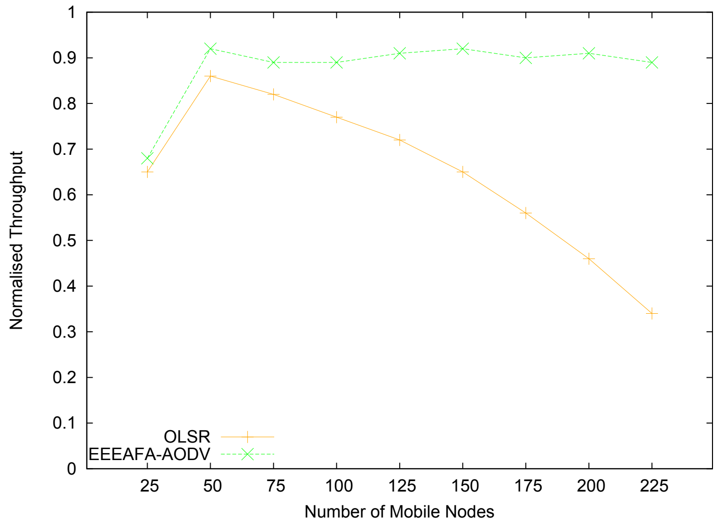


Figure 6.5: Normalised throughput vs. network density.

6.4.1.5 Delay

Figure 6.6 illustrates the effects of network density on the performance of both OLSR and EEEAFA-AODV in terms of end-to-end delay. As shown in the figure, in a relatively high-density network (e.g. 150, 175, 200 and 225) the delay increases in OLSR. This is because in a dense network, the packet collusion rate is high causing most packets to fail in reaching their destination. In comparison, EEEAFA-AODV performs better in highly dense networks, because the control packets generated are properly controlled which reduces channel contention and packet collision. This can potentially decrease the latency incurred in transmitting data packets from source to destination nodes (end-to-end delay).

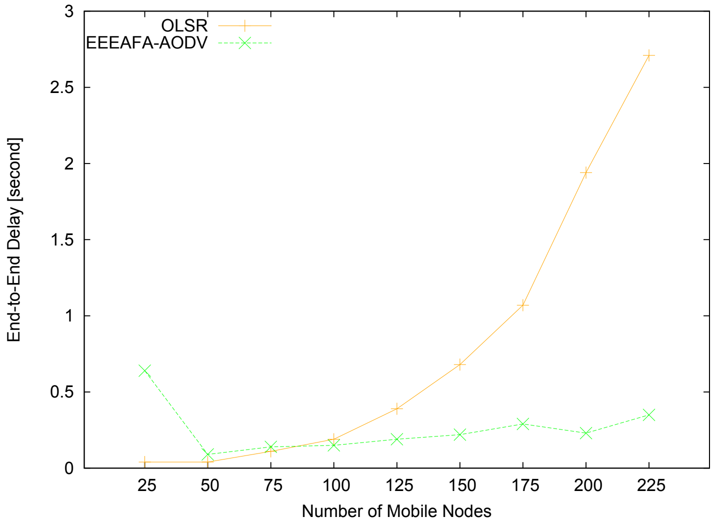


Figure 6.6: End-to-end delay vs. network density.

6.4.1.6 Energy Consumption

Figure 6.7 shows overall energy consumption by both routing protocols OLSR and EEEAFA-AODV, where it can be observed that the power consumption for OLSR becomes noticeably higher with an increase in the network density. This is because OLSR has a greater collision rate, which in turn causes the retransmission of packets on the MAC layer, thus wasting energy, which is dissipated in the retransmission and reception of colliding frames. In contrast, EEEAFA-AODV was relatively constant in its power consumption. EEEAFA-AODV energy saving is achieved by using variable range of transmission power which reduces the level of interference, overhearing, the number of collisions and thus the overall power consumed.

As mentioned before, we used a column chart type in performance evaluation of energy consumption, to illustrate the comparisons among routing protocols, which is give more observation of the thesis goal.

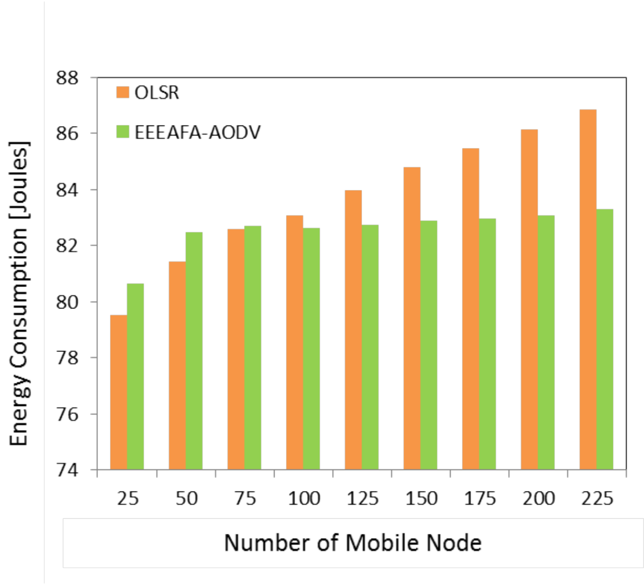


Figure 6.7: Energy consumption vs. network density.

6.4.2 Impact of Node Mobility

In order to reduce the effect of node density on network performance, the number of nodes operating in the network is fixed at 100 nodes, which indicates the median value of node density [198]. The aim is to avoid sparse and dense scenarios and to get an overview of how node mobility affects the performance avoiding any effects caused by a dense network. A number of simulation experiments were conducted in which 100 mobile nodes were distributed over a 1000 m^2 area and the maximum node speed in the network was varied. To simulate different movement patterns in MANETs applications, the maximum speed was increased from $1m/sec$ to $30m/sec$ with a pause time of 0 *sec* (dynamic network). In addition, to reduce the effect of traffic load, an offered load of 12 *connections* was selected in each simulation scenario. The source nodes generated data packets (CBR 512 bytes) at a rate of 4 packets per second.

6.4.2.1 Routing Overhead

The routing overhead size (measured in bytes) was plotted against the maximum node speed for both OLSR and EEEAFA-AODV, as shown Figure 6.8. The results indicate that the routing overhead of OLSR increases as maximum node speed rises.

The reason behind this is that OLSR needs to send TC control messages periodically to maintain a routing table at each node for the entire network. This means that, as the node mobility increases, the network topology is constantly changing, causing more frequent link breakages. In contrast as node mobility increases EEEAFA-AODV remains relatively constant.

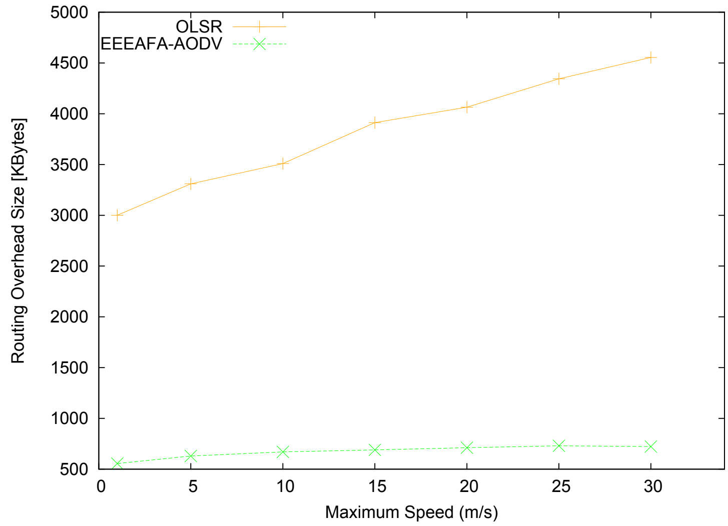


Figure 6.8: Routing overhead vs. node mobility.

6.4.2.2 Normalised Routing Load

Figure 6.9 indicates that the normalised routing load in OLSR has increased dramatically as the node speed increases. This is because OLSR maintains complete information about network topology changes. This is done at the cost of bandwidth and it constraints the scalability of OLSR. On the other hand, EEEAFA-AODV remains steady and is not affected by node speed.

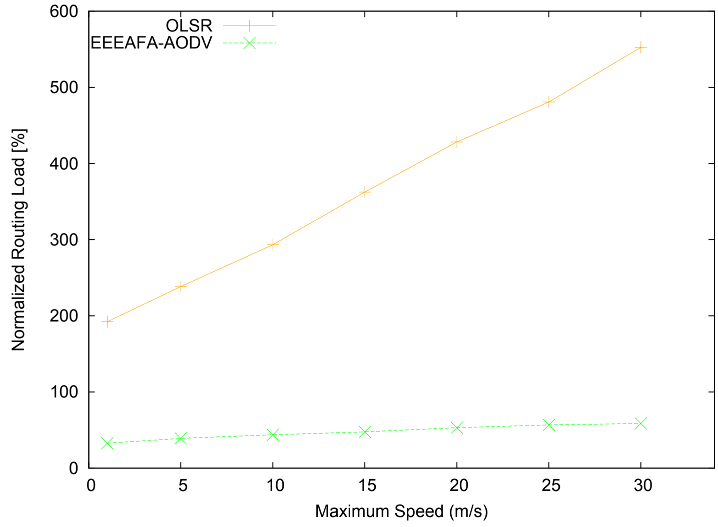


Figure 6.9: Normalised routing load vs. node mobility.

6.4.2.3 Collision Rate

It can be observed in Figure 6.10 that there is a rise in the average collision rate of OLSR with increased node mobility. In comparison, the average collision rate of EEEAFA-AODV is steady.

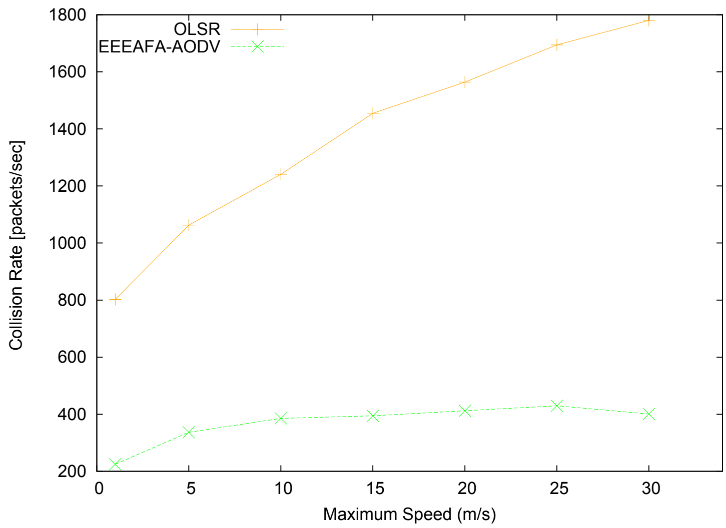


Figure 6.10: Collision rate vs. node mobility.

6.4.2.4 Normalised Throughput

Figure 6.11 shows that EEEAFA-AODV performs better than OLSR in the normalised network throughput. The reason is that due to the low convergence of OLSR in high mobility, overall throughput gradually decreases because mobility increases the unavailability of valid routes due to its proactive nature. Moreover, OLSR relies on two-hop neighbours' information in calculating the MPR node (a forwarding node). This means the protocol has a slow reaction to changes as two time intervals are required to update all its two-hop neighbours with the changes. On the other hand, EEEAFA-AODV relies on one-hop information which lets the protocol rapidly react to topology changes.

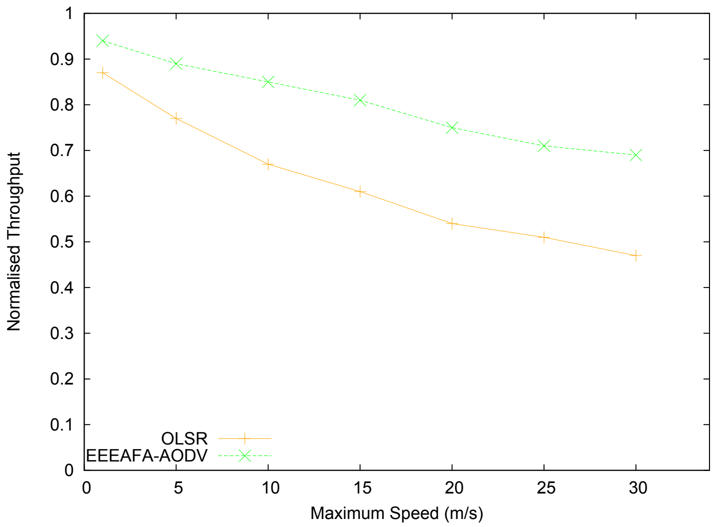


Figure 6.11: Normalised throughput vs. node mobility.

6.4.2.5 Delay

Figure 6.12 shows that for both OLSR and EEEAFA-AODV, the average delay incurred by each of the routing protocols is prolonged with higher maximum node speed, which is attributed to the frequency of path breakages that occur as the nodes move faster. It can also be seen that the average delay recorded for EEEAFA-AODV is not as long as that incurred by OLSR.

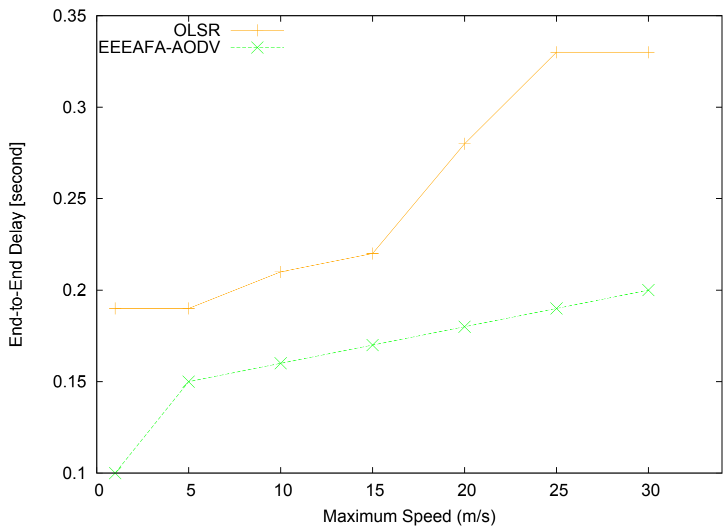


Figure 6.12: End-to-end delay vs. node mobility.

6.4.2.6 Energy Consumption

Figure 6.13 demonstrates the overall energy consumed by both OLSR and EEEAFA-AODV. As shown in the figure, EEEAFA-AODV achieves lower energy consumption compared to OLSR. The fact behind this lower energy consumption is that nodes in EEEAFA-AODV disseminate the broadcast packets with variable range transmission power. Thus the energy cost in overhearing nodes is reduced.

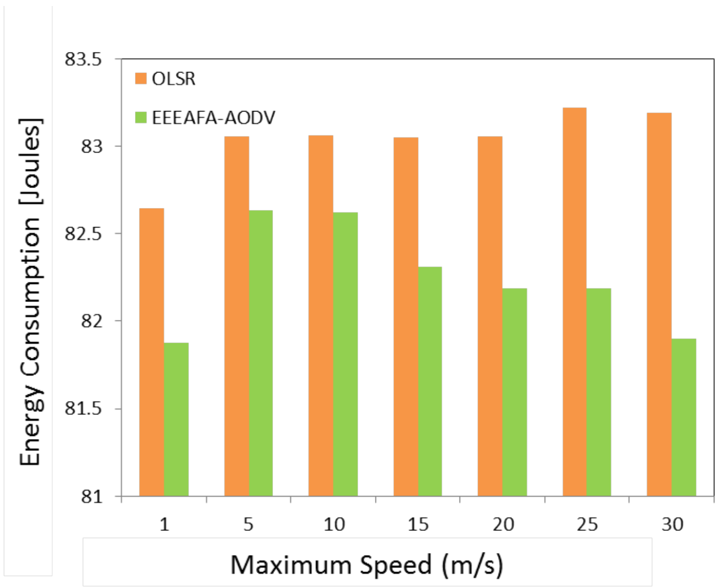


Figure 6.13: Energy consumption vs. node mobility.

6.4.3 Impact of Offered Load

To compare how the offered load affected the performance of the two routing protocols, different numbers of source-destination pairs (referred to as connections) were examined. In order to reduce the influence of node density on network performance, the number of nodes in the network was fixed at 100 nodes, which is a median value of node density [198]. The aim was to avoid sparse and dense scenarios and to get a general trend for the impact of traffic load on the performance. A dynamic network was considered for this study where the maximum node speed is $5m/sec$ with a pause time of 0 *sec* (dynamic network) to avoid the effect of high node speed mobility on network performance. The offered load was incrementally increased in steps of 5, 10, 15, 20, 25, 30, 35 and 40 *connections*. Data packets (CBR 512 bytes) are generated at 4 packets per second.

6.4.3.1 Routing Overhead

Figure 6.14 illustrates the routing overhead size (measured in bytes) generated by both the OLSR and EEEAFA-AODV protocols. In the figure, OLSR is showing higher overhead than EEEAFA-AODV. Although OLSR generated more overhead, its performance is consistent. The fact behind it is that OLSR is a proactive protocol that produces higher routing efficiency than reactive protocols in the network with increasing overload (connections). The reason is that the routing information is obtained from periodic updates and no additional overhead is incurred in searching for new routes. However, more bandwidth and resources are used by proactive protocols than in reactive protocols. Thus, proactive protocols like OLSR are not recommended to be used in environments with restricted resources (bandwidth and energy). However, the overhead of EEEAFA-AODV gradually increases as the number of connections increase. This is because the reactive nature of EEEAFA-AODV invokes route discovery flooding to find new routes for any new connection on demand.

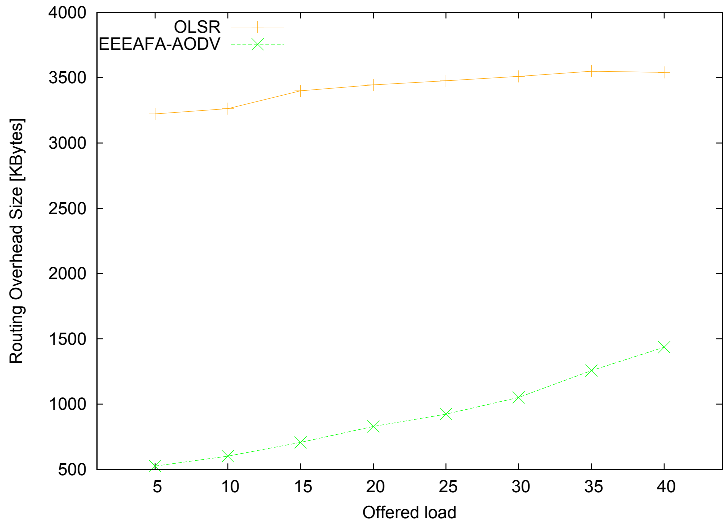


Figure 6.14: Routing overhead vs. offered load (number of connections).

6.4.3.2 Normalised Routing Load

As the normalised routing load measures the ratio of the total packet size of control packets sent to the total size of the data packet delivered. Figure 6.15 shows that EEEAFA-AODV performs significantly better than OLSR. The reason is that EEEAFA-AODV uses fewer control packets to deliver data packets because the control messages sizes are kept small, thus less bandwidth is required to maintain the routes and the routing table is also kept small. Although each node in EEEAFA-AODV broadcasts periodic *hello message* to monitor connectivity, this activity is limited and smaller-sized control are sent compared with those used by OLSR.

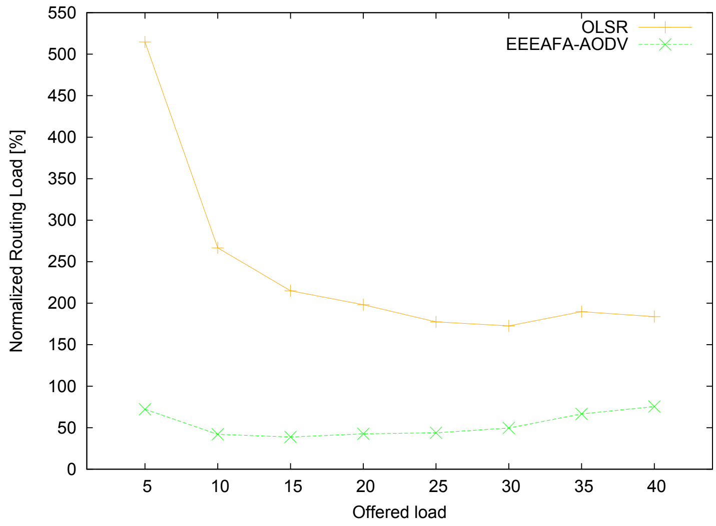


Figure 6.15: Normalised routing load vs. offered load (number of connections).

6.4.3.3 Collision Rate

In Figure 6.16, it can be seen that there is a linear increase in the collision rate of all the packets colliding in the MAC layer for both the EEEAFA-AODV and OLSR protocols along with the increased offered load. This is brought about by the higher number of connections used to increase the load, which requires more route discovery control packets to be generated and transmitted, resulting in a higher rate of packet collisions. The figure also reveals the superior performance of EEEAFA-AODV over OLSR with low offered load (e.g. 5 - 35 connections). However, the collision rate of EEEAFA-AODV increases as the number of connections increase. This is because the reactive nature of EEEAFA-AODV invokes route discovery flooding to find new routes for any new connection on demand.

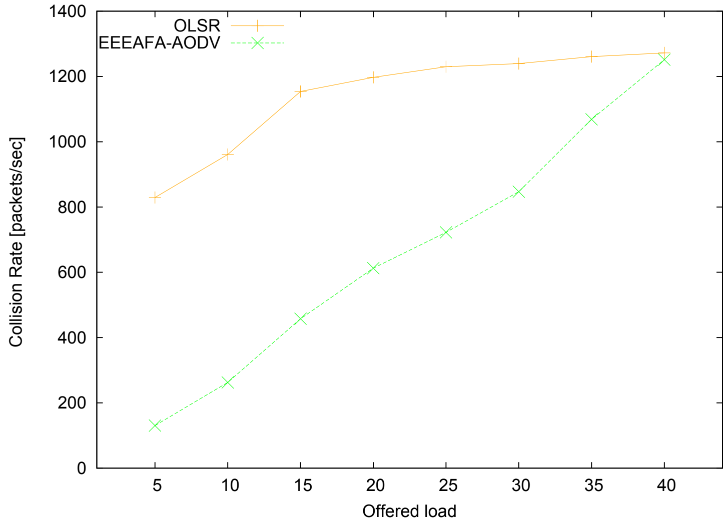


Figure 6.16: Collision rate vs. offered load (number of connections).

6.4.3.4 Normalised Throughput

In Figure 6.17, as with the other metrics, network throughput is affects by a higher offered load increases, for both the EEEAFA-AODV and OLSR. This is a result of the rise in the number of nodes initiating route discovery operations when the offered load increases in EEEAFA-AODV. The resulting rise in route discovery operations leads to more packet collisions and consequently fewer data packets being successfully reaching their intended destinations, which reduces overall network throughput. Interestingly, the figure also shows that EEEAFA-AODV's superiority over OLSR becomes less significant when the offered load increases.

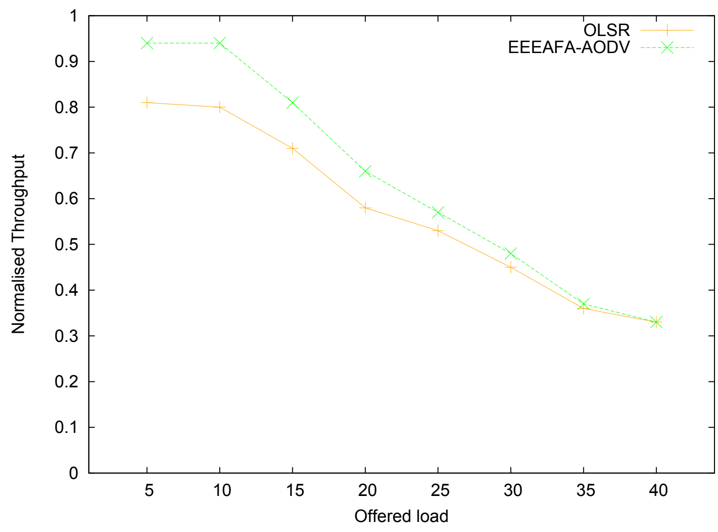


Figure 6.17: Normalised throughput vs. offered load (number of connections).

6.4.3.5 Delay

In Figure 6.18, it can be seen that both OLSR and EEEAFA-AODV exhibit similar behaviour in terms of the end-to-end delay incurred when they are dealing with high offered loads. The reason for this is that extra contention is caused by increasing the number of connections, resulting in longer queuing delays at the transmitter buffer and more collisions, and consequently a higher packet loss rate. However, as the EEEAFA-AODV works with variable range transmission, more hops are created between source and destination which negatively affects the end-to-end delay as can be seen in the graph.

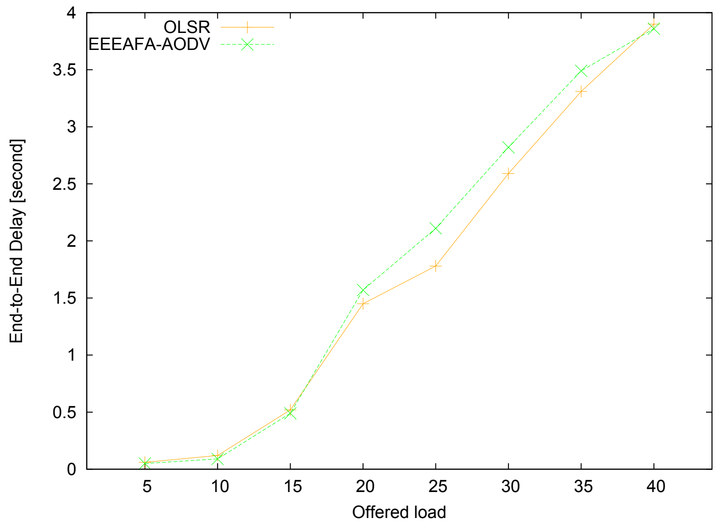


Figure 6.18: End-to-end delay vs. offered load (number of connections).

6.4.3.6 Energy Consumption

Figure 6.19 shows the average energy consumed by both OLSR and EEEAFA-AODV. It can be seen that, the power consumption for both OLSR and EEEAFA-AODV increases with the rise in the offered load. This is due to the higher number of connections required to increase the offered load, which means more discovery packets are generated and transmitted in EEEAFA-AODV. As a result, more contention and collisions occur in the MAC layer which leads to more retransmissions and thus more power consumption.

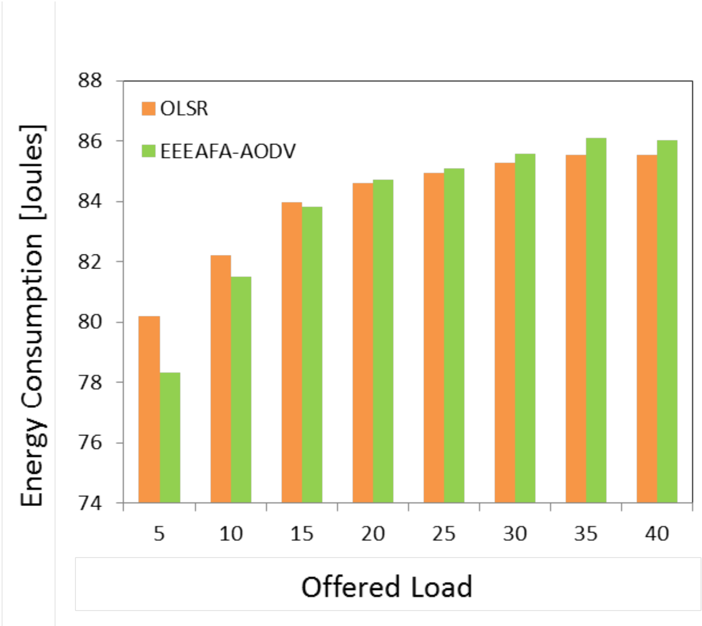


Figure 6.19: Energy consumption vs. offered load (number of connections).

6.5 Conclusion

This chapter has compared the performance of the OLSR routing protocol to that of the proposed EEEAFA-AODV protocol in Chapter 5. Both protocols are topology-based and are both designed for a densely deployed network. They both utilise *hello messages* to exchange topology information periodically. These two routing protocols are based on optimising network flooding by reducing the number of forwarding nodes and thus minimising routing overheads and overall energy consumption. However, in order to optimise flooding and reduce the routing overheads, OLSR uses two-hop information to calculate and select a subset of nodes (MPRs) as a set of forwarding nodes to carry out the flooding for the entire network. On the other hand, EEEAFA-AODV uses one-hop local information to determine the set of forwarding nodes that participate in relaying broadcast messages through the network. This chapter shows that protocols that uses one-hop information perform better than protocols which rely on two-hop information which need two time intervals to update all neighbours with changes.

The results of the performance evaluation indicate that EEEAFA-AODV can be considered as a promising and efficient protocol for a large size (number of nodes) and high mobility network. On the other hand, in OLSR there is a need to broadcast *hello messages* periodically to exchange two-hop topology information (large size packets) which consumes network resources (bandwidth and energy). This significantly increases the size of the control traffic overhead. Thus, it is unsuitable for a large size network.

On the other hand, EEEAFA-AODV is not suitable for large traffic (i.e. high number of connections), which is gives the worst performance after 40 connections than OLSR. The fact behind it is that OLSR is a proactive protocol that produces higher routing efficiency than reactive protocols in the network with increasing overload (connections). The reason is that the routing information is obtained from periodic updates and no additional overhead is incurred in searching for new routes. However, more bandwidth and resources are used by proactive protocols than in reactive protocols. Thus, proactive protocols like OLSR are not recommended to be used in environments with restricted resources (bandwidth and energy).

Chapter 7

Conclusions

7.1 Introduction

In mobile ad hoc networks (MANETs) choosing an appropriate algorithm for broadcasting is not a simple task. There is a trade-off between reliability and efficiency in designing broadcast algorithms [220]. Reliability is measured by the number of nodes which deliver the message and efficiency by the number of nodes forwarding the message [72]. Simple flooding is considered a reliable approach which insures maximum coverage of the entire network. By using this approach, a broadcast packet has a high likelihood of reaching every node in the network. However, a simple flooding approach means that the radio signals will be likely to overlap with others within a geographical area. This is usually very costly and will lead to a high level of redundancy in duplicated rebroadcasts, together with channel contention and high packet collision rates. These drawbacks comprise the broadcast storm problem. By optimising the number of forwarders, resources such as battery power can be conserved. However, this increases the risks that some nodes may not receive messages [72].

The efficiency of a topology-based broadcasting algorithm highly depends on the effectiveness of maintaining a topology information. A topology with less interference and collisions is considered more reliable in broadcasting operations. Therefore, in this study a topology control algorithm has been introduced, to enhance the scalability of routing protocols by minimising interference via a power control approach.

The transmission power (and hence the transmission range) of nodes are adjusted so that there is reduced interference amongst neighbouring nodes. This not only helps to increase the spatial reuse of the channel bandwidth but also reduces collision among transmitted packets, resulting in higher throughput, better performance and higher power saving.

7.2 Thesis Contributions

The major contributions of this thesis are:

1. A comprehensive state of the art literature review of broadcasting protocols and energy aware algorithms has been conducted. Additionally, a classification of the broadcasting schemes and studied algorithm systems has been provided.

2. A cross-layer approach is used in constructing a power control based topology structure that utilises lightweight variable-range beaconing messages in maintaining this topology. Every node in the network dynamically adjusts its transmission power range to different pre-defined levels based on their local density (number of neighbours).

3. A new Energy Efficient Adaptive Forwarding Scheme (named EEAFA) that is designed to work over the constructed topology structure mentioned above, and uses the one-hop information provided by this topology for making wise rebroadcast decisions. This proposed scheme focuses on reducing the number of redundant retransmissions, end-to-end delay, bandwidth usage and energy consumption by selecting a subset of nodes to forward packets using one-hop information provided by the topology structure without relying on GPS or any distance calculations.

4. Optimisation of the proposed route discovery algorithm has been introduced, and an Enhanced EEAFA scheme (named E-EEAFA) was designed to tackle some drawbacks in the previous EEAFA. This enhanced version of this scheme uses the concepts of colouring and sectoring to reduce the overlap among forwarding nodes. These two concepts can collaborate to reduce both contention

and collisions and at the same time achieve stable performance in high-density environments.

5. Extensive simulation-based evaluation has been carried out to investigate the performance of the proposed algorithms using a Random Way Point mobility model. The performance of the proposed protocol has been compared with a simple flooding scheme (conventional AODV). It was also compared with the well known neighbour-knowledge approach (OLSR routing protocol) which relies on two-hop neighbour knowledge to provide more topology information.

7.3 Directions for Future Work

As discussed in the previous section, this thesis has managed to make additional contributions that were developed from the initial aim of introducing a route discovery scheme. This mindset could encourage further research on areas in different applications; for example: in ad hoc sensor networks. Further research directions are briefly outlined below.

- As mentioned earlier in the literature chapter, there are four strategies for saving energy. This research has utilised two of them: Transmission power control and Limiting the number of retransmissions. The other two: Energy efficient routing and Scheduling device behaviour (node status). It would be promising to gather all of them in a future scheme. As for energy efficient routing, we could improve the routing quality of service through knowing the best end-to-end data transmission path in terms of energy cost (transmission power level used for each hop).

- Scheduling device behaviour is one direction of investigation in this pursued research. Since the energy consumed in the sleep mode is lesser than the one consumed in the transmit, receive and idle modes. Node scheduling mechanism could proposed to maximise the network lifetime in wireless ad hoc networks. This solution allows router nodes to sleep, while ensuring the network functionality and the end-to-end communication.

- This research has focused on a comprehensive analysis of the performance of topology-based broadcast algorithms in reactive routing algorithms, such as AODV. The use of topology-based broadcast algorithms such as Optimized Link State Routing Protocol (OLSR) [137] and hybrid routing protocols, such as Zone Routing Protocol (ZRP) [221] in proactive routing protocols could be explored in a further study.

- Dynamic adjustment of the *hello* timer in routing protocols for reducing overhead is one direction of investigation in this pursued research. To dynamically adapt the *hello message* intervals, some suggestions for the metric include link change rate estimation (time to a network partition), varying the *Hello* period according to node mobility or variance in battery life of nodes. We could work on the *hello message* interval time by making it more adaptive based on specific parameters. This will decrease the overhead, collision rate and overall power consumption.

- In this study the nodes that act as a Colour-head node consume higher energy levels than other nodes. This is because when they receive a RREQ broadcast message, they ignore any restriction and forward the route request packet to insure the reachability of the packet in its colour members. In this situation, it could be advisable to work on the criteria of choosing the Colour-head nodes so that it could select nodes with an energy harvesting source to play this role.

- It would be interesting to analyse the effects of implementing the mechanism of dynamically adjusted transmission power in multi-path routing protocols, such as AOMDV [222]. This provides multiple opportunities for improving the AOMDV routing protocol.

- Concerning the power control based topology algorithm, it would be useful to compare the cost of creating and maintaining it with that of other underlying topologies, such as Tree based ones, or connected dominant sets (CDS).

- It would be interesting to analyse the network performance and the cost of power consumption with MPR-AODV [223] reactive routing protocol. It utilises 2-hop topology information in order to minimise the number of retransmissions and ensure that a packet reaches all nodes in the network.

Appendix A

Modified *trace/cmu-trace.cc* File

```
void
CMUTrace::format_aodv(Packet *p, int offset)
{
        struct hdr_aodv *ah = HDR_AODV(p);
        struct hdr_aodv_request *rq = HDR_AODV_REQUEST(p);
        struct hdr_aodv_reply *rp = HDR_AODV_REPLY(p);

struct hdr_cmn *ch = HDR_CMN(p);


        switch(ah->ah_type) {
        case AODVTYPE_RREQ:

      if (pt_->tagged()) {
          sprintf(pt_->buffer() + offset,
             "-aodv:t %x -aodv:h %d -aodv:b %d -aodv:d %d "
             "-aodv:ds %d -aodv:s %d -aodv:ss %d "
             "-aodv:c REQUEST ",
             rq->rq_type,
                           rq->rq_hop_count,
                           rq->rq_bcast_id,
                           rq->rq_dst,
                           rq->rq_dst_seqno,
                           rq->rq_src,
                           rq->rq_src_seqno);
      } else if (newtrace_) {

          sprintf(pt_->buffer() + offset,
         "-P aodv -Pt 0x%x -Ph %d -Pb %d -Pd %d -Pds %d -Ps %d -Pss %d -Pc
             REQUEST -Plevel %s ",
         rq->rq_type,
                       rq->rq_hop_count,
                       rq->rq_bcast_id,
                       rq->rq_dst,
                       rq->rq_dst_seqno,
                       rq->rq_src,
                       rq->rq_src_seqno,
                       power_level(ch->num_of_nbrs_) == 1 ? "HIGH" :
                 (power_level(ch->num_of_nbrs_) == 2 ? "MEDIUM" :
```

```
                "LOW"));


    } else {

         sprintf(pt_->buffer() + offset,
        "[0x%x %d %d [%d %d] [%d %d]] (REQUEST)",
        rq->rq_type,
                      rq->rq_hop_count,
                      rq->rq_bcast_id,
                      rq->rq_dst,
                      rq->rq_dst_seqno,
                      rq->rq_src,
                      rq->rq_src_seqno);
    }
              break;

        case AODVTYPE_RREP:
        case AODVTYPE_HELLO:
   case AODVTYPE_RERR:

    if (pt_->tagged()) {
         sprintf(pt_->buffer() + offset,
            "-aodv:t %x -aodv:h %d -aodv:d %d -adov:ds %d "
            "-aodv:l %f -aodv:c %s ",
            rp->rp_type,
            rp->rp_hop_count,
            rp->rp_dst,
            rp->rp_dst_seqno,
            rp->rp_lifetime,
            rp->rp_type == AODVTYPE_RREP ? "REPLY" :
            (rp->rp_type == AODVTYPE_RERR ? "ERROR" :
             "HELLO"));
    } else if (newtrace_) {

        sprintf(pt_->buffer() + offset,
            "-P aodv -Pt 0x%x -Ph %d -Pd %d -Pds %d -Pl %f -Pc %s ",
           rp->rp_type,
           rp->rp_hop_count,
           rp->rp_dst,
           rp->rp_dst_seqno,
           rp->rp_lifetime,
           rp->rp_type == AODVTYPE_RREP ? "REPLY" :
           (rp->rp_type == AODVTYPE_RERR ? "ERROR" :
            "HELLO"));
         } else {

        sprintf(pt_->buffer() + offset,
           "[0x%x %d [%d %d] %f] (%s)",
           rp->rp_type,
           rp->rp_hop_count,
           rp->rp_dst,
           rp->rp_dst_seqno,
```

```
          rp->rp_lifetime,
          rp->rp_type == AODVTYPE_RREP ? "REPLY" :
          (rp->rp_type == AODVTYPE_RERR ? "ERROR" :
           "HELLO"));
     }
              break;

       default:
#ifdef WIN32
              fprintf(stderr,
             "CMUTrace::format_aodv: invalid AODV packet type\n");
#else
     fprintf(stderr,
             "%s: invalid AODV packet type\n", __FUNCTION__);
#endif
              abort();
       }
}

int
CMUTrace::power_level(int no_of_nbrs)
{
   //int no_of_nbrs_=
if(no_of_nbrs <= 7) // low number of neighbours
return 1;
if(no_of_nbrs > 7 && no_of_nbrs < 14)
return 2;
if(no_of_nbrs >= 14) // high number of neighbours
return 3;

}
```

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