Variable Power Transmission in Highly Mobile Ad-Hoc Networks

Alwi M Bamhdi

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Abstract

Mobile Ad Hoc Networks pose challenges in terms of power control, due to their fixed transmission power, the mobility of nodes and a constantly changing topology. High levels of power are needed in wireless networks, particularly for routing. As a result of the increase in the number of communication devices being used, there is the challenge of increased density within these networks, and a need to extend the battery life of communication devices.

In order to address this challenge, this thesis presents the development of a new protocol (Dynamic Power AODV), which is an enhancement of the Ad Hoc On Demand Distance Vector (AODV) protocol. The new protocol dynamically adjusts the transmission power based on the range, which depends on node density.

This thesis provides a systematic evaluation of the performance of DP-AODV, in a high speed and high density environment, in comparison with three other routing protocols. The experiments demonstrated that DP-AODV performed better than two of the protocols in all scenarios. As compared to the third protocol (AOMDV), DP-AODV gave better performance results for throughput and Power Consumption, but AOMDV performed better in terms of Packet Delivery Fraction rate and End-to-End Delay in some cases.

To my Wife and my Son

Manal and Mohammed

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Declaration

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Chapter 1

Introduction

Wireless networks are an interesting area of research as they now play an essential role in the field of communication. There are two types of wireless networks: infrastructure, where a path is established using a base station; and non-infrastructure, where there is no base station and the nodes can move freely and organise themselves arbitrarily. An example of a non-infrastructure network is a Mobile Ad Hoc Network (MANET), which has many applications, including both personal and military use.

The motivation for carrying out this research stems from previous reading on the topic of energy and energy conservation and the advancement of wireless devices, which has resulted in MANETs becoming a key area of research for both the academic and industrial sectors. Moreover, MANETs were chosen for the purpose of this research due to the ease and speed of deployment and the fact that they decrease dependency on infrastructure. Ad hoc networks have become increasingly common since the 1990s, with more and more applications being developed. Nowadays, many people have a device that they want to connect, resulting in increased density and consequently increased interference. This has given rise to the question of how to cope with density, and how to extend the lifetime of battery powered devices in order to improve efficiency in communications.

1.1 Statement of the problem and scope of the study

MANETs have many applications, not least in developing countries, disaster areas, and on the battlefield, and there are many routing algorithms designed to effectively route packets through such networks.

MANETs allow versatile communication between hosts that are moving around. Routing of packets in such networks, which have no fixed infrastructure, is a continuing challenge. As the number of nodes in an area increases, the scope for increased interference between nodes increases and, as nodes move around faster, the stability of links, i.e. their longevity, is reduced. Moreover, the topology of the network is constantly changing due to the mobility of the radios. If there is a high density of radios, then the throughput of the network will be reduced due to mutual interference.

This thesis focuses on the routing algorithm for multi-hop MANETs, where a signal is transmitted via multiple stops, rather than using a continuous path. One of the main challenges in mobile communication is the transmission of packets at a fixed transmission power, which may drain the power consumption of the communication interface. Packets transmitted at a common maximum power trigger considerable loss of power consumption. Consequently, when node pairs are close to each other, then the power transmission required for them to communicate may be kept at a minimum. In such a scenario, transmitting packets at a high power level may generate significant interference to the network and consume more power than required. This research assesses whether it is possible to improve the battery life of mobile devices and communication efficiency by improving the level of interference within a MANET.

The present research develops a new routing protocol (Dynamic Power AODV) in response to the challenges posed by increased density. It attempts to increase throughput, decrease interference and improve power consumption in mobile devices. AODV was chosen as the basis for the new protocol as it is an on-demand routing protocol where source nodes choose the shortest path; it is scalable to large networks; it is loop-free and reliable; and it reponds to link breakages quickly and repairs routes with minor errors.

1.2 Aims and objectives

This thesis aims to investigate suitable routing algorithms for mobile ad hoc networks, based on the DP-AODV protocol. It is anticipated that varying the transmission power in MANETs will improve the protocols by reducing the level of interference between nodes, increasing the throughput in the network, and optimising energy consumption, thereby extending the battery life of communication devices

The principal objectives are:

- To study and investigate the existing routing protocols of ad hoc wireless networks.
- To improve the AODV protocol by combining the hello message mechanism, which is an unsolicited RREP packet containing the sender address and sequence number, and the power control mechanism, using the NS2 simulator.
- To develop the Dynamic Power AODV (DP-AODV) protocol which dynamically modifies the transmission power to attempt to minimise interference and maximise the throughput, identifying the number of neighbours in the transmission range and the optimum power, based on this number.

- To investigate DP-AODV with a very high density of nodes and a high rate of change of neighbours.
- To evaluate the performance of DP-AODV by comparing it with three existing routing protocols: AOMDV, AODV and DSR.

1.3 Contribution of this thesis

Power control minimises the transmission power by controlling the transmitting range. A dynamic transmission range is more effective in maintaining connectivity while minimising adverse effects of a high transmission power. Node density has a great impact on the performance of ad hoc networks in that it influences factors such as routing efficiency, capacity and delay.
This thesis improves the existing Ad-Hoc On-Demand Distance Vector (AODV) protocol to dynamically increase or decrease the transmission power, based on the node density, to keep a constant number of radios within range of each other (see Chapter 4). This protocol determines the power required to preserve connectivity through the nodes, in order to decrease interference between nodes and reduce power consumption, as well as to improve the throughput in the network to be adapted in high density and high mobility networks. It uses the NS2 network simulator tool [29] to test and evaluate the DP-AODV protocol (see Chapters 5 and 6).

1.4 Publications

- **Alwi M. Bamhdi** and Peter J.B. King and Idris S. Ibrahim.“ Impact of High Density and High Speed on AODV and DSR Routing Protocols“. In PG Net‘2011: Proceedings of the 12^{th} Annual Conference on the Convergence of Telecommunications, Networking and Broadcasting, pages 155-160, Liverpool, UK, June 2011. Liverpool John Moores University (discussed in Chapter 2).

- **Alwi M. Bamhdi** and Peter J.B. King.“ Dynamic-Power AODV Routing Protocol Based on Node Density”. In iCOST’2012: The International Conference on Selected Topics in Mobile & Wireless Networking, pages 95-100, Avignon, France, July 2012.IEEE (discussed in Chapter 4).

- **Alwi M. Bamhdi** and Peter J.B. King.“Performance Evaluation of Dynamic-Power AODV, AOMDV, AODV and DSR Protocols in MANET”. 4^{th} IEEE Technical CoSponsored International Conference on SmartCommunications in Network Technologies 2013 (SaCoNeT 2013), pages 1-5, France, June 2013.IEEE (discussed in Chapters 5 and 6).

- **Alwi M. Bamhdi** and Peter J.B. King.“AODV with Dynamic Power Enhancement: Performance Evaluation in MANETs”. Journal of Communications Engineering and Networks, vol.2, no.(1), pp.23-33, 2014.

1.5 Organisation of thesis

The rest of this thesis is organised as follows: Chapter 2: introduces wireless and mobile ad hoc networks (MANETs), with a definition of MANETs, with their characteristics and applications. It then presents the different types of routing protocols, and the concept of density. Finally, it looks at MANET mobility and using a simulator tool. Chapter 3: introduces the concepts of power control, power management and power aware routing protocols. It describes power control and then gives descriptions of power management and power aware protocols. These concepts are then summarised, and there is an overview of all the related work. Chapter 4: outlines the model of the Dynamic Power AODV routing protocol used in this research and the proposed method. There are descriptions of the energy model and the transmission power model. There is explanation of why AODV was chosen; an introduction to DP-AODV. Details of the proposed method and the modification of the NS2 files are given. Both the function testing and functionality testing are presented, followed by a chapter summary. Chapter 5: presents the methodology, performance evaluation metrics, simulation environment, results of the simulation, and a chapter summary. Chapter 6: outlines the methodology and then presents the performance evaluation metrics, the simulation environment, the results of the simulation, followed by a chapter summary. Chapter 7: provides a summary of the thesis, and highlights the opportunities for further study.

Chapter 2

Background

This chapter presents wireless and mobile ad hoc networks (MANETs) in section 2.2. Section 2.3 gives a definition of MANETs, with their characteristics and applications. Types of routing protocols (unipath and multi-path) are outlined in section 2.5. The concept of density in mobile ad hoc networks is introduced and discussed in section 2.6. Sections 2.7 and 2.8 look at MANET mobility and using a simulator tool respectively. A chapter summary is provided in section 2.9.

2.1 Introduction

Interest in wireless networks has been growing in recent years due to their decreasing cost and the advantages they offer compared with wired networks. There is an increasing amount of research being carried out in this field, although there is still much to be done as the technology is relatively new and constantly evolving. Wireless networks can be divided into infrastructure wireless networks and non-infrastructure wireless networks. MANETs, a type of non-infrastructure wireless network, were developed in the 1970s, moving to a 2^{th} generation network, then to 3^{th} generation with a higher data rate [126], and there is now a 4^{th} generation of mobile phones on the market.

These networks use multiple hops between nodes to conserve energy and have a dynamic topology. As with any type of network, there are specific issues with this type of network, which are yet to be resolved, including interference, node mobility and routing. The node mobility is closely linked to the dynamic topology of mobile ad hoc networks. As regards routing, the protocols can be categorised as unipath and multi-path, both of which will be studied in this thesis.
Simulation tools are often used in order to analyse mobile networks and predict the performance and efficiency of a network. They act as a model of the reality of the network, and allow various scenarios to be tested.

2.2 Wireless Networks

Wireless devices can include laptops, wireless sensors, mobile terminals, PDAs, cellular phones and satellite receivers [22].

Wireless networks have seen a sharp increase in popularity in recent years as a result of their flexibility and a decrease in costs. These networks offer advantages over the traditional, wired networks as they do not require any physical cables which in turn offers greater freedom for users. However, there are disadvantages of wireless networks, as they have a high error rate and are subject to interference between nodes.

2.2.1 Infrastructure Wireless Network

An infrastructure wireless network (cellular network) is composed of fixed, wired network nodes and gateways. Communication between the nodes occurs using centralised access points. Thus, these networks require both centralisation and infrastructure for their configuration and operation. The services come via preset networks such as cellular networks and Wireless Local Area Networks (WLAN) [1].

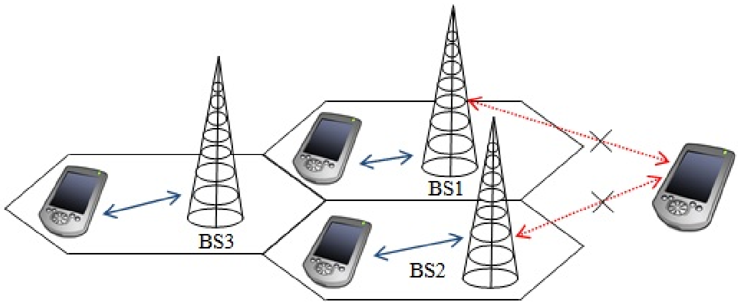

Figure 2.1: Example of Wireless Network Infrastructure

As illustrated in Figure 2.1, a Cellular Network uses cells and has a two way simultaneous voice communication. It uses a fixed base station and services a coverage area divided into a set of non-overlapping cells, allowing communication within each cell. Cellular Networks have come in different generations such as 1^{th}G which used an analogue signal, Advanced Mobile Phone System (AMPS); 2^{th}G which used digital transmission mechanisms, for example Code Division Multiple Access and Timed Division Multiple Access (CDMA and TDMA); 3^{th}G which improved multimedia, bandwidth and capability; and finally 4^{th}G, which combines wireless networks and backbone wireline networks, and uses a single IP-based core network for voice, multimedia and data traffic [108]. It is built from a backbone, switches, a base station and mobile host.

A WLAN is one of the best known wireless networks because it uses services in places which enable users to establish a wireless connection within a 100m range, in areas such as public spaces and campus buildings. It is a flexible system of communication that is used in temporary networks. In wireless local area networks the node is called the Access Point (AP) and functions as a bridge between the station and backbone. Although wireless networks are difficult and expensive networks because they need cabling for the wire line, they are still a cheaper and easier option than using a complete wired network. WLANs have two main standards: IEEE 802.11 and Hiper lan2 [2] .

2.2.2 Non-infrastructure Wireless Network

A Non-Infrastructure Wireless Network is a dynamic network formed arbitrarily and dependent on a collection of independent nodes. There is no prearranged rate and all decisions are made independently. This infrastructure-less method requires a speedy configuration of wireless connections. Examples of non-infrastructure are Wireless Sensor Network and Mobile Ad Hoc Network (MANET).

MANET is defined as a temporary network for a particular application which consists of a set of home-computing devices, handheld PCs and laptops. It is a flexible network which may be established in any situation without using centralised administration or an infrastructure network (base station), shown in figure 2.2. It is used for tactical network related applications to improve survivability and battlefield communication. Mobile ad hoc networks have many applications such as emergency operations, military application, civilian environments and personal area networks [3].

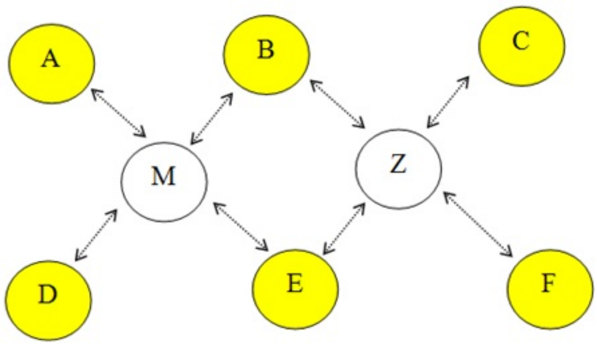

Figure 2.2: Example of Non-Infrastructure Wireless Network, where the circles represent nodes. The white circles are the intermediary nodes, and the lines show nodes which are within transmission range of each other

A Wireless Sensor Network is a special type of ad hoc network, defined as a network that consists of a number of wireless sensors across a geographical area. Data is gathered at the wireless sensor network, then compressed before being sent to the gateway directly [4]. Transmitted data is then delivered to the system by gateway connection.

A key feature of any wireless sensor node is to minimise the power consumed by the system. Wireless Sensor Networks have problems in mobility because sensor nodes are mobile in the given application [5]. Table 2.1 outlines the principal characteristics of both cellular and ad hoc wireless networks.

Cellular Networks	**Ad Hoc Wireless Networks**
Fixed infrastructure	Non-infrastructure
Single-hop links	Multi-hop links
Guaranteed bandwidth	Shared radio channel
Centralised routing	Distributed routing
Routing and call admission aim to maximise call acceptance ratio and minimise the call drop ratio	Routing aims to find paths with minimum overheads and quick reconfiguration of broken paths
Seamless connectivity	Frequent path breaks
Circuit-switched	Packet-switched
High cost and time of deployment	Quick and cost-effective deployment
Easier to achieve time synchronisation	Difficult time synchronisation, which consumes bandwidth
High network maintenance cost	Self-organisation and maintenance properties built into the network

Table 2.1: Main difference between cellular networks and ad hoc wireless networks

2.3 Mobile Ad Hoc Networks (MANETs)

Wireless communication has developed a lot in recent years. In infrastructure wireless networks, the developments have been seen in applications and wireless devices such as PDAs and laptops, where the capabilities are becoming increasingly powerful. Earlier wireless networks were formed by hosts and routers but in a more modern wireless

network the router can send data packets to others, and the host is the source or sink of data flow. In communication networks, there are some differences between wired and wireless networks. Firstly, wired networks transfer data packets through cables, but a wireless network is totally different in that communication between devices may be via a wired or wireless network. In conclusion, one of the biggest advantages in wireless communication is that cables are not a constraint to communication and the routers and hosts have a freedom of mobility [6].
According to IETF MANET Working Group (2002) [119], a MANET consists of a stand-alone system of mobile routers (associated hosts) linked wirelessly, which together make a random graph. The routers can move and arrange themselves at random, meaning the networks wireless topology can change quickly and unpredictably. This kind of network may operate independently or may be part of the larger internet [7].

2.3.1 History

MANETs date back to the 1970s, with the establishment of the Advanced Research Projects Agency's (ARPA) multi-hope multiple access Packet Radio Networks (PRNET) program in 1972 [127], allowing packet switching technology to function without requiring a fixed or wired infrastructure. A 2^{th} generation was created in the 1980s with packet switched networks in an infrastructure-less setting. This led to further development of the PRNET, which was used as part of the Survivable Adaptive Radio Networks (SURAN) program, with a key role in military applications [128]. The term 'ad-hoc networks' was coined in the 1990s when this type of network was used with wireless computers and other devices. Subsequently, in the late 90s/early 2000s personal wireless local area networks became both more common and more affordable. The early/mid 2000s saw the introduction of commercial applications, including Bluetooth, designed to enable speedy communication between personal local area networks without requiring wired networks.

The 4^{th}th generation of MANETs aims to provide an ultra-high transmission speed of

100mbps, 50 times faster than 4^{th}generation networks. It will be cheaper and more efficient than 3G networks and will support a range of devices, in order to enable communication in any location at any given time.

Examples of the use of MANETs are in military forces or disaster recovery personnel, particularly when infrastructure is completely destroyed or unavailable in the affected area. There are some other examples, such as students who need to interact with a professor during a lecture at the time of explanation, and also commercial companies operating in an airport terminal who want to share files with each other. When each host wants to communicate it has a wireless local area network interface, so that a MANET of the group of the mobile host can be created.

2.3.2 Overview

MANETs consist of a set of mobile nodes and form a temporary network. By its nature, an ad-hoc network can adapt to take different forms, including mobile, standalone and networked. It is also used with no help from a base station (infrastructure) or central administration.

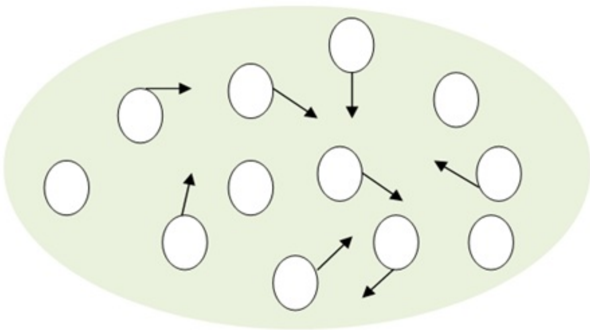

Figure 2.3: Nodes in MANETs move randomly at different speeds and direction

Figure 2.3 shows how nodes in an ad hoc network move randomly, however, they need self-organisation to make sure that the network continues to work even if one of the nodes moves outside the transmission range of others. Nodes must be able to enter/leave the network as they want. As transmission is limited to the nodes, they need several hops until they reach the other nodes. Nodes in ad hoc networks that wish to participate should be prepared to send packets to other nodes. Each node acts as a router and host at the same time. A host and router are different in meaning: a host is an IP-addressable host/entity but a router is a device which runs a protocol.

An ad hoc network is characterised by dynamic topology which is the reason that the nodes are in constant motion and can also change their positions continuously. The host node is limited in bandwidth, battery power, storage capacity and CPU capacity. A key feature of a MANET is the capacity to deal with malfunctions and topology changes in nodes which are fixed through the restriction of the network. In particular, when a node wishes to depart from the network or when a node moves out of the transmission range, thereby breaking the link with other nodes.

2.3.3 Characteristics

According to Basagni *et al.* [8], mobile ad hoc networks have a lot of different features from other kinds of network such as wired or infrastructure wireless networks.

- **Multi-Hopping:** in mobile ad hoc networks, transmitting data in every node uses wireless channels, probably with a restricted number of neighbours, and independent intermediate nodes are used to send the packet. Mobile ad hoc networks often display multiple hops due to limited transmission range.
- **Dynamic Topology:** In MANETs, the mobile nodes can move arbitrarily in any direction, because the network topology can change rapidly at unpredictable times. To solve this problem the system needs to handle this change and find another path that is available quickly.
- **Energy Conservation:** The concept of energy conservation is important in ad hoc wireless networks due to the limited energy resources. There is an increasing gap

between the power consumption requirements and the power which is available, thus requiring energy conservation. In MANETs, the nodes are wireless sensor nodes, PDAs or laptops. They are restricted in both processing power and transmission power by the restricted energy supply.

- **Self-Organisation:** Mobile ad hoc networks are independent systems and the nodes, after being deployed, should be able to form themselves into a network. The main activities in self-organisation are: neighbour discovery, where each node in the network collects information about its neighbours and stores the information in data structures; topology organisation, where each node collects information about the whole network, or part of the network to maintain topological information; and topology reorganisation, which involves updating the topological information by including the topological changes which have taken place in the network. Self-organisation means that a central administration or infrastructure is not created.

- **Security:** Routing protocols in ad hoc wireless networks must be able to defend against threats and vulnerabilities. MANETs have higher vulnerability to security risks than infrastructure based wireless networks or wired networks. Compared to other networks, the mobile ad hoc network is easier to jam/spoof and eavesdrop.

- **Scalability:** This is the routing protocol's ability to perform efficiently in a network with a large number of nodes. One of the major concerns in MANETs is the scalability which is suffered as a result of channel capacity. This is because mobile ad hoc networks are usually restricted and the maximum channel capacity can be reached faster, in comparison to infrastructure based networks or wired networks.

2.3.4 Applications

The applications for mobile ad hoc networks go from small, stationary networks limited by mobile power sources, to extremely dynamic networks on a large-scale [6] [9]. They are particularly useful in situations where there is no infrastructure available, for example in outdoor settings where there is a need for group collaboration using mobile devices.

- **Personal Area Network:** In MANETs, the purpose of a personal area network (PAN) is to make a network of nodes connected to one person. These nodes can be carried in a handbag or clipped onto a belt. Possibly in the future people will have virtual reality devices attached around the head and other parts of the body. These devices might not require a connection to the internet, but they will probably need to communicate between themselves while in operation. In the personal area network (PAN), mobility is not the overriding consideration, but does become important in situations where communication between several PANs is required.

- **Emergency Operation:** MANETs are often important in emergencies, for example, search and rescue. Every year people have their lives destroyed by natural disasters around the world. As the internet grows in use, loss of network connectivity becomes more noticeable as a consequence of the disaster. Mobile ad hoc networks will be the best way to enable the operation of the network when fixed or centralised infrastructure elements have been disabled by the calamity.

- **Military Use:** Mobile ad hoc networks are helpful to the nodes of the military when surviving on the battleground. It is impossible to set up a fixed base station for communication among a set of soldiers in a battleground. In such environments, airplanes, soldiers, tanks and other military equipment can carry wireless electronic devices to form mobile ad hoc networks which support communication among them, in order to achieve the objective of the military in the battle.

- **Conferencing:** Perhaps the prototypical application requiring the establishment of an ad hoc network is mobile conferencing. When mobile computer users meet away from the standard office location, the business network infrastructure is frequently absent. But it might be even more crucial in these situations to communicate effectively. Sometimes an ad hoc network for collaborative mobile computer users is necessary even when there may be internet infrastructure available. This is due to the likely cost of an infrastructure link, which might involve awkward routing between office environments which are far apart.

2.3.5 Issues

Ad hoc networks also share some of the typical challenges faced by wireless communication and networking, including a lack of boundaries for node ranges; a weak wireless channel which is unprotected from external signals; time-varying and propagation properties in the wireless channels; and potential hidden-node and exposed-node problems. Although there are advantages of a MANET network, its specific characteristics create a variety of network issues.

- **Interference:** occurs when two or more packets collide, which creates a problem in MANETs as the hidden terminal can prevent detection of these collisions. This is when transmissions from two, separate source nodes creates interference at the destination, as they are hidden from the sender of the packet, but are reachable to the receiver of the data. As they cannot detect the transmission from each other, collisions may take place at the destination node, resulting in interference. Hidden terminals can greatly decrease the throughput of the Medium Access Control (MAC) protocol, whichis a sublayer of the data link layer and communicates with the physical layer in ad hoc wireless networks. The MAC protocol is required ti efficiently share the wireless medium in multihop MANETs. Thus, the MAC protocol should be able to reduce the impact of hidden terminals. Interference is also affected by the existence of exposed terminals, where transmission may not occur between two nodes which are in the transmission range of other nodes which are transmitting data, although this would not have resulted in interference. The efficiency of the MAC protocol would be improved by enabling a controlled transmission to occur, which does not impact on the existing data transfer.

- **The mobility of nodes:** creates further issues for wireless medium as the nodes act as both hosts and routers. When nodes move, this results in a change to the topology of the network and can result in frequent path breaks, packet collisions, transient loops, stale routing information and difficulty in resource reservation. Routing protocols used in ad hoc networks must be able to efficiently and effectively manage mobility.

- **Routing:** protocols are required in order to create communication paths between nodes, without resulting in too much control overhead or overload on devices with limited power. They are based on hop length, minimum power required, lifetime of the wireless link, obtaining information about path breaks, repairing broken paths, and using minimum bandwidth. These protocols should be reactive, where each node maintains information on-demand (see p21), rather than proactive routing, where each node maintains information continuously (see p20).

2.4 Types of communication used in MANETs

There are four main types of communication used in MANETS [68], which are:

- **Unicast transmission:** Where only two nodes are communicating directly with one another to exchange data.

- **Broadcast transmission:** Only one node transmits data, which is received by every node connected to the network.

- **Anycast transmission:** Data transmission from a single node to a group of several receivers, based on the nearest nodes from the sender.

- **Multicast transmission:** Data transmission from a single node to several receivers, not dependent on the proximity of the receivers.

2.5 MANETs Routing Protocols

The purpose of the routing information collection module is to collect the necessary information to support other routing processes. There are some important criteria and considerations when comparing and designing the new routing protocol such as rapid route convergence, scalability, distribution, simplicity and ease of implementation, security and reliability, supporting quality of service requirement and bandwidth, power and computing efficiency with minimum overhead [10].

The need for routing protocols is more important at times when it is important to make mutliple hops before conveying a packet to the destination. Routing protocols have two main functions: choosing the path between the source and destination, and also the delivery of each package in the right direction. The second task is conceptually straightforward using a variety of different routing tables and protocols.

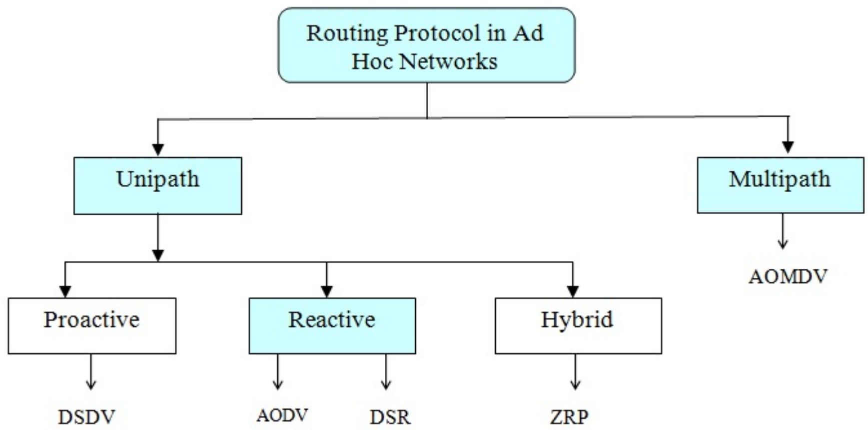

Figure 2.4: MANET categories of routing protocols

Routing protocols in ad-hoc networks enable point-to-point communication. These protocols ensure packet delivery between nodes which are outside the transmission range. There are typical properties which are expected in MANETs. These include distributing the routing protocols with a view to increasing the reliability; designing the protocols so that they can function using unidirectional links; and ensuring that the routing protocol is energy efficient, particularly in the case of using battery powered devices. MANET routing protocols can be divided into two main categories [99]: unipath [100] and multipath [100], with three sub-categories of unipath routing protocols (proactive, reactive and hybrid) (see figure 2.4).

2.5.1 Unipath Routing Protocols

These protocols identify a single route between a source node and destination node. Every route break requires a new route discovery, which creates high overheads. Unipath routing protocols consist of route discovery illustrated in figure 2.5, identifying a route between two nodes, and route maintenance, shown in figure 2.6, fixing a broken route or identifying an alternative route. Within this category, there are three sub-categories: proactive, reactive and hybrid routing protocols.

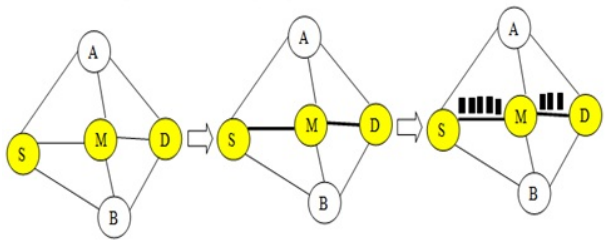

Figure 2.5: An example of a route request, where the source node (S) must identify a route to the destination node (D) to send data. It discovers a route via node M and can begin transmitting data, shown by the thick lines

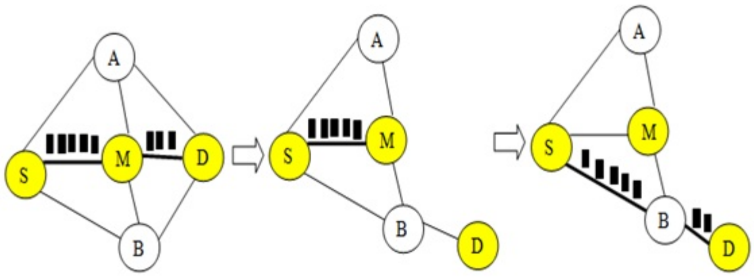

Figure 2.6: An example of route maintance, where the route from the source node (S) to the destination node (D) is shown via node M. When the destination node is out of the range of node M, the route breaks and a new route is established via node B

Proactive Routing Protocols

A proactive routing protocol is also called a table-driven routing protocol. With this approach all nodes in the network try to maintain routing information continuously. In a table-driven routing protocol, there are a number of mobile nodes which exchange routing information to update the network topology. Therefore, a source can get a path to a destination immediately if necessary. There are some disadvantages in a proactive routing protocol, for example there is a high overhead involved in maintaining up-to-date information about the network topology. Proactive Routing Protocols have many typical protocols, such as Destination Sequenced Distance-Vector Routing Protocol (DSDV) [9] [11].

Destination Sequenced Distance Vector (DSDV)

This proactive routing protocol, developed by Perkins and Bhagwat in 1994 [12] [32], is based on the Bellman-Ford routing algorithm [31] and maintains routes, regardless of their usage. It addressed the count to infinity problem found in contemporary distance vector protocols, and ensured loop-free paths to each destination. Each node creates its own routing table with destinations, next hop, hop count and sequence number. The routing table entries are either updated by a full dump (sending all the entries to neighbouring nodes), or using an incremental update (only sending the entries which have changed since the last full dump).

Although this protocol reacts immediately to topology changes, broadcasting routing updates may result in a high traffic load between nodes if there is a high node density. Thus, this protocol works best with a low density ad hoc network. Moreover, these routing update broadcasts may cause time delays if the node has high mobility [14], when there is a high rate of change of neighbours. The main advantages of DSDV are that is ensures loop-free paths and reduces the count to infinity problem, where a node is informed that a path exists but it does not know if it forms part of that path. The routing table only contains the necessary information, as it only maintains the best path for each destination and not a choice of paths, thus reducing the space required in the table.

The main problems of this protocol are: wasting bandwidth as a result of unnecessary advertising of routing information; the fact that it doesn't support multi-path routing; the difficulty of maintaining the routing table's advertisement for a larger network; and the time required to converge as routes cannot be used after some time has elapsed from the periodic broadcast [15] [16].

Reactive Routing Protocol

Reactive is also called on-demand routing protocol, and with this approach all nodes try to explore the network topology. Not every node in the network maintains routing information at all times. The required information will be obtained when the node wishes to transmit a data packet and lacks the necessary information for delivery to the destination. This routing protocol has the benefit of a wireless channel which means that routing table maintenance does not have to carry a lot of routing overhead. One famous type of reactive routing protocol is the Ad Hoc On-Demand Distance-Vector (AODV) protocol, which was the first reactive routing, proposed by Elizabeth Royer and Charles Perkins in 1997 [11] [12].

Ad hoc On-demand Distance Vector Routing Protocol (AODV)

AODV [36] [18] is a single-path, reactive routing protocol based on the DSDV routing protocol. AODV is hop-by-hop in which each intermediate node decides where the routed packet must be forwarded next. It brings together both the route discovery and route maintenance mechanisms used in the Dynamic Source Routing (DSR) protocol, and the idea of destination sequence numbers in DSDV. As a result, the node in AODV routing contains a route table, with one entry per destination, to maintain new route information with three important fields: a hop count, next hop node and a sequence number. These numbers are used at each destination in order to update the routing information and prevent routing loops. AODV also introduces low overhead, low memory overhead, quick adaptation to dynamic link conditions and low processing.

AODV is dependent on the distance vector algorithm. It requests a path when necessary and does not require nodes which are not actively used in connection to maintain routes to the destination. There are some features of AODV including loop free and link breakages which lead to the property group of nodes being notified. The algorithm uses individual packets to find and maintain links. Another benefit is the hello message which is broadcast at periodic intervals to the immediate neighbours. AODV has a multicast route invalidation message. The AODV routing protocol consists of three different message types (see figure 2.7):

- **Route Request (RREQ)** which is broadcast throughout the ad hoc network when a router to a destination is wanted.
- **Route Reply (RREP)** that is sent back to the creator from a destination or intermediate nodes which have new route to the destination.
- **Route Error (RERR)** that is used to tell other nodes the broken links.

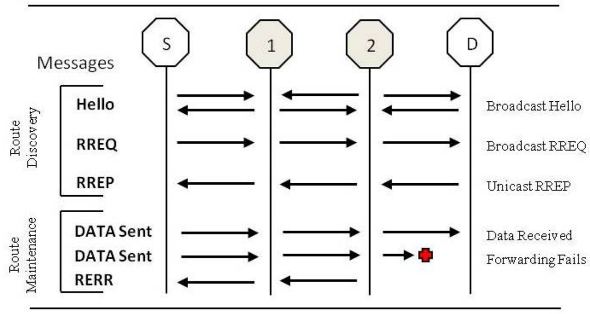

Figure 2.7: Basic operation of AODV, where S is the source node, D is the destination node, and 1 and 2 are the intermediate nodes

In the route discovery phase, when a node wants to send a data packet (message) to a destination, firstly, it will examine the route table to decide if the route to the endpoint of communication is a valid connection or not. If the route is valid, this node will decide to send a message to the next hop node. If not, it begins route discovery by broadcasting a RREQ packet. A RREQ packet consists of the broadcast ID, the source node IP address, the sequence number of the destination and the current sequence number of the source. Each node that receives the RREQ should update information for the source node and establish backwards pointers to the source node in the route table. The RREQ arrives either at the destination or at an intermediate node from where there is a route to the destination, where the RREP is made.

Once the real route is made by unicast RREP to the origin of the RREQ, every node receiving the RREP caches a route back to the origin of the RREQ. The intermediate nodes send back RREP to the previous node and become a part of the route to the destination. If the nodes receive the same RREQ packet later, they ignore it and do not send it on. In the case of the source node, it refreshes the entry in the route table and uses this route in the future [9] [17] [18].

In the route maintenance phase, if there is no hello message received between neighbouring nodes over a set period of time, then the link between these nodes is regarded as being broken. A local repair mechanism may be initiated to rebuild the route to the destination node or, alternatively, a RERR is sent to the neighbouring nodes, and subsequently forwarded to nodes which may have routes affected by the broken link.

Dynamic Source Routing Protocol (DSR)

DSR (Dynamic Source Routing) [37] is a reactive routing protocol which is designed for use in multihop MANETs. It is a loop free source using demand routing protocol. It can use both symmetric and asymmetric links during routing. The DSR routing protocol can allow each node to find a source route across multiple network hops to any destination in a MANET. When using source routing, the header of every packet to be routed includes the full, ordered list of nodes through which the packet has to travel.

To forward a packet to a different host, the sender creates a source route in the packet's header. This gives the address of the host in the network which the packet must be sent on through to arrive at the destination host. Next, the sender forwards the packet across its wireless network interface to the first hop picked out in the source route. When a host which is not the final destination receives a packet, it forwards it on to the next hop identified in the source route in the packet's header, as well as extracting routes to all downstream nodes.

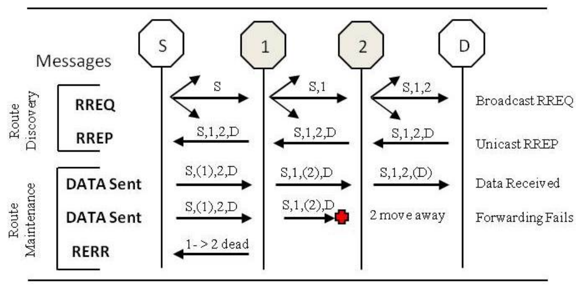

Figure 2.8: Basic operation of DSR, where S is the source node, D is the destination node, and 1 and 2 are the intermediate nodes

After the packet arrives at its final destination, it is delivered to the network layer software on that host. Every host in the MANET carries a route cache containing learned source routes. Before transmitting a message, the sender first checks its route cache for a source route to the destination. If it finds one, it uses this to transmit the packet. If not, the sender can try again with the route discovery protocol [19] [20] (see figure 2.8).

DSR Caches

The DSR routing protocol is based on two types of operations in the source routing: Route Discovery and Route Maintenance. In Route Discovery, the source is used to find the route and deliver the packet to the destination. It begins with the source node broadcasting a RREQ, and each node which receives this message adds its unique identification number into the route record, until it arrives at the destination node, or an intermediary node with a valid route cache to the destination. A RREP is then sent back to the node which initiated the route discovery. The host can continue to operate as normal, sending and receiving data packets with other hosts, while the route discovery is in progress.

Route Maintenance deletes link failures and then repairs them. One of the most important factors in DSR protocols is caching, which avoids the overhead of finding a new route before sending a packet. In fact, every node holds the information learnt in a cache.

The source uses caching to attempt to ease route finding in delivering a packet to its destination. Route finding is a costly operation which also has the consequences of flooding, increasing the delay of the data packet which initiated it, and collecting a great deal of information about the topology state of the network. However, use of the cache also causes some problems, cached information becomes stale easily due to topology changes in ad hoc networks. To combat this, a good strategy in caching is to update the cache of nodes to the new topology when needed.

According to Garrido [129], link cache structure is better than path caching. Link cache can effectively utilise all of the potential information that a node learns about the state of the network. Cached links easily become stale due to mobility, so it is necessary to have a mechanism to delete invalid links from the cache. Another reason for stale caches in DSR is incomplete error notification, meaning that when a link failure is detected, each node sends back a route error to the source of data packet that could not be delivered. The last reason for stale caching is no expiry, when an invalid link is not removed through the route maintenance mechanism, it will be forever in the cache.

There are many effects of stale links which can be summarised as:

- Causing packet drops at intermediate nodes with the result of increasing the average delay in new re-finding and routing overhead due to the sending of a route error.
- Degrading TCP performance, because TCP does not make a distinction between the packets lost due to congestion and the packets dropped at intermediate nodes due to stale links. It invokes congestion control mechanisms, reducing the traffic load.
- Wasting the energy of source nodes and intermediate nodes. If these stale links are not removed quickly, TCP re-transmits lost packets still using them.

In conclusion, the AODV approach has many similarities with DSR. They both feature route discovery modes utilising request messages to locate new routes. However, unlike AODV, DSR is based on source routing and will be able to learn a greater number of routes. In addition, DSR carries the benefit of supporting unidirectional links. The disadvantage of DSR is that source routes have to be carried in each packet. This may involve high cost, especially when a high quality service will be used. Table 2.2 provides an overview of the similarities and differences between the two protocols.

Metric	DSR	AODV
Multiple routes	Yes	No
Reactive	Yes	Yes
QoS Support	No	No
Security	No	No
Periodic broadcasts	No	Yes
Loop free	Yes	Yes
Distributed	Yes	Yes
Unidirectional link support	Yes	No
Multicast	No	Yes
Power conservation	No	No
Sequenced data	No	No

Table 2.2: Comparison between DSR and AODV Routing Protocols

Hybrid Routing Protocol

Protocols are designed to take advantage of the benefits of both proactive and reactive routing protocols. In general, a hybrid routing protocol is a non-uniform routing protocol which, for the optimum solution, uses proactive routing locally and also reactive routing globally. An ideal hybrid routing protocol should be: efficient, incorporating suitable elements in order to optimise performance; adaptive, altering each component in order to achieve the aims in a variety of network conditions; and simple, with minimal overhead control. The latter property aims to increase scalability, which is achieved by proactively maintaining routes to the near nodes and using a route discovery system to define routes to more distant nodes [11] [13].

Zone Routing Protocol (ZRP)

The Zone Routing Protocol (ZRP) was the first hybrid routing protocol, proposed by J.Haas in 1997 [33] [21] [34] [35]. It was developed based on the zones (clustering) concept, in order to decrease the control overheads in proactive routing protocols and reduce the latency resulting from routing discovery in reactive routing protocols. It combines a proactive routing strategy, within a node's local neighbourhood, known as an Intra-zone routing protocol (IARP), and a reactive routing protocol, for communication between neighbourhoods, called Inter-zone routing protocol (IERP). Every node determines a zone (a group of neighbours around a node) surrounding it, the radius of which is the number of hops to the perimeter of the zone.

ZRP operates differently when the value of the radius is altered. With a large zone radius, ZRP works as a proactive protocol, however, with a small zone radius, it operates as a reactive protocol [21]. The principal advantage of ZRP is that it has less control overheads than both proactive and reactive protocols.

2.5.2 Multipath Routing Protocols

These protocols are techniques to identify multiple paths between a single source node and a single destination node and are one method of improving the reliability of the transmitted information. Unlike single path protocols, new routes are only required when all the paths fail, which results in less interruptions to the data traffic and possible lower routing overheads as there are fewer route discovery operations. They also offer load balancing, fault tolerance and bandwidth aggregation [69].

Many of these protocols generate disjoint paths, which have the advantage of being more likely to fail independently. These paths can be divided into two categories, namely node disjoint paths and link disjoint paths. The only common nodes in node disjoint paths are the source and destination nodes. In contrast, there may be common nodes in link disjoint paths, but there are no common links. There are two types of multipath routing protocols, either back-up routes for fault tolerance or data transfer routes for load balancing, based on how they use multiple routes.

Ad Hoc On-Demand Multipath Distance Vector (AOMDV) Routing Protocol

The AOMDV(Ad Hoc On-Demand Multipath Distance Vector) [38] [39] multipath routing protocol has been developed from the AODV routing protocol. AOMDV is not only capable of determining multiple routes from the source to the destination node, but it is also capable of repairing route errors as well as generating efficient fault tolerance (figure 2.9).

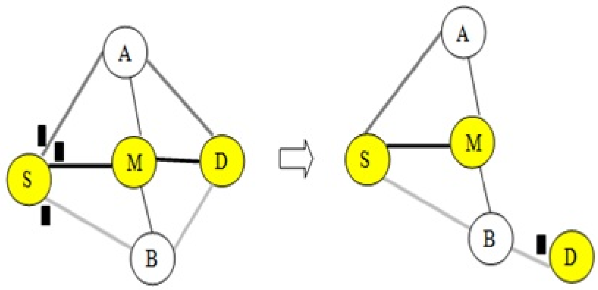

Figure 2.9: An example of AOMDV fault tolerance, where S is the source node, D is the destination node. In the first example the routes are SAD, SMD and SBD. When the D moves, the SAD and SMD routes are broken, but route SBD still functions

The two essential elements of the AOMDV are the route update rule and the distributed protocol. Whereas the former establishes and maintains several loop-free routes at every node, the latter identifies link-disjoint routes between the source and the destination node. In order to determine link disjoint routes, the initial and final hops of the routes are fixed, whilst the all the routes between them are considered to be disjoint paths.

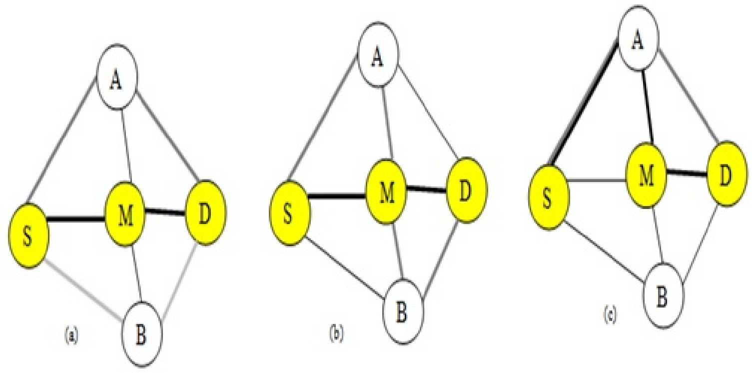

Figure 2.10: AOMDV (a) Node disjoint, with potential routes SAD, SMD and SBD and no common links or nodes (b) Link disjoint, with potential routes SAMBD and SMD and node M in common (c) Non-disjoint, with potential routes SAD and SAMD and node A and link SA in common

In the route discovery phase, the routes can be identified by considering the paths between two nodes as disjoint paths, where each hop, except the first and last hops, are distinct. Figure 2.10 shows the difference between node disjoint, link disjoint and non-disjoint paths, highlighting the routes used in bold. These routes are created when a source node wants to send a RREQ (route request) to a destination node. Thus, every RREQ which comes from one of the source's neighbours requires a node-disjoint path. Duplicate request copies result in the creation of alternate loop-free reverse paths at the intermediate and destination nodes. Upon receiving a reverse path through a duplicate RREQ, the intermediate node establishes whether one or more valid paths to the destination exist. When the destination node receives multiple RREQs, it creates reverse paths in the same manner as the intermediate node. Route replies are formed by the destination node for each RREQ copy received through a loop-free path to the source. However, reverse paths are generated using only RREQ copies received through loop-free and disjoint alternate paths to the source. After the first hop, RREPs follow the node-disjoint and link-disjoint paths, which can intersect at an intermediate node, but which will follow a distinct reverse path to the source, therefore ensuring link-disjointness.

There is a high degree of similarity between AOMDV and AODV with regard to the use of destination sequence numbers in order to provide loop-freedom. One or more route paths to a destination are maintained by each node, corresponding to the highest sequence number for the destination. In terms of route maintenance, the only difference is that, in the case of AOMDV, a node only transmits a RERR to the source node when every path to the destination has broken. Moreover, it uses alternative paths to re-forward packets which were forwarded using failed links.

2.6 Node Density

Density in ad hoc networks refers to the number of nodes in the network area shown in figure 2.11. The number of neighbour nodes is determined as the number of nodes within transmission range of a particular node [40]. Neighbouring nodes can send directly to one another, but when a node is required to transmit a packet to a non-neighbouring node, the message is routed using a series of multiple hops, via intermediate nodes. There are many definitions of node density, for example:

- The number of nodes divided by the total simulation area. For instance, 200 nodes placed randomly within 2000*2000 m^2 [120].
- The radio coverage density, which is the total radio coverage of the nodes divided by the maximum radio coverage graph-walk, which equals the sum of the edge lengths and the diameter of the radio range [121].
- The number of neighbours within a node's radio reach, which is called geographical density [122].

There are two methods of determining the density of an ad hoc network: population census and traffic analysis. The former method surveys an entire population on a scientific basis within a set time frame; and the latter method, which is often used in a military context, monitors all signals, communication and activity.

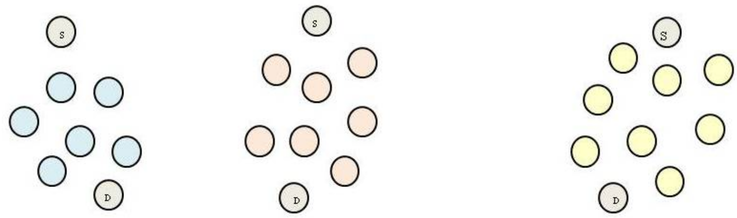

Figure 2.11: An example of node density, where S is the source node, D is the destination node, and the contrasting colour represents the neighbouring nodes. The examples show increasing numbers of neighbours between the source and destination

Density is one of the context parameters for ad hoc networks and can affect the behaviour of these networks as an increase in node density in an area can lead to congestion and collisions, or, if there are few nodes, coverage may be poor. In addition, the higher the number of nodes, the higher the power consumption and the lower the network efficiency.

There are several factors affecting density in wireless networks, including network joining/departure activations, malfunctioning nodes, mobility and energy depletion. The density of wireless networks can change because of energy depletion, device failure, or both. The density may also vary because of nodes joining or leaving a network and thus changing the number of nodes in the network area. Changes in density affect the performance of a wireless network, especially an ad hoc network.

In general, mobility has an effect on density, when the nodes in MANETs are in motion. A few examples demonstrate the impact of mobility and density on MANETs:

- When density is high, it leads to collision and congestion.
- Decreasing density can result in coverage that will be poor.
- Nodes in the network might be static or continuously in motion for a long period of time. High mobility and high density create a routing problem due to the overhead of numerous routing protocols, particularly those functioning on-demand which increase as a result.

- The power consumption rises alongside the growth in density, while the efficiency of the network goes down.

Advances in wireless technologies and wireless networks continue to happen at a rapid pace, alongside the increasing availability of computing devices such as smart-phones, (PDAs) and the application of MANETs in a greater variety of contexts. When these devices are used on a large scale the environment of networks becomes large and dense.

A large and dense network environment refers to a large-scale network with a high density population of mobile nodes. Firstly, large-scale is relative to the radio coverage of mobile nodes. The network is said to be large if the network diameter, i.e., the ratio of network topology area to a mobile node's radio coverage area, is larger than 8. However, the physical density of mobile nodes may be defined as the ratio of the total radio coverage area of all mobile nodes to the geographical network area.

Previous studies on the effect of MANET node density have shown that MANET operation is highly dependent on the availability of neighbour nodes. In 1978, Silvester and Kleinrock [23] published their paper "Optimum Transmission Radii for Packet Radio Networks" . This paper gives an analysis which explores the tradeoff between increased communication radius, resulting in fewer hops to reach a destination, and the effective bandwidth missing at each node as a result of the increase in transmission range. The paper shows that the best number of neighbours for a given node is 5.89 (rounded to six), and concludes that a node's transmission radius must be adjusted so that it has six neighbours. A study carried out by Royer, Melliar-Smith and Moser [24] looked at transmission power tradeoff in mobile networks in order to identify the optimum node density to deliver the maximum number of data packets. It concluded that in order to deliver the maximum number of data packets, the transmission power should be increased as the mobility speed of nodes increases. For a stationary network, the optimum connectivity has been suggested to be seven or eight neighbours per node, which is similar to Kleinrock's conclusion of six neighbours per node.

However, research by Tagaki and Kleinrock [76] proposed an optimum number of five and seven; Hou and Li [77] obtained the number six and eight; Hajek [78] mentioned an average number of three; and Mathar and Mattfeldt also concluded that there was a magic number, although they did not specify any particular number. A study by Xue and Kumar [74] concluded that there is in fact no magic number if connectivity is taken into account, and that as the number of nodes increases, the number of nearest neighbours per node should not remain constant.

Network node density for an entire network may be differentiated into physical density versus connectivity density. Network physical density is dense when a large number of nodes are in close proximity to one another within a particular area, and sparse when vice versa is the case. On the other hand, when determining density for a particular network; one must consider the connectivity of the network in terms of the communication range which covers the particular area. Therefore, the network density depends on the number of nodes found in a particular area and the connectivity of the nodes. Even though the number of nodes found in a small area may not be packed, given a high communication range then it may be determined that the nodes in the area are dense. On the other hand, given either a great or low transmission rate the node density might be determined as sparse. The problem of connectivity density has been studied and discussed determining the network connectivity which depends on the density of collection of neighboring nodes. The density is defined based on the transmission range of the nodes [73] [75].

2.7 Mobility of MANETs

An ad hoc network is a network of nodes linked in an arbitrary fashion for a temporary period of time. A MANET is a type of wireless ad hoc network with changing topology and mobility, consisting of mobile routers connected wirelessly with each node able to move about. Mobility is one of the most important characteristics of MANETs which will affect the dynamic topology. This mobility means that the network topology, and other essential features of the network, can change at any time. Mobility is one of the biggest problems that causes frequent link failures in MANETs, resulting in serious performance failings in the case of high mobility of nodes. The cause is the routing protocols for MANETs not being equipped to handle high mobility.

The mobility model aims to describe mobile users' movement patterns, looking at changes in their location, velocity and acceleration over time. As mobility patterns are important aspects of determining the protocol performance, it is important that they simulate the movement pattern of real life applications.

There are different definitions of mobility. The Carnegie Mellon University (CMU)monarch project uses the pause time, the rest time of the nodes, in waypoints as the definition of mobility. If the node has a short pause time meaning it will almost always be moving, then a high mobility is expected. If a node has a long pause time then it will stay still most of the time and mobility will be low. This definition may not be acceptable however, since if the pause time is high and every node is constantly moving, they could all be in motion at very high speed simultaneously. Another definition of mobility is the average change in distance between every node over the period when some nodes travel. Mobility is a function of both the speed of the nodes and their movement pattern, which is calculated with a fixed sampling rate [25] [26] [27] [28].

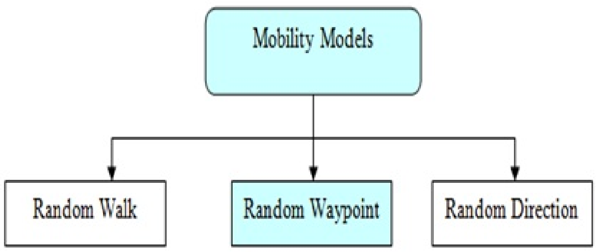

Figure 2.12: Mobility models

Mobility models [41] can be categorised into three main groups of the random walk mobility model, the random waypoint mobility model and the random direction mobility model (see figure 2.12).

2.7.1 The Random Walk Mobility Model

The Random Walk Mobility Model has nodes which move randomly and choose both speed and direction from pre-defined ranges, and in constant time intervals [42]. In this model, if a node reaches a simulation boundary, it bounces off the border and continues on a new path. This is a popular choice of model as it is easy to implement in simulations. However, due to the memoryless nature of the behaviour, it may produce unrealistic movements [43].

2.7.2 The Random Waypoint Mobility Model

In the Random Waypoint Mobility Model [14] the node begins by pausing for a period of time, known as Pause Time, and then begins its journey towards its randomly selected destination (x, y), at a speed selected from a pre-defined range (min. speed and max. speed). Upon arriving at the destination, the node pauses once again, and repeats the process with a new destination. This model is the most commonly used for research simulations [44].

2.7.3 The Random Direction Mobility Model

The third model, the Random Direction Mobility Model [45], is similar to the previous model, but was created to address the problem of clustering of nodes in one section, near the centre, of the simulation area. In this model, the node travels in a random direction at a random speed selected from a pre-defined range (min. speed and max. speed) until it reaches the boundary of the simulation area where it pauses for a specific pause time, before selecting a new direction. This pause time results in this model having a far higher hop count than most other models [46].

In a paper by Yoon *et al.* [124], it has been shown that the average speed of mobile nodes decreases as time goes by. This is due to the fact that low speed nodes take longer sending to their destinations than high speed nodes. In fact, it has been shown that nodes are distributed with a higher frequency nearer the centre of the simulation area while variation of density is dependent on the nodes' average speed and pause time. It is shown that raising the nodes' speed results in higher network connectivity.

Mobility causes frequent link failures in MANETs. When a node is moving at high speed, the links with its neighbours are valid only during a short time interval. This problem will take effect in some places and performance will be poor in these ways: overhead over the network for high mobility, data loss leading to poor average packet delivery ratio, average delay and energy consumption.

According to spatial and termporal dependencies, there are different types of mobility models. However, before discussing these, it is necessary to explain the meaning of the terms spatial and temporal when talking about mobility in MANETs:

- Spatial dependency means the way two nodes depend on each other for motion. For example, if we assume two nodes are travelling in the same direction then we can say they have high spatial dependency.
- Temporal dependency means how current speeds are related to previous speed. When nodes have the same speed, we can say that they have high temporal dependency.

2.8 Simulator

There are several methods which can be used to analyse both wireless and wired networks [47]. The first of these is an analytical method which is based on mathematics and uses probability, calculus and queuing network models, where networks of queues are connected. Although this method may be exact, the accuracy may be affected by the use of simplifying assumptions. Model checking is also a potential option, to enable correctness to be checked.

There is also a simulation approach, which is a technique used to recreate real-life situations by using both software and mathematical models in order to assess a system and how it operates. It is a technique, rather than technology, which gives a clearer insight into real experiences by building-up significant features artificially to a practical point of view. It allows testing and assessment of various potential situations without requiring testing to be performed on a real test system.

Simulation is a very important technique as it allows testing without the expense and potential problems encountered when using a real test scenario. Moreover, simulation provides an accurate outcome in real time and is a scalable system which is also reproducible, unlike testing in a real life scenario. Planning expansion of networks is also made easier by simulation as it offers a precise idea of the network capacity, and network designers can gain a better understanding of network performance in a manner which is far easier than using trial or error real test scenarios.

Although simulation is easier to use and analyse than real test beds, there are more factors which have an impact on the results, including the selection of proper components and understanding system behaviour. Thus, the selection of simulator must be made, carefully with four principal simulator categories [49]: discrete event simulator, agent-based simulator, continuous simulator and hybrid simulator.

2.8.1 Commercial network simulators

There are various commercial network simulators which can be used. Below are two of the most popular simulators, mentioned due to their interesting characteristics and features, namely OPNET and QualNet Developer [109] [110] (see figure 2.13).

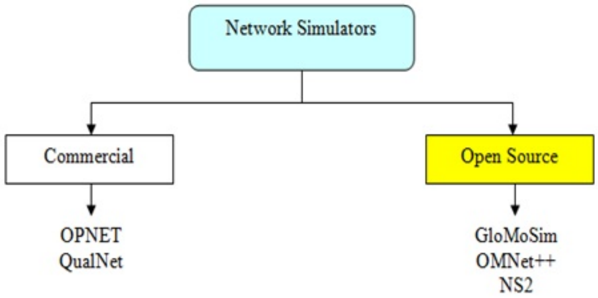

Figure 2.13: simulator categories

OPNET

OPNET (Optimised Network Engineering Tool) [48] is a discrete event simulator which was first introduced in 1986 and initially developed by Massachusetts Institute of Technology. It is a commercial network simulator, using the C++ programming language, which enables object-orientated components modelling.

It is the most commonly used network simulator in both teaching and research [48], and is also reputed to be the fastest simulator. It is a scalable simulator which works well with both wired and wireless networks and has an optional system-in-the loop to enable it to interface with other live systems. The flexibility of the simulator allows it to integrate easily with other libraries and systems. It contains various modules and tools, such as a modeller, planner, model library, and analysis tools [50].

QualNet

Like OPNET, QualNet Developer [110] is also based on the C++ programming language. Scalable Network Technolgies (SNT) first launched it in 2000 as a parallel and distributed network simulator [111]. It is used to simulate large networks with a large volume of traffic. It is made up of a QualNet scenario designer, QualNet animator, QualNet protocol designer, QualNet analyser and Qualnet packet tracer [112] [113].

The advantages of using QualNet as a network simulator are that it supports a vast quantity of nodes and can operate on a wide variety of machines and operating systems.

2.8.2 Open source network simulators

There are also a variety of open source network simulators which can be used, including GloMoSim [49], OMNeT++ [130], and NS-2 [60].

GloMoSim

GloMoSim (Global Mobile Information System Simulator) [49] was developed by the University of California, in Los Angeles, using PARSEC (Parallel Simulation Environment for Complex System), which is an extension of C for parallel programming. It is a library-based parallel simulator, designed to offer a scalable environment for both wireless and wired networks [51] [52], although, at present, it only supports wireless networks. It also enables simulation on multiple machines.

OMNet++

OMNet++(Objective modular network testbed in C++) [130] is a discrete event simulator designed by Andras Varge from the Technical University of Budapest [114]. It is an Open Source code with both simple and compound modules. It operates with both the Linux and Windows operating systems, and can be used by the academic, research and commercial sectors. OMNet++ has an easy-to-use graphical user interface, and it can be easily expanded or adapted. The basic output analyser provides an overview of all the statistics collected in a graphic format. It is well documented, and also has discussion forums.

NS-2

NS-2 (Network Simulator 2) [60] [125] is an object-orientated discrete event simulator which was created at Lawrence Berkeley Laboratory, at the University of California[115]. It was originally developed to simulate routing algorithms, multicast and TCP/IP protocols. It was expanded by the Monarch project at Carnegie Mellon University with support for node mobility [116]. It is the most widely used network simulator in the research field and is available for free. It is an open source simulator, based on two languages, an object-orientated simulated language (written in C++), and OTcl (the extension of Tcl, used as a command and configuration interface). It adopts a layered approach, and is supported by a rich set of protocols, such as AODV, AOMDV, DSR, DSDV and TORA (Temporary Ordered Routing Algorithm). NS-2 provides a Network Animator (NAM) [30], which is a Tcl/TK based tool to view NS-2 trace files for subsequent processing, review and repeating simulations.

The features of NS-2 include an energy-model and the ability to easily produce both traffic and movement patterns. Moreover, it can be downloaded, free of charge, on a variety of operating systems. It is popular within the research community as the original NS-2 used in papers is often published, enabling it to be further developed by other academics.NS2 has all the essential features like abstraction, visualisation, emulation, and traffic and scenario generation. Simulation of wired as well as wireless network function and protocols (e.g., routing algorithms, TCP, UDP) [29].

2.9 Summary

Research into wireless networks has become increasingly popular among the research community. There are two types of wireless networks: infrastructure and non-infrastructure networks. Mobile ad hoc networks (MANETs) are a type of infrastructureless networks which are commonly used in the field of mobile communication. The characteristics of this type of network are that it is multi-hop, has a dynamic topology and is self-organising. It is widely used for personal use, military use and for emergency and rescue operations. However, it is affected by issues such as interference between nodes, the mobility of nodes and routing problems. In order to address the routing problems, several routing protocols have been proposed for MANETs. These include both unipath (including proactive, reactive and hybrid protocols) and multi-path routing protocols.

Node density can have a significant impact on the performance of mobile ad hoc networks as interference among nodes increases as the network density increases, and there is also a high risk of congestion and collision among nodes. Another factor which particularly affects mobile ad hoc networks is the mobility of nodes. Highly mobile nodes create a high rate of change of connectivity in the network, resulting in links between nodes having a very short useful life.

In order to evaluate protocols, a simulator tool can be used as an inexpensive way of recreating a real situation. There are two types of simulator: commercial and open source. For the purposes of this study, an open source simulator will be used as it is widely used within the research community, and so facilitates easy comparison of results. Moreover, it is free to download and can be modified or extended.

Chapter 3

Control of Transmission Power

Energy conservation is a significant problem in mobile ad hoc networks. This chapter introduces an energy conservation approach in section 3.2, with section 3.3 detaling wireless network layers in communication. Section 3.4 addresses the concepts of power control, power management and power aware routing protocols. A detailed description of power control is provided in section 3.4 as this is a key concept for our research, with descriptions of power management and power aware protocols given in sections 3.5 and 3.6 respectively. A brief summary of these concepts is given in section 3.7, and an overview of all the related work is included in section 3.8.

3.1 Introduction

Energy conservation is very important in MANETs, particularly as many MANET devices operate using battery power. Various approaches have been suggested to address this issue. The first of these is power control, as by altering the transmission power, the lifetime of the network can be increased. Power control is primarily dependent on the transmit power, receive power and transmission range. When two nodes are communicating from two different ranges, multi-hop transmissions must be used, thereby requiring packet forwarding or routing. Both the network topology and the energy consumption are significantly affected by the value of the radio transmission range. If the transmission range is large, then the distance progress of the data packets towards the destination is increased, although this uses a higher energy consumption per transmission. However, if the transmission range is short, more hops are required for packets to arrive at the destination, but there is lower energy consumption per hop [117].

This thesis will focus on the idea of dynamically adjusting the power control in order to increase the lifetime of the network, without negatively affecting the efficiency of the network. The other two approaches identified as methods for energy conservation are: power management, where nodes change between different modes; and power aware routing protocols, where routing decisions are dependent on nodes' available energy. There are a range of protocols within each type of energy conservation approach, and a variety of routing algorithms which can be used.

Section 3.7 provides an overview of the literature on related topics, demonstrating that there are some fields within mobile ad hoc networks which have benefitted from more research than others. It also shows that there is no single approach identified as the optimum method for energy conservation, with differences in opinions among the different works reviewed, and that further research is needed in the field.

3.2 Energy Conservation Approaches

Mobile nodes in battery-operated MANETs have a limited energy supply, and energy conservation is one of the key elements for all communications protocols (physical wireless, MAC, routing and application layers) used in mobile ad hoc networks[101]. There are two main categories within energy efficient MAC layer protocols [102]: power control, where the transmission output power of a device is controlled to reduce interference; and power management, where nodes switch into different states (transmit, receive, idle, sleep) in order to conserve energy. Both of these concepts can be implemented at the MAC layer in MANETs in order to save energy.

3.3 Wireless Network Layers in communications

There are five layers which form part of all communications [6] [67], as illustrated in figure 3.1. The first of these is the physical layer, which should enable adaptation to changes in the transmission environment. A minimal level of transmission power should be used in order to maintain links and avoid interference with other hosts.
The data link layer uses retransmission request schemes and sleep mode operation in order to conserve energy. The appropriate time and power level for retransmission by mobile hosts must be identified, and a node's transceiver should be switched off when not in use.
The network layer has a routing algorithm to evenly share packet-relaying loads among nodes to stop nodes from being overused. The path selection must be done in terms of power constraints as part of route stability. The transport layer affects the quality of service in the network. The main aims of this layer are to establish and maintain end-to-end connections, ensure reliable end-to-end delivery of data packets, flow control and congestion control.
Transport layer protocols include both simple, connectionless protocols (e.g. UDP), and reliable, connection-orientated protocols (e.g. TCP).
The application layer affects security in the network and acts as an interface providing mechanisms to support communication, for example, data transmission between users. This layer is usually modelled as a constant bit rate (CBR) flow or a file transport protocol (FTP) transfer. The transport layer used depends on the traffic of the application layer: CBR flows are used with UDP, and FTP flows with TCP.

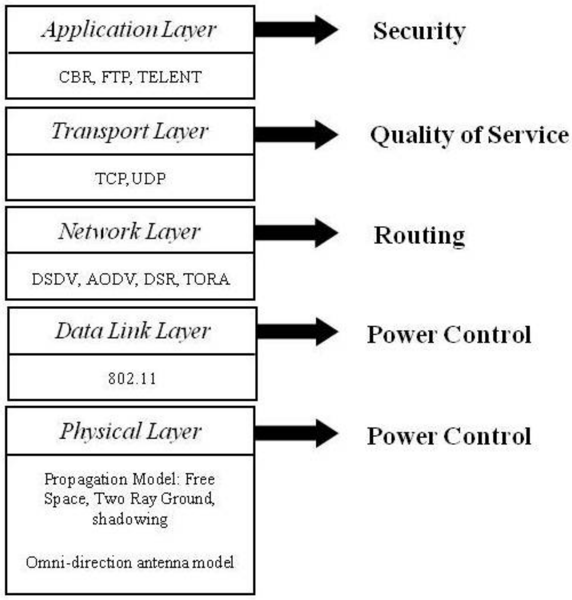

Figure 3.1: Wireless Network Layers

3.4 Power Control Approaches

Power control [53] affects the system's performance level by opting for the lowest power level that can be used in order for an ad hoc network to remain connected to the network, and has been successfully used in mobile networks. It enables ad hoc networks to improve many key aspects, including interference distribution, power consumption, routing, throughput, clustering, connectivity, organisation and backbone management [8].

The importance of power control in ad hoc networks

Power control in ad hoc networks is more important than in cellular networks as the nodes in an ad hoc network communicate by sending data to neighbouring nodes [103]. The choice of power level is extremely important as it has an indirect impact on the system's physical layer, network layer and transport layer by determining the quality of received signal, transmission range and level of interference [61]. When looking at the concept of power control in ad hoc networks, there are some key terms which must be defined [131]:

- **The transmit power** is "the output power of the signal transmitted by the transceiver of a sender".
- **The received power** is "the strength of the signal received at the receiver. The received power is typically smaller than the transmit power due to signal attenuation between the sender and the receiver".
- **The transmission range** is "a 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".
- **The carrier sense range**, which is "a 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".

Both the transmission range and the carrier sense range (see figure 3.2) can be altered in two different ways, either by varying the transmit power and/or varying the receive or carrier sense threshold. The former method enables energy saving at the sender, whilst the latter only affects the sensitivity of the receivers and does not affect the output power of the sender. Changing the sensitivity can also save power as it can limit unnecessary overhearing by some nodes.

Effects of low and high transmission power control

Low transmission power results in lower energy consumption, thereby extending the network's lifetime. As the density is lower, there is a low overhead in creating routing tables and less interference which, in turn, creates a higher capacity, and there is also a lower packet loss rate. However, as the network is sparse the network connectivity is

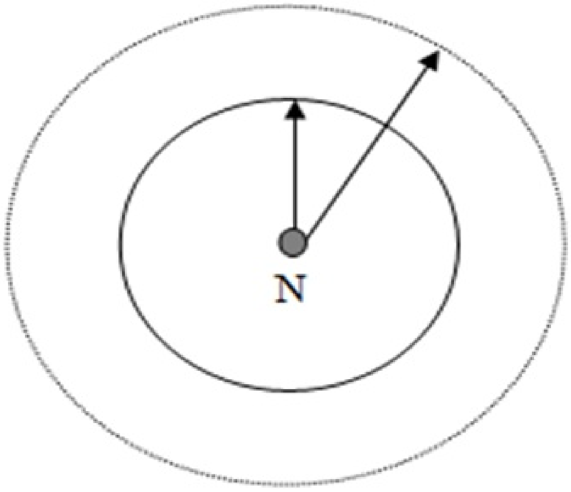

Figure 3.2: The transmission range (solid line) and the carrier sense range (dashed line) of node N

reduced. The network diameter is larger due to a smaller number of links, and there is a larger number of hops to the destination. The end-to-end latency is lower with high network loads.

In contrast, high transmission power involves higher energy consumption and a short network lifetime. There is also higher interference, decreasing the capacity and resulting in a higher packet loss rate. The network is dense and network connectivity is increased by adding more links. As there are more routing options, there is a higher overhead in creating routing tables. The network diameter is smaller as there are fewer node degrees, and there are also fewer hops. The end-to-end latency is lower with low network loads, higher loads results in delays due to interference.

Effects of common and variable transmission power

As regards the MAC layer, common transmission power ensures that two nodes within the same range can hear one another. Whereas, variable power may result in more problems as two nodes may not be in the same range and so one node can hear the other, but the reverse is not true [108].

Energy consumption is better using variable power as nodes only use the energy required to send data to the next hop, while common power may waste energy by using more than is needed to deliver data to the next hop. Common power ensures that links are bidirectional, which is assumed in most distributed routing algorithms. However, there are fewer routing algorithms suitable for variable power as the links are not bidirectional.

Benefits of power control in ad hoc networks

Transmission power control has some key benefits [105]:

- **The connectivity** relies on receiving and decoding frames correctly, and transmission power control can affect this process as the transmission power has an impact on whether a frame will overcome interference, attenuation and signal distortions. It can be used in order to provide a stable level of connectivity by increasing the transmission power if the link reliability drops below a set level. Moreover, asymmetric links, which are common in wireless networks, can be mitigated.
- **The number of nodes within a transmission range** has a direct impact on the throughput of the links, due to contention among the nodes. By altering the transmission power, the number of competing nodes will be reduced and so fewer retransmissions will be needed in order to send data. It is also possible that one node in the transmission range does all the work, creating an issue of fairness.
- **In terms of energy**, the higher the transmission power, the higher the energy consumption. However, if the transmission power is too low then there may be problems with the link's data rate and quality. The transmission power control must therefore seek to find a balance between energy consumption and efficiency.

3.4.1 Examples of Power Control Protocols

There are various power control protocols used in mobile ad hoc networks. One of these is COMPOW [62], which ensures that all nodes in the network use the same power level and that links between transmitters and receivers are bidirectional. COMPOW uses six different power levels. Receivers may not have common SINR (signal to noise plus interference ratio), thus the transmission powers should remain low, meaning that all nodes have almost equal SINR value, creating less interference. It also ensures the connectivity of the network, maximises the traffic load capacity, provides power aware routes, limits MAC contention and is compatible with all proactive routing protocols. There are three protocols used for joint power control and clustering. The first of these is called CLUSTERPOW [61] which forms node clusters, according to the transmit power level, regardless of their physical location. Power control and clustering issues can be used effectively in non homogeneously built networks. This protocol uses loop free routes with minimum power assignment and aims to enhance network capacity.

The second of these is Tunnelled CLUSTERPOW [63], which enables finer optimisation of achievement, but is more complex to implement. This protocol transmits packets to the destination hop by hop, rather than by direct transmission, thus using lower power levels.

The third protocol using joint power control and clustering is MINPOW [63] which provides a routing solution with an optimal energy consumption solution for awake nodes. It is based on the concept of link cost and is implemented at the network layer.

LOADPOW uses higher power levels in order to reduce end-to-end delay when the network load is low. Finally, PARO [64] is a power aware routing optimisation protocol which minimises the transmission power required for forwarding packets between nodes by using one or more intermediate nodes, called “redirectors”. The more redirectors used, the lower the transmission power of packets. It is efficient in static and dynamic environments and is primarily based on overhearing, redirecting and route maintenance. As a result of its power conserving point-to-point design, it is more efficient than traditional, broadcast-based routing protocols, reduces the overall transmission power needed and increases the operational lifetime of networked devices.

3.5 Power Management Approaches

Power management involves nodes switching between different modes. Nodes can switch into a power-saving mode when they are not required to send or receive packets, and can wake up when needed.

3.5.1 Energy Consumption States

Table 3.1 shows the different operating modes used by nodes in ad hoc networks [65]:

- **The transmit mode** sends packets to neighbouring nodes using wireless links. This mode has the highest power consumption of all of the modes.
- **The receiving mode**, which uses slightly less power than the transmit mode, receives data from neighbouring nodes over wireless links and uses energy to demodulate the packet frame and forward it to the next neighbouring node.
- **In idle (listening) mode** nodes continuously listen to the wireless link (medium), even when there are no messages being transmitted, and detect incoming packets. In this mode the nodes can either transmit or receive data to/from neighbouring nodes, however there is a constant power consumption resulting from listening to the network, even when there is no communication between nodes.
- **Sleep mode** consumes the lowest level of power of all the modes as the nodes neither transmit nor receive packets. The radio is turned off and therefore the nodes are unable to detect signals, preventing any communication. Moreover, the nodes do not listen to the wireless link.

The importance of power management in ad hoc networks

As mobile devices used in ad hoc networks are generally battery-powered, they have a

	Mode			
	On			DOZE
	Trnsmit	Receive	Idle	Sleep
Power	140 mW	100 mW	83 mW	3 mW
Consume	More	$\Longrightarrow$		Less

Table 3.1: The node operation modes in Ad Hoc Network, showing the modes with the highest consumption at the left, and those with the least at the right

limited power supply and so the capability of the devices is restricted. Power management is therefore important in order to maximise the use of the available power. The principal reasons for power management are as follows [66]:

- **Limited energy reserve:** Mobile devices' use of battery power is very restrictive and development in this field lags behind progress made in terms of mobile computing and communication.
- **Difficulties in replacing the batteries:** There are situations which may arise, particularly in times of crisis, where it is very difficult, or indeed impossible, to replace or recharge the batteries and so energy management is crucial.
- **Selection of optimal transmission power:** The higher the transmission power, the higher the energy consumption. The transmission power affects the reachability of the nodes and thus the ideal transmission power must decrease interference between nodes, consequently increasing the number of simultaneous transmissions.

3.6 Power Aware Routing

Power-aware routing decisions are based on nodes' available energy. These protocols look at the heterogeneity of the nodes' energy resources, and try to minimise variations in the node power levels by distributing the load evenly among every node in the network. Moreover, by distributing the routing load evenly among the cut-set (a subset of nodes in the network, without which there would be partitions in the network), the network connectivity is maximised. They attempt to minimise the energy consumption per packet in the journey from source node to destination node. The cost per packet is reduced as the battery charge is increased. Therefore, the battery charge can be used as a metric to calculate the routing cost, and enables a minimum cost per packet to be used. There is also a metric to minimise the maximum cost per node after routing a number of packets or at the end of a determined period. These protocols also take account of the impact of the network topology and data flows, which can create uneven energy consumption. They aim to save power or to maximise the lifetime of the network, using the battery life as the routing metric and choosing routes which optimise the battery life [107] [70] [71] [72].

3.7 Related Work

There have been many studies conducted in the field of power control in mobile ad hoc networks. This is an important area of research in ad hoc networks due to the structure of these networks and their absence of central management [53].

Both Pattanayak *et al.* [56] and Ryataro *et al.* [59] looked at the concept of power control using different power levels within the context of a power aware AODV, incorporating route discovery and link-by-link power adjustment, in order to identify the minimum power level route to transmit data. Ryataro *et al.* focused on the concept on clustering and controlling the transmission power of each node. This paper uses seven power levels and, as Pattanayak stated, the higher the number of power levels, the more overheads will be used during information exchange among nodes.

The notion of hop count also has an impact on power control, for both single path and multipath networks. Research by Vijayaragavan *et al.* [57] and Xing *et al.* [55] both concluded that routing based on the maximum hop count resulted in better network performance, with minimal power consumption and minimal packet delays. Another aspect of power control is the routing selection implemented. Zhaoxiao *et al.* [58] suggested an energy-aware AODV (EAODV) using routing based on the dynamic priority-weight, with the aims of minimising the energy consumed per packet, which is also mentioned by Singh *et al.* [107], and maximising the network lifetime.

Effective consumption of battery power in mobile nodes also affects power control and the network lifetime. According to Kim *et al.* [54], this can be enhanced with the use of an Energy Mean Value Algorithm, creating better load balancing among nodes.

Thus, a combination of these various power control techniques can result in increasing the network throughput, maximising the network lifetime, reducing radio interference, better packet delivery, limiting end-to-end delay, reducing overheads and overall better ad hoc network performance.

Much of the literature on power management in mobile ad hoc networks has suggested different methods to improve power management. ElBatt *et al.* [84] and Cheng *et al.* [83] both suggest varying the transmit power in order to assess the power balancing and to reduce the power consumption. The study by ElBatt *et al.* used clusters of nodes in the network and concluded that networks using this power management scheme performed better than those without it. Dynamic Power management was used by Cheng *et al.* with power variance to assess the effects of power balance, and concluded that this scheme balanced power consumption among mobile nodes, extended the network lifetime and reduced the power consumption.

According to Taneja *et al.* [80], power awareness during route selection is important, monitoring the power status of each node (danger, critical or active) and performing rapid route selection. This notion of reducing the time period for route selection is also mentioned by Huang *et al.* [82], stating that a higher transmission power can be used to reduce the transmission delay time and select the shortest route, avoiding a route break. A study by Zheng and Kravets [81] looks at a power management framework using timers for nodes, adapting to traffic load and determining power management transitions. Routing control messages and data transmission are monitored, and timers are set so that nodes not actively involve switch into sleep mode, as supported by the MAC protocol. A more recent study by Nema *et al.* [79] focuses on the link lifetime in the network layer and nodes' residual energy to enhance the route discovery process, and sets a minimum energy limit for mobile nodes, upon reaching which they switch to sleep mode, saving energy. Much of the research done in the power aware field has looked at the concept of routing, and how it can be used and adapted to reduce energy consumption. Lee *et al.* [85] put forward a routing mechanism, focusing on location and energy consumption, to improve Location-Aided Routing (LAR), which suggests two concepts: requested and expected zones. This proposal uses information about the location of mobile nodes, through GPS, in order to minimise the spread of unnecessary control messages and uses a suitable transmission power, based on the distance between nodes. Works by Latha *et al.* [86], Nie *et al.* [87] and Vadivel and Narasimhan [88] look at the effect on energy consumption of routing at the MAC layer. The first of these works [86] attempts to establish the minimum energy required to transmit information between the source and the destination in a multicast ad hoc on demand distance vector routing protocol (MAODV), while Nie *et al.* [87] uses beamforming to improve the physical layer and introducing an energy based routing measure in an energy aware AODV (EA-AODV). Vadivel and Narasimhan [88] focus on a power aware range based MAC routing mechanism to address the collision problem in mobile ad hoc networks. These three studies showed an improvement in power consumption, with the AODV based study concluding that using an optimal SIR (Signal Interference Rate) threshold can improve the network performance; the MAODV-based study concluding that energy minimisation is achieved by concentrating the network and MAC layers; and the power aware range based MAC protocol resulting in a better delivery ratio and reduced overheads.

Power aware research into routing protocols has also looked at the routing of packets in wireless ad hoc networks. According to a study by Gelenbe *et al.* [89], packet networks can be used to create an intelligent environment where smart packets acquire information and are able to make decisions, thus identifying paths with better energy and increasing mobile nodes' lifetime. Bae *et al.* [90] suggested a priority-based packet sending scheme using a power aware route search protocol (PARS), alongside discrete power control, thereby improving data delivery, as compared with other routing protocols.

A paper by Jie *et al.* [91] proposes a method for low mobility AODV networks, which dynamically controls the transmission power, uses a cost metric equation and a passive reactive route refresh scheme, while maintaining a power balance among nodes. This mobility aware concept is also studied by Ahmed *et al.* [92] who proposed a heterogeneity and mobility-aware AODV (H-MAODV), based on the distance and relative velocity between each node and one hop neighbour in order to avoid losing routes, and concluded that this H-MAODV resulted in a higher packet delivery.

An Energy Aware AODV (EAAODV) is proposed to combine load balancing and transmission power control to maximise the lifespan of the mobile ad hoc network [93]. This study showed that this method required less average transmission energy per packet than traditional AODVs.

Another aspect of power aware route selection which has been studied is an Energy Aware Adaptive AODV [94], which suggests an algorithm to delete stale paths after a specified timeout period. The approach used involved load balancing, power control and adaptive timeout, resulting in a reduction in the number of control packets, an increase in the packet delivery ratio and a decreased power consumption.

Other areas of power aware route selection research include using an energy mean value to make nodes energy aware [95]; using optimised power reactive routing [96]; using a cross-layer approach which uses residual node energy for route selection and maintenance [97]; and reducing consumer power in the routing protocol in a wireless sensor network [98]. All of these studies concluded that there was an increase in the lifetime of the network. A study by Abusaimeh *et al.* [98] also showed a decrease in the energy consumption of each wireless sensor node. Research by Bharathis *et al.* [96] also showed a reduction in the burden of network resources, improves the stability, scalability and reliability of the network; and the work by Veerayya *et al.* [97] demonstrated an increase in the packet delivery ratio, compared to AODV.

3.8 Summary

This chapter has outlined several routing protocols relating to power control, power management and power aware protocols. This chapter has given an overview of all of the routing protocols, within the field of power control, which is the central focus of this thesis, and highlights important differences among them.

Firstly, COMPOW is a bidirectional protocol which uses the same power level for all nodes. Both CLUSTERPOW and Tunnelled CLUSTERPOW form clusters of nodes, based on the power level and provide loop-free routes. However, Tunnelled CLUSTERPOW is more complex to implement, though it does offer enhanced optimisation of achievement. MINPOW is a routing protocol based on awake nodes. LOADPOW uses high power levels in order to ensure an effective network and, finally, PARO uses intermediate nodes, known as redirectors, in order to minimise the transmission power required.

Chapter 4

DP-AODV protocol Design and Implementation

This chapter details the development of the Dynamic Power AODV routing protocol proposed in this research. The chapter is organised as follows: Section 4.1 describes the energy model; section 4.2 describes the transmission power model; section 4.3 outlines why AODV was chosen; section 4.4 presents DP-AODV; section 4.5 details the proposed method; section 4.6 describes the modification of the NS2 files; section 4.7 describes the function testing; section 4.8 details the functionality testing; and section 4.9 gives a chapter summary.

4.1 Introduction

As discussed in Chapter 2, the field of mobile wireless networks has seen rapid developments and consequently new issues arising. The main issues identified in this research are those of high density and high mobility in networks, resulting in interference. There has also been a significant amount of research into developing new routing protocols, however there is not currently any protocol that caters for the issue of interference. Thus, there is a need for a new protocol to be developed in order to address this problem, which is an issue likely to continue and become more serious in the future. The aim of this research is to investigate the effect of high density and also high mobility on mobile ad hoc networks. This would have the effect of causing a high rate of change of network connectivity, as the links between individual nodes would become unusable very quickly. However, if there is also high density, then there would be many remaining neighbours and the routes could be quickly re-established. Analysis of such situations should enable the optimal parameters to be set for existing routing protocols, and the development of protocols designed specifically with high speed.

Density is a key aspect of ad hoc networks, since high density can cause collision and congestion due to fixed transmission power which leads to high loss packets in the networks. Another key aspect is the mobility. Since high mobility may cause frequent line breaks which lead to re-route discovery, hence wasting a lot of power. The expected outcomes of dynamically changing the transmission power are detailed below: A node initially increases its transmission power until it detects a set of neighbours around it and adjusts its power according to the number of neighbours. As the transmission power increases, the number of neighbours increases, and as the transmission power decreases, the number of neighbours decreases, enhancing the network throughput. Ultimately, the transmission power varies between minimum and maximum values.

Although there has been a lot of research in the field of power varying protocols, the majority of this type of power management protocol, for example COMPOW, aims to conserve power and do not specifically address the idea of reducing interference in the wireless network. However, the enhancements made to the existing AODV protocol are intended to reduce mutual interference of radios as this directly impacts on energy consumption within the network. The variation of transmission power in order to reduce interference has recently increased in importance within the field of power management research.

4.2 Energy Model

In order to carry out an energy analysis, each node is given an initial value of 100 Joules, thereby giving each node a finite battery energy of 100 Joules at the start of the simulation. The following code is written in Tcl script to configure the energy model, which is a node attribute, for the purposes of this research.

- $setopt(energymodel) EnergyModel;$
- $setopt(initialenergy) 100; \quad \#InitialenergyinJoules$

Subsequently, the energy will decrease in accordance with the following values of Tx and Rx (the energy spent in transmitting and receiving packets):

- $energyModelopt(energymodel)$
- $rxPower\ 0.6 \quad \#reception\ energy\ W$
- $txPower\ 0.9 \quad \#transmission\ energy\ W$
- $initialEnergyopt(initialenergy)$

To calculate the energy consumption value, the energy consumed by a node is deducted from its present energy value, as follows:

$$Energy\ Consumed\ =\ Transmitting\ (or\ Receiving)\ Power\ *\ Transmission\ (or\ Reception)\ Time \tag{4.1}$$

4.3 Transmission Power Model

In the standard NS-2, radio propagation models can be used to identify the transmission power required to successfully send data packet between neighbouring nodes. There are two propagation models used to calculate the expected received signal power of each data packet, namely the free-space propagation model, and the two-ray ground reflection model [6] [9]. The free-space model assumes that there is a clear, line-of-sight path between the transmitter node and the receiving node. The relation between the transmitted signal power (P_t) and the received signal power (P_r) is shown below:

$$P_r = \frac{P_t * G_t * G_r * \lambda^2}{(4\pi)^2 d^2 L} \tag{4.2}$$

Where, P_r : Received Signal Power, P_t : Transmitted Signal Power, G_t and G_r are Transmission and Receiver Gain of Antenna (1.0), d : Distance between the Transmitter and Receiver, L : System Loss, λ : Wavelength.

In addition to the line-of-sight path, the two-ray model also takes account of the ground reflection of the path. This model gives a more accurate prediction for longer distances, where h_r and h_t are Height of antenna for receiver and transmitter (1.5 m). The equation for this model is:

$$P_r = \frac{P_t * G_t * G_r * {h_t}^2 * {h_r}^2}{d^4 L} \tag{4.3}$$

If the distance is less than, or equal to, the cross-over distance then the free-space propagation model will be used. Otherwise, the transmission is regarded as a two-ray propagation model.The equation used to calculate the cross-over distance is as follows:

$$d_c = \frac{4\pi * h_t * h_r}{\lambda} \tag{4.4}$$

Where, d_c : Cross Over Distance (the reference distance of the receiver).

Transmission between a transmitting node and a receiving node is only successful if the received power of the radio signal is above a certain threshold [118], however if the received power is below this threshold then the transmission will be undetected. Moreover, if there are multiple transmissions at the same time, then only the transmission with the highest power will be received.

4.4 Simulator and protocol choice for Implementation

The main tool used to examine routing protocols is a simulation tool. NS2 was chosen as the simulator tool for this research as it is a popular tool within the research community and can be downloaded free of charge. In addition, it is open source and has been developed by the research community. A benefit of using NS2 is that it has been used extensively and the results of many studies are obtained by using it. It also has user documentation and there are mailing lists for NS2, to allow users to communicate with one another.
AODV is a popular on-demand routing protocol, which is always loop-free, and on demand protocols usually use less power. It is based on the DSDV routing protocol and combines elements of both DSR and DSDV protocols. The Route Discovery and Route Maintenance mechanisms are taken from DSR, and the use of sequence numbers for route freshness, hop-by-hop routing, and periodic beacons are copied from DSDV.

4.5 Dynamic Power-AODV Protocol Development

The methodology for developing the DP-AODV protocol is simulation-based prototyping. It extends the existing AODV protocol and uses the NS2 simulator to test and evaluate the enhanced protocol in a variety of scenarios, and to compare the results with AODV, AOMDV and DSR routing protocols. Simulation is used to test the protocol as, unlike real experiments, it is easy to conduct, less expensive and enables the adjustment of parameters for different scenarios. In this section, a Dynamic Power Ad hoc On-Demand Distance Vector (DP-AODV) protocol, that is an improvement of an existing AODV routing protocol, is developed. A detailed description of the existing AODV routing protocol is provided in chapter 2 (section 2.5.1). In this extension, due to adding some fields in the ns2 packet header itself, modifications are made to all the packets. As routing protocols are learned, we need to modify the standard hello request and reply by adding some additional fields. Any packet sent or forwarded in the routing layer also needs some information to calculate the distance of nodes. Every hello packet dispatched from the routing layer will contain the modified packet header with the distance information of the destination and neighbour count.

The transmission power is only decided in the wireless physical layer just before transmitting the packet, and is calculated by using the cross-over distance information. Location information can be obtained by using GPS, however this uses a lot of battery power, but there is another method of establishing location information which is to modify the hello packets of AODV by including x-position and y-position fields to store the location of the node.

In sending hello messages, each node sends a packet with its co-ordinates to obtain the exact location information of a node, which was used by the routing protocol to determine the route. When a node receives a hello message, it calculates a distance for neighbours using co-ordinates; the distance of the neighbouring nodes is an important aspect in route discovery. As all the nodes within the coverage of a particular node can receive the route request messages and process them. Thus, increasing or decreasing the transmission power of a node will increase or decrease the one hop neighbours involved. So, our algorithm selects the power needed to reach the destination node and maintain the connectivity among the nodes and hence reduce the overall power. Then, each node is added to the neighbour table with transmission power and distance. This implies that the selected path will be stable, based on the densities of the different locations and consequently may not necessarily be the shortest path.

Along with the normal information which will be in the AODV routing table, the distances for all the neighbouring nodes will be kept in the routing table and the routing table entry has not changed. Every packet that is leaving from a node will contain the distance information about the destination node and the node's neighbour count.

DP-AODV uses different power levels to determine a route for transmission of a packet. The transmission power can be changed with respect to the neighbour count, the distance and the transmitter. For a small number of neighbours in the area, transmission is done at maximum power; otherwise transmission power is reduced.

4.6 Hello Message

Hello messages are unsolicited RREP packets, containing the address and sequence number of the sender. These messages are broadcast to collect information of topology change in a timely fashion. This mechanism reduces traffic exchange delay and reduces the cost of increasing link connectivity by managing overheads, and enables quick reactivity to any changes in the route. It keeps track of neighbouring nodes and generates a routing table, local broadcasts, known as hello messages [18] are exchanged periodically among neighbouring nodes. Nodes should only use hello messages if they are part of an active route. Nodes regularly check whether they have sent broadcasts within the last $hello\_interval$ and, if not, they may broadcast a hello message. Neighbouring nodes, which are all the nodes that a source node can communicate directly with, can determine connectivity by listening for packets from its neighbours. When a node receives a hello message, it must ensure that it has an active route to this neighbour, or create one, and it then updates the relevant neighbour information in the routing table. All nodes should maintain accurate information of both their continued connectivity to their active next hop, and for neighbours that have transmitted hello messages during the last period. However, if a node does not receive communication from a neighbour within a specified period of time, this may indicate link failure and thus an invalid route. Hello messages are only ever broadcast, and never forwarded, and are limited by range and so do not generate excess overhead in the network.

Despite being a reactive protocol, AODV uses hello messages to confirm that a link is still valid, using two parameters: $allowed\_hello\_loss$ and $hello\_interval$. AODV uses a periodic interval of one second to transmit hello messages, with a maximum latency time of 2 seconds for each message, which has been determined as the optimal value for the $allowed\_hello\_loss$ parameter [36]. Hello messages are the only type of message used to test the DP-AODV protocol as they are the only broadcast messages used in the original AODV protocol.

4.7 DP-AODV Proposed Method

As the proposal is based on the AODV routing protocol, the basic data packet mechanism is the same. The proposed algorithm automatically adjusts the transmission power at each node so as to keep its number of neighbours within a specified range. Consequently, this leads to a reduction in unwanted interference and unnecessary overhearing by other nodes and thus increases the throughput in the network. However, in DP-AODV, the basic mechanism of neighbour based Variable-Power Transmission is implemented.

1. ***Initially each node broadcasts a hello message with its co-ordinates to determine its neighbours***
   Each node uses broadcasting which sends a packet to every neighbour and the hello packets are generally broadcast only up to one hop neighbours. Normally, AODV will use network wide multihop broadcasting. Unlike AODV, hello messages are enabled in the proposed method and each node periodically broadcasts a hello packet which is reveived by its neighbour. Furthermore, each node maintains a neighbour table to keep track of its neighbours. The send hello message is altered to contain a node's location details (with x and y co-ordinates), which are sent to all other nodes, to identify its neighbours. Each node position is updated dynamically using hello messages (see figure 4.1).

Type	Reserve
Destination IP Address	
Destination Sequence Number	
Hop Count	
Lifetime	
co-ordinates	

Figure 4.1: Hello packet format in DP-AODV

The original aodv.cc source code file is written in C++ (compiler) and OTcl (interpreter). It contains hello packets (which are disabled by default in the AODV protocol), timers (used to delay or repeat specific actions), and functions (general, routing table management, neighbour management, broadcast ID management, packet transmission management, and packet reception management). This source code file is located in the AODV folder in the ns2 base directory. The principal modification made to the aodv.cc file when developing the DP-AODV protocol is to include co-ordinates, which means the current position of the node in the topology. The following two lines have been added to the hello packet code in aodv.cc (send hello function). This function is used to get the current position of the node.

```
void
AODV::sendHello() {
.
rh->xpos=node_->X();  // sending packet with node x pos
rh->ypos=node_->Y();  // sending packet with node y pos
.
}
```

2. ***The neighbour node receives a hello message, calculates distance, and adds an entry in its neighbour table***

   Neighbouring nodes receive the hello message and update the send information. For example the address, calculates the distance between nodes (neighbours). Each node knows its neighbour information and the neighbour table contains $neighbour\_Id$, $txpower$, $distance$, $flag$ and $neighbour\_count$ information. An active neighbour node list is maintained in order to monitor the neighbours which use the entry for data packet routing.The distance between two nodes can be calculated using the Euclidean distance formula (as detailed in Chapter 4.5). This is only based on the exact co-ordinates of nodes that are received through the hello packet. The nodes send and update their location and neighbour table through a hello reply message. In this case, each node knows its neighbour information. When the node knows the distance, then it knows the best transmission power level to choose, where x_1 and y_1 are the co-ordinates for the current location and x_2 and y_2 are the co-ordinates for the neighbour node, as follows:

$$d(x,y) = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{4.5}$$

To calculate the distance, the following lines have been added to the aodv.cc source code file.

```
double AODV::getDistance(double x,double y){
float dis = sqrt(pow ((node_->X() - x),2) + pow((node_->Y() - y),2));
return dis;
}
```

In aodv.cc, the transmission power and distance are added to the receive hello function. In addition, the neighbour table is updated by adding received information in aodv.cc.

Transmission power and distance were added to neighbour table in aodv.cc as follows:

```
//The following nb_insert function is inserting or updating that
routing table entry.
//maintaining neighbour table with distance and transmission power.
void AODV::nb_insert(nsaddr_t id,double txpower,double distance){
AODV_Neighbor *nb = new AODV_Neighbor(id);
.
 assert(nb);
 nb->txpower=txpower;
 nb->distance=distance;
 nb->nb_expire = CURRENT_TIME +
                (1.5 * ALLOWED_HELLO_LOSS * HELLO_INTERVAL);
 LIST_INSERT_HEAD(&nbhead, nb, nb_link);
 seqno += 2;             // set of neighbours changed
 assert ((seqno%2) == 0);
}
```

The nodes are sending and updating their location and neighbour table through hello reply message. In this case, each node knows its neighbour information.

When the node knows the distance, then it would know the best transmission power level to choose.

3. ***Identify power level according to number of neighbours***

   In our implementation, while transmitting a packet to a next hop node, the transmitting node will select the power level based on the distance as this function does not exist in AODV and it enables the enhanced protocol to select the appropriate power level.

4. ***During data transmission from source to destnation, node estimate number of neighbours by using neighbours count function***

   In the process of data transmission from source to destination, the node estimates the number of neighbours between itself and sending nodes through the neighbour count function. The algorithm finds how many neighbours each node has and adjusts the transmission power of each node so that the number of neighbours stays within the desired range. This function is already available in default AODV through hello request and reply mechanism. In DP-AODV, the distance of the neighbour is added, using the same hello mechanism and number of entries found in the neighbour table. The neighbour count is given by the received hello function in aodv.cc.

```
//The following function will increase the neigbour count for each
//received hello message
int AODV::get_nbrs_count(){
int nbrs=0;
AODV_Neighbor *nb = nbhead.lh_first;
for(; nb; nb = nb->nb_link.le_next)
nbrs++;
return nbrs;
}
```

The neighbour table is modified to include neighbour_Id, txpower, distance, flag and neighbour_count information.

5. ***Transmission power required based on power level with respect to number of neighbours***

   The transmission power is divided into three levels (low, medium and high) based on node density in range (see figure 4.2) [23] [24]. The number of neighbours in transmission range used to define each transmission power level is based on the findings of previous research [23] [24]. If the number of neighbours is less than, or equal to, 7 then the density is low. If the number of neighbours more than 7, but less than 16, then the density is medium. The node density is considered to be high when there are more than 15 neighbours. The purpose of using three different power levels is to maintain appropriate links while reducing the power consumption and interference between nodes. When a node can be reached only by using the power needed to transmit up to cross over distance, then using power more than that is not necessary. So, at that location, the node will use a lower level of power to maintain connectivity. Similarly, different levels of powers are used to maintain connectivity at different density areas, decrease interference and save power.

$$\mathbf{P_t} = \begin{cases} \textbf{Level 1}, & \text{if density is low} \\ \textbf{Level 2}, & \text{if density is medium} \\ \textbf{Level 3}, & \text{if density is high} \end{cases}$$

Figure 4.2: DP-AODV Power Levels

The source code file wireless_Phy.cc simulates the wireless physical layer and handles the propagation model, energy management model and antenna models and modulations. After the aodv.cc source code file has performed the neighbour count at the network layer, the wireless_Phy.cc source code file at the physical layer calculates the neighbour levels. The following function has been added to calculate neighbour levels in wireless_Phy.cc.

```
// function to calculate neighbour levels
int Level(int no_of_nbrs)
{
if(no_of_nbrs<=7) // low number of neighbours
return 1;
if(no_of_nbrs>7 && no_of_nbrs<=15)
return 2;
if(no_of_nbrs>15) // high number of neighbours
return 3;
}
```

The following function has been added to calculate power levels in wireless_Phy.cc. The numbers in the code are based on previous experiments to identify the appropriate transmission power for different number of neighbours.

```
// assigning transmission power according to neighbours level
int level=Level(num_of_nbrs);
 if(level==1)
  Pt_ = 0.28183815; // for 250 m transmission range
 if(level==2)
  Pt_ = 0.24169726;
 if(level==3)
  Pt_ = 0.20191908; // for 170 m transmission range
printf("\nnum_of_nbrs:%d level:%d \\
power:%.6f\n",ch->num_of_nbrs,level,Pt_);
}
```

6. ***Adjust the transmission power***

Two propagation models [6] [9] are used to determine the power required to transmit the packet to the corresponding neighbour, based on the estimated distance. If the distance is less than, or equal to, the cross-over distance then the free-space propagation model will be used. Otherwise, the transmission is regarded as a two-ray propagation model. The transmission power required to reach the next hop or destination is adjusted to minimise overlap interference among neighbouring nodes. The following code was developed during this research, based on the cross-over distance and the two propagation models. It is contained within the wireless physical layer in order to estimate and addign the transmission power.

```
double Cod = 4.0*3.143*getAntennaZ()*getAntennaZ()/getLambda();
//calculating COD distance
if(ch->dist <= Cod)
{
double temp = 4.0*3.1432*ch->dist;
// estimate and assign transmission power
double TP_ = getCSThresh()*temp*temp/(getLambda()*getLambda());
cout<<TP_<<endl; //free space
powerfile(TP_,Scheduler::instance().clock());
.
Pt_=TP_;  // store prevous transmission power
}
else
{
double d4 = ch->dist * ch->dist * ch->dist * ch->dist;
double hr2 = getAntennaZ()*getAntennaZ()*getAntennaZ()*getAntennaZ();
double TP_ = d4*getCSThresh() /hr2;
cout<<TP_<<endl; // two-ray
powerfile(TP_,Scheduler::instance().clock());
.
Pt_=TP_;
}
```

7. ***Forward the packet***

The packet is transmitted using the minimum energy required, by selecting the appropriate power level (low, medium or high) depending on the number of neighbours. If the location is known to be very close, then even less power can be used. Each packet is handled in the wireless physical layer, and the current node will be transmitted as per the number of neighbours of the nodes as well as the next hop determined from the routing table (destination).

4.8 Modification of NS2 Files

NS2 is an event-driven simulation tool that is used in order to analyse and evaluate the DP-AODV communication protocol. It supports protocols including AODV, DSDV, DSR, AOMDV and TORA and consists of two main programming languages: C++ and OTcl. A Tcl scripting file is input into the tool, an ASSCII trace file (corresponding to the event registered at network level and organised according to certain fields) and a network animator visualisation tool (NAM), used to disply the nodes in the network, are then produced. The NS2 outputs text-based simulation results.

Figure 4.3 shows where our extensions are arranged within the NS-2 framework. The major additions and modifications are explained below, and the next subsection shows how our extensions fit into NS-2's class hierarchy.

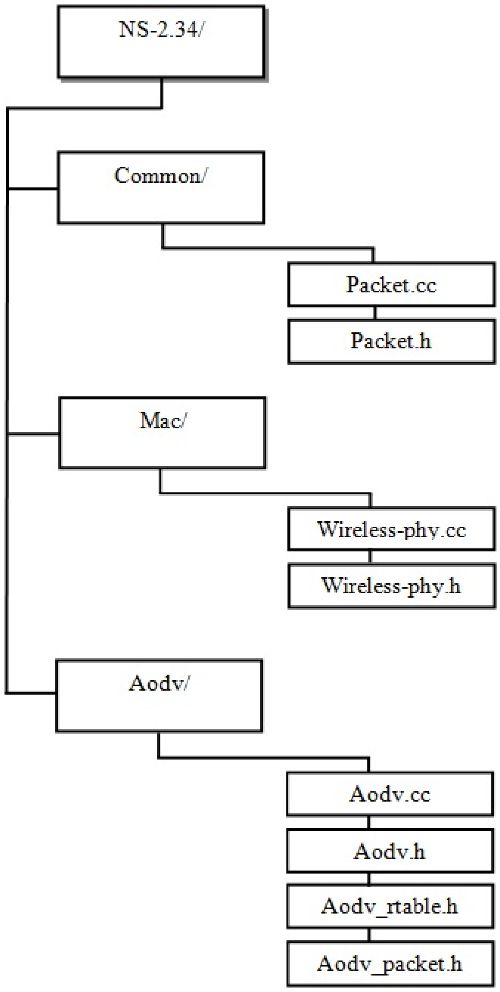

Figure 4.3: Files in the NS-2 framework that were modified

The diagram represents the modified modules. C++ is used under NS2 in order to implement the DP-AODV routing protocol, with the use of TCL (Tool Command Langauge) scripts to describe the simulation scenarios. The files for the modified modules are as follows:

- **Mac/wireless-phy.cc:** NS-2 contains an energy model for wireless nodes that is useful for assessing the advantages of different energy conservation techniques, such as sleep mode, or using optimal network densities. The model allows the power requirements for transmitting and receiving packets, or for idle mode, to be specified. In Mac/wireless-phy.cc, we have included the routing agent that will add the distance of the destination and the neighbour count inside the packet.

- **Mac/wireless-phy.h:** This is the header file where we defined the power timer and power file (double power, double time) to store all the events.

- **Aodv/aodv.cc:** It contains send and receive hello messages, send and receive aodv function and routing table to maintain the information of each node. In this file, all timers, routing agent and Tcl hooks are actually implemented.

- **Aodv/aodv.h:** This header file is where we define the mobile node, getDistance (double x, double y), number of neighbours, flag and neighbour tables. We also define the neighbour list (neighbour IDs, txpower and distance).

- **Aodv/packet.h:** This is the header file where the AODV reply header (xpos, ypos and transmission power) is declared.

- **Aodv/rtable.h:** This is the header file where the routing table and neigbours table (txpower and distance) are declared.

- **Common/packet.h:** Each packet in NS-2 is associated with a unique type that associates it with the protocol to which it belongs, such as TCP, ARP, $AODV$, FTP, etc. We defined x, y, $txpower$, num_of_nbrs in the packet.h header file.

- **Common/packet.cc:** This file contains the size of a packet's header, free list, offset of common header and offset of flag's header, which is accessible through Tcl. It is used to manage active packet header types. Each packet in NS-2 is used to exchange information between objects in the simulation. We defined num_of_nbrs in the packet.cc source file.

The structure of the protocol was created using an agent, which represents the endpoints and can be used to implement the protocol at various layers. The agent is the principal class for implementing the protocol and provides a link with the Tcl interface, for control of the protocol using TCL scripts. New control packets parameters are defined by DP-AODV, in the common/packet.h header file, to represent the format of the control packets. The protocol can send packets periodically or following a delay after the occurrence of an event.

4.9 Function Testing of Implementation

In order to verify that the DP-AODV protocol functions correctly, it is necessary to carry out a form of testing. One of the ways in which this can be done is by using an extensive set of tests. These tests ensure that the protocol achieves the intended aims and is fully functional. Function testing compares the results of a new protocol with previous results from other protocols which have already been tested, to see if the results meet expectations. In the case of DP-AODV, it is anticipated that this new protocol will produce better results for the metrics tested as this protocol obtains location information for neighbouring nodes in the network, selects the next hop based on node density, and thus identifies the shortest path length, which is more stable and efficient than AODV. Every developer aims to produce products with as few issues as possible, which can be helped by function testing.
To check the functionality of DP-AODV, several tests are carried out, with a variety of situations, using NS 2.34. The results from these tests are compared with the expected results for each senario. In order to perform more accurate testing, each situation is run using different standard protocols (AODV, DSR and AOMDV).

4.9.1 TCL Testing

The basic method used for the integration of the DP-AODV code was to carry out all of the changes specified in some basic AODV files to the ns-allinone-2.34.tar.gz package. This package contains all of the required components to run NS2 and some optional components. There were some areas where the code had to be significantly modified as

a result of changes in the latest version of NS2 (2.34), which the original implementation of DP-AODV was designed for.
The test case used during conversion was DP-AODV.tcl, located in the ns-2.34 directory. It allowed the testing of the effects on other wireless implementations, in addition to the DP-AODV implementation. The changes made to the AODV files are only effective if no other wireless protocols are running simultaneously, as implementation of the changes in DP-AODV can cause Segmentation Faults for other wireless routing protocols simulation.
Figure 4.3 demonstrates the general setup for all script files used in the DP-AODV function testing. The same scenario configuration and setup as shown in thew diagram were used, with the only change being the routing agent setting to DP-AODV as shown below:

```
set val(routing)  DPAODV ;# Routing protocol (DSDV DSR AODV AOMDV)
```

The default setting of the network is used in all scenarios for the mobile node configuration process. The values and descriptions for the most commonly used options in all tcl scenarios are detailed below. These are the same values as used when testing the DP-AODV protocol.

```
#global node setting
$ns_ node-config -adhocRouting $val(routing)\
-llType LL \;\;\;\;# link layer type
-macType Mac/802_11  \;\;\;\;# MAC type
-ifqType Queue/DropTail/PriQueue  \;\;\;\;# interface queue type
-ifqLen 50  \;\;\;\;# max packet in ifq
-antType Antenna/OmniAntenna  \;\;\;\;# antenna model
-propType Propagation/TwoRayGround  \;\;\;\;# radio-propagation model
-phyType Phy/WirelessPhy  \;\;\;\;# network interface type
-channelType Channel/WirelessChannel  \;\;\;\;# channel type
-topoInstance $topo \;# an OTcl instance which identifies topography
-energyModel $opt(energymodel) \
-rxPower 0.6  \;\;\;\;# reception energy W
-txPower 0.9  \;\;\;\;# transmission energy W
-initialEnergy $opt(initialenergy) \
-agentTrace ON \;\;\;\;# turning agent trace ON
```

```
-routerTrace ON \;\;\;\;# turning router trace ON
-macTrace ON \;\;\;\;# turning MAC trace ON
```

Using these parameters, a large number of scenarios were run during the DP-AODV implementation, improvement and performance comparison stages. This new trace file command is used for all scenarios.

```
$ns_ use-newtrace
```

This scenario positions 100 nodes in a 1000x1000 m^2 flat grid area, using a simulation time of 100 seconds.

```
set val(x)        1000   ;# X dimension of the topography
set val(y)        1000   ;# Y dimension of the topography
set val(nn)       100    ;# how many nodes
set val(stop)     100.0  ;# simulation time
set val(routing)  DPAODV ;# Routing protocol
```

The following lines describe the initial trace file, which creates a trace object for ns.

```
set t [open out.tr w]
$ns_ trace-all $t
$ns_ use-newtrace ;# trace file type

The lines below describe the second trace file, which creates a trace object for nam.

set nt [open out.nam w]
$ns_ namtrace-all-wireless $nt $val(x) $val(y)
```

The creation of the movement file requires the following parameters to be defined: node positions and their movement, using a Carnegie Mellon University (CMU) setdest shell utility generator. For example:

```
./setdest -n 200 -p 25.0 -s 20.0 -t 100 -x 1000 -y 1000 $>$ scen-200-test
```

This is used for random scenario setup positions using 200 nodes with a maximum speed of 20m/s, with a pause time of 25s, for a maximum simulation time of 100s within a topology area of 1000 x 1000. There is a separate file containing the Nodes movement model, as shown below in the tcl file.

```
source rdm_N200_M20_1
```

The creation of the traffic-connection file requires the following parameters to be defined: the traffic connection type (CBR/UDP or TCP/FTP), the number of nodes and the maximum number of connections to be established among nodes, a random seed and increase of CBR connections, and a rate with an inverse value, which is used to calculate the interval time between CBR packets. For example:

```
ns cbrgen.tcl -type cbr -nn 200 -seed 1.0 -mc 20 -rate 4.0 $>$ cbr-20-test
```

This is for connections created between 20 pairs of nodes, with a data rate of 4 packets per second. There is a separate file specifying the connection pattern, as shown below.

```
source flows_20_N200
```

4.10 Functionality Testing

Figure 4.4 shows the power change based on the number of neighbours. For example, on line 1, when the number of neighbours of a specific node is 10, the power is at level 2, whereas when the number of neighbours of another node in the network is 5, as shown on line 3, the power is changed to level 1.

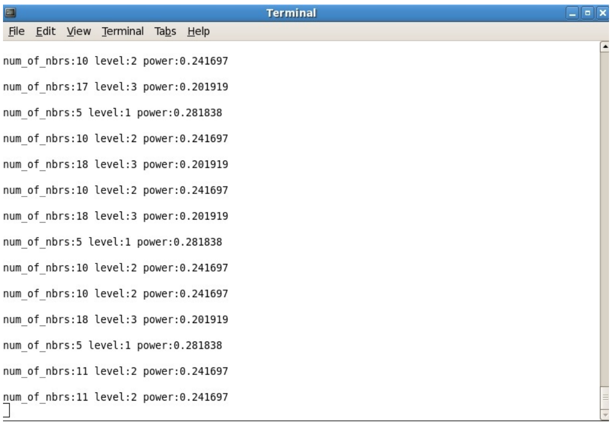

Figure 4.4: Neighbour and power information used to check the DP-AODV protocol

Figure 4.5 shows a power.txt file containing the stored time and the power. All times and power which occur throughout the simulation period are recorded and stored in a file to enable subsequent checks and verification that the DP-AODV protocol did indeed improve power consumption.

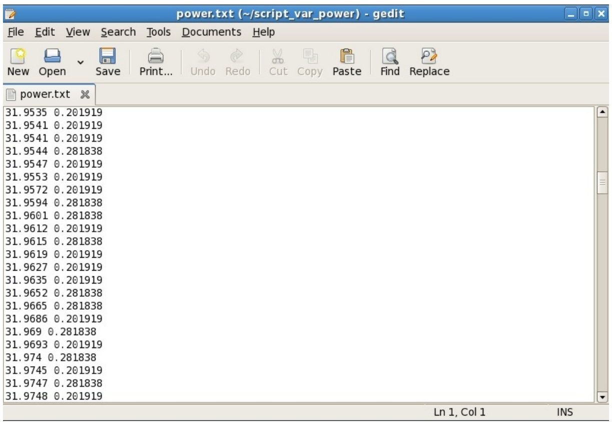

Figure 4.5: Power and time information used to check the DP-AODV protocol

Figures 4.6 and 4.7 show a network of 100 randomly placed nodes controlling the transmission range in the area, which can vary. This shows a decrease in interference between nodes in the network, thus enhancing the throughput of the network that were modified

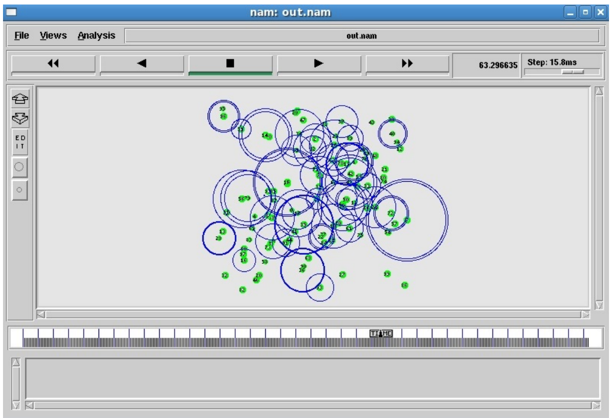

Figure 4.6: Snapshot of a simple network with variable transmission power

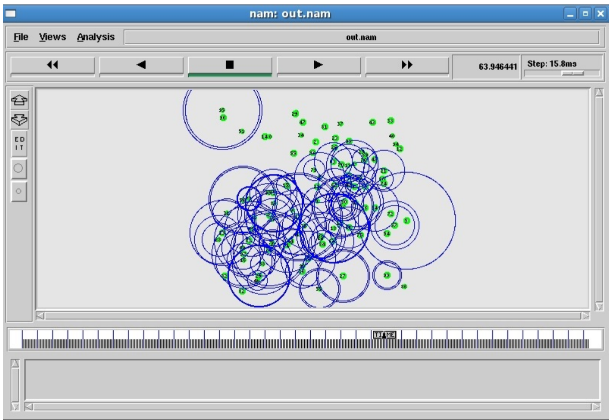

Figure 4.7: Snapshot of a simple network with variable transmission power

Figures 4.8 and 4.9 illustrate the same scenario as above, but using a network of 200 randomly connected nodes. This scenario exemplifies why interference between nodes is reduced, with a full connection between nodes.

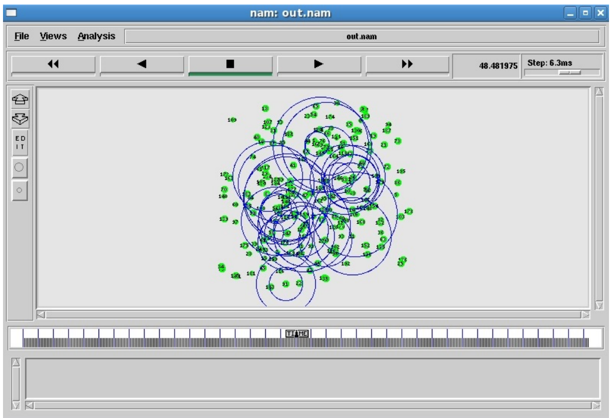

Figure 4.8: Snapshot of a high-density simple network with variable transmission power

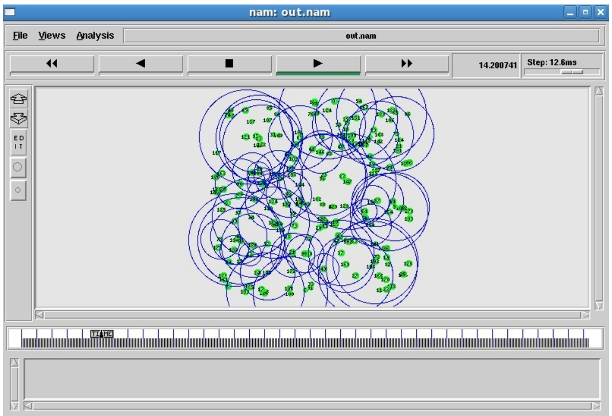

Figure 4.9: Snapshot of a high-density simple network with variable transmission power

4.11 Summary

Due to the problems of interference and loss of data packets resulting from fixed transmission power in a high-density environment with a fixed area, the DP-AODV routing protocol is proposed. This chapter provides an overview of the structure of the enhanced protocol. A Hello message played a key role in designing our model as it demonstrated communication, at periodic intervals, to immediate neighbouring nodes. The results of the tested scenarios demonstrate the effects of modifications to the NS2 files. These modifications are detailed and resulted in the DP-AODV protocol working as expected.

Finally, the function testing provided verification that the modified protocol was operating correctly, and the functionality testing gave a good indication that DP-AODV was performing as expected.

Chapter 5

Comparing Performance with AODV

This chapter is organised as follows: Section 5.2 outlines the methodology; section 5.3 presents the performance evaluation metrics; section 5.4 details the simulation environment; section 5.5 presents the results of the simulation; and a chapter summary is provided in section 5.6.

5.1 Introduction

The aim of this chapter is to illustrate the enhancements of DP-AODV as compared with AODV, using a particular set of metrics. The results of the analysis carried out offer a clear demonstration of the advantages of the improvements made in DP-AODV, in comparison with basic AODV. Comparison of the results of the analysis is more accurate as both the routing protocols used are single-path. Varying movement patterns and traffic patterns scenario files were run with both routing protocols in order to ensure a fair comparison.

5.2 Methodology

In this chapter, we use CBR (Continuous Bit-Rate) traffic and a random waypoint mobility model, where each node is stationary for pause time seconds, a variable, before randomly choosing and moving to a new destination. 40 CBR flows are used, with 4 packets per second, and a packet size of 512 bytes. The source-destination node pairs are randomly spread across the network and the MAC layer protocol is IEEE 802.11. Each traffic session is created independently, at different times, and stays active until the simulation time ends. Four factors are varied (Density, Speed of Nodes, Pause time, and Number of sources) in order to analyse their effect on the protocol. The simulation is carried out using four different experiments to compare DP-AODV and basic AODV.

- In the first experiment, the impact of network density on the performance of DP-AODV and basic AODV was tested by varying the number of nodes. The networks used were 75, 100, 150 and 200 nodes.
- In the second experiment, the effect of the speed of the nodes (movement of the nodes) on the performance of the protocol was studied. Three different maximum speeds of nodes were used: 10, 20 and 30 m/s.
- The third experiment looked at the movement patterns created by four different pause times: 0 (Dynamic network), 25, 50 and 75 (static network) seconds.
- In the fourth experiment, the number of source-destination pairs was varied (10, 20 and 40 traffic sources) in order to alter the network's offered load.

An average of 10 runs, using different randomly generated mobility scenarios, but identical traffic models, represents each data point. The graphs (figures 5.1 - 5.32) contain error bars which represent 95% confidence interval of the mean. All four experiments use the same fixed simulation time parameter. Table 5.1 shows all of the fixed parameters used to test all routing protocols. Tables 5.2, 5.3, 5.4 and 5.5 all list the variable parameters (see pages 86 onwards).

5.3 Performance Evaluation Metrics

In order to evaluate the performance, several metrics can be used, however for the purposes of this research the four metrics that will be used are: packet delivery fraction (PDF), end-to-end delay (EED), throughput and power consumption (PC). The most important metrics for best-effort traffic are the packet delivery fraction and the end-to-end delay. However, these metrics are not entirely independent as a shorter delay does not necessarily mean a higher packet delivery fraction, as only successfully delivered packets are used to measure the delay. A lower packet delivery fraction and longer delay may, however, cause a larger overhead.

5.3.1 Packet Delivery Fraction (PDF)

This metric is the ratio between the number of data packets sent by the CBR sources, a type of traffic, and the number of data packets received by the CBR sinks at their destination. It shows how reliable a protocol is by showing how the protocol successfully delivers packets from the source node to the destination node. The higher the PDF, the better the results.

$$Packet\ Delivery\ Fraction\ (PDF) = (\frac{packets\ received\ by\ CBR\ sinks}{packets\ sent\ by\ CBR\ sources}) * 100 \tag{5.1}$$

5.3.2 Average End-to-End Delay (EED)

This concerns the average length of time, measured in seconds, necessary to deliver a set of data from the source to the destination node. It includes all potential delays resulting from queuing at the interface queue, propagation and transfer times, and retransmission delays at the MAC layer.

$$End\ to\ End\ Delay\ (EED) = (\frac{(packets\ received\ time - packets\ sent\ time)}{pckkets\ received\ by\ destinations} \tag{5.2}$$

5.3.3 Throughput

The number of bytes successfully transferred to the destination during a specified amount of time(s).

$$Throughput = (\frac{size\ of\ received\ data}{transmission\ stop\ time\ start\ time}) * \frac{8}{1000} \tag{5.3}$$

5.3.4 Power Consumption (PC)

The average power consumption for all nodes in the network is calculated based on the ratio of the total energy consumed by every node in the network divided by the total number of nodes.

$$Power\ Consumption\ (PC) = (\frac{(total\ energy\ consumed)}{total\ number\ of\ nodes} \tag{5.4}$$

5.4 Simulation Environment

The simulation environment uses CBR (real time) traffic and a random waypoint mobility model. The simulation of 200 nodes, forming a network over a fixed area of 1000 x 1000 m^2, is used for the evaluation. The random waypoint model is used to determine the movement of the nodes. The simulation time is fixed at 100 seconds. The Distributed Coordination Function (DCF) of IEEE 802.11 for wireless LANs is used as the MAC layer protocol, with a bandwidth of 2 Mbps. An Omni-antenna model is used, with a wireless channel.

Initial energy for each node is set at 100 Joules at the start of every simulation in each scenario, and a node will consume 0.9W for sending packets and will consume 0.6W for receiving packets. The traffic is generated by 40 CBR sources distributing the traffic among all nodes. The sending rate was fixed at 4 packets per second, with a data packet size of 512 bytes. Table 5.1 lists the parameters used in the simulation.

Parameter	Value
Simulator version	NS 2.34
Node placement	Uniform
Mobility model	Random Waypoint
Physical/MAC layer	IEEE 802.11
Antenna Model	Omni-Antenna
Channel type	Wireless
Network interface type	WirelessPhy
Simulation area	1000*1000m^2
Interface queue type	DropTail/PriQueue
Simulation time	100 (s)
Initial Energy of the nodes	100 Joules
Txpower of the nodes	0.9 (W)
Rxpower of the nodes	0.6 (W)
Traffic type	CBR over UDP
Packet size	512 (byte)
Transmission rate	4 packets/s
Bandwidth	2 (Mbps)
Iteration	10

Table 5.1: Baseline parameters used in the simulations

5.5 Simulation Results

5.5.1 Varying number of nodes

The number of nodes used in the simulation is set at 75, 100, 150 and 200 nodes, using two pause times of 0 and 75 seconds (0 as a dynamic network and 75 as a static network).

A dynamic network is when the nodes move continuously throughout the simulation period, which is the worst case scenario for the network performance. A static network has very low mobility where nodes are completely static. The maximum speed of the nodes was limited to 30 m/s. The number of CBR sources used was set at 40. These parameters, which different from the fixed parameters given in table 5.1, are illustrated in table 5.2.

Parameter	Value
Number of nodes	75, 100, 150, and 200 nodes
Max. speed of nodes	30 m/s
Pause time	0, and 75 seconds
Number of sources	40 sources

Table 5.2: Variable number of nodes parameter used in the simulations

Packet Delivery Fraction (PDF)

Figures 5.1 and 5.2 compare the PDF for DP-AODV and AODV. They show that DP-AODV gives a better PDF compared to AODV. Figure 5.1 shows that in a dynamic network, as the density decreases, the PDF for DP-AODV increases, from 51.63% for a density of 200 nodes, to 73.97% with a density of 75 nodes. Likewise, with AODV, as the density decreases, the PDF increases, from 42.07% with a density of 200 nodes, to 53.19% with a density of 75 nodes. Whereas, in figure 5.2, in a static network, the PDF for DP-AODV decreases, from 72.27% for a density of 75 nodes, to 59.44% with a density of 200 nodes. Likewise, with AODV, as the density increases, the PDF decreases, from 63.08% with a density of 75 nodes, to 45.47% with a density of 200 nodes. These results occur as the proposed method (DP-AODV) restricts the density by controlling the transmission power, but with AODV many packets are lost due to fixed transmission power and extensive interference between nodes.

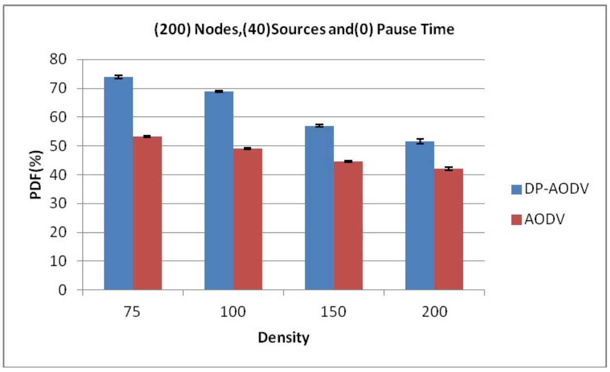

Figure 5.1: PDF vs Density (Pause Time 0 sec - Dynamic)

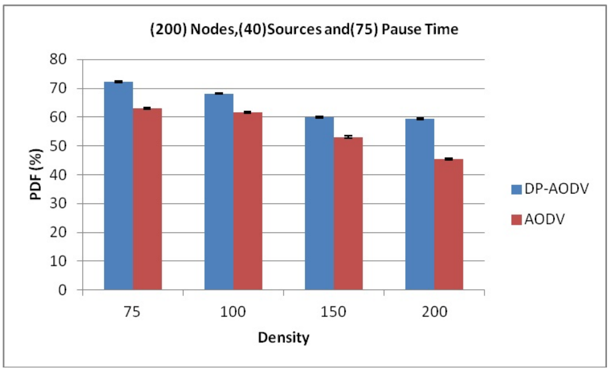

Figure 5.2: PDF vs Density (Pause Time 75 sec - Static)

End-to-End Delay (EED)

Figures 5.3 and 5.4 compare the EED for DP-AODV and AODV. They show that DP-AODV gives a shorter EED as compared to AODV. In a dynamic network (figure 5.3), as the density increases, the EED for DP-AODV increases, though there is a decrease from 150-200 nodes. Likewise, with AODV, as the density increases, the EED increases. Similarly, in a static network (figure 5.4), as the density increases, the EED for DP-AODV increases. Likewise, with AODV, as the density increases, the EED increases. The reason is that finding a routing with a higher success possibility (DP-AODV) will definitely use less time to send data from the source node to the destination node.

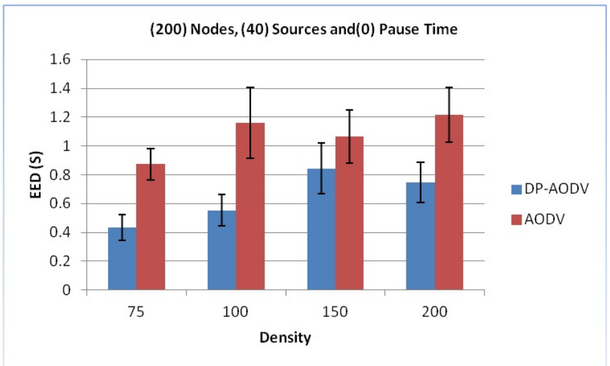

Figure 5.3: EED vs Density (Pause Time 0 sec - Dynamic)

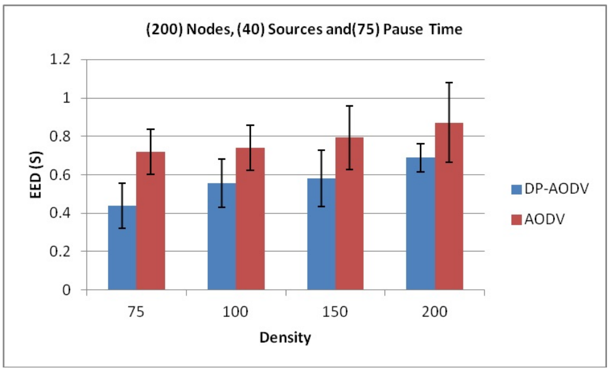

Figure 5.4: EED vs Density (Pause Time 75 sec - Static)

Throughput

Figures 5.5 and 5.6 compare the throughput for DP-AODV and AODV. They show that DP-AODV gives a better throughput as compared to AODV. In a dynamic network, as the number of nodes increases, the throughput for DP-AODV decreases. Likewise, with AODV, as the number of nodes increases, the throughput decreases. The same is seen in a static network (figure 5.6) where, as the number of nodes increases, the throughput for DP-AODV decreases. Likewise, with AODV, as the number of nodes increases, the throughput decreases. This is because DP-AODV has a large throughput due to the reduction of bandwidth waste by route request process (RREQ) in route discovery. However, in AODV there is more possibility for some errors to occur in the routing discovery process, using the default transmission power.

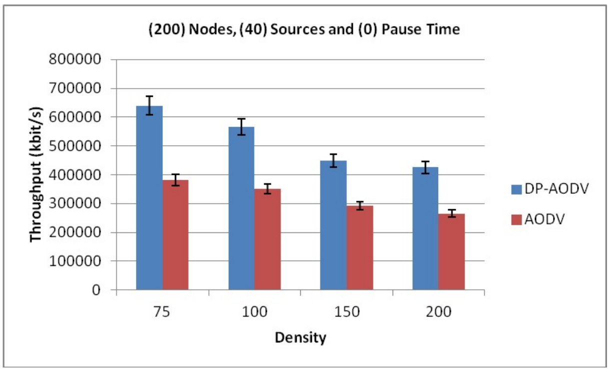

Figure 5.5: Throughput vs Density (Pause Time 0 sec - Dynamic)

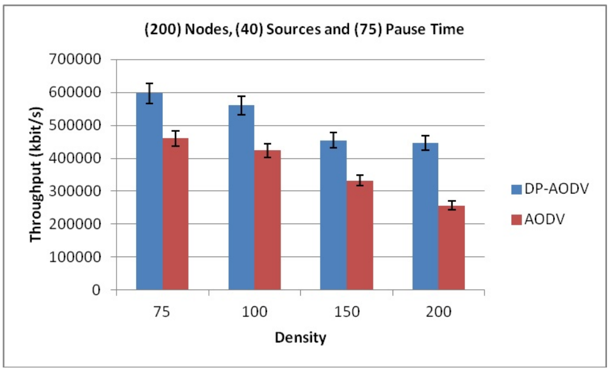

Figure 5.6: Throughput vs Density (Pause Time 75 sec - Static)

Power Consumption (PC)

Figures 5.7 and 5.8 compare the power consumption for DP-AODV and AODV. They show that DP-AODV has a better power consumption as compared to AODV. In a dynamic network (figure 5.7), as the number of nodes increases, the power consumption increases. For DP-AODV, with a density of both 75 and 200 nodes, the power consumption is 10% higher than for AODV. In a static network (figure 5.8), as the number of nodes increases, the power consumption for both DP-AODV and AODV increases. The difference between DP-AODV and AODV varies from 7% to 10%. DP-AODV has a lower power consumption due to the reduction of interference between nodes in the network and by using the minimum number of nodes to forward a packet to a destination node. This leads to an increase in the number of packets successfully delivered, whereas in a dense AODV network, there may be more collisions between neighbouring nodes, which means that more energy is wasted at the constant radio level.

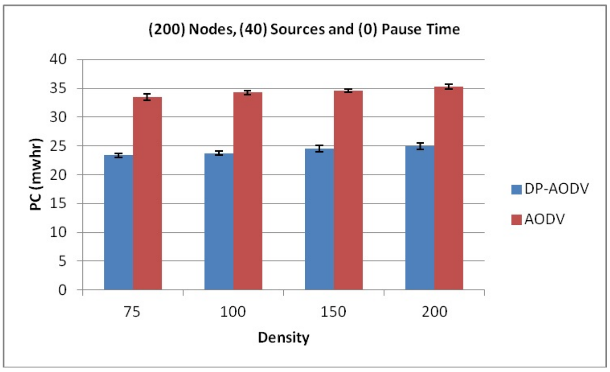

Figure 5.7: PC vs Density (Pause Time 0 sec - Dynamic)

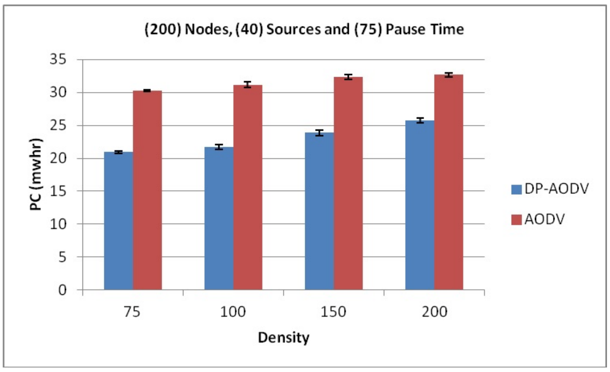

Figure 5.8: PC vs Density (Pause Time 75 sec - Static)

5.5.2 *Varying speed of nodes*

The maximum speed of the nodes was set at three different speeds of 10, 20 and 30 m/s, where mobility increases as the speed of the nodes increases. The number of nodes used in the simulation is set at 200 nodes, using two pause times of 0 and 75 seconds (0 as a dynamic network with continuous motion, and 75 as a static network with low motion). The number of source-destination pairs used was set at 40. These parameters, which differ from the fixed parameters given in table 5.1, are illustrated in table 5.3.

Parameter	Value
Max. speed of nodes	10,20, and 30 m/s
Number of nodes	200 nodes
Pause time	0, and 75 seconds
Number of sources	40 sources

Table 5.3: Variable speed of nodes parameter used in the simulations

Packet Delivery Fraction (PDF)

Figures 5.9 and 5.10 compare the PDF for DP-AODV and AODV. They show that DP-AODV gives a better PDF as compared to AODV. Figure 5.9 shows that in a dynamic network with a pause time of 0 seconds, as the speed increases, the PDF for DP-AODV decreases, from 60.98% with a speed of 10 m/s, to 51.63% with a speed of 30 m/s. Likewise, with AODV, as the speed increases, the PDF decreases, from 49.98% with a speed of 10 m/s, to 42.07% with a speed of 30 m/s. In figure 5.10, in a static network with a pause time of 75 seconds, the PDF for DP-AODV fluctuates, with 63.53% with a speed of 10 m/s, 56.49% for 20 m/s, and 59.74% for 30 m/s. However, with AODV, as the speed increases, the PDF decreases, from 54.60% with a speed of 10 m/s, to 45.47% with a speed of 30 m/s.

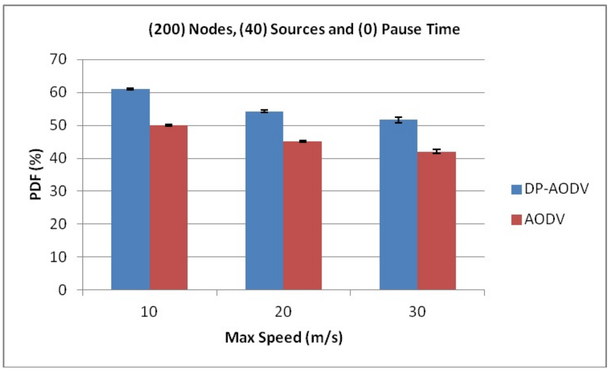

Figure 5.9: PDF vs Max Speed (Pause Time 0 sec - Dynamic)

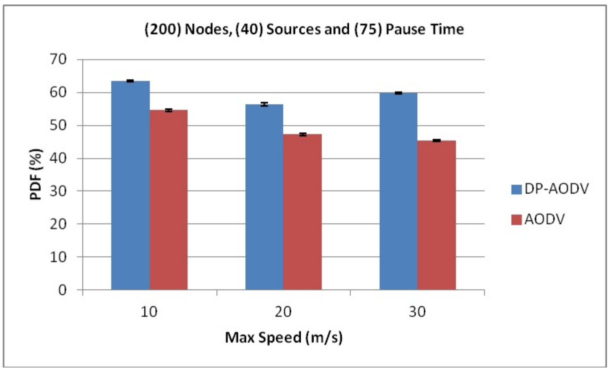

Figure 5.10: PDF vs Max Speed (Pause Time 75 sec - Static)

End-to-End Delay (EED)

Figures 5.11 and 5.12 compare the EED for DP-AODV and AODV, using two different pause times of 0 and 75 seconds. Both figures show that DP-AODV has a shorter EED compared to AODV. Figure 5.11 shows that when the pause time is 0 seconds, there is a fluctuation in the EED for DP-AODV as the speed increases. Likewise, the EED for AODV also fluctuates as the speed increases. Whereas, in a static network (figure 5.12), as the speed increases, the EED for DP-AODV decreases. However, the EED for AODV fluctuates as the speed increases.

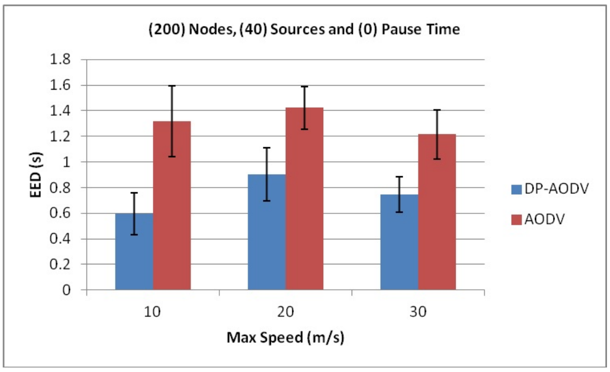

Figure 5.11: EED vs Max Speed (Pause Time 0 sec - Dynamic)

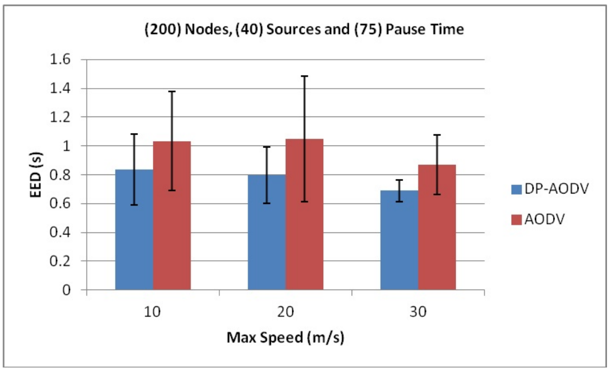

Figure 5.12: EED vs Max Speed (Pause Time 75 sec - Static)

Throughput

Figures 5.13 and 5.14 compare the throughput for DP-AODV and AODV, with two pause times of 0 and 75 seconds. Both figures demonstrate that DP-AODV has a higher throughput than AODV. Figure 5.13 shows that with a pause time of 0 seconds, the throughput for DP-AODV fluctuates. However, for AODV, as the speed increases, the throughput decreases. When the pause time is 75 seconds (figure 5.14), the throughput for both DP-AODV and AODV decreases as the speed increases.

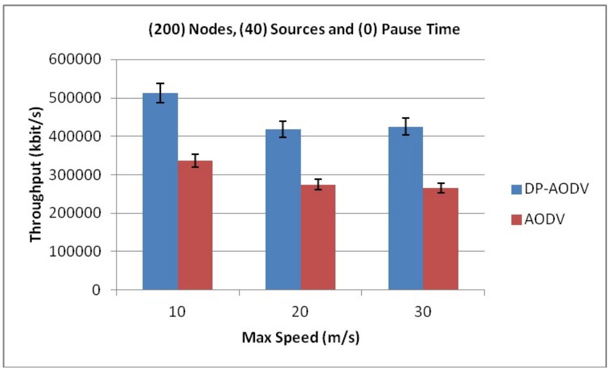

Figure 5.13: Throughput vs Max Speed (Pause Time 0 sec - Dynamic)

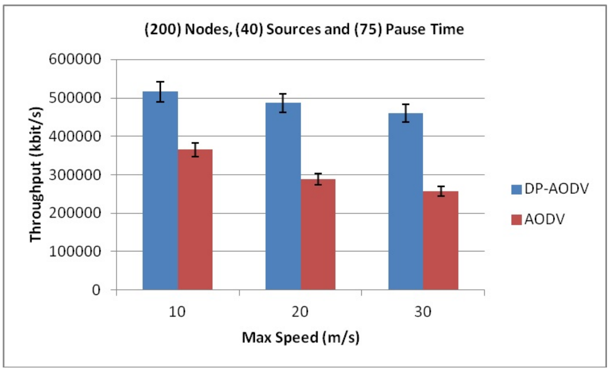

Figure 5.14: Throughput vs Max Speed (Pause Time 75 sec - Static)

Power Consumption (PC)

Figures 5.15 and 5.16 compare the power consumption for DP-AODV and AODV, using two pause times of 0 and 75 seconds, with both figures showing a lower power consumption for DP-AODV, as compared with AODV. Figure 5.15 shows that, with a pause time of 0 seconds, the Power Consumption for DP-AODV fluctuates as the speed increases. However, for AODV, as the speed increases, the PC also increases. The difference between the power consumption for DP-AODV and AODV varies from 8% to 11%. Whereas, with a pause time of 75 seconds (figure 5.16), as the speed increases, the DP-AODV PC decreases. This is contrary to the results for AODV which show that as the speed increases, the PC also increases. The difference in the power consumption for DP-AODV and AODV varies from 5% to 9%.

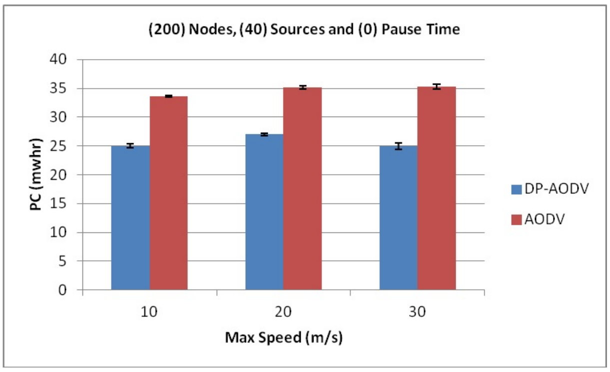

Figure 5.15: PC vs Max Speed (Pause Time 0 sec - Dynamic)

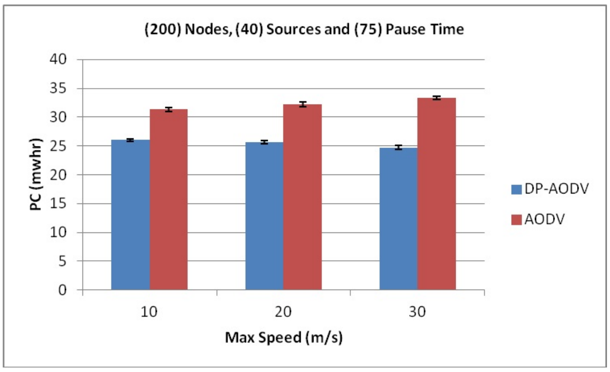

Figure 5.16: PC vs Max Speed (Pause Time 75 sec - Static)

5.5.3 *Varying Number of Sources*

The number of sources (CBR) pairs used was varied, using 10, 20 and 40 sources. The number of nodes used in the simulation is set at 200 nodes, using two pause times of 0 and 75 seconds (0 as a dynamic network and 75 as a static network). The maximum speed of the nodes was limited to 30 m/s. These parameters, which differ from the fixed parameters given in table 5.1, are illustrated in table 5.4.

Parameter	Value
Number of sources	10,20, and 40 sources
Number of nodes	200 nodes
Max. speed of nodes	30 m/s
Pause time	0, and 75 seconds

Table 5.4: Variable number of sources parameter used in the simulations

Packet Delivery Fraction (PDF)

Figures 5.17 and 5.18 compare the PDF for DP-AODV and AODV, using 10, 20 and 40 sources. They show that DP-AODV gives a better PDF as compared to AODV. Figure 5.17 shows that in a dynamic network with a pause time of 0 seconds, as the number of sources increases, the PDF for DP-AODV decreases, from 86.84% with 10 sources, to 51.63% with 40 sources. Likewise, with AODV, as the number of sources increases, the PDF decreases, from 81.57% with a 10 sources, to 42.07% with 40 sources. In figure 5.18, in a static network with a pause time of 75 seconds, the PDF for DP-AODV decreases as the number of sources increases, from 89.53% for 10 sources, to 59.74% for 40 sources. Similarly, the PDF for AODV also decreases as the number of sources increases, from 84.60% for 10 sources, to 45.47% for 40 sources.

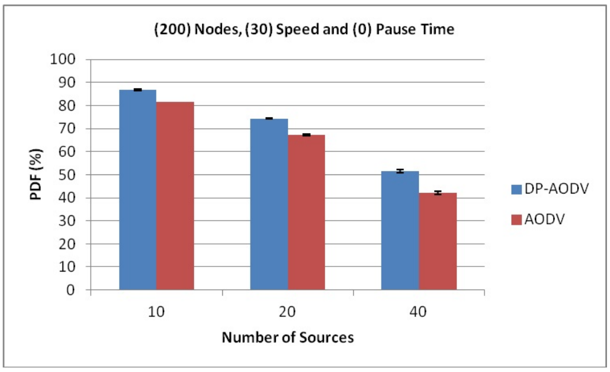

Figure 5.17: PDF vs Number of Sources (Pause Time 0 sec - Dynamic)

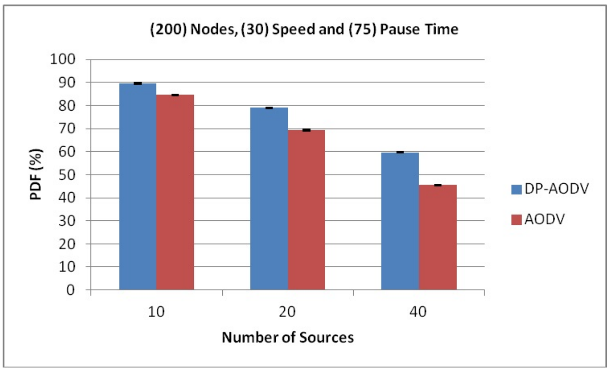

Figure 5.18: PDF vs Number of Sources (Pause Time 75 sec - Static)

End-to-End Delay (EED)

Figures 5.19 and 5.20 compare the EED for DP-AODV and AODV, using two different pause times of 0 and 75 seconds. Both figures show that DP-AODV has a shorter EED compared to AODV. Figure 5.19 shows that when the pause time is 0 seconds, as the number of sources increases, the EED for DP-AODV increases. Likewise, the EED for AODV also increases as the number of sources increases. Similarly, in a static network (figure 5.20), as the number of sources increases, the EED for DP-AODV increases. The EED for AODV also increases as the number of sources increases.

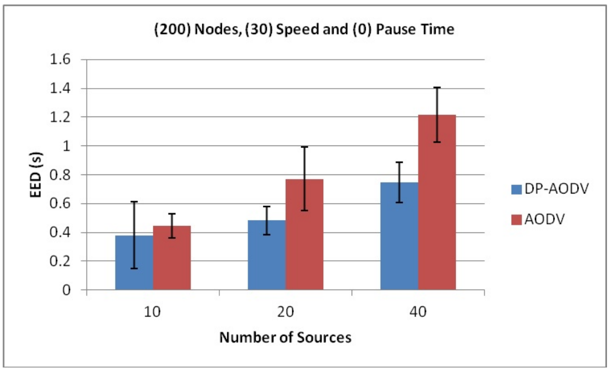

Figure 5.19: EED vs Number of Sources (Pause Time 0 sec - Dynamic)

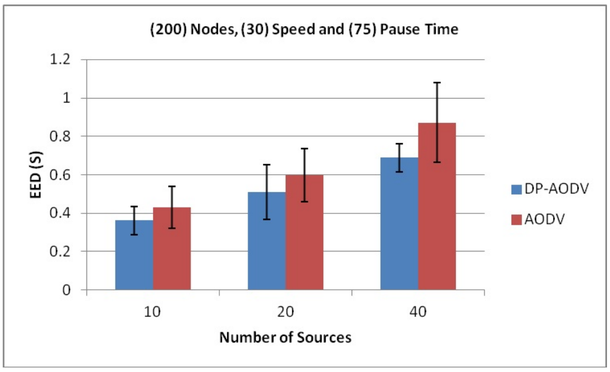

Figure 5.20: EED vs Number of Sources (Pause Time 75 sec - Static)

Throughput

Figures 5.21 and 5.22 compare the throughput for DP-AODV and AODV, with two pause times of 0 and 75 seconds. Both figures demonstrate that DP-AODV has a higher throughput than AODV. Figure 5.21 shows that with a pause time of 0 seconds, the throughput for DP-AODV increases as the number of sources increases. The throughput for AODV also increases as the number of sources increases. When the pause time is 75 seconds (figure 5.22), the throughput for both DP-AODV and AODV increases as the number of sources increases.

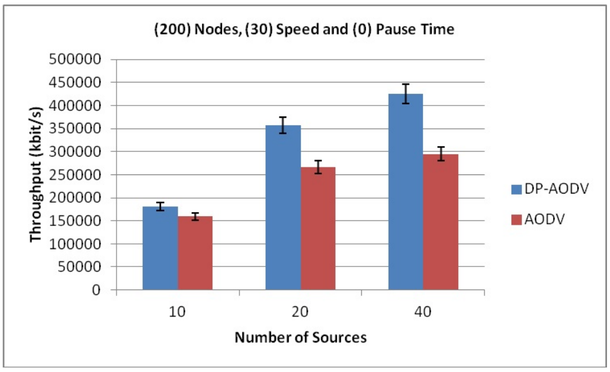

Figure 5.21: Throughput vs Number of Sources (Pause Time 0 sec - Dynamic)

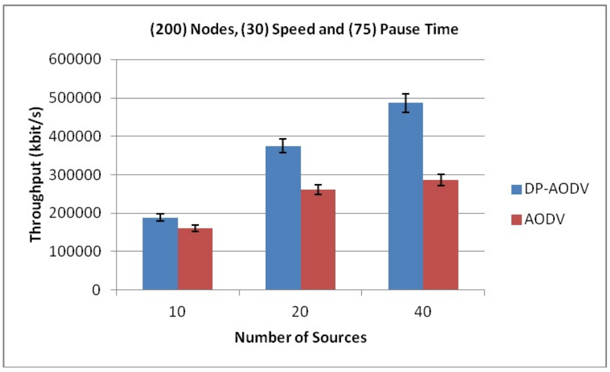

Figure 5.22: Throughput vs Number of Sources (Pause Time 75 sec - Static)

Power Consumption (PC)

Figures 5.23 and 5.24 compare the power consumption for DP-AODV and AODV, with two pause times of 0 and 75 seconds, with both figures showing a lower power consumption for DP-AODV, as compared with AODV. Figure 5.23 shows that, with a pause time of 0 seconds, the Power Consumption for DP-AODV increases as the number of sources increases. Similarly, for AODV, as the number of sources increases, the Power Consumption increases. There is an 11% difference in power consumption between DP-AODV and AODV. Moreover, with a pause time of 75 seconds (figure 5.24), as the number of sources increases, the power consumption for both DP-AODV and AODV increases. The difference in power consumption for the two protocols is between 3% and 7%.

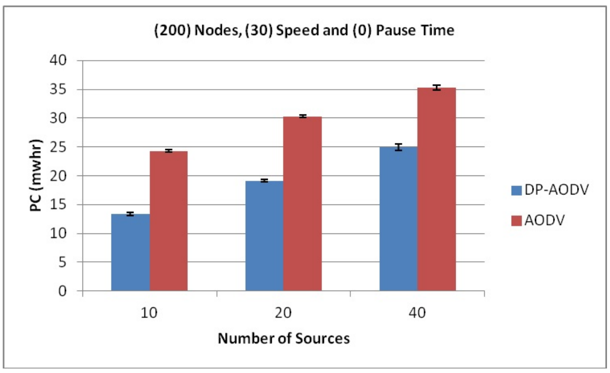

Figure 5.23: PC vs Number of Sources (Pause Time 0 sec - Dynamic)

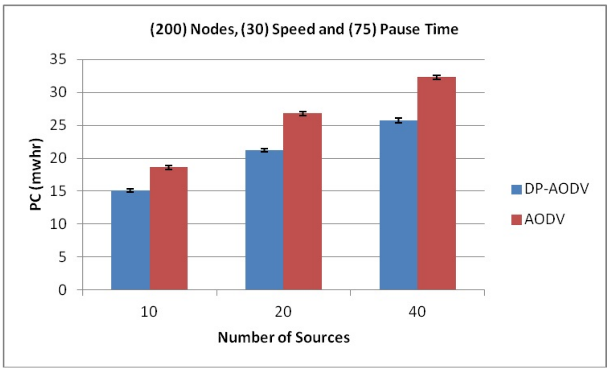

Figure 5.24: PC vs Number of Sources (Pause Time 75 sec - Static)

5.5.4 Varying Pause Time

The pause time was varied in order to examine the impact of mobility on performance. The pause time was varied, using 0 (high mobility), 25, 50 and 75 (no mobility) seconds. The number of nodes used in the simulation was set at 200 nodes. Two speeds of nodes were used, 10 m/s and 30 m/s. The number of source-destination pairs used was set at 40. These parameters, which differ from the fixed parameters given in table 5.1, are illustrated in table 5.5.

Parameter	Value
Pause time	0,25,50 and 75 seconds
Number of nodes	200 nodes
Max. speed of nodes	10 and 30 m/s
Number of sources	40 sources

Table 5.5: Variable number of sources parameter used in the simulations

Packet Delivery Fraction (PDF)

Figures 5.25 and 5.26 compare the PDF for DP-AODV and AODV, using pause times of 0, 25, 50 and 75 seconds. Figure 5.25 uses a speed of 10 m/s and figure 5.26 uses a speed of 30 m/s, but both show that DP-AODV gives a better PDF compared to AODV. Figure 5.25 shows that as the pause time increases, the PDF for DP-AODV also increases, from 60.98% with a pause time of 0 seconds, to 63.53% with a pause time of 75 seconds. Likewise, with AODV, as the pause time increases, the PDF increases, from 49.89% with a pause time of 0 seconds, to 54.60% with a pause time of 75 seconds. In figure 5.26, with a speed of 30 m/s, the PDF for both DP-AODV and AODV increases as the pause time increases, from 51.63% for 0 seconds to 59.74% for 75 seconds in DP-AODV, and from 42.07% for 0 seconds to 45.47% for 75 seconds in AODV.

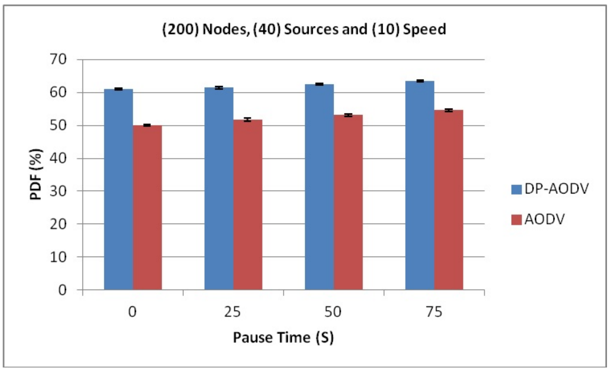

Figure 5.25: PDF vs Pause Time (Max Speed 10 m/s)

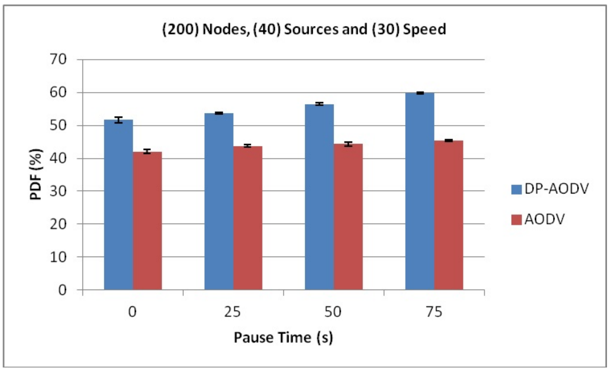

Figure 5.26: PDF vs Pause Time (Max Speed 30 m/s)

End-to-End Delay (EED)

Figures 5.27 and 5.28 compare the EED for DP-AODV and AODV, using two different speeds of 10 m/s and 30 m/s. Both figures show that DP-AODV has a shorter EED as compared to AODV. Figure 5.27 shows that when the speed is 10 m/s, as the pause time increases, the EED for DP-AODV fluctuates. Likewise, the EED for AODV also fluctuates as the pause time increases. Figure 5.28 also shows fluctuation in the EED for DP-AODV as the pause time increases. However, the EED for AODV decreases as the pause time increases.

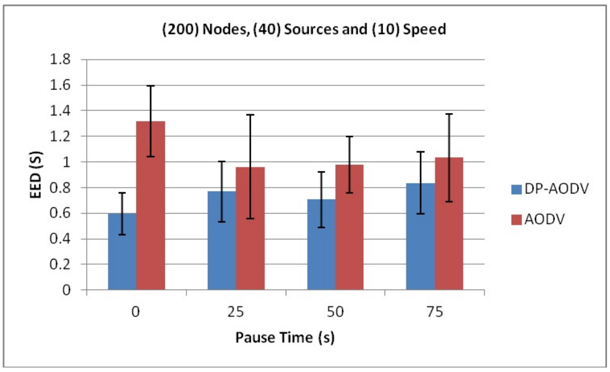

Figure 5.27: EED vs Pause Time (Max Speed 10 m/s)

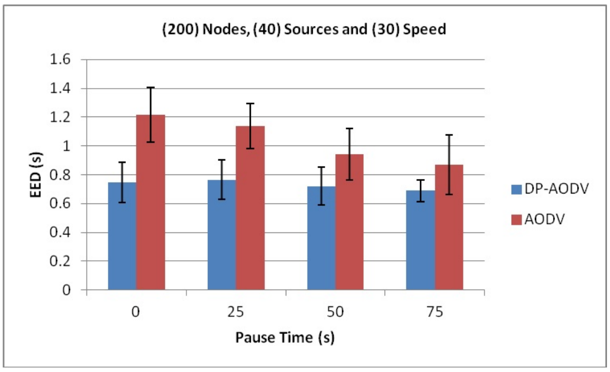

Figure 5.28: EED vs Pause Time (Max Speed 30 m/s)

Throughput

Figures 5.29 and 5.30 compare the throughput for DP-AODV and AODV, with two speeds of nodes of 10 m/s and 30 m/s. Both figures demonstrate that DP-AODV has a higher throughput than AODV. Figure 5.29 shows the throughput for DP-AODV increases as the pause time increases. The throughput for AODV also increases as the pause time increases. When the speed of nodes is 30 m/s (figure 5.30), the throughput for both DP-AODV and AODV increases as the pause time increases.

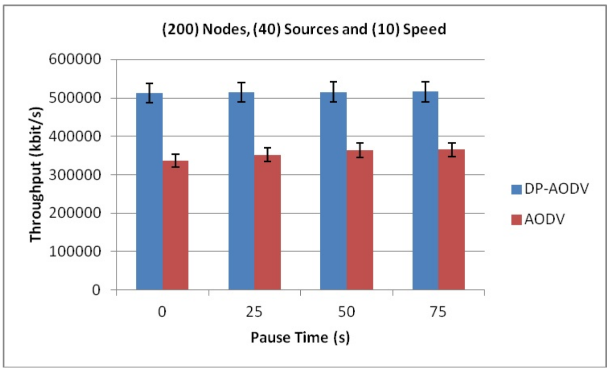

Figure 5.29: Throughput vs Pause Time (Max Speed 10 m/s)

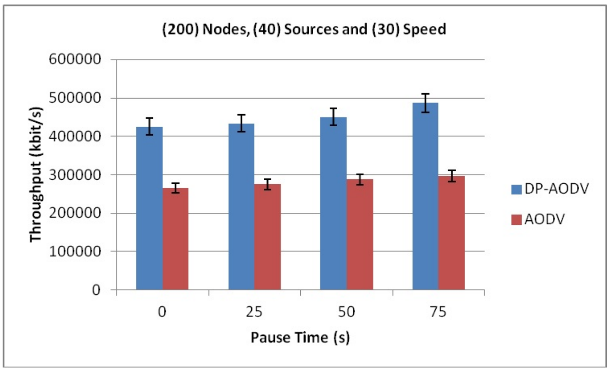

Figure 5.30: Throughput vs Pause Time (Max Speed 30 m/s)

Power Consumption (PC)

Figures 5.31 and 5.32 compare the power consumption for DP-AODV and AODV, with two speeds of nodes of 10 m/s and 30 m/s, with both figures showing a lower power consumption for DP-AODV, as compared with AODV. Figure 5.31 shows that, with a speed of 10 m/s, the PC for DP-AODV increases as the pause time increases. However, for AODV, as the pause time increases, the PC decreases. The difference in power consumption between DP-AODV and AODV is 5%-8%. Similarly, with a speed of 30 m/s (figure 5.32), as the pause time increases, the power consumption for DP-AODV increases. For AODV, the power consumption decreases as the pause time increases. The difference in the power consumption for the protocols is between 7% and 11%.

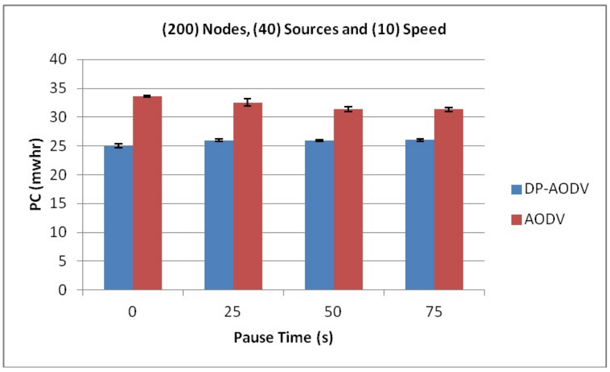

Figure 5.31: PC vs Pause Time (Max Speed 10 m/s)

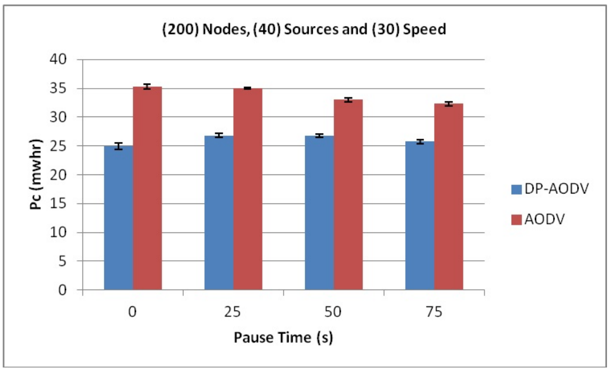

Figure 5.32: PC vs Pause Time (Max Speed 30 m/s)

5.6 Summary

The aim of this chapter was to compare the performance of DP-AODV with the basic AODV routing protocol. Four metrics (Packet Delivery Fraction, End-to-End Delay, Throughput and Power Consumption) were used in four different scenarios: varying the number of nodes, varying the speed of nodes, varying the number of sources and varying the pause time. The results reveal that DP-AODV is more effective than AODV, with the following observations:

- **Packet Delivery Fraction:** The results illustrate that DP-AODV gives a higher PDF rate than AODV in all four scenarios. The number of nodes has the greatest impact on the PDF performance of DP-AODV, while varying the pause time had relatively little impact. As the number of sources increases, the PDF decreases, resulting from a higher level of interference generated by a higher level of traffic. Moreover, there is a greater effect on the PDF in a dynamic environment when both the numberof sources and speed of nodes is varied.

- **End-to-End Delay:** The results show that DP-AODV gives a shorter EED than AODV in all four scenarios. The EED is lower in a static environment than in a dynamic environment for both protocols, except for DP-AODV when the speed of nodes is 10 m/s, when the number of sources is 20, or when the pause time is 0 and 25 seconds.

- **Throughput:** All scenarios illustrate that DP-AODV has a higher throughput than AODV. The results for varying the number of nodes are similar in both a static and dynamic environment; while the throughput is higher in a static environment when varying the speed of nodes and the number of sources. Moreover, the throughput is higher when the pause time is 10 m/s, as compared with 30 m/s.

- **Power Consumption:** DP-AODV has a lower power consumption than AODV in all four scenarios. Moreover, the power consumption is lower for both protocols in a static environment, with the exception of DP-AODV as the number of sources is varied. The pause time results show that the DP-AODV power consumption is constant with a pause time of both 10 m/s and 30 m/s, while the power consumption for AODV decreases in both situations.

The results demonstrate that the enhanced protocol (DP-AODV) generates better performance results as compared with basic AODV. DP-AODV has different characteristics to AODV as it has a higher Packet Delivery Fractionand throughput, a shorter End-to-End delay and a lower power consumption. These characteristics are the result of both the power control mechanism and the enhanced hello message mechanism, which provide both a better success rate for packet delivery and demonstrate that the enhanced algorithm is more energy efficient.

The improved performance of DP-AODV compared to AODV can be attributed to several design factors. One of the major factors is the incorporation of the hello mechanism, which lowers the rate of problems in the algorithm. Nodes use hello messages to dynamically update the routing information which ensures a more stable link and a more successful packet delivery to destination nodes.

Chapter 6

Comparing Performance with AOMDV and DSR

This chapter is organised as follows: section 6.2 outlines the methodology; section 6.3 presents the performance evaluation metrics; section 6.4 outlines the simulation environment; section 6.5 presents the results of the simulation; and a chapter summary is provided in section 6.6.

6.1 Introduction

The aim of this chapter is to compare the performance of DP-AODV with the AOMDV and DSR routing protocols, using a particular set of metrics. AOMDV was chosen for comparison as it is a reactive, multi-path routing protocol, capable of determining multiple routes from the source to the destination node. DSR was chosen as it is a reactive routing protocol which can allow each node to find a source route across multiple network hops to any destination. Varying movement pattern and traffic pattern scenario files were run with all three routing protocols in order to ensure a fair comparison.

6.2 Methodology

The loads and environmental conditions used to test the protocols in this chapter are the same as those used to test the protocols in chapter 5. This enables a fair comparison of the results of the different protocols. We used CBR (Continuous Bit-Rate) traffic and a random waypoint mobility model. 40 CBR flows were used, with 4 packets per second, and a packet size of 512 bytes. The source-destination node pairs were randomly spread across the network and the MAC layer protocol was IEEE 802.11. Each traffic senario was created independently, at different times, and stayed active until the simulation time ended. Four factors were varied (Density, Speed of Nodes, Pause time, and Number of sources) in order to analyse their effect on the protocols. The simulation was carried out using four different experiments to compare DP-AODV with AOMDV and DSR.

- In the first experiment, the impact of network density on the performance of DP-AODV, with AOMDV and DSR, was tested by varying the number of nodes. The number of nodes used were 75, 100, 150 and 200.
- In the second experiment, the effect of the speed of the nodes on the performance of the protocol was studied. Three different maximum speeds of nodes were used: 10, 20 and 30 m/s.
- The third experiment looked at the movement patterns created by four different pause times: 0 (dynamic network), 25, 50 and 75 (static network) seconds.
- In the fourth experiment, the number of source-destination pairs was varied (10, 20 and 40 traffic sources) in order to alter the network's offered load.

An average of 10 runs, using different randomly generated mobility scenarios, but identical traffic models, represents each data point. The graphs contain error bars which represent 95% confidence interval of the mean. All four experiments used the same fixed simulation time parameter, identical to the one used in chapter 5. Table 5.1 (see chapter 5, page 86) shows all of the fixed parameters used to test all routing protocols. Tables 6.1, 6.2, 6.3 and 6.4 all list the variable parameters see page 111 onwards).

6.3 Performance Evaluation Metrics

This chapter compares the performance of DP-AODV with AOMDV and DSR. The metrics used are the same as those used in chapter 5: packet delivery fraction (PDF), end-to-end delay (EED), throughput and power consumption (PC).

6.4 Simulation Environment

Similar to the performance evaluation metrics, the simulation environment used the same as in the previous chapter. As the parameters used are also identical, they are listed in table 5.1.

6.5 Simulation Results

6.5.1 *Varying number of nodes*

The number of nodes used in the simulation was set at 75, 100, 150 and 200 nodes, using two pause times of 0 and 75 seconds (0 as a dynamic network and 75 as a static network). The maximum speed of the nodes was limited to 30 m/s. The number of source-destination pairs used was set at 40. These parameters, which differ from the fixed parameters given in table 5.1, are illustrated below in table 6.1.

Parameter	Value
Number of nodes	75, 100, 150, and 200 nodes
Max. speed of nodes	30 m/s
Pause time	0, and 75 seconds
Number of sources	40 sources

Table 6.1: Variable number of nodes parameter used in the simulations

Packet Delivery Fraction (PDF)

Figure 6.1 (dynamic environment) shows that as the density increases, the PDF for both DP-AODV and DSR decreases. The PDF for AOMDV also decreases, although there is a slight fluctuation with an increase in the PDF from 150 to 200 nodes. The PDF for DP-AODV is better than for the other two protocols. However, figure 6.2 shows the results in a static environment where the PDF for AOMDV is better than that for DP-AODV with a density of 75 and 100 nodes. This may be due to the fact that it is able to find alternative routes from source to destination when a link is broken, therefore improving the PDF and reducing the number of packets dropped. When the node density is 150 or 200 nodes, the PDF for DP-AODV is better than for AOMDV and DSR. For each of the three protocols, as the density increases, the PDF decreases. The PDF results in a static environment are better than in a dynamic environment, where the nodes are always in motion. The PDF rate for the DSR protocol is significantly lower than for the other two protocols as each destination in DSR may have several route options in the cache. If a stale route is used, this may result in some packets being dropped and a lower PDF.

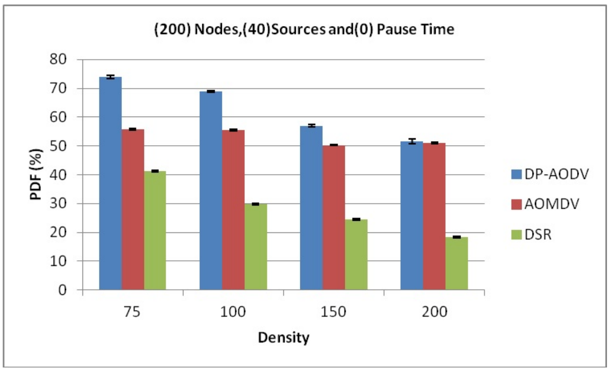

Figure 6.1: PDF vs Density (Pause Time 0 sec - Dynamic)

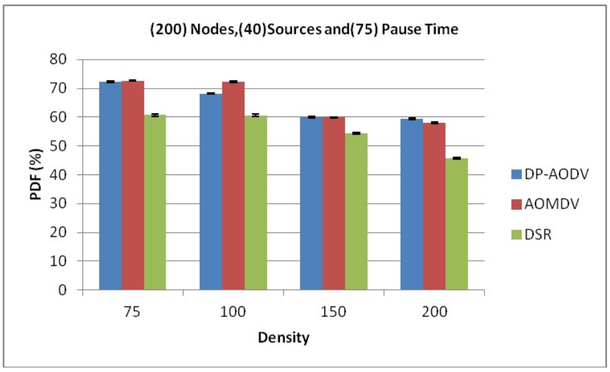

Figure 6.2: PDF vs Density (Pause Time 75 sec - Static)

End-to-End Delay (EED)

Figure 6.3 (dynamic environment) shows that as the density increases, the EED for DP-AODV and AOMDV increases; while the EED for DSR decreases with a slight fluctuation in the result from 150 to 200 nodes. For each density tested, AOMDV showed the best EED. In a static environment (figure 6.4), as the density increases the EED for both DP-AODV and AOMDV increases, with a minor fluctuation in the results for AOMDV with 150 and 200 nodes. Similar to figure 6.3, as the density increases, the EED for DSR decreases, again with a small fluctuation between 150 and 200 nodes. In both static and dynamic environments, DSR has a significantly greater EED than DP-AODV and AOMDV as it does not have a mechanism to remove unused routes from the caches, and it also establishes valid routes by using an aggressive flood network.

However, AOMDV has a shorter EED than other protocols as there are multiple paths available between source and destination nodes, and fewer nodes offer alternative routes.

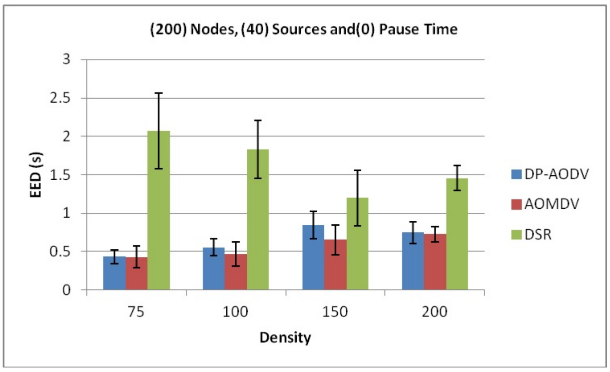

Figure 6.3: EED vs Density (Pause Time 0 sec - Dynamic)

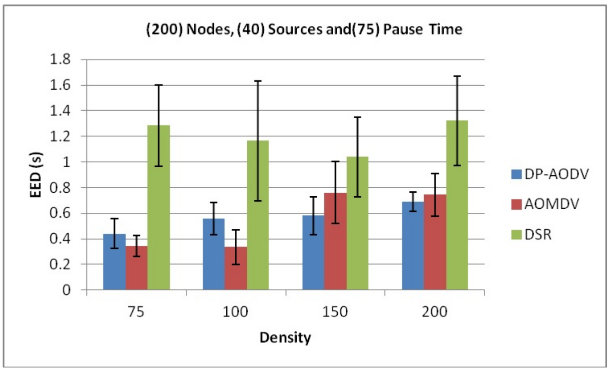

Figure 6.4: EED vs Density (Pause Time 75 sec - Static)

Throughput

As shown in figure 6.5 (dynamic environment), as the number of nodes increases, the throughput for all three protocols decreases, though there is a slight fluctuation for AOMDV for 150 and 200 nodes. The results for a static environment (figure 6.6) reveal the same pattern as for a dynamic environment. The throughput for DP-AODV is also better in both environments, while the throughput for DSR is the lowest of the three protocols in both environments.

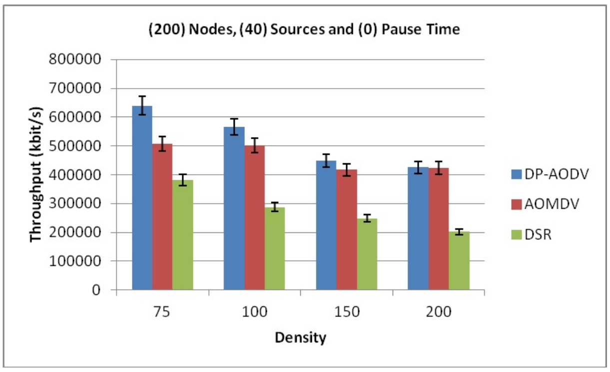

Figure 6.5: Throughput vs Density (Pause Time 0 sec - Dynamic)

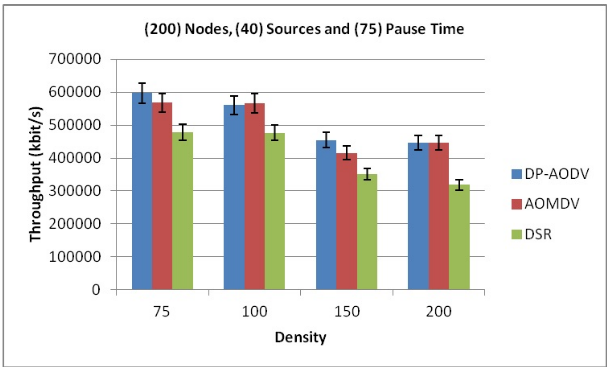

Figure 6.6: Throughput vs Density (Pause Time 75 sec - Static)

Power Consumption (PC)

Figure 6.7 (dynamic environment) shows that as the number of nodes increases, the power consumption for all three protocols also increases. Figure 6.8 (static environment) shows that as the number of nodes increases, the power consumption for DP-AODV increases. However, for both AOMDV and DSR, the power consumption decreases between 75 and 100 nodes, before increasing with densities of 150 and 200 nodes. DP-AODV has a lower power consumption than the other protocols for both dynamic and static environments. In a dynamic environment, DSR has the highest power consumption. It is interesting to note that in a static environment, with a high density of 150 and 200 nodes, AOMDV has the highest power consumption.

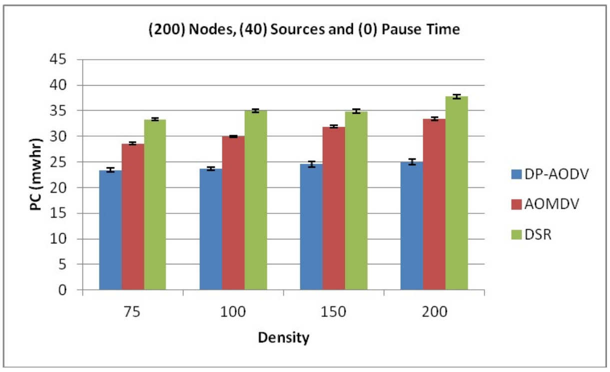

Figure 6.7: PC vs Density (Pause Time 0 sec)

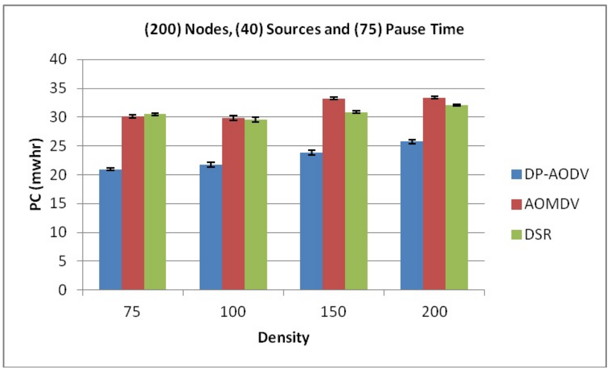

Figure 6.8: PC vs Density (Pause Time 75 sec)

6.5.2 *Varying speed of nodes*

The maximum speed of the nodes was set at three different speeds of 10, 20 and 30 m/s. The number of nodes used in the simulation was set at 200 nodes, using two pause times of 0 and 75 seconds (0 as a dynamic network and 75 as a static network). The number of source-destination pairs used was set at 40. These parameters, which differ from the fixed parameters given in table 5.1, are illustrated in table 6.2.

Parameter	Value
Max. speed of nodes	10,20, and 30 m/s
Number of nodes	200 nodes
Pause time	0, and 75 seconds
Number of sources	40 sources

Table 6.2: Variable speed of nodes parameter used in the simulations

Packet Delivery Fraction (PDF)

Figure 6.9 (dynamic environment) shows that as the speed increases, the PDF for all three protocols decreases, although there is a slight increase for AOMDV between 20 and 30 m/s. The PDF for DP-AODV is better than for the other two protocols. Figure 6.10 shows the results in a static environment, the PDF for DP-AODV is higher than for AOMDV and DSR. The results for all three protocols show a decrease in the PDF from 10 to 20 m/s, however, the PDF then increases when the density is 30 m/s. DSR has the lowest PDF in both dynamic and static environments.

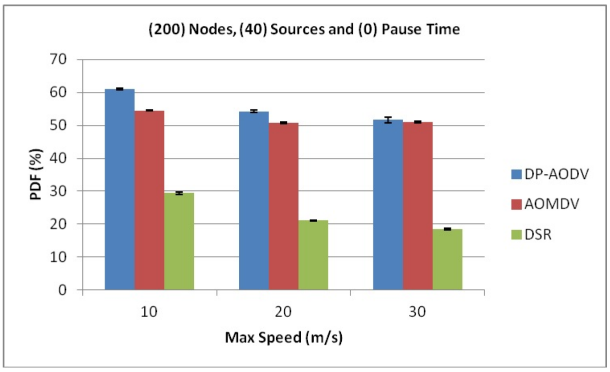

Figure 6.9: PDF vs Max Speed (Pause Time 0 sec - Dynamic)

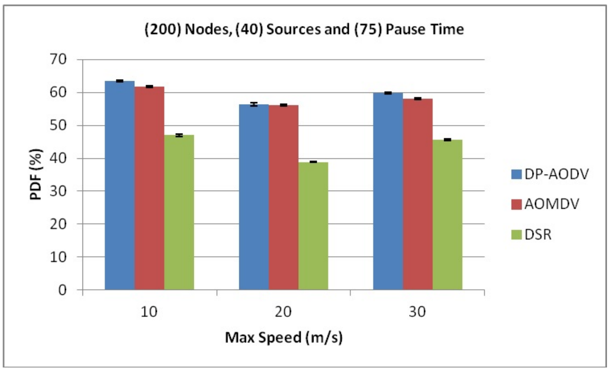

Figure 6.10: PDF vs Max Speed (Pause Time 75 sec - Static)

End-to-End Delay (EED)

Figure 6.11 (dynamic environment) shows that as the speed increases, the EED fluctuates for all protocols. It is interesting that the EED for DP-AODV is better with a speed of 10 m/s, whereas for AOMDV it is better with a speed of 20 and 30 m/s. In a static environment (figure 6.12), as the speed increases the EED for DP-AODV decreases. For both AOMDV and DSR, as the number of nodes increases, the EED also decreases, though there is a fluctuation at 20 m/s. In both static and dynamic environments, DSR has a significantly greater EED than DP-AODV and AOMDV. In a static environment, DP-AODV has a shorter EED than others.

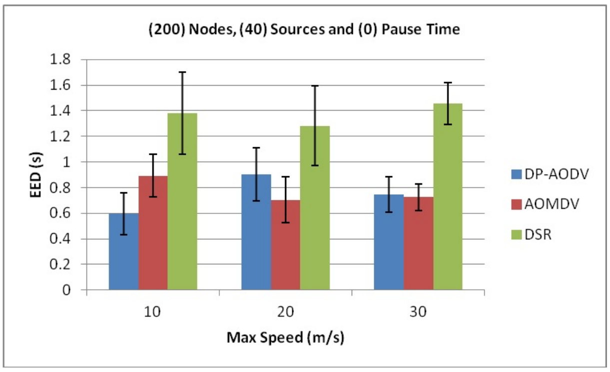

Figure 6.11: EED vs Max Speed (Pause Time 0 sec - Dynamic)

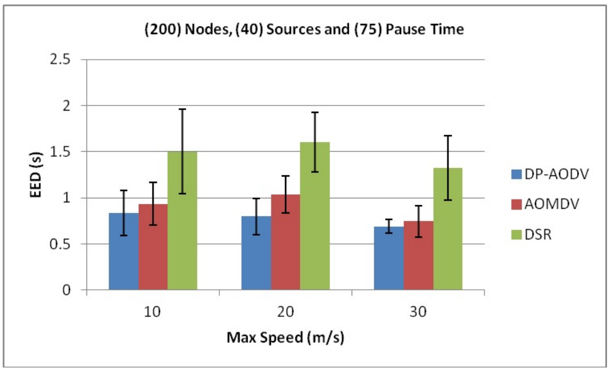

Figure 6.12: EED vs Max Speed (Pause Time 75 sec - Static)

Throughput

As shown in figure 6.13 (dynamic environment), as the speed increases, the throughput for DP-AODV and AOMDV decreases, with a fluctuation at a speed of 20 m/s. The throughput for DSR decreases as the speed increases. Whereas, the results for a static environment (figure 6.14) reveal that as the speed increases, the throughput for DP-AODV decreases. For AOMDV and DSR, as the speed increases, the throughput also decreases, although there is a fluctuation at 20 m/s. In both dynamic and static environments, DP-AODV gives the best throughput, while DSR has the lowest throughput for all node speeds as it generates many overheads during re-route discovery. DSR is also significantly affected by rapid mobility, in comparison to other protocols. DSR functions better with a low data transmission rate as the automatic updating method provides connectivity, instead of providing bandwidth for application data.

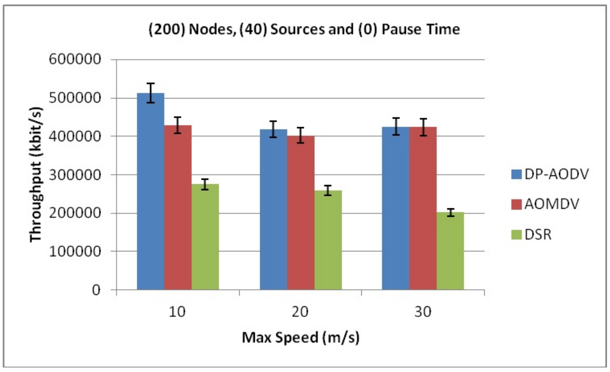

Figure 6.13: Throughput vs Max Speed (Pause Time 0 sec - Dynamic)

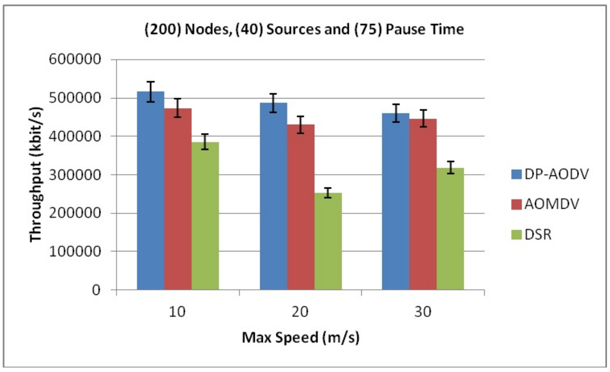

Figure 6.14: Throughput vs Max Speed (Pause Time 75 sec - Static)

Power Consumption (PC)

Figure 6.15 (dynamic environment) shows that as the speed increases, the power consumption for both AOMDV and DP-AODV decreases, though there is a fluctuation for DP-AODV at 20 m/s. In contrast, as the speed increases, the power consumption for DSR also increases. Figure 6.16 (static environment) shows that as the speed increases, the power consumption for both DP-AODV and AOMDV decreases, with a fluctuation for AOMDV at 20 m/s. For DSR, as the speed increases, the power consumption again increases, with a fluctuation at 20 m/s. DP-AODV has a lower power consumption than the other protocols for both dynamic and static environments. However, there is a change in the protocol with the highest power consumption: in a dynamic environment DSR has the highest; whilst in a static environment, AOMDV has the highest power consumption.

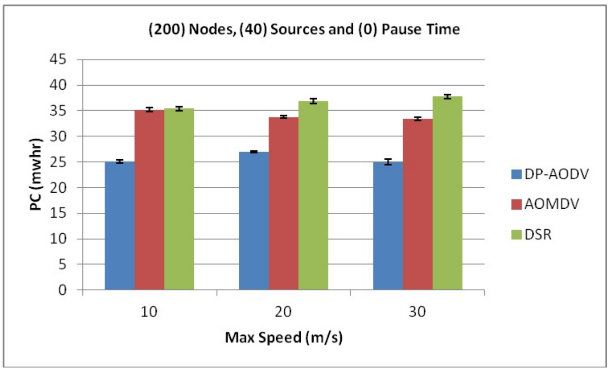

Figure 6.15: PC vs Max Speed (Pause Time 0 sec - Dynamic)

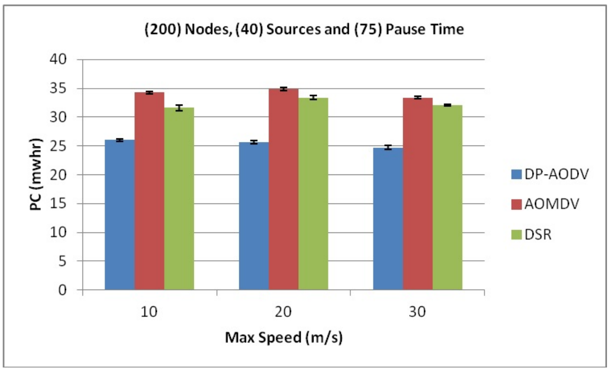

Figure 6.16: PC vs Max Speed (Pause Time 75 sec - Static)

6.5.3 Varying Number of Sources

The number of source-destination pairs used was varied, using 10, 20 and 40 sources. The number of nodes used in the simulation was set at 200 nodes, using two pause times of 0 and 75 seconds (0 as a dynamic network and 75 as a static network). The maximum speed of nodes was limited to 30 m/s. These parameters, which differ from the fixed parameters given in table 5.1, are illustrated in table 6.3.

Parameter	Value
Number of sources	10,20, and 40 sources
Number of nodes	200 nodes
Max. speed of nodes	30 m/s
Pause time	0, and 75 seconds

Table 6.3: Variable number of sources parameter used in the simulations

Packet Delivery Fraction (PDF)

Figure 6.17 (dynamic environment) shows that as the number of sources increases, the PDF for all three protocols decreases. Likewise, figure 6.18 shows the results in a static environment where the PDF for all three protocols shows a decrease as the number of sources increases. DSR has the lowest PDF in both dynamic and static environments, while DP-AODV has the highest PDF in both environments.

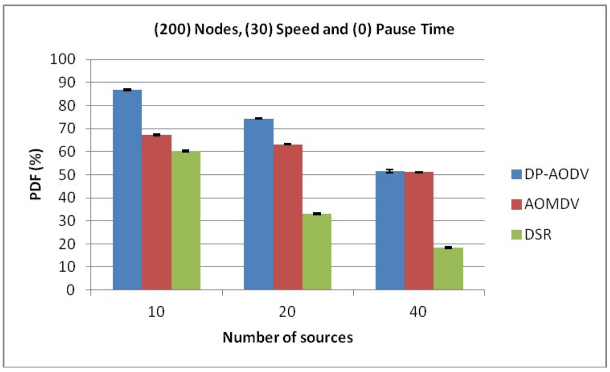

Figure 6.17: PDF vs Number of Sources (Pause Time 0 sec - Dynamic)

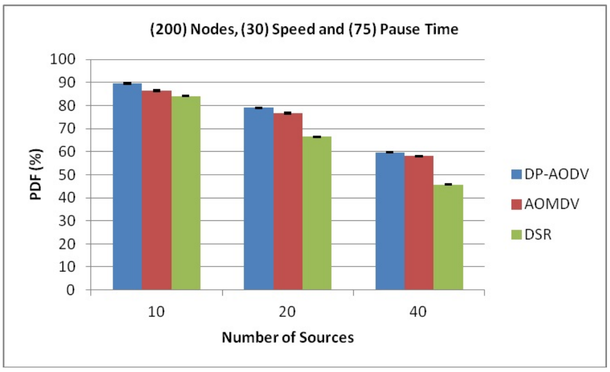

Figure 6.18: PDF vs Number of Sources (Pause Time 75 sec - Static)

End-to-End Delay (EED)

Figure 6.19 (dynamic environment) shows that as the number of sources increases, the EED increases for all protocols. Similarly, in a static environment (figure 6.20), as the number of sources increases the EED for all protocols also increases. In a dynamic environment, DSR has a significantly greater EED than DP-AODV and AOMDV. In this environment, AOMDV has a shorter EED than the other protocols. In a static environment, when the number of sources is 10 or 20, DP-AODV has the highest EED, and AOMDV has the shortest. However, when the number of sources is 40, DSR has the highest EED and DP-AODV has the shortest.

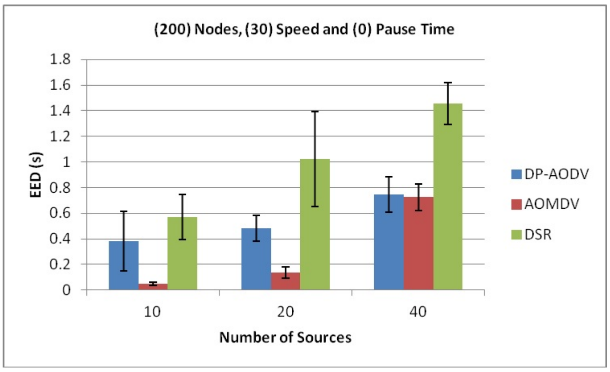

Figure 6.19: EED vs Number of Sources (Pause Time 0 sec - Dynamic)

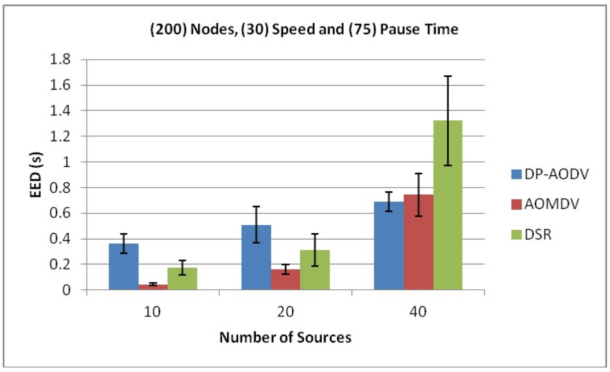

Figure 6.20: EED vs Number of Sources (Pause Time 75 sec - Static)

Throughput

As shown in figure 6.21 (dynamic environment), as the number of sources increases, the throughput for all three protocols increases. Likewise, the results for a static environment (figure 6.22) reveal that as the number of sources increases, the throughput for all three protocols also increases. In both dynamic and static environments, DP-AODV gives the best throughput, while DSR has the lowest throughput for all number of sources.

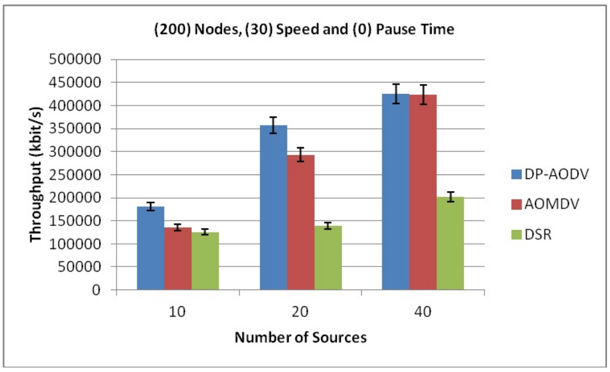

Figure 6.21: Throughput vs Number of Sources (Pause Time 0 sec - Dynamic)

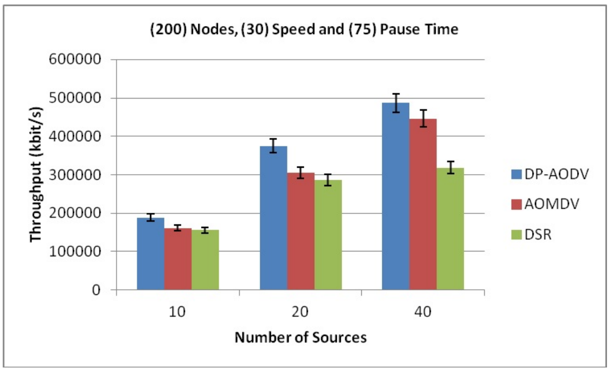

Figure 6.22: Throughput vs Number of Sources (Pause Time 75 sec - Static)

Power Consumption (PC)

Both figures 6.23 (dynamic environment) and 6.24 (static environment) show that as the number of sources increases, the power consumption for all three protocols increases. DP-AODV has a lower power consumption than the other protocols for both dynamic and static environments. However, it is interesting that there is a change in the protocol with the highest power consumption, in a dynamic environment DSR has the highest power consumption as it consumes a significant part of the network resources just to find the next optimum routes. Whereas, in a static environment, AOMDV has the highest power consumption as it requires more energy per node, sending and receiving packets using a constant maximum energy level. AOMDV also maintains multiple routing lists, resulting in routing overheads and high power consumption.

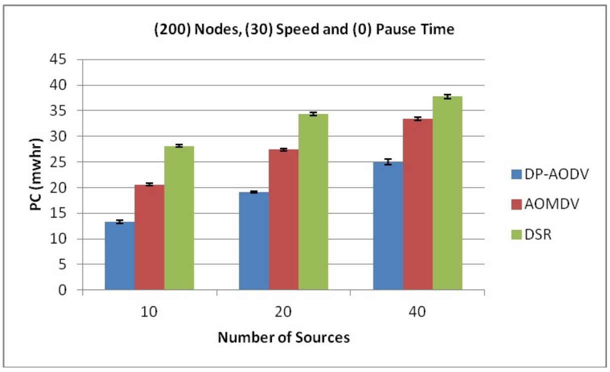

Figure 6.23: PC vs Number of Sources (Pause Time 0 sec - Dynamic)

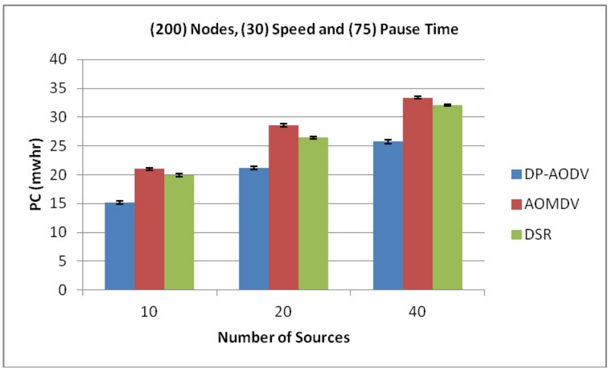

Figure 6.24: PC vs Number of Sources (Pause Time 75 sec - Static)

6.5.4 Varying Pause Time

The pause time was varied in order to examine the impact of mobility on performance. The pause time was varied, using 0 (high mobility), 25, 50 and 75 (no mobility) seconds. The number of nodes used in the simulation was set at 200 nodes. The maximum speed of nodes was limited to 30 m/s. The number of source-destination pairs used was set at 40. These parameters, which differ from the fixed parameters given in table 5.1, are illustrated in table 6.4.

Parameter	Value
Pause time	0,25,50 and 75 seconds
Number of nodes	200 nodes
Max. speed of nodes	10 and 30 m/s
Number of sources	40 sources

Table 6.4: Variable number of sources parameter used in the simulations

Packet Delivery Fraction (PDF)

Figure 6.25 (dynamic environment) shows that as the pause time increases, the PDF for all three protocols also increases. Likewise, figure 6.26 shows the results in a static environment where the PDF for all three protocols shows an increase as the pause time increases. DSR has the lowest PDF in both dynamic and static environments, while DP-AODV has the highest PDF in both environments.

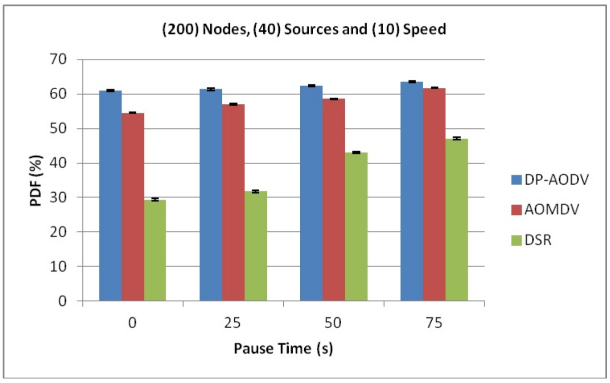

Figure 6.25: PDF vs Pause Time (Max Speed 10 m/s)

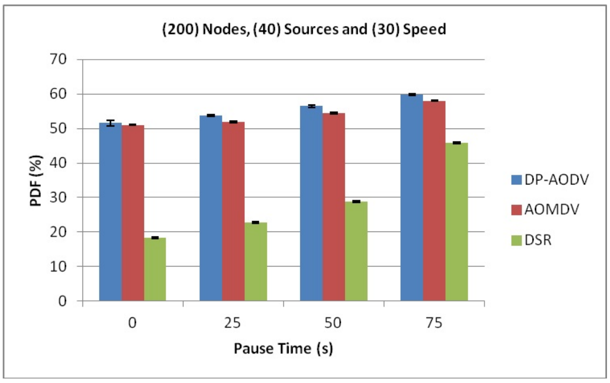

Figure 6.26: PDF vs Pause Time (Max Speed 30 m/s)

End-to-End Delay (EED)

Figure 6.27 (dynamic environment) shows that as the pause time increases, the EED increases for both DP-AODV and AOMDV, whilst it fluctuates for DSR. However, in a static environment (figure 6.28), as the pause time increases, the EED for all protocols fluctuates. In a dynamic environment, DSR has a greater EED than DP-AODV and AOMDV. In this environment, DP-AODV has a shorter EED than the other protocols. In a static environment, DSR again has the highest EED.

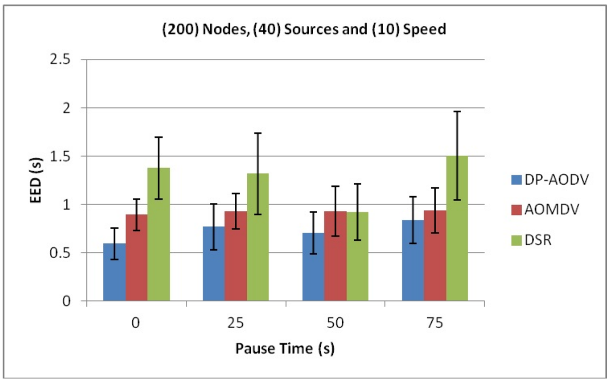

Figure 6.27: EED vs Pause Time (Max Speed 10 m/s)

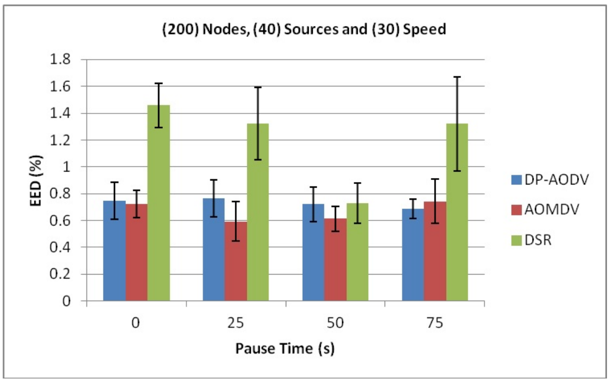

Figure 6.28: EED vs Pause Time (Max Speed 30 m/s)

Throughput

As shown in figure 6.29 (dynamic environment), as the pause time increases, the throughput for all three protocols increases, although there is only a slight difference for DP-AODV, which remains fairly constant. Likewise, the results for a static environment (figure 6.30) reveal that as the pause time increases, the throughput for all three protocols also increases. In both dynamic and static environments, DP-AODV gives the best throughput, while DSR has the lowest throughput for all pause times.

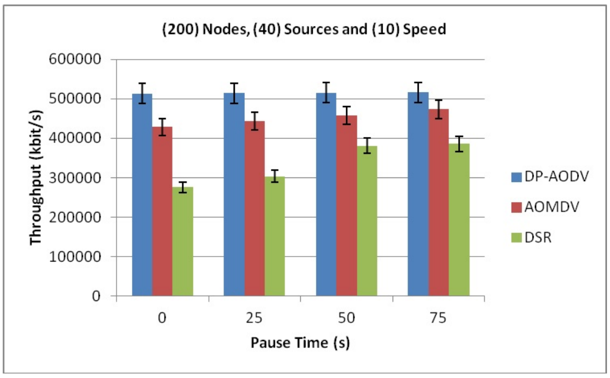

Figure 6.29: Throughput vs Pause Time (Max Speed 10 m/s)

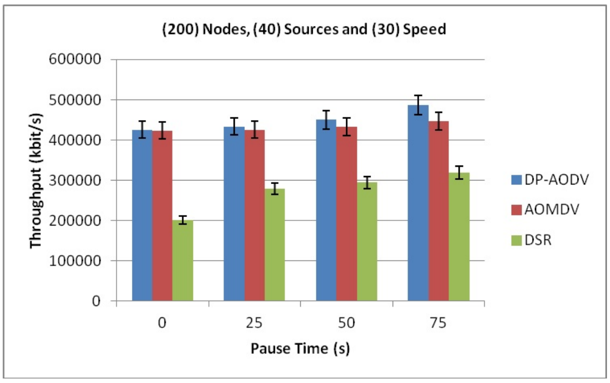

Figure 6.30: Throughput vs Pause Time (Max Speed 30 m/s)

Power Consumption (PC)

Figure 6.31 (dynamic environment) shows that as the pause time increases, the power consumption for DP-AODV increases; while for AOMDV it fluctuates; and for DSR it decreases. Figure 6.32 (static environment) demonstrates that as the pause time increases, the power consumption for both DP-AODV and AOMDV fluctuates, whilst for DSR it decreases. DP-AODV has a lower power consumption than the other protocols for both dynamic and static environments.

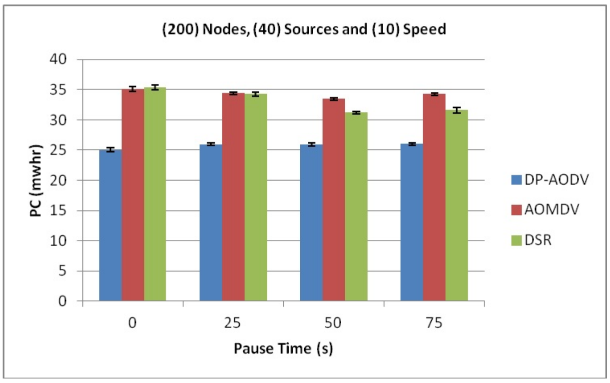

Figure 6.31: PC vs Pause Time (Max Speed 10 m/s)

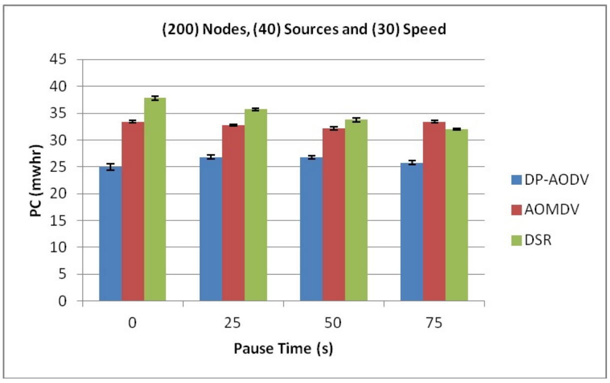

Figure 6.32: PC vs Pause Time (Max Speed 30 m/s)

6.6 Summary

The aim of this chapter was to compare the performance of DP-AODV with both the AOMDV and DSR routing protocols. As in the previous chapter, four metrics (Packet Delivery Fraction, End-to-End Delay, Throughput and Power Consumption) were used in four different scenarios: varying the number of nodes, varying the speed of nodes, varying the number of sources and varying the pause time. The simulation results highlighted differences in the performance of the three protocols, with the following observations:

- **Packet Delivery Fraction:** The results illustrate that, in both dynamic and static environments, DSR gives a lower PDF rate than both AOMDV and DP-AODV in all four scenarios. In dynamic environments, DP-AODV gives a better PDF in all four scenarios; whereas in a static environment, DP-AODV only gives a better PDF when varying the number of sources and the pause time, with a speed of both 10 and 30 m/s. It can be seen that in both dynamic and static environments, as the number of nodes or the number of sources increases, the PDF decreases. However, as the pause time increases, the PDF also increases. Varying the speed had relatively little impact on the PDF.

- **End-to-End Delay:** The results show that DSR gives a higher EED than the other protocols in all four scenarios, with the exception of varying the number of sources in a static environment. When increasing the number of nodes or the number of sources, in both a dynamic and static environment, the EED also increases. However, increasing the speed has little impact on the EED. It is interesting to observe that as the number of sources increases in a dynamic environment, AOMDV gives the lowest EED. Another interesting result is that as the pause time increases, with a speed of 10 m/s, the EED also increases. However, using a speed of 30 m/s, as the pause time increases, the EED decreases for all three protocols.

- **Throughput:** All scenarios illustrate that DP-AODV has the highest throughput, with the exception of the number of nodes of 100 in a static environment. DSR gives the lowest throughput in all scenarios. As both the number of sources and the pause time increase, the throughput also increases. However, as the number of nodes increases, the throughput decreases.Varying the speed of nodes had relatively little impact on the throughput.

- **Power Consumption:** DP-AODV has a lower power consumption than AOMDV and DSR in all four scenarios. It is interesting to observe that in a static environment, AOMDV has the highest power consumption, which is also the case when varying the pause time with a speed of 10 m/s. However, in a dynamic environment, it is DSR that has the highest power consumption, which is also true when varying the pause time with a speed of 30 m/s. By increasing the number of nodes or the number of sources, the power consumption increases. However, varying the speed has little effect on the power consumption. When varying the pause time, using speeds of 10 and 30 m/s, the power consumption for DP-AODV remains constant, whereas for DSR it decreases, and for AOMDV, it fluctuates.

The results demonstrate that the enhanced protocol (DP-AODV) performs better overall than both AOMDV and DSR in terms of both throughput and power consumption. However, there are exceptions in the Packet Delivery Fraction and End-to-End delay results. In a static environment, AOMDV gives the highest PDF result, and in terms of End-to-End delay, AOMDV also gives a better result in a dynamic environment and in a static environment when the number of nodes is 75 or 100.

The improved performance of DP-AODV compared to AOMDV and DSR is due to the reduced interference between nodes as a result of increasing the throughput in the network and overall power consumption efficiency. Moreover, the performance of DSR is affected by its use of source routing and route caches without periodic advertisements. The use of aggressive caching and maintenance of multiple routes in DSR delays route discovery and has negative effects on performance. As regard to performance of AOMDV, it does not have the mechanism to handle congestion with high loads. It is also affected by high mobility, which results in a decrease in the PDF. Varying the speed of nodes has a major impact on the performance of AOMDV as with higher node speeds, the potential for alternative paths failing increases, thereby lowering the utility of multiple paths.

Chapter 7

Conclusion

This chapter provides a conclusion of the thesis in section 7.1. section 7.2 highlights opportunities for further study.

7.1 Summary

The original hypothesis that varying the transmission power in MANETs would improve the protocols by reducing the level of interference between nodes, increasing the throughput in the network, and optimising energy consumption, thereby extending the battery life of communication devices has been proven to be true. This research has succesfully demonstrated that the DP-AODV protocol performs better than AODV, AOMDV and DSR routing protocols for the four metrics evaluated.

The concept of routing in mobile ad hoc networks continues to pose challenges and difficulties due to the nature of the network being wireless. These challenges include breaks in the routes, interference between nodes, limited resources and bandwidth, and limited power consumption. High node mobility and high node density are two key factors that have a significant impact on the network performance in a mobile ad hoc network. In order to address these problems, several routing protocols have been proposed, some of which focus on the concept of power control.

Power consumption is a problem in mobile networks which use a fixed transmission power as this drains the power levels in the nodes. In order to optimise the network performance and network connectivity, several power control and management protocols have been suggested. These protocols introduce the concept of energy conservation and transmission power management with the aim of maximising the lifetime of the network. This thesis proposes an enhanced version of an existing routing protocol, to investigate the possibility of adjusting the transmission power of the radios in such networks to take account of the number of radios active in the area.

Although the topic of power management has been the subject of extensive research, there has been very limited work on the topic of interference. The approach adopted in this research of enhancing an existing protocol in order to address the issue of interference is not therefore directly comparable with previous work in this field. It offers an innovative idea to tackle a growing problem.

The principal research contributions of this thesis are as follows:

Design of the enhanced protocol (DP-AODV)

AODV was chosen as the basis for the enhanced protocol as it one of the most popular and widely researched routing protocols. In addition, it only finds routes as required; uses sequence numbers to track the accuracy of information; and only stores information for the next hop in a route, and not a complete route. When considering enhancements which could be made to an existing protocol, the hello message mechanism was identified as important as it detects and monitors links between neighbours. Nodes periodically broadcast hello messages to track neighbours and, if these messages are not received, this demonstrates a link break. This mechanism is used by the AODV protocol to monitor connectivity, and thus AODV was considered suitable to be modified and improved.

The improvements made to the AODV routing protocol involved modifying the hello packets to contain co-ordinates information when sending hello messages, at the network layer. When hello messages are received, the node will increase its neighbour count and calculate the distance from its neighbour. This distance will be recorded in the routing table, along with the hop information. The neighbour count is stored with the channel information, at the network layer. When scheduling a packet for transmission, the distance information of the hop is included in the packet implemented at the network layer. During transmission of the packet from source to destnation, the node adjusts its transmission power according to the neighbour information and neighbour count from the channel information, with the aim of calculating the power needed to communicate between nodes and thereby reduce the overall power consumption, implemented at the physical layer. DP-AODV uses different power levels in order to reduce interference between nodes and find a packet transmission route. If there are a small number of neighbours in the range, then the maximum power is used for transmission. Otherwise, the transmission power is reduced.

Evaluation of DP-AODV compared with AODV

The results in chapter 5 illustrate that DP-AODV performed better than basic AODV across all four of the metrics analysed. DP-AODV gave a higher Packet Delivery Fraction rate than AODV, particularly in a dynamic environment where the speed of nodes (figures 5.9 and 5.10) and number of sources (figures 5.17 and 5.18) where varied. DP-AODV also gave a shorter End-to-End delay than AODV across all metrics, with a typically lower End-to-End delay in a static environment, though there were exceptions (figures 5.11 and 5.12; 5.19 and 5.20; and 5.27 and 5.28). The throughput results were also higher for DP-AODV, particularly in a static environment when varying the speed of nodes (figures 5.13 and 5.14) and number of sources (figures 5.21 and 5.22). The Power Consumption results revealed that DP-AODV has a lower power consumption than basic AODV, and that power consumption for both protocols was lower in a static environment, with the exception of DP-AODV when the number of sources was varied (figure 5.24). The power consumption for DP-AODV remained constant when the pause time was varied (figures 5.15 and 5.16).

Evaluation of DP-AODV compared with AOMDV and DSR

The results in chapter 6 showed that DP-AODV gave better performance results than DSR in all scenarios. However, the comparison with AOMDV was not as clear as there were some cases where AOMDV gave better performance results than DP-AODV. The Packet Delivery Fraction rate was lowest for DSR in both dynamic and static environments. In a dynamic environment, DP-AODV gave the best PDF rate for all four metrics, whereas, in a static environment, it only performed better than AOMDV when varying the number of sources (figures 6.18) and the pause time (figures 6.25 and 6.26). The End-to-End delay results again showed that DSR has the highest delay, with the exception of varying the number of sources in a static environment (figure 6.20). Moreover, varying the number of sources, in a dynamic environment, showed that AOMDV had the shortest End-to-End delay (figure 6.19). DP-AODV gave the shortest End-to-End delay in a static environment when varying the speed of nodes (figure 6.12) and when varying the pause time with a speed of 10 m/s (figure 6.27).

As regards to throughput, DSR gave the lowest throughput results, and DP-AODV gave the highest for all four metrics (figures 6.5, 6.6, 6.13, 6.14, 6.21, 6.22, 6.29 and 6.30), except when the number of nodes was varied and 100 nodes were used in a static environment (figure 6.6). The analysis of power consumption showed that DP-AODV had lower power consumption than both AOMDV and DSR for all cases (figures 6.7, 6.8, 6.15, 6.16, 6.23, 6.24, 6.31 and 6.32). The power consumption increased when the number of nodes (Figures 6.7 and 6.8) or the number of sources (figures 6.23 and 6.24) was increased. However, increasing the speed (figures 6.15 and 6.16) only had a slight effect on the power consumption. Varying the pause time affected the power consumption for both AOMDV and DSR, whereas it remained constant for DP-AODV (figures 6.31 and 6.32).

Performance Summary

The simulation results from chapters 5 and 6 demonstrate that DP-AODV improved the performance results for AODV with regards to packet delivery fraction in all scenarios, with a shorter End-to-End delay, a higher throughput and lower power consumption. In addition, it performed better than DSR in all scenarios. In comparison to AOMDV, DP-AODV had better performance results for throughput and power consumption in both dynamic and static environments. The Packet Delivery Fraction rate was also higher for DP-AODV in a dynamic environment, but was only better in a static environment when varying the number of sources or the pause time. The End-to-End delay for DP-AODV was only shorter than for AOMDV in a static environment when varying the speed of nodes and the pause time, with a speed of 10 m/s. The most important metrics for this research were throughput and power consumption as they were shown to reduce interference between nodes by dynamically adjusting the transmission power.

7.2 Future Work

This section highlights areas for potential future research, based on the contributions of this thesis. Dynamically adjusting the transmission power in a mobile ad hoc network can result in an increase in the network throughput, and reduce interference between nodes and power consumption. DP-AODV uses a hello message mechanism to implement the idea of transmission power control, however there is still scope for further research in this area. The overheads could be reduced by dynamically altering the hello message interval, using short intervals. By increasing the duration of hello messages, the overheads would be significantly reduced, with a resulting improvement in the performance. In order to estimate the overhead at a node, RREQ and RREP messages can be used as a metric and, depending on the frequency of these messages, the parameters of the algorithm can be altered to optimise performance across the network.

Moreover, RREQ and RREP message generation can be controlled by local conditions (e.g. neighbour count) and global conditions (e.g. end-to-end delay). By minmising the forwarding of these messages to intermediate nodes, the overhead will be reduced and new routes will be discovered. In order to confirm the results of this research on a wider scale, DP-AODV must be compared with other mobility models, types of traffic (e.g. TCP/FTP) and power aware routing protocols.

The mechanism to dynamically adjust transmission power could also be implemented in multi-path routing protocols, such as AOMDV, in order to analyse the effects. This provides many opportunities for the improvement of the AOMDV routing protocol. In addition, DP-AODV could be investigated using longer simulation times or different network/topological area sizes in order to study behavioural changes depending on variations in the topological size.

Glossary

Autonomous system

a system that is self-sufficient without relying on human intervention.

Bandwidth

the range of frequencies used to transmit a signal, and the rate of data transfer.

Broadcast

the process of a source node sending data to all other nodes in the network.

Cache

a temporary storage location in the node, used to store routing information.

Capacity

the throughput for an application, per session.

CMU Generator

Carnegie Mellon University (CMU) setdest shell utility generator.

Congested nodes or links

nodes or links which are over-used, or congested due to the network topology or the routing protocol, resulting in longer delays or packet loss.

Connectivity

link strength within a particular node's transmission range.

Cross-Over Distance

the reference distance of the receiver.

Direction of mobility

the direction of a node's travel, moving to areas where there are less or no neighbouring nodes.

Dynamic network

nodes move continuously throughout the simulation period.

Dynamic topology

the structure or topology of the network may change unpredictably, based on the mobility of nodes

Flooding

nodes send data to other nodes in the network through the Mac layer.

Hidden terminal

various nodes using the same communication channel at the same time without detecting each other, causing interference through collision.

Hop-by-Hop message

packet forwarding to the next hop, following validation. If validation fails, packets are dropped.

Internet gateway

internet connection for nodes in a MANET provided through a router.

Link failures

breaks in links between nodes.

Medium Access Control (MAC) protocol

a sublayer of the data link layer that acts as an interface between the logical link and physical layer.

Mobile ad hoc networks (MANET)

a wireless network with mobile nodes without any fixed infrastructure.

Mobility model

a model to simulate the movement of mobile nodes.

Multihop

transmitting signals using multiple stops, rather than one continuous path.

Multipath

a set of alternate routes between source node and destination node.

Multicast

sending data (message, information, data transmission) to a set of destination nodes.

Neighbour

two nodes, within the transmission range of each other, which can communicate directly.

Node

a network entity, such as a Laptop or PC.

Node converge

the area coverage at particular times.

Node failures

nodes leaving the network at any time, due to various network conditions.

On demand protocols

nodes only search for routes as required.

Pause time

the amount of time a node is stationary at a destination.

QoS (Quality of service)

network performance (including applications, hosts, and infrastructure devices) in terms of minimising traffic delays and maximising availability to send data.

Random Way Point Model (RWP)

a type of mobility model used where each node randomly selects, and moves towards, a destination at a uniform speed, pauses for a uniform time and then repeats the process.

Relative Velocity

The difference of speed between any two nodes.

Route breakage

where node or link failures occur, breaking a link in the route path.

Route Discovery

identifying from a source to a destination node.

Route error message (RERR)

the message sent from a destination to a source node upon discovery of a broken link.

Route Maintenance

fixing a broken route or finding an alternative in the event of route failure.

Route Reply (RREP)

the message sent from a destination or intermediate node to the source node with details of a new route.

Route Request (RREQ)

the message sent from the source node to all nodes when a router to a destination is wanted.

Routing

the selection of network routes to transmit data or send physical traffic.

Simulator

software that imitates the behaviour of a specific system.

Security

protecting a system and preventing unauthorised access to data.

Self-configuring

alterations made by nodes to adapt to a changing environment or improve performance.

Speed of nodes

the velocity of mobile nodes within a MANET.

Static network

a network with very low mobility where nodes are static.

Tables based protocols

Each node has a routing table with route information for all nodes in the network.

Traffic flow in a network

defined by its source, destination, traffic protocol, and (optionally) intensity.

Transmission Error

error in sending or receiving packets.

Unicast

sending packets from a single source node to a single destination node.

Unipath (Single) path

find a single path between two nodes.

Appendix A

Performance Analysis I

There are different simulators available for designing MANETs and analyze their performance by collecting different simulation results. In our design and implementation part we use NS2 simulator [109] [110]. To run the idea of this proposal based on simulator [113] [115], the following steps should follow that is shown:

- implement the idea based on NS2 simulator.
- Create a movement scenario files.
- Create a traffic/connection pattern files.
- Create a trace file.
- Analysis of trace file.
- Draw Graphs.
- Analysis of such situations should enable the optimal parameters to be set for existing routing protocols.

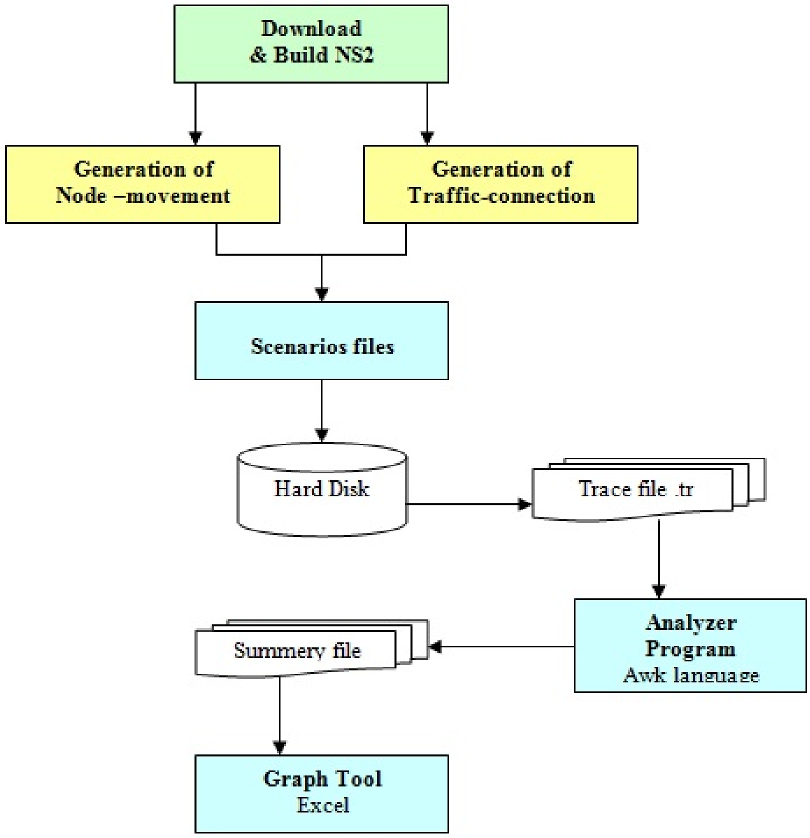

Figure A.1: General NS2 Methodology

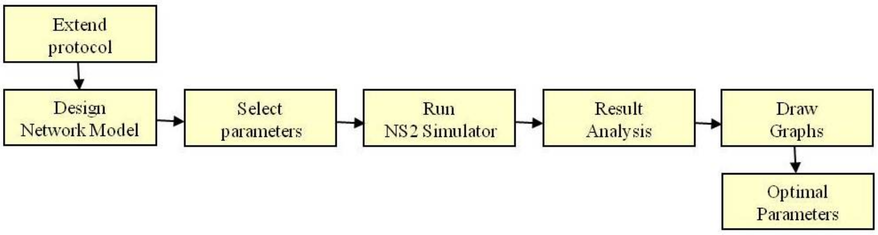

Figure A.2: Extension NS2 Methodology

Appendix B

Results of comparison between DP-AODV and AODV

	DP-AODV			AODV		
Nodes	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	73.98	0.80	0.57	53.20	0.48	0.34
100	68.89	0.28	0.20	48.99	0.47	0.33
150	56.95	0.53	0.38	44.60	0.35	0.25
200	51.63	1.11	0.80	42.08	0.89	0.64

Table B.1: PDF vs Density (related to figure 5.1 in chapter 5)

	DP-AODV			AODV		
Nodes	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	73.97	0.79	0.57	63.08	0.43	0.31
100	68.88	0.28	0.20	61.60	0.32	0.23
150	56.94	0.52	0.37	53.05	0.54	0.39
200	51.63	1.11	0.80	45.47	0.35	0.29

Table B.2: PDF vs Density (related to figure 5.2 in chapter 5)

Nodes	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	0.43	0.13	0.90	0.87	0.15	0.11
100	0.55	0.15	0.11	1.16	0.34	0.25
150	0.84	0.25	0.18	1.07	0.26	0.18
200	0.75	0.19	0.14	1.22	0.27	0.19

Table B.3: EED vs Density (related to figure 5.3 in chapter 5)

Nodes	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	0.44	0.16	0.12	0.72	0.17	0.19
100	0.56	0.18	0.13	0.64	0.16	0.12
150	0.50	0.21	0.15	0.79	0.23	0.16
200	0.69	0.10	0.07	0.87	0.31	0.21

Table B.4: EED vs Density (related to figure 5.4 in chapter 5)

Nodes	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	596984.2	1.69	0.92	460893.7	1.76	1.26
100	560861.4	1.08	0.63	423620.7	1.22	1.01
150	454912.2	1.84	0.74	332731.1	1.99	1.14
200	486905	1.53	0.81	256446.8	1.82	1.57

Table B.5: Throughput vs Density (related to figure 5.5 in chapter 5)

	DP-AODV			AODV		
Nodes	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	639764.9	1.86	1.26	382586.1	1.81	1.44
100	565696.2	1.49	1.18	350617.8	1.27	1.04
150	449420.7	1.90	1.08	291680.4	1.79	1.28
200	425573.5	1.71	1.34	265268.7	1.58	1.12

Table B.6: Throughput vs Density (related to figure5.6 in chapter 5)

	DP-AODV			AODV		
Nodes	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	23.37	0.54	0.39	33.46	0.77	0.55
100	23.72	0.46	0.33	34.28	0.53	0.38
150	22.56	0.81	0.58	34.64	0.42	0.30
200	24.98	0.79	0.56	35.31	0.53	0.38

Table B.7: PC vs Density (related to figure 5.7 in chapter 5)

	DP-AODV			AODV		
Nodes	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	20.93	0.30	0.22	31.33	0.17	0.12
100	21.72	0.55	0.39	30.16	0.56	0.40
150	21.73	0.59	0.42	32.34	0.47	0.35
200	25.74	0.52	0.37	32.31	0.44	0.30

Table B.8: PC vs Density (related to figure 5.8 in chapter 5)

	DP-AODV			AODV		
Speed	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	60.99	0.33	0.23	49.90	0.32	0.23
20	54.24	0.52	0.37	45.08	0.35	0.25
30	51.63	0.12	0.80	42.08	0.89	0.64

Table B.9: PDF vs Max speed of node (related to figure 5.9 in chapter 5)

	DP-AODV			AODV		
Speed	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	63.53	0.32	0.23	54.60	0.29	0.31
20	56.49	0.05	0.49	47.22	0.36	0.38
30	59.75	0.26	0.19	45.47	0.36	0.24

Table B.10: PDF vs Max speed of node (related to figure 5.10 in chapter 5)

	DP-AODV			AODV		
Speed	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	0.59	0.22	0.16	1.32	0.39	0.28
20	0.90	0.29	0.21	1.42	0.23	0.17
30	0.75	0.19	0.14	1.21	0.27	0.19

Table B.11: EED vs Max speed of node (related to figure 5.11 in chapter 5)

	DP-AODV			AODV		
Speed	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	0.84	0.23	0.24	1.03	0.33	0.34
20	0.80	0.27	0.20	1.05	0.41	0.43
30	0.69	0.10	0.07	0.87	0.31	0.21

Table B.12: EED vs Max speed of node (related to figure 5.12 in chapter 5)

Speed	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	513157.9	1.32	1.09	336088.8	1.37	1.11
20	418467.9	1.88	1.06	274257.9	1.06	0.99
30	425573.5	1.70	1.13	265268.7	1.65	1.22

Table B.13: Throughput vs Max speed of node (related to figure 5.13 in chapter 5)

Speed	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	516443.4	1.96	1.40	365006.3	1.07	0.87
20	486547	1.15	0.83	288478.2	1.17	1.03
30	460905	1.53	1.10	256446.8	1.82	1.27

Table B.14: Throughput vs Max speed of node (related to figure 5.14 in chapter 5)

Speed	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	25.02	0.45	0.32	33.68	0.19	0.14
20	26.99	0.27	0.19	35.15	0.48	0.34
30	24.98	0.79	0.56	35.31	0.53	0.38

Table B.15: PC vs Max speed of node (related to figure 5.15 in chapter 5)

Speed	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	26.02	0.29	0.21	31.37	0.34	0.36
20	25.69	0.35	0.25	32.26	0.42	0.44
30	24.74	0.52	0.37	33.31	0.44	0.30

Table B.16: PC vs Max speed of node (related to figure 5.16 in chapter 5)

	DP-AODV			AODV		
Sources	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	86.85	0.32	0.23	81.58	0.20	0.14
20	74.39	0.27	0.19	67.31	0.37	0.27
40	51.63	1.12	0.80	42.08	0.89	0.64

Table B.17: PDFvs number of sources (related to figure 5.17 in chapter 5)

	DP-AODV			AODV		
Sources	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	89.53	0.40	0.28	84.61	0.26	0.19
20	78.99	0.30	0.22	69.45	0.35	0.25
40	59.75	0.26	0.19	45.47	0.36	0.24

Table B.18: PDF vs number of sources (related to figure 5.18 in chapter 5)

	DP-AODV			AODV		
Sources	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	0.38	0.33	0.23	0.44	0.12	0.09
20	0.48	0.14	0.10	0.77	0.31	0.22
40	0.75	0.19	0.14	1.22	0.27	0.19

Table B.19: EED vs number of sources (related to figure 5.19 in chapter 5)

	DP-AODV			AODV		
Sources	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	0.36	0.10	0.07	0.43	0.15	0.11
20	0.51	0.20	0.14	0.60	0.19	0.14
40	0.69	0.10	0.07	0.87	0.31	0.21

Table B.20: EED vs number of sources (related to figure 5.20 in chapter 5)

	DP-AODV			AODV		
Sources	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	180892	1.60	1.18	159234.1	1.65	1.13
20	356981.9	1.12	0.98	266682.7	1.90	1.08
40	425573.5	1.70	1.23	295268.7	1.25	1.02

Table B.21: Throughput vs number of sources (related to figure 5.21 in chapter 5)

	DP-AODV			AODV		
Sources	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	188168.9	1.90	1.07	161240.5	1.10	0.93
20	375374.1	1.35	1.14	260616.4	1.32	1.09
40	486905	1.53	1.11	286446.8	1.82	1.27

Table B.22: Throughput vs number of sources (related to figure 5.22 in chapter 5)

	DP-AODV			AODV		
Sources	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	13.35	0.47	0.34	24.32	0.31	0.22
20	19.10	0.30	0.22	30.32	0.32	0.23
40	24.98	0.79	0.56	35.31	0.53	0.38

Table B.23: PC vs number of sources (related to figure 5.23 in chapter 5)

	DP-AODV			AODV		
Sources	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	15.15	0.37	0.26	18.61	0.40	0.28
20	21.19	0.38	0.27	26.80	0.36	0.26
40	25.74	0.52	0.37	31.31	0.44	0.30

Table B.24: PC vs number of sources (related to figure 5.24 in chapter 5)

Pause Time	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	60.99	0.33	0.23	49.99	0.32	0.23
25	61.40	0.52	0.37	51.76	0.50	0.53
50	62.49	0.32	0.23	53.10	0.39	0.37
75	63.53	0.33	0.23	54.60	0.29	0.31

Table B.25: PDF vs pause time (related to figure 5.25 in chapter 5)

Pause Time	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	51.63	1.12	0.80	42.08	0.89	0.64
25	53.73	0.34	0.24	43.76	0.29	0.36
50	56.45	0.48	0.40	44.29	0.27	0.66
75	59.75	0.26	0.19	45.47	0.36	0.24

Table B.26: PDF vs pause time (related to figure 5.26 in chapter 5)

Pause Time	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	0.59	0.22	0.16	1.32	0.39	0.28
25	0.77	0.33	0.24	0.96	0.39	0.41
50	0.71	0.30	0.22	0.98	0.24	0.22
75	0.84	0.34	0.24	1.03	0.33	0.34

Table B.27: EED vs pause time (related to figure 5.27 in chapter 5)

Pause Time	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	0.75	0.19	0.14	1.22	0.27	0.19
25	0.77	0.19	0.14	1.14	0.22	0.16
50	0.72	0.16	0.13	0.98	0.25	0.18
75	0.69	0.10	0.08	0.87	0.31	0.21

Table B.28: EED vs pause time (related to figure 5.28 in chapter 5)

Pause Time	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	513157.9	1.32	1.09	336088.8	1.37	1.13
25	514708	1.49	1.08	351612.2	1.70	1.19
50	515283.2	1.21	1.01	363540.3	1.13	1.02
75	516443.4	1.96	1.40	365006.3	1.07	0.98

Table B.29: Throughput vs pause time (related to figure 5.29 in chapter 5)

Pause Time	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	425573.5	1.70	1.93	265268.7	1.25	1.62
25	433773.6	1.87	1.49	275613.6	1.45	1.80
50	450344.1	1.22	1.70	287422.3	1.69	1.16
75	486905	1.53	1.81	296446.8	1.82	1.57

Table B.30: Throughput vs pause time (related to figure 5.30 in chapter 5)

Pause Time	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	25.02	0.45	0.32	33.68	0.19	0.14
25	25.98	0.29	0.20	32.52	0.62	0.65
50	25.93	0.29	0.21	31.43	0.44	0.40
75	26.02	0.29	0.21	31.37	0.40	0.36

Table B.31: PC vs pause time (related to figure 5.31 in chapter 5)

Pause Time	DP-AODV			AODV		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	24.98	0.79	0.56	35.31	0.53	0.38
25	26.81	0.48	0.35	35.02	0.27	0.19
50	26.73	0.32	0.27	33.01	0.46	0.33
75	25.74	0.52	0.37	32.30	0.44	0.30

Table B.32: PC vs pause time (related to figure 5.32 in chapter 5)

Appendix C

Results of comparison between DP-AODV, AOMDV and DSR

	AOMDV			DSR		
Nodes	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	55.78	0.38	0.27	41.21	0.33	0.24
100	55.38	0.36	0.26	29.90	0.34	0.25
150	50.31	0.20	0.14	24.52	0.31	0.22
200	50.05	0.24	0.17	18.39	0.36	0.26

Table C.1: PDF vs Density (related to figure 6.1 in chapter 6)

	AOMDV			DSR		
Nodes	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	72.62	0.27	0.19	53.08	0.47	0.34
100	72.29	0.37	0.26	48.99	0.46	0.33
150	59.86	0.32	0.23	44.60	0.35	0.25
200	58.05	0.26	0.19	42.07	0.89	0.63

Table C.2: PDF vs Density (related to figure 6.2 in chapter 6)

Nodes	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	0.43	0.20	0.14	2.07	0.69	0.49
100	0.46	0.22	0.16	1.83	0.53	0.38
150	0.66	0.27	0.19	1.20	0.51	0.36
200	0.72	0.14	0.10	1.46	0.23	0.16

Table C.3: EED vs Density (related to figure 6.3 in chapter 6)

Nodes	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	0.34	0.11	0.08	1.28	0.45	0.32
100	0.33	0.19	0.14	1.17	0.65	0.47
150	0.76	0.34	0.24	1.04	0.43	0.31
200	0.74	0.23	0.17	1.32	0.49	0.35

Table C.4: EED vs Density (related to figure 6.4 in chapter 6)

Nodes	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	507670.6	1.70	1.23	381570.1	1.52	1.12
100	501475	1.49	1.14	287849.4	1.10	1.04
150	417673.1	1.71	1.25	248333.7	1.40	1.13
200	423573.5	1.17	1.02	201629.7	1.89	1.27

Table C.5: Throughput vs Density (related to figure 6.5 in chapter 6)

	AOMDV			DSR		
Nodes	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	567775	1.19	1.04	478712	1.54	1.07
100	566333.6	1.06	0.99	476492.3	1.83	1.03
150	415327.2	1.02	0.94	350778.8	1.94	1.10
200	446401.7	1.26	1.03	318567.3	1.25	1.01

Table C.6: Throughput vs Density (related to figure 6.6 in chapter 6)

	AOMDV			DSR		
Nodes	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	28.58	0.30	0.21	33.32	0.35	0.25
100	29.94	0.28	0.20	34.99	0.36	0.26
150	31.91	0.30	0.21	34.87	0.59	0.42
200	33.43	0.36	0.25	37.81	0.53	0.38

Table C.7: PC vs Density (related to figure 6.7 in chapter 6)

	AOMDV			DSR		
Nodes	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
75	30.11	0.35	0.25	30.50	0.27	0.19
100	29.81	0.54	0.39	29.56	0.53	0.38
150	33.26	0.34	0.24	30.87	0.35	0.25
200	33.38	0.33	0.23	32.07	0.23	0.16

Table C.8: PC vs Density (related to figure 6.8 in chapter 6)

	AOMDV			DSR		
Speed	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	54.51	0.15	0.11	29.37	0.40	0.29
20	50.68	0.36	0.26	21.06	0.32	0.23
30	51.05	0.24	0.17	18.39	0.36	0.26

Table C.9: PDF vs Max speed of node (related to figure 6.9 in chapter 6)

	AOMDV			DSR		
Speed	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	61.74	0.23	0.17	47.00	0.49	0.35
20	56.13	0.36	0.26	38.88	0.23	0.16
30	58.05	0.26	0.19	45.73	0.32	0.23

Table C.10: PDF vs Max speed of node (related to figure 6.10 in chapter 6)

	AOMDV			DSR		
Speed	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	0.89	0.23	0.16	1.38	0.45	0.32
20	0.70	0.25	0.18	1.28	0.43	0.31
30	0.72	0.14	0.10	1.46	0.23	0.16

Table C.11: EED vs Max speed of node (related to figure 6.11 in chapter 6)

	AOMDV			DSR		
Speed	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	0.93	0.33	0.23	1.50	0.64	0.46
20	1.04	0.28	0.20	1.60	0.45	0.32
30	0.74	0.23	0.17	1.32	0.46	0.35

Table C.12: EED vs Max speed of node (related to figure 6.12 in chapter 6)

Speed	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	428531	1.32	1.07	275479.6	1.83	1.22
20	402474.9	1.28	1.14	259487.6	1.04	0.98
30	423573.5	1.17	1.06	201629.7	1.89	1.27

Table C.13: Throughput vs Max speed of node (related to figure 6.13 in chapter 6)

Speed	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	473541.6	1.51	1.13	385514.3	1.21	1.09
20	430015.9	1.06	0.97	252520.9	1.67	1.17
30	446401.7	1.26	1.07	318567.3	1.25	1.04

Table C.14: Throughput vs Max speed of node (related to figure 6.14 in chapter 6)

Speed	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	35.15	0.55	0.39	35.42	0.53	0.38
20	33.75	0.31	0.22	36.88	0.58	0.41
30	33.43	0.36	0.25	37.81	0.53	0.38

Table C.15: PC vs Max speed of node (related to figure 6.15 in chapter 6)

Speed	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	34.26	0.34	0.24	31.60	0.65	0.47
20	34.89	0.38	0.27	33.39	0.52	0.37
30	33.38	0.33	0.23	32.07	0.23	0.16

Table C.16: PC vs Max speed of node (related to figure 6.16 in chapter 6)

	AOMDV			**DSR**		
Sources	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	67.29	0.28	0.20	60.27	0.31	0.22
20	63.23	0.38	0.27	33.04	0.35	0.25
40	51.05	0.24	0.17	18.39	0.36	0.26

Table C.17: PDFvs number of sources (related to figure 6.17 in chapter 6)

	AOMDV			**DSR**		
Sources	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	86.47	0.36	0.26	84.14	0.36	0.26
20	76.65	0.33	0.24	66.44	0.36	0.26
40	58.05	0.26	0.19	45.73	0.32	0.23

Table C.18: PDF vs number of sources (related to figure 6.18 in chapter 6)

	AOMDV			**DSR**		
Sources	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	0.05	0.02	0.01	0.57	0.25	0.18
20	0.14	0.06	0.04	1.02	0.52	0.37
40	0.72	0.14	0.10	1.46	0.23	0.16

Table C.19: EED vs number of sources (related to figure 6.19 in chapter 6)

	AOMDV			**DSR**		
Sources	*Mean*	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	0.04	0.01	0.01	0.18	0.08	0.06
20	0.16	0.06	0.04	0.31	0.17	0.12
40	0.74	0.23	0.17	1.32	0.49	0.35

Table C.20: EED vs number of sources (related to figure 6.20 in chapter 6)

Sources	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	135177.6	1.61	1.38	125540.9	1.13	1.04
20	293543.6	1.13	1.04	138571.1	1.70	1.33
40	423573.5	1.17	1.02	201629.7	1.89	1.07

Table C.21: Throughput vs number of sources (related to figure 6.21 in chapter 6)

Sources	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	161474.4	1.12	1.03	155453.6	1.70	1.25
20	305390.1	1.19	1.08	287013.1	1.22	1.02
40	446401.7	1.26	1.03	318567.3	1.25	1.01

Table C.22: Throughput vs number of sources (related to figure 6.22 in chapter 6)

Sources	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	20.54	0.31	0.22	28.12	0.33	0.24
20	27.40	0.31	0.22	34.31	0.42	0.30
40	33.43	0.36	0.25	37.81	0.53	0.38

Table C.23: PC vs number of sources (related to figure 6.23 in chapter 6)

Sources	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
10	21.01	0.25	0.18	19.94	0.37	0.26
20	28.55	0.37	0.26	26.44	0.30	0.21
40	33.38	0.33	0.23	32.07	0.23	0.16

Table C.24: PC vs number of sources (related to figure 6.24 in chapter 6)

Pause Time	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	54.51	0.15	0.11	29.37	0.40	0.29
25	56.99	0.27	0.20	31.76	0.37	0.26
50	58.60	0.23	0.16	43.04	0.23	0.16
75	61.74	0.23	0.17	47.00	0.49	0.35

Table C.25: PDF vs pause time (related to figure 6.25 in chapter 6)

Pause Time	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	51.05	0.24	0.17	18.39	0.36	0.26
25	51.83	0.35	0.25	22.70	0.39	0.28
50	54.54	0.30	0.22	28.86	0.38	0.28
75	58.05	0.26	0.19	45.73	0.32	0.23

Table C.26: PDF vs pause time (related to figure 6.26 in chapter 6)

Pause Time	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	0.89	0.23	0.16	1.38	0.45	0.32
25	0.93	0.25	0.18	1.32	0.59	0.42
50	0.92	0.36	0.26	0.92	0.40	0.29
75	0.93	0.33	0.23	1.50	0.64	0.46

Table C.27: EED vs pause time (related to figure 6.27 in chapter 6)

Pause Time	**AOMDV**			**DSR**		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	0.72	0.14	0.10	1.46	0.23	0.16
25	0.59	0.21	0.15	1.32	0.37	0.27
50	0.61	0.13	0.09	0.73	0.21	0.15
75	0.74	0.23	0.17	1.32	0.49	0.35

Table C.28: EED vs pause time (related to figure 6.28 in chapter 6)

Pause Time	**AOMDV**			**DSR**		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	428531	1.32	1.07	275479.6	1.83	1.02
25	443001.7	1.08	0.95	303282.6	1.37	1.3
50	457686.2	1.30	1.02	381120.6	1.81	1.01
75	473541.6	1.51	1.14	385514.3	1.21	1.04

Table C.29: Throughput vs pause time (related to figure 6.29 in chapter 6)

Pause Time	**AOMDV**			**DSR**		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	423573.5	1.17	1.07	201629.7	1.89	1.02
25	425586.5	1.52	1.21	278374.7	1.98	1.24
50	433408.3	1.46	1.19	294442.5	1.55	1.04
75	446401.7	1.26	1.03	318567.3	1.25	1.01

Table C.30: Throughput vs pause time (related to figure 6.30 in chapter 6)

Pause Time	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	35.15	0.55	0.39	35.42	0.53	0.38
25	34.42	0.27	0.19	34.27	0.51	0.37
50	33.47	0.29	0.21	31.20	0.24	0.17
75	34.26	0.34	0.24	31.60	0.65	0.47

Table C.31: PC vs pause time (related to figure 6.31 in chapter 6)

Pause Time	AOMDV			DSR		
	Mean	*StD*	*Coln*	*Mean*	*StD*	*Coln*
0	33.43	0.35	0.25	37.81	0.53	0.38
25	32.80	0.24	0.17	35.69	0.38	0.27
50	32.22	0.41	0.29	33.74	0.58	0.41
75	33.38	0.33	0.23	32.07	0.23	0.16

Table C.32: PC vs pause time (related to figure 6.32 in chapter 6)

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