# ENERGY AWARE ROUTING PROTOCOLS IN AD HOC WIRELESS NETWORKS

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# ENERGY AWARE ROUTING PROTOCOLS IN AD HOC WIRELESS NETWORKS

by

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*To my wife for her endless support, encouragement and love*

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## Abstract

In Mobile Ad hoc Network, communication at mobile nodes can be achieved by using multi-hop wireless links. The architecture of such a network is based, not on a centralized base station but on each node acting as a router to forward data packets to other nodes in the network. The aim of each protocol, in an ad hoc network, is to find valid routes between two communicating nodes. These protocols must be able to handle high mobility of the nodes which often cause changes in the network topology. Every ad hoc network protocol uses some form of a routing algorithm to transmit between nodes based on a mechanism that forwards packets from one node to another in the network. These algorithms have their own way of finding a new route or modifying an existing one when there are changes in the network.

The novel area of this research is a proposed routing algorithm which improves routing and limits redundant packet forwarding, especially in dense networks. It reduces the routing messages and consequently power consumption, which increases the average remaining power and the lifetime of the network. The first aim of this research was to evaluate various routing algorithms in terms of power. The next step was to modify an existing ad hoc routing protocol in order to improve the power consumption. This resulted in the implementation of a dynamic probabilistic algorithm in the route request mechanism of an ad hoc On-Demand Distance Vector protocol which led to a 3.0 % improvement in energy consumption. A further extension of the approach using Bayesian theory led to 3.3 % improvement in terms of energy consumption as a consequence of a reduction in MAC Load for all network sizes, up to 100 nodes.

# Acknowledgments

## Declaration

"While registered as a candidate for the above degree, I have not been registered for any other research award. The results and conclusions embodied in this thesis are the work of the named candidate and have not been submitted for any other academic award."

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# Glossary of Abbreviations and Symbols

## List of Abbreviations

2GFSK 2-level Gaussian Frequency Shift Keying

ACK   Acknowledgment

AODV   Ad Hoc On-Demand Distance Vector Routing

APs   Access Points

BIP   Broadcast Incremental Power

BSS   Basic Service Set

CBR   Constant Bit Rate

CCA   Clear Channel Assessment

CCK   Complementary Code Keying

CDS   Connected Dominating Set

CMU   Communication Management Unit

CTS   Clear-To-Send

DARPA   Defense Advanced Research Projects Agency

DBPSKDifferential Binary Phase Shift Keying

DCF   Distributed Coordination Function

DLL   Data Link Layer

DQPSK   Differential Quadrature Phase Shift Keying

DSDV   Destination-Sequenced Distance-Vector Routing

DSR   Dynamic Source Routing

DSSS   Direct-Sequence Spread-Spectrum

EAODV   Enhanced Ad Hoc On Demand Distance Vector Routing

EIRP   Equivalent Isotropically Radiated Power

ER-AODV   Energy Reverse Ad Hoc On Demand Distance Vector Routing

FHSS   Frequency-Hopping Spread-Spectrum

| | |
|---|---|
| FTP | File Transfer Protocol |
| GPS | Global Position System |
| GSM | Global System for Mobile Communications |
| IDs | Identifiers |
| IEEE | Institute of Electrical and Electronics Engineers |
| IR | Infrared Band |
| ISO | International Organization for Standardization |
| LANs | Local Area Networks |
| LCAP | Load-Based Concurrent Access Protocol |
| LLC | Logical Link Control |
| LMR | Lightweight Mobile Routing |
| MAC | Medium Access Control |
| MANET | Mobile Ad Hoc Network |
| MIMO | Multiple/Input-Multiple/Output |
| MPR | Multipoint Relaying |
| MST | Minimum Spanning Tree |
| NS-2 | Network Simulator 2 |
| NSF | National Science Foundation |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OLSR | Optimized Link State Routing |
| OOK | On-Off Keying |
| OSI | Open System Interconnection |
| PDAs | Personal Digital Assistants |
| PLCP | Physical Layer Convergence Protocol |
| PMD | Physical Medium Dependent |
| PPM | Pulse Position Modulation |
| PS | Power-Saving |

| | |
|---|---|
| RAD | Random Assessment Delay |
| RBBP | Residual Battery Capacity Broadcast Routing Problem |
| RERR | Route Error |
| RREP | Route Reply |
| RREQ | Route Request |
| RTS | Request-To-Send |
| SCPS | Self-Configuring Power-Saving |
| TCL | Tool Command Language |
| TCP | Transmission Control Protocol |
| TORA | Temporally Ordered Routing Algorithm |
| UDP | User Datagram Protocol |
| UMTS | Universal Mobile Telecommunications System |
| WDS | Wireless Distribution System |
| Wi-Fi | Wireless Fidelity |
| WiMAX | Worldwide Interoperability for Microwave Access |
| WLANs | Wireless Local Area Networks |
| WSN | Wireless Sensor Networks |
| ZRP | Zone Routing Protocol |

## List of Symbols

| | |
|---|---|
| $C_f$ | It is a control factor which can be used to adjust the probability |
| $P_i$ | according to the application or average expected node density of the network,$(1 < C_f \leq 1)$. |
| $d$ | Minimum number of neighbouring nodes - if the number of neighbours at a forwarding node, $F_i$, is less than or equal to $d$, then that node will forward the RREQ message to avoid path failure or network partitioning. |
| $F_i$ | Any node $F_i$, i = 1,2,...n that receives the RREQ message |
| $m$ | Percentage of $n$ nodes |
| $n_{priority}$ | The priority number of the received RREQ message |
| $n$ | The total nodes in the network |
| $N$ | Each node in the network |
| $P(AB)$ | The joint probability of two events, A and B |
| $P(H/D)$ | The probability of the observed data D resulting from hypothesis H |
| $P_{tx}$ | The power that consumes a node when it transmits a packet |
| $P_{total}$ | The energy level that a node has at any time |
| $P_{rx}$ | The power that consumes a node when it receives a packet |
| $P_{init}$ | The energy level that a node initially has |
| P(H) | The prior knowledge |
| P(D) | The total probability of all the pathways that lead to D |
| $P_s$ | The total power of all nodes |
| $P_i$ | Packet forwarding probability derived from neighbourhood node count. |
| $P_{(D/D_i)}$ | The probability of the message that has broadcasted by the node being forwarded by each node $D_i$ (i = 1, 2 ..., n) |

| | |
|---|---|
| $R$ | Random number (between 0 and 100). This is used to generate varying conditions in the network. |
| $RREQ_{ID}$ | The RREQ packet from a specific node with specific ID |
| $sq(N_j)$ | The sequential number of node j |
| $sq(N_i)$ | The sequential number of node i |
| $t_{tx}$ | The time that a packet need to be transmitted |
| $t_{rx}$ | The time that a packet need to be received |
| $\beta_i$ | The number of nodes neighbouring node $F_i$. |
| $\sum_{j=i+1}^{l} hop(N_i, N_j)$ | The number of hops from the current node to the destination node |
| $\sum_{j=i+1}^{k} hopC(N_i, N_j)$ | The number of hops from node $N_i$ to node $N_j$ |

# CHAPTER 1

# BACKGROUND AND GENERAL INTRODUCTION

*Abstract: This chapter explains the background and significance of the research undertaken. The importance of developing a new algorithm is explained with respect to the overall objectives of the research. The author's contributions and layout of the thesis are also presented.*

## 1.1    Background and Objectives

Wireless systems, both mobile and fixed, have become an indispensable part of communication infrastructure. Their applications range from simple wireless low data rate transmitting sensors to high data rate real-time systems such as those used for monitoring large retail outlets or real-time broadcasting of sport events. Most of the existing mobile wireless technology is based on point-to-point technology. An example is the Global System for Mobile communication (GSM) with an architecture that is based on mobile nodes communicating directly with central access points. Sometimes there are networks that do not rely on centralized connectivity such as Mobile Ad Hoc Networks (MANET). MANET is a wireless network that has mobile nodes with no fixed infrastructure. These kinds of networks are used in areas such as environmental monitoring or in rescue operations. The main limitation of ad hoc systems is the availability of power. In addition to running the onboard electronics, power consumption is governed by the number of processes and overheads required to maintain connectivity.

The main objectives of this research are to evaluate existing protocols and routing algorithms for power efficiency and, identify and develop techniques (protocol and/or routing algorithm) that will improve ad hoc network power efficiency.

The objectives are summarized as follows:

- Evaluate existing protocols for power efficiency and modify or develop a more efficient power conservation scheme;

- Investigate, develop and modify an existing protocol or routing algorithm to improve energy efficiency;

- Test and critically analyse the protocol and the routing algorithm;

- Evaluate the performance of the modified protocol and routing algorithm in small, medium and large scale networks;

## 1.2 Achievements

In order to conduct this research, extensive investigation of the advantages and disadvantages of ad hoc network protocols were carried out. Different simulation platforms were considered and NS-2 was chosen for this research because it is cost effective, less demanding on the computer system and has a large user community.

- The performances of the Dynamic Source Routing (DSR), Destination-Sequenced Distance-Vector Routing (DSDV), Temporally Ordered Routing Algorithm (TORA), Optimized Link State Routing (OLSR) and Ad hoc On-Demand Vector (AODV) routing protocols have been compared in terms of power consumption, routing overhead, network throughput and MAC Load, in order to find out the advantages and disadvantages of each protocol. AODV has been selected because of its flexibility and good performance in comparison to the other protocols. The Route Request (RREQ) mechanism of AODV has been modified to reduce the flooding, routing overhead load and, therefore, the power consumption.

- Two probability schemes have been implemented in the RREQ forwarding mechanism of AODV to reduce re-transmissions. These are: a dynamic random probability scheme, the AODV_EXT, and an approach based on Bayesian probability theory, the AODV_EXT_BP. These proposed algorithms alleviate the storm phenomenon and thus reduce the total network power consumption.

- Test results show that the average MAC Load is reduced by 25.1% and 44.9% using the two new protocols, AODV_EXT and AODV_EXT_BP, respectively, compared to the standard AODV. A 25.9% and 89.5% reduction in dropped packets is also achieved for AODV_EXT and AODV_EXT_BP, respectively. In terms of power consumption AODV_EXT and AODV_EXT_BP based networks show 3.0% and 3.3%, respectively, improvements in the remaining battery power compared to standard AODV. However AODV_EXT has a 2.5% poorer performance in data throughput compared to the standard AODV but AODV_EXT_BP achieves a 3.5% better performance.

- In small (0-10 nodes)*, medium (10-30 nodes) and large (more than 30 nodes) [1.1] scale networks AODV_EXT achieves 1.8%, 5.7% and 1.9%, energy efficiencies, respectively, compared to standard AODV protocol. For the same network sizes, AODV_EXT_BP exhibits 2.2%, 4.3% and 2.8% improvements in power consumption. Overall, the results show that the developed algorithms will improve the network life span by more than 2%.

  * The definition of network scale depends on the application that the wireless ad hoc devices are intended to be used for. This research tries to approach an application of monitoring buses and cargo vehicles in an airport terminal. In such cases the network scale depends on the traffic, so when the traffic is low the assumption is that the network is small (0-10 nodes), when the traffic is medium there is an assumption that the network is medium size (10-30 nodes) and when the traffic is high then there is an assumption that the network is large (30-100 nodes).

## 1.3   Introduction

Wireless communication, has become one of the fastest growing technologies worldwide due to the technological advancements in mobile computing devices and wireless technology. Mobile devices such as laptops, netbooks and mobile phones have reduced in size and yet have large memories and high processing power. Wireless communication networks provide a variety of advantages over traditional wired networks. Firstly wireless

networks allow anywhere and anytime connectivity and can be deployed in areas without any other existing wired communication infrastructure or wherever it is difficult to setup a wired network. Examples include where the law prohibits the installation of cables such as in heritage buildings. In addition the installation of a wireless network is much cheaper than a wired infrastructure making wireless networks an attractive solution, especially in less developed world. Furthermore, wireless networks provide flexibility and enable easy communication setup. For instance, mobile users can turn on their laptops or Personal Digital Assistants (PDAs) and immediately connect to the Internet in public places such as university campuses, cafés or airports.

Wireless communication technologies include Global System for Mobile Communication (GSM), satellite communication, Wireless Local Area Networks (WLANs) and Worldwide Interoperability for Microwave Access (WiMAX). WLANs and Wireless Fidelity (Wi-Fi) technology use the IEEE 802.11 standard which guarantees interoperability of wireless devices. This standard specifies the first two network layers, Physical and Data Link of the Open System Interconnection (OSI) protocol stack [1.2].

The IEEE 802.11 standard [1.3] classifies two major wireless networks for WLANs depending on the ways that they are deployed:

1. With infrastructure

2. Without infrastructure (Ad Hoc networks).

The WLANs with infrastructure depends on special nodes called Access Points (APs), which are connected via existing wired Local Area Networks (LANs). The APs are used to bridge communication between the mobile nodes and wired networks. This kind of configuration is used to provide services through Wi-Fi hotspots [1.4], i.e., to provide wireless access. The number of mobile nodes that are associated with a specific AP is called the Basic Service Set (BSS) [1.5]. In order to extend the Wi-Fi coverage area, there is a Wireless Distribution System (WDS) within which a group of APs can have point-to-point or point-to-multipoint links with WDS, forming a mesh like network. Currently, there

are many products which offer automatic WDS service configuration and self-healing system when a link drops or an access point fails [1.6].

Some networks do not rely on centralized connectivity such as Mobile Ad Hoc Networks (MANETs). These mobile devices could set up a possibly short-lived network for the communication needs of the moment, in other words, an ad hoc network. Ad hoc networks are self-organizing networks and create a communication network without relying on any fixed infrastructure. These kinds of networks are used in areas such as environmental monitoring or in rescue operations. The main limitation of ad hoc network systems is the availability of power. In addition to running the onboard electronics, power consumption is governed by the number of processes and overheads required to maintain connectivity [1.7][1.8].

## 1.4    Summary of Ad Hoc Wireless Networks

Many efforts have been targeted towards the reduction of power consumption in wireless communication. Some researchers have proposed the adjustment of data transmission rate of mobile devices according to traffic conditions as a means of conserving energy [1.9]. For example, by switching to a lower data transmission rate, a mobile device consumes less energy. Active power control mechanisms that adjust the transmitted power based on the distance of the destination node have also been proposed. This is used in some mobile and fixed wireless systems [1.10]. New energy aware routing protocols have also been designed to distribute packet relay tasks to multiple mobile devices.

Engineering developments in this area have highlighted some advantages. Shih-Chang et al. [1.11] found that the life expectancy of an ad hoc network can be increased using a Self-Configuring Power-Saving (SCPS) protocol based on a one-hop scheme. This allows a node to go into a special Power-Saving (PS) mode. In SCPS, every node maintains the wake up information of all other stations, which is kept in the Wake up Information Table (WIT) and added in the beacon frames. In order to synchronize the clocks of the nodes there is a Timer Synchronization Beacon Interval (TSBI), in which all nodes synchronized

their clocks with that of the beacon. This type of configuration can optimize the number of stations awake in each beacon interval so as to minimize the probability of transmission collision, which results in more efficient energy usage. Reported test results showed that SCPS scheme successfully balances the number of stations that wake up in each beacon interval, increases the sleep ratio, and reduces the collision probability. The combined effect reduces total energy consumption. In summary, by dynamically adjusting the wakeup schedule, SCPS conserves energy in two ways:

1.  stations sleep longer;

2.  the number of active nodes in each beacon intervals is balanced. This reduces packets collision and hence re-transmission.

Research reported in [1.12] has also found that ad hoc network life expectancy can be increased with the implementation of a link layer protocol which provides several levels of power save modes and a routing protocol that uses this link layer effectively. Each power save mode provides a different energy–latency trade-off (i.e. a level with a lower latency requires more energy). By using multiple power save modes, it allows applications (e.g., sensor reports) to achieve an acceptable latency while reducing energy consumption in the network.

The use of multi-level hardware design in order to get acceptable tradeoffs is very common in computer science. In computer architecture for example, accessing cache is much faster than main memory, but the main memory, in terms of cost per byte (is calculated from the data that is Read/Write in terms of time), is cheaper and can store much more data [1.13].

Knowledge of the power level of each node in the network has also been used to extend the whole network lifetime. Research reported in [1.14] has shown that incorporating current estimates of battery levels into routing metrics can reduce the demand on radios with little remaining energy and allow them to participate in the network longer. In addition to the knowledge of current battery power levels, an estimate of how quickly a radio node consumes energy may also be helpful in extending network lifetime. To use this principle, a

family of routing metrics that incorporate each node's rate of energy consumption has been proposed.

In large networks, relatively few nodes may be able to communicate directly with their intended destination nodes. Instead, most nodes must rely on radio nodes to forward their packets. Some nodes may be especially critical because they provide the only connection between certain pairs of nodes. If such a node depletes its battery power and stops operating, some nodes may no longer be able to communicate. For this reason, a number of researchers have focused on the design of communication protocols which consume less energy and prevent fast node failures and hence network segmentations [1.15].

Energy-preserving routing protocols for ad hoc networks continue to receive ongoing attention. In general, incorporating information about network nodes battery levels into routing can help to preserve radio with little remaining energy. By routing in such a way as to preserve energy in critical nodes, node failure and network partitioning can be delayed. Examples of routing metrics which depend on the remaining energy levels are presented in[1.16][1.17]. Metrics incorporating remaining energy levels are used to construct multicast trees. Remaining energy information is also useful in a sensor network, a special case of an ad hoc network in which a single node, called the base station, is the only traffic sink. Several routing protocols designed specifically for sensor networks also use battery-level information. Additional information for routing can be obtained by noting the rate at which a node depletes its energy. By combining depletion rate information with knowledge of remaining battery power, the time duration over which the node can be used before the power is depleted can be estimated. Routes can be selected to maximize the expected time before a node failure occurs. In some cases it may be better to utilize a node with relatively little remaining energy than to utilize one that the remaining energy is high and depleted rapidly.

Results from simulation studies have shown that using rates of energy consumption in addition to remaining battery power levels when making routing decisions can significantly extend the lifetimes of battery-limited nodes in ad hoc networks [1.15]. The remaining

lifetime metrics give very good performance in a variety of scenarios, particularly in situations where a small number of nodes become traffic bottlenecks. It should also be noted that in non-mobile networks, deployment issues may make such situations unavoidable. In mobile networks the very nature of mobility may cause bottlenecks to arise at any time. The remaining energy metrics with large values also do well in several cases. However, it is difficult to choose a ''best'' metric for all situations. It may be possible to identify situations in which traffic is unpredictable and ''switch'' routing metrics in these cases.

Some research activities have focused on improving network energy residue through the use of broadcast trees [1.18]. A new routing algorithm called Residual Battery Capacity Broadcast Routing Problem (RBBP) algorithm has been proposed. It has been shown that RBBP is optimally solvable as a polynomial. A new heuristic algorithm for computing achievable minimum power consumption has been proposed.

The construction of broadcast trees with maximum residual battery resource depends on various factors which include node mobility, energy resource, transmitted power level, etc. In order to assess these complex trade-offs one at a time, the nodes have to be assumed to be fixed [1.18]. Nevertheless, as argued in [1.19][1.20], the impact of mobility can be incorporated into this static model because transmitter power can be adjusted to accommodate the new location of the nodes, where necessary. The issue of constructing energy efficient broadcast trees which attempts to balance the energy usage throughout a given network has been addressed by Wieselthier et al.[1.21]. They introduced the notion of residual battery power into the cost metric that is used in the construction of a broadcast tree with the aim of prolonging the network's lifetime (which is thus related to RBBP). However, this approach is heuristic and no claim of optimality is made. In [1.22], Kang et al. addressed the issue of maximizing the network lifetime of wireless broadcast ad hoc networks by using another approach, called Minimum Spanning Tree (MST). In this version there was a development of a continuously updated periodic tree which controls, more effectively, the network load and therefore the lifetime of the whole network.

A new algorithm, called the Broadcast Incremental Power (BIP) which creates broadcast trees to minimize total power consumption is proposed in[1.20][1.21]. BIP is based on Prim's Algorithm for the construction of the MST, where new nodes are added to the tree one at a time until all nodes become part of the same tree. Adding a new node to an existing partial tree has the same cost as adding an amount of energy that needs to be consumed. The main difference between the two algorithms is as follows: when a new node is added to the tree then there is a link cost to the Prim's algorithm; however, BIP updates dynamically the costs at every step to overcome the cost of adding a new node.

Other proposed techniques include the application of directional antennas to improve the throughput of wireless ad hoc [1.23]. In [1.23] a Load-based Concurrent Access Protocol (LCAP) is proposed. This protocol allows for dynamic adjustment of the transmission power for both data and Clear-To-Send (CTS) packets to optimize energy consumption. This technique results in an increase in spatial reuse of each channel.

Moreover there was another approach from Idrissi [1.24] who has tried to minimize the power consumed at the mobile ad-hoc network by using an approach based on the Dijkstra's algorithm and called MANED. The MANED algorithm is a hybrid algorithm which allows finding the minimum of energy to consume when sending a message from the device s to the device d in the mobile ad-hoc network.

Arai and Lipur [1.25] also provided a solution in which a framework based on the principle that additional relay nodes with suitable energy and routing metric between source and destination node significantly reduces the energy consumption necessary to deliver packets in Wireless Ad-Hoc Network while keep the connectivity of dynamic nodes.

Vazifehdan et al [1.26] proposed the Least Battery-powered Nodes Routing (LBNR) algorithm, which take into account the power supply of nodes and their consumed energy for packet transmission and reception, and Minimum battery cost with Least battery-powered Nodes Routing (MLNR) algorithm, which take into account the residual battery power of nodes.

Zarifzadeh et al [1.27] proposed a new algorithm TC game algorithm in which nodes are able to dynamically adjust their transmission power in a per-packet manner, and try to minimize their energy usage through considering both traffic load and transmission power parameters.

## 1.5 Layout of Thesis

This thesis is divided into seven chapters. The background of the research conducted, the objectives and a brief review of work reported in open literature that act as the basis for this research programme is given in Chapter 1. Chapter 2 gives a more detailed overview of some of the principles of Ad Hoc Wireless Networks. It also highlights significant research reported in published literature. Chapter 3 describes the AODV protocol and compares it against other protocols in terms of energy consumption. Justification for the decision to develop a new algorithm that reduces energy consumption is presented. In Chapter 4, a detailed description of the proposed algorithms is given. Chapter 5 explains the measurement methodology and the simulation that has been conducted. The results of the simulations are presented in Chapter 6. A review of the proposed algorithm is given. This is followed by the results of the proposed algorithms against the original AODV protocol in various scenarios (number of nodes and different coverage areas). Chapter 7 summarises the research work described in this thesis, re-iterates the author's contributions and gives details of future work.

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# CHAPTER 2

# PRINCIPLES OF AD HOC WIRELESS NETWORKS AND PROTOCOLS

*Abstract: A review of ad hoc wireless networks is given in this chapter. The classifications of Ad hoc wireless networks are presented. An overview of protocols and the mechanism that are used in order to communicate between nodes is also presented.*

## 2.1   OSI Model and AD HOC Wireless Networks

In the early 1980s the International Organization for Standardization suggested (ISO) the Open System Interconnection (OSI) reference model [2.1], which was designed originally to allow multi-vendor computers to communicate. The OSI model architecture describes a general framework for creating modular systems (Figure 2.1). The network functionalities are divided into two main categories at the OSI model:

1.   those that are involved in end-to-end data transmission;

2.   those that are in hierarchical layers that contain sub-functions.

OSI consists of seven layers from the physical to the application layers. Currently, OSI is still the reference model and used to specify and imprint the different levels of networking protocols and their relationships with each other. The MANET communication mechanisms are related to the protocols operating in layers 1 to 3 of the OSI reference model. The higher layers are active only in the source and destination nodes.

| | |
|---|---|
| **Application Layer** | |
| **Presentation Layer** | |
| **Session Layer** | |
| **Transport Layer** | |
| **Application Layer** | |
| **Network Layer** | |
| **Data Link Layer** | **Logical Link Control Sub- Layer** |
| | **802.11 MAC Sub- Layer** |
| **Physical Layer** | **802.11 FHSS PHY** |
| | **802.11 DSSS PHY** |
| | **802.11a OFDM PHY** |
| | **802.11b HR/DSSS PHY** |
| | **802.11g ERP PHY** |
| | **802.11n MIMO/OFDM PHY** |
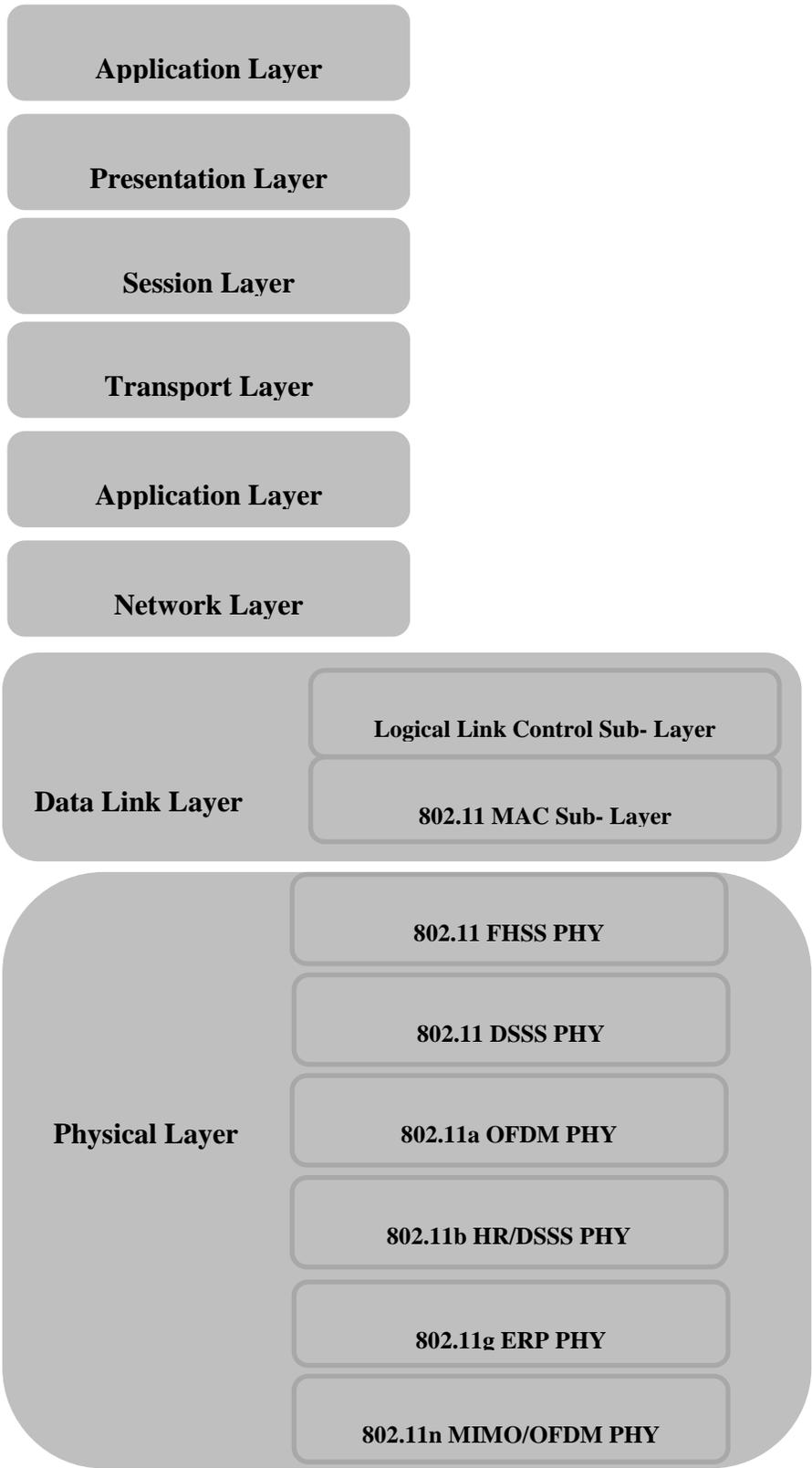
Figure 2.1: MANET (802.11) protocols according to OSI reference model

## 2.2 The Physical Layer Structure

The physical (PHY) layer [2.2] functions as an interface between the Medium Access Control (MAC) sub-layer and the wireless medium where there is transmission and reception of frames. The PHY layer offers sensing mechanisms, known as Clear Channel Assessment (CCA), for the wireless channel which indicates to the MAC sub-layer when a signal is detected or when the channel is idle. In Figure 2.2, there is a depiction of the physical layer structure which is divided into two sub-layers: the Physical Layer Convergence Protocol (PLCP) sub-layer and the Physical Medium Dependent (PMD) sub-layer. The PLCP is responsible for the channel status that the physical layer has to offer to the MAC sub-layer while PMD handles signal encoding, decoding, and modulation procedure.

LAYER 2: DATA link (MAC)

LAYER 1: Physical

PLCP

PMD
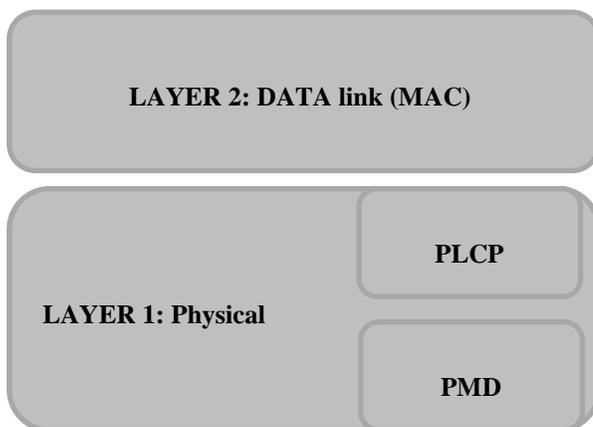
Figure 2.2: Physical Layer Structure

Initially there were three standards for 802.11 [2.3]:

1. the frequency-hopping spread-spectrum (FHSS);

2. the direct-sequence spread-spectrum (DSSS);

3. The infrared band (IR).

The 802.11 (FHSS) standard uses a set of channels with limited bandwidth for data transmission, i.e. is the 2.4 GHz frequency band is fragmented into 70 channels of 1 MHz

each. The data is transmitted through all the channels in a predefined sequence. In a predefined time window between 20 and 400 milliseconds the transmission utilises a new channel following a specific cyclic pattern. The modulation scheme that the system uses is a 2-level Gaussian frequency shift keying (2GFSK) with 1 Mbps data rate [2.3][2.4] while the 2 Mbps uses a 4-level GFSK modulation [2.3][2.4].

The 802.11 (DSSS) standard spreads the data stream using a larger bandwidth by applying a shifting sequence [2.3][2.5]. The 802.11 (DSSS) operates in the same frequency band of 2.4 GHz like the FHSS standard but it uses Differential Binary Phase Shift Keying (DBPSK) modulation scheme for 1 Mbps data rate [2.3][2.5] and Differential Quadrature Phase Shift Keying (DQPSK) modulation scheme for 2 Mbps data rate [2.3][2.6] instead of GFSK modulation.

The Infrared (IR), which is the third physical layer of the 802.11 standard, can support data rates of more than 4Mbps. The IR system uses modulation with direct detection such as Pulse Position Modulation (PPM) [2.7] [2.8] and On-Off keying (OOK) [2.8]. The RF signal in most cases, is preferred to be used instead of IR because it has the ability to penetrate walls and opaque objects [2.9].

In the past five years, there has been rapid development in integrated circuit technology. The RF signal encoding and modulation techniques of 802.11 operating devices have left further physical sub-standards layer: 802.11a PHY, 802.11b PHY, 802.11g, PHY802.11n PHY [2.3]. The 802.11a uses orthogonal frequency division multiplexing (OFDM) modulation which offers speeds up to 54Mbps in the 5GHz band. The advantage of OFDM modulation is that the wideband signal carrier is separated into many sub-carriers, each of which has a narrow bandwidth. The disadvantage of this is the absence of backward compatibility with the original 802.11 standards. The 802.11b standard is an extended version of 802.11 (DSSS) offering data rates of up to 1 Mbps, 2Mbps, 5.4 Mbps and 11 Mbps by using an improved algorithm known as Complementary Code Keying (CCK) [2.11] for signal modulation. The 802.11g offers data rates as high as the 802.11a, uses the

OFDM modulation [2.3][2.10] and provides backward compatibility with 802.11b whilst still operating in the 2.4 GHz band.

The 802.11n standard [2.3][2.12] is the latest offering from the IEEE standard committee tasked with the provisioning of a more robust, secure high data rate wireless communication systems. The data rate is close to 300 Mbps net throughput, after subtracting all the overhead for protocol management features. The 802.11n standard is built on previous 802.11 standards, especially 802.11a, by incorporating Multiple-Input/Multiple-Output (MIMO) antennas [2.13]. The previous versions of 802.11n had a single antenna or two antennas in a diversity configuration and normally choose only the one that provided the better signal quality. However, MIMO provides simultaneous reception/transmission using more than one antenna. The simultaneous reception and processing of multiple RF signals at various antennas of a node has the advantage of mitigating multipath fading, and improving the quality of the received signal.

## 2.3   The Data Link Layer

The data link layer (DLL) executes multiple important operations such as flow control, error control, addressing and communication with medium access control [2.1]. The DLL has two sub-layers (Figure 2.1):

1   the medium access control sub-layer, which is responsible for addressing, framing, and medium access control and

2   the logical link control sub-layer (LLC), which takes care of error control and flow control.

In MANETs because the nodes use the same communication channel, collisions may occur when there are more than one node transmitting simultaneously. Therefore, the sub-layer of the MAC is assigned to control access to the common channel amongst nodes in a MANET. The major challenge to the MAC sub-layer is the hidden node problem [2.14]. When there is a hidden terminal that is transmitting, a packet collision may occur at the node that is going to receive the transmission because a visible node may also be

transmitting. In Figure 2.3, when node A transmits data to node B, node C and node D (a hidden node) is not aware of the transmission due to its distance from node A. If nodes C and D simultaneously transmit data to node B, a collision occurs at node B.
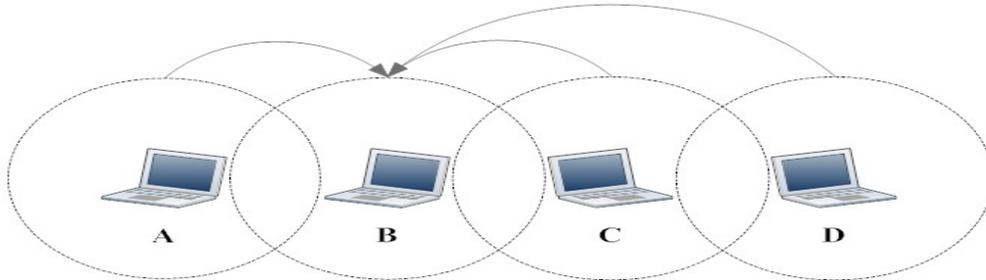


Figure 2.3: A hidden terminal problem in a MANET collision situation

There are many MAC protocols [2.15][2.16] that have been proposed to minimise or eliminate the effects of the hidden terminal problem through collision avoidance. Many of these collision avoidance schemes are sender-initiated, including an exchange of channel reservation control frames between the communicating nodes prior to data transmission. In this case, all the nodes in the nearby area of a given communicating node need to be aware that the channel will be pre-occupied for a specific time. In Figure 2.4, if node A, wants to transmit a data frame to node B, first it broadcasts a request-to send (RTS) frame containing the length of the data and the address of node B.  Once it receives the RTS, node B responds by transmitting a clear to send (CTS) frame containing the length of the data that is to be sent to node A. Any node that receives either of these two control frames stays silent for the entire transmission period. This silent period is known as virtual carrier sense. Random reception of RTS or CTS from neighbouring nodes can prevent same nodes from transmitting to other nodes outside the communication range. For example, in Figure 2.4, the communication between nodes A and B will inhibit node D from initiating communication with node C.
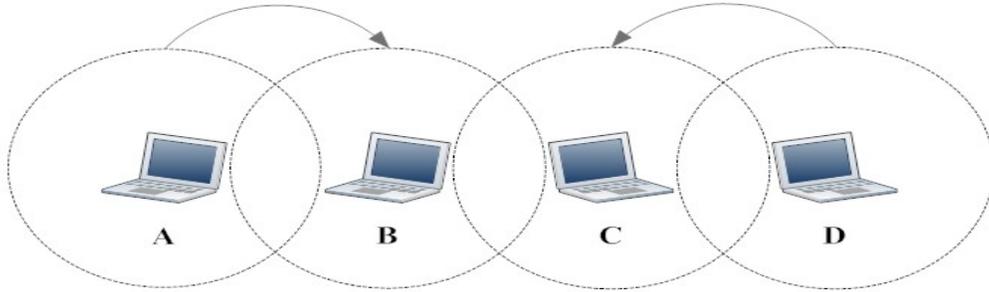
Figure 2.4: An exposed terminal problem in a MANET

This problem is referenced to the exposed terminal problem and can lead to inefficient usage of the communication channel. One solution that can solve the exposed terminal problem is the use of smart antennas or directional antennas [2.15][2.17] where the propagation of CTS, RTS and data frames is transmitted only to the intended nodes (Figure 2.5). Some devices employ smart antennas which allow them to use beamforming techniques to change the beamwidth and direction of transmission or reception. This allows the device to use large beamwidth to listen and, small beamwidth to transmit.
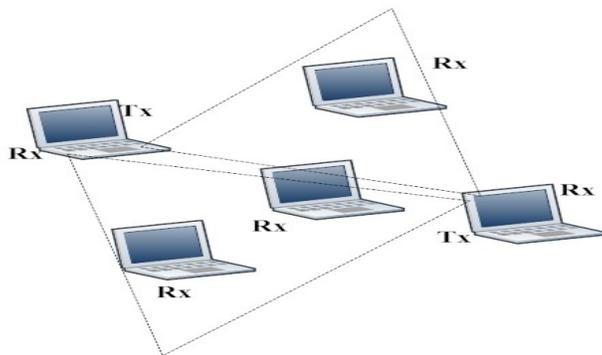


Figure 2.5: MANET with directional antennas

## 2.4   The Network Layer

An end-to-end transmission service can be provided from the Network layer, which includes the routing information exchange, searching a valid route to a destination,

repairing broken links and providing better usage of the available communication bandwidth [2.1]. In MANETs mobility can cause various problems such as [2.18]:

    a.  route breaks,

    b.  packet collisions,

    c.  transient loops,

    d.  stale routing information

    e.  difficulty in resource reservation.

The above problems may be reduced with the use of suitable routing protocol with a low communication overhead.

In MANETs because of the limitation of available battery lifetime and bandwidth, the use of a routing protocol with a low communication overhead is important. In order to reduce overhead, the routing control packets for discovering a new route or maintaining existing routes should be reduced. The control packets, due to the use of low bandwidth, cause data packets collision [2.19]. Consequently, it is desirable to develop routing protocol that uses only a small number of routing control packets.

## 2.5   The Transport Layer

The objectives of transport layer protocols are the following [2.1][2.20][2.21]:

    1.  set up and maintenance of end-to-end connections;

    2.  reliable end-to-end delivery of data packets;

    3.  flow control;

    4.  congestion control

The two most important protocols in the transport layer are:

    a)  Transmission Control Protocol (TCP) [2.20]

b) User Datagram Protocol (UDP) [2.21]

c) Stream Control Transmission Protocol (SCTP) [2.23]

TCP [2.20][2.22] offers reliability in data transmission/reception making it suitable for applications like file transfer (FTP) and email. The protocol is optimized for reliable delivery rather than speedy delivery. Therefore TCP can sometimes cause notable delays while waiting for non-delivered data or retransmissions of lost data packets, and it is not particularly adequate for real time applications such as video casting.

UDP [2.21] enables communicating nodes to receive/transmit short messages, also known as datagrams. This protocol does not ensure delivery reliability as the TCP does. Data may arrive out of order, be duplicated or lost without notice. Avoiding the overhead of checking if every packet actually arrives makes UDP faster and more efficient, at least for applications that do not require guaranteed delivery, such as broadcasting, video streaming and VoIP.

Many of the features of the TCP and UDP can also be found in the (SCTP) [2.23] which has been standardized as RFC 2960 in 2000 [2.24]. It provides acknowledged error-free non-duplicated transfer of data. SCTP provides reliability in flow control mechanisms but can also like the UDP can support unreliable transmission [2.25]. SCTP can provide multi-stream and multi-homing services for a single connection.

When a TCP connection first commence between a source and a destination, TCP enters to the slow-start phase [2.20][2.22] which is one of the algorithms that TCP uses to control congestion inside the network. During the slow-start phase, the TCP increases the congestion window every time the acknowledgment is received. The window size is increased by the number of segments acknowledged. This occurred until either an acknowledgment is not received for some segment or a predetermined threshold value is reached. In case that a loss event occurred, TCP assumes that happened because of the network congestion and takes steps to reduce the offered load on the network. Using the congestion control mechanism, TCP has been shown to have a good performance in wired networks [2.22].

In MANETs, TCP shows a poorer performance due to the following problems:

1. Lacks ability to detect packet loss due to congestion re-transmitting packets

2. Existence of stale routing information

3. High channel error rate

4. Frequent network partitions

Many researchers have carried out studies [2.26] in order to evaluate TCP's performance under different routing protocols over MANETs. Details of proposed modifications of TCP over MANETs have been presented by Papanastasiou in [2.27].

The research reported in this thesis focuses on the protocols that are used in the first four layers of the OSI reference model so the other three layers session, presentation and application will not be discussed in this thesis.

## 2.6   Mechanism of Broadcasting and Routing in MANETs

Broadcasting in MANETs is the procedure of dissemination of information to all reachable nodes [2.28][2.29]. Broadcasting is used in both unicast routing protocols and multicast routing protocols [2.30].

Flooding is a form of broadcasting where the source node transmits a packet to nodes in the neighborhood [2.31]. Each node in the neighborhood that receives the transmitted packet for the first time re-transmits it to other nodes. The broadcast procedure terminates when every node has received and transmitted the broadcast packet exactly once.

The flooding procedure ensures that it will cover the entire network, i.e. in a static network (with reliable communication) the broadcast packet is guaranteed to reach all nodes in the whole network [2.32]. Nevertheless the flooding procedure in large area and dense network may need many re-transmissions in order for the broadcast packet to reach every node. Figure 2.6 shows a sample network of 6 nodes with redundant transmission. When node 1 broadcasts a packet, nodes 2 and 6 will receive it. Nodes 2, 6 and node 3 will only forward

the packet after receiving it from nodes 2 and 6. Transmitting the broadcast packet only by nodes 1 and 6 is enough for the broadcast operation.
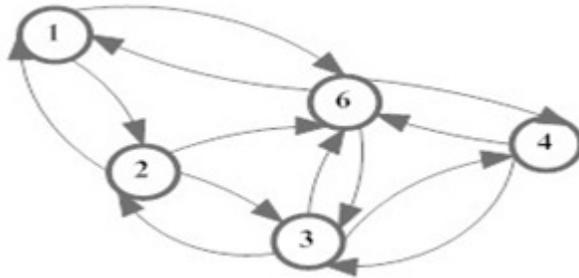


Figure 2.6: Example of MANET consisted of 6 nodes with redundant transmissions

In cases where the number of nodes in the network increases, the redundancy phenomenon will occur, causing collision and contention which will degrade the performance of the entire network. Such a situation is called the broadcast storm problem [2.30].

## 2.7    MANET Broadcasting Algorithms

The broadcast storm problem [2.33][2.37] can be solved by decreasing the number of nodes that re-transmit (forward) the broadcast packet. Ni et al. [2.33] have classified broadcasting algorithms into two categories:

1. Probabilistic;

2. Deterministic

Comparisons have been made by William and Camp [2.32] of the performance of various proposed broadcast approaches which include the following:

a. Probabilistic;

b. counter-based;

c. area-based;

d. neighbour-designated;

e. cluster-based

**Probabilistic broadcasting** is one of the simplest broadcast techniques that have been described in the literature [2.33]. In this approach, each intermediate node is assigned a probability p while it re-broadcasts received packets. To determine the correct level of probability to assign to each node, Sasson et al. [2.34] has proposed a technique based on the transition phase phenomenon [2.35], using random graph technique [2.36].

**In a counter based technique** [2.33], each time that a node receives a broadcast packet, it starts a random assessment delay (RAD) process, which counts the number of received duplicate packets. When the RAD expires, the node re-broadcasts the packet only if the counter does not exceed a threshold value. In case that RAD expires and the counter already exceeded this value, there is an assumption that all the nodes in the neighborhood have received the same packet, and does not forward the packet.

**In area based methods,** a node is allowed to forward a broadcast packet based on the additional coverage area. The additional coverage area is specified by a distance-based scheme or location-based scheme, i.e. if the node that receives the packet is located a few meters away from the transmitter, the probability of forwarding the packet at the additional area is quite low [2.33]. However, when the node that receives the packet is located at the edge of the sender's transmission range, then the probability of re-broadcasting the packet would be very high [2.37].

Using a **distance based scheme** [2.33], a node compares the distance between itself and each nearby node that has previously forwarded a given packet. During the reception of the forwarded packet, a process of random assessment delay (RAD) is started and redundant packets are cached. When the RAD expires, there is an examination of the locations of all the sender nodes in order to find out if any node is closer than a threshold distance value and if it is true, the node does not rebroadcast.

Consequently, the use of a distance-based scheme demands awareness of the locations of nearby nodes in order to decide whether to re-broadcast or not. In this case the signal

strength can be used for calculating the distance to the source and the destination or alternatively, the location information could be retrieved by the use of a GPS receiver. In this distance-based scheme, nodes rebroadcasts packets irrespective of whether there are other nodes within its communication range. This scheme does not result in a reduction of in the number re-broadcast.

In a **location based scheme** [2.33][2.37], each node is expected to be aware of its own position relative to the position of the sender using a geo-location technique such as GPS. Whenever a node transmits or receives a broadcast packet it adds its own location to the header of the packet. When a nearby node initially receives the packet, it notes the location of the sender and calculates the additional coverage area obtainable if it were to re-broadcast. If the additional area is less than a threshold value, the node will not re-broadcast, and all the future receptions of the same packet will be ignored, else the node assigns a RAD before delivery. In case that node receives a redundant packet during the RAD, it re-calculates the additional coverage area and compares that value to the threshold. Comparison is also made with all redundant broadcasts received until the packet reaches either the predefined send time or is dropped.

The **neighbour knowledge based scheme** [2.32][2.30][2.33] nodes keep fresh information about their neighborhood by sending periodic "hello" packets, which are used to decide whether to re-broadcast or not. The main goal of this scheme is to predefine a small subset of nodes, which is known as forwarding set, for broadcasting packets with the aim that every node in the network will receive them. There are many neighbour - knowledge based algorithms that include forwarding neighbor, dominant pruning scalable, scalable algorithms etc. Some are discussed at the following lines.

In **forwarding neighbours schemes** [2.38], the forwarding process of each node is specified by its neighbours. Each sender selects a subset of its 1-hop neighbours as forwarding nodes. The forwarding nodes are selected using an algorithm known as connected dominating set (CDS) while the identifiers (IDs) of the selected forwarding

nodes are part of the forwarder list. Every assigned forward node defines its own list of forwarder nodes before forwarding the broadcast packet.

The **dominant pruning algorithm** [2.39] is a classic example of the forwarding neighbours scheme. The basic idea is that in order to reduce the number of redundant transmissions it needs to decrease the number of forwarding nodes.

On broadcasting based on a self -pruning scheme [2.39]-[2.41] each node can define its own status whether it is a forwarder node or not, after the reception of the first or several copies of a broadcast packet. Wu et al [2.40] have proposed that each node must have information form at least 2-hop neighbours which are collected via a periodic transmit/receive of "hello" packets amongst nearby nodes. A node keeps its list of known 1-hop nearby nodes in the headers of "hello" packets and broadcast the packets. Each node that receives the packet creates a list of its 2-hop and 1-hop nearby nodes that will be covered by the broadcasting process. If the receiving node will not reach any additional nodes, it abstains from broadcasting; otherwise it continues to re-broadcast the packet.

The **scalable broadcast algorithm** [2.30], demands from all nodes to acquire knowledge of their neighbours within a two hop radius. A combination of the information from the nearby nodes and the identity of the node from which a packet is received allow a receiving node to determine whether it will reach more nodes by forwarding the broadcast packet or not. Collecting information about 2-hop neighbours is feasible via a periodic exchange of " hello" packets. Every "hello" packet includes information regarding the node's identifier and the list of known neighbours. After a node receives a "hello" packet from all its neighbours, it has information regarding 2-hop topology around itself.

In multipoint relaying [2.42] , every node chooses a small group of its 1-hop neighbours called Multipoint Relays (MPRs) that are adequate to cover its 2-hop nearby nodes. When a broadcast packet is transmitted by a node, only the MPRs of a given node are allowed to

forward the packet. Using some heuristics, every node is capable of calculating its own MPRs based on information of its neighbourhood topology. This information is acquired through a periodic exchange of "hello" packets among neighbouring nodes.

In **cluster-based broadcast schemes** [2.43], the entire network is fragmented into several clusters creating a simple backbone infrastructure. Every cluster has one cluster head that controls all other members in the cluster, and it is responsible for forwarding packets and selecting which node use to forward packets on behalf of the cluster. The overlapped clusters are connected by gateway nodes. Although in MANETs clustering can be deliberate, it is insignificant the overhead associated with the formation and preservation of clusters. Cluster heads and gateway nodes of a specified MANET together create a connected dominating set [2.44]. The Non-deterministic Polynomial time (NP)-complete gives solution to a problem of finding the least number of forwarding nodes that creates the minimum connected dominating set [2.36].

The MANET routing protocols are mainly developed to maintain routes inside MANET, and they do not use any access points to connect to other nodes in the network and Internet. Routing protocols can be classified into three categories depending on their properties. The three main categories of routing protocols for MANETs are:

- Reactive

- Proactive

- Hybrid

## 2.8  Reactive (On-Demand) routing Protocols

For protocols in this category there is an initialisation of a route discovery mechanism by the source node to find the route to the destination node when the source node has data packets to send. When a route is found, the route maintenance is initiated to maintain this route until it is no longer required or the destination is not reachable. The advantage of

these protocols is that overhead messaging is reduced. One of the drawbacks of these protocols is the delay in discovering a new route.

Ad hoc On-Demand Distance Vector Routing (AODV) (Figure 2.7) and Dynamic Source Routing (DSR) belongs to this category of protocols. Example of reactive it finds a route [2.28] to a destination on-demand basis, meaning that a route is established only when it is needed. This is important in MANETs since fully up-to-date knowledge of all routes in the network can only be achieved with large communication traffic (high number of receive/transmit packets). The mechanism of route discovery in AODV routing protocol consists of two processes:

1. route discovery ;

2. route maintenance

If a node needs to send data but does not already have a valid route to the destination, it starts a route search process in order to find the destination node by broadcasting a Route Request Packet (RREQ) to the whole network via a simple flooding process [2.28]. The RREQ packet includes the following main fields:

a. source identifier;

b. destination identifier;

c. source sequence number;

d. destination sequence number;

e. broadcast identifier;

f. time-to-live (TTL)

The destination sequence number is used by AODV to guarantee that routes are loop-free and contain up to date information about the route [2.28][2.45].

Every intermediate node that forwards an RREQ packet establishes a reverse route back to the source node by mapping the next hop information in its routing table. When the RREQ

packet finds an intermediate or the destination or node with a valid route, the intermediate or the destination node responds by unicasting a route reply (RREP) packet to the source node using the reverse route. The route validation at the intermediate nodes is defined by comparing its sequence number with the destination sequence number. Any node that takes part in forwarding the RREP packet back to the source creates a forward route to the destination by imprinting the next hop information in the routing table. Nodes that form the route from source to destination are not required to be aware of nodes that are forming the path other than the next hop nodes to the source and destination. Every intermediate node, while forwarding a RREQ, keeps the previous node address and its broadcast identifier. A timer (time-to-live) is used to delete this entry in case a RREP is not received before the timer expires. By this way can be stored an active path at the intermediate node because AODV cannot use source routing of data packets.

The next step of the routing mechanism is the route maintenance process. After the route discovery process and, as long as the discovered route is used, the intermediate nodes along the active route maintain an up-to-date list of their 1-hop neighbours by exchanging periodic "hello" packets. In cases where the route becomes inactive, a timer is initiated, after the expiration of which the route is considered stale and expires. If the routing agent at a node is aware of a link breakage for an active route, a Route Error (RERR) packet is generated at the point of breakage. This (RERR) packet is broadcasted to the nodes that are actively using the route and those nodes participating in the route's formation. In this way, the RERR packet disseminates to the source node which can then start the discovery process of a new route.
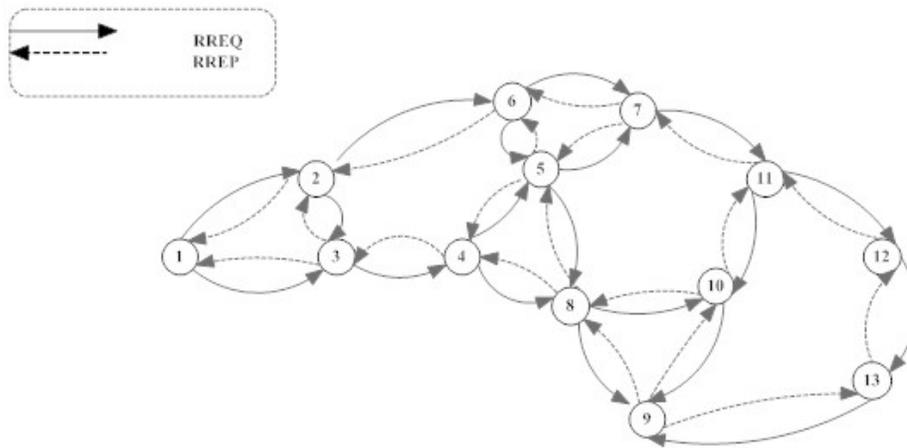
Figure 2.7: A typical AODV network

In Dynamic Source Routing (DSR) [2.29] every packet that is transmitted contains ordered information in its header about all the nodes through which it should be routed. The advantage of this kind of routing is that the intermediate nodes do not need to keep up-to-date routing information in order to route the data packets towards the destination since the packets includes all the routing decisions. In this way are reduced periodic route advertisement and neighbour detection packets that are used in other protocols [2.45][2.46]. The routing mechanism of the DSR protocol includes two phases:

1. route discovery

2. route maintenance

When a node using DSR routing agent, tries to send a data packet to a destination for which it does not know of the route, it initiates a route discovery process to find the route. In the route discovery process there is a broadcasting of RREQ packets to the network using the simple flooding process, in which each node that receives an RREQ packet rebroadcasts it, until it reaches the destination or it has route information about the destination in its route cache. Such a node replies to the request with an RREP packet that is forwarded back to the source node.

The RREP packet is sent back to the source node using the reverse path established by the RREQ mechanism. The information regarding the route is kept as a RREP packet and cached at the source node for future use. In route discovery process, every data packet transmitting from source to destination includes the complete route to the destination. Route preservation is responsible for detecting changes in the network topology that affects the used routes. Whenever a link breakage happens, a RERR packet is transmitted back to the source node from the node where the link breakage has occurred. The transmitted RERR packet erases all the entries in the route caches along the path that contains the broken link. The source node must restart the route discovery process, if this route is still needed and no alternate route is found in the cache.

The Temporally Ordered Routing Algorithm (TORA) [2.51][2.52][2.53] routing protocol is based on the Lightweight Mobile Routing (LMR) protocol and the "link reversal algorithm". The TORA is an adaptive loop-free distributed routing algorithm which relies on the link reversal concept. TORA is used to work in environments with highly dynamic mobile networking. It uses a process which is source-initiated that offers a variety of paths for any source/destination pair. Generally, it has the ability to quickly follow the topological changes that may occur and re-create valid routes. In order to do this, nodes need to keep routing information about nearby (one-hop) nodes. The basic functions that the protocol performs are the following:

   a. Route creation

   b. Route maintenance

   c. Route cancellation

Hence when a node seeks a route to a given destination it sends a QUERY message which includes the address of the destination node. This packet travels through the network until it reaches the destination or an intermediate node that has a route to the destination node. The receiver node then broadcasts an UPDATE packet listing the number of direct links that has been used in order to reach the destination. As this propagates through the network, each

node updates its list by adding another pair of nodes (source-destination). This creates a series of directed links from the node that originated the QUERY to the destination node. When the node finds a specific destination which is unreachable, it sets a local maximum value of direct links for that destination. If the node cannot find any adjacent node which has a list of direct links to the destination, it attempts to search a new route. If there is a network partition then the node sends a CLEAR message that resets all routing states and removes invalid routes from the network. Figure 2.8 illustrates typical MANET which uses the TORA routing protocol. In Figure 2.8 (part A) presented a situation that there is link failure between 4 and 6 node. The other parts of Figure 2.8 outline searching attempts for a new route to node 6.
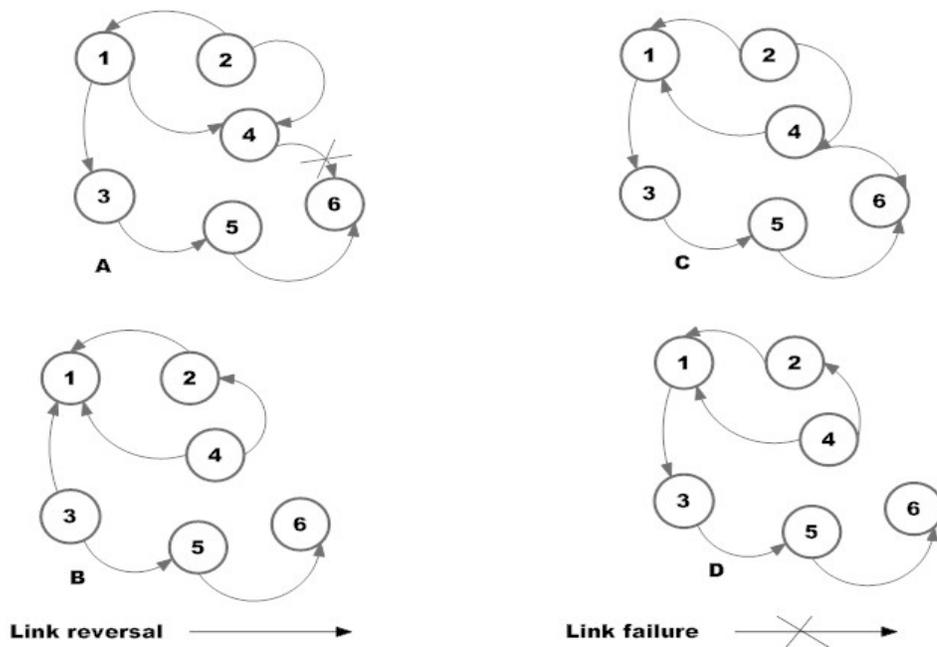


Figure 2.8: TORA Routing Protocol

## 2.9 Proactive (Table-Driven) Routing Protocols

In this family of protocols, nodes maintain one or more routing tables about nodes in the network. These routing protocols update the routing table information either periodically or in response to a change in the network topology. The advantage of these protocols is that a

source node does not need route-discovery procedures to find a route to a destination node. On the other hand, the drawback of these protocols, is the maintenance of a consistent and up-to-date routing table, that causes substantial messaging overhead (a well-known problem route flapping), which consumes bandwidth and power, and decreases throughput, especially in case of a large number of mobile nodes. In order to evaluate the table-driven routing protocols, needs to be measured the convergence time, an indicator that measures how quick and reliable exchanged the information between the nodes, an issue that this research did not take into account.

Destination-Sequenced Distance-Vector Routing (DSDV) [2.47] [2.48]  is another table-driven routing protocol like the Optimized Link State Routing (OLSR) [2.51] protocol for MANETs based on the algorithm of Bellman-Ford [2.49]. The main objective of the algorithm is to fix the Routing Loop problem by separating the stale routes from new routes [2.48]. Every entry in the routing table contains a sequence number, which is generated by the destination, which becomes even when a valid route is present and in any other case an odd number is used [2.47][2.49].

The DSDV protocol requires that each node in the network should continuously; send to the adjacent nodes, its own routing table [2.48][2.49]. Due to the fast change of the entries, the information regarding the updated routing table should be transmitted more frequently so that every node will be aware of the adjacent nodes in the network. This way will ensure the smallest number of hops between a source and a destination node.

The broadcast data packet that DSDV protocol uses in order to keep up-to date route to adjacent nodes, contains the following information:

- The destination address
- The number of hops required to reach the destination and
- The new sequence number, originally stamped by the destination

When the new information is received from the adjacent node it will be retransmitted soon effecting the most rapid possible dissemination of routing information among all the

cooperating mobile hosts. The mobile host cause broken links as they move from place to place within the network. The broken link may be detected by the layer2 which describes the MAC protocol and may be described as infinity. When the route is broken in a network, then immediately that metric is assigned an infinity metric, by determining that there is no hop and the sequence number is updated. Sequence numbers originating from the mobile hosts are defined to be even number and the sequence numbers generated to indicate infinity metrics are odd numbers.

In the case where an information packet is received from another node, it compares the sequence number with the available sequence number for that entry. If the sequence number is larger, then it will update the routing information with the new sequence number otherwise, if the information arrives with the same sequence number it searches for the metric entry and if the number of hops is less than the previous entry the new information is updated. While the nodes information is being updated the metric is increased by one and the sequence number is also increased by two. In case a new node enters the network, it will announce itself in the network and the nodes in the network update their routing information with a new entry for the new node [2.48][2.49].

During broadcasting, the mobile hosts will transmit their routing tables periodically or when the network topology changes. In cases that the network topology changes occurred faster, this could lead to a continuous creation of new routes transmissions upon every new sequence number from that destination. The solution for this is to delay the broadcasting of such routes until it shows up a better metric.

Consider Figure 2.9 which has 6 hosts in the network. The changes to the node 2 routing table with reference to the movements of node 3 will be examined. Every node broadcasts the routing information to all nodes in the network and hence the routing table of node 2 in Figure 2.9 will be as shown in Table 2.1.

But, when node 3 moves its location as shown in Figure 2.9 nearer to node 6 then, the links between node 2 and node 1 will be broken resulting in the assignment of infinity metric at

node 2 for node 1 and the sequence number will be changed to odd number in the routing table at node 2. In the next step it will update this information to its neighbours' hosts. Since, there is a new neighbour host for node 4 and node 6; they update their information in the routing tables and they broadcast. Now, node 4 will receive its updated information from node 3 where node 4 will receive two information packets to reach node 3 with the same sequence number, but different metric. The selection of the route will depend on less hop count when the sequence number is the same. Now the routing table will be as shown in Table 2.2.
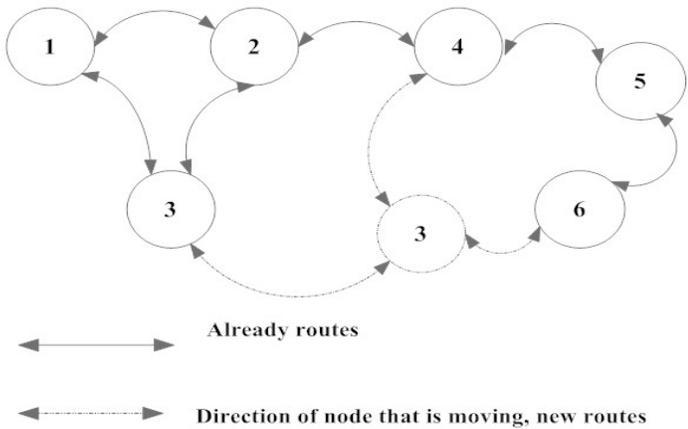


Figure 2.9 An example of the DSDV routing protocol

Table 2.1: Routing Table of node 2

| Destination | Next Hop | Metric | Sequence Number |
| --- | --- | --- | --- |
| 1 | 1 | 1 | SQN402_1 |
| 2 | 2 | 0 | SQN124_2 |
| 3 | 3 | 1 | SQN306_3 |
| 4 | 4 | 1 | SQN564_4 |
| 5 | 4 | 2 | SQN688_5 |
| 6 | 4 | 3 | SQN64_6 |

Table 2.2 Routing Table of node 2 after the movement of node 1

| Destination | Next Hop | Metric | Sequence Number |
| --- | --- | --- | --- |
| 1 | 1 | 1 | SQN204_1 |
| 2 | 2 | 0 | SQN256_2 |
| 3 | 4 | 2 | SQN64_3 |
| 4 | 4 | 1 | SQN512_4 |
| 5 | 4 | 2 | SQN256_5 |
| 6 | 4 | 3 | SQN712_6 |

The Optimized Link State Routing (OLSR) protocol [2.54] [2.73] [2.75] is also a proactive routing protocol for MANETs. The OLSR protocols creates and maintains routing tables by omitting partial link state information to all nodes in the network using an optimized flooding control protocol, called MultiPoint Relaying (MPR). In this flooding control protocol, a node re-transmits a packet only once after having received the packet the first time from MPR selector.

OLSR operates in order to minimize the organization of high traffic rates. The use of MPRs reduces the effect of flooding messages in the network. To do this, during each topology update, each node in the network selects a set of adjacent nodes to forward its packets. This group of nodes is known as the multipoint relays of that node. Every node that is not part of

the group can only process each packet but without the capability for re-transmission. The selection of the MPRs starts by broadcasting to each node periodically a list of one-hop nearby nodes using hello messages. From the produced list of nodes in the "hello" messages, each node selects a group of one hop nearby nodes, which covers all of its two hop neighbours. Each node defines the best route to every known destination using information topology which is kept in a routing table. In this way, routes to any valid destination are immediately available when data transmission begins.

## 2.10    Hybrid routing mechanism

Hybrid routing protocols [2.73] are protocols, which are both proactive and reactive in nature. These protocols provide flexibility by allowing nodes that are in the neighborhood to work together and create a small network that decrease the route discovery overheads. This is achieved by proactively storing information on adjacent nodes and defining routes to distant nodes using a route discovery process. Many hybrid protocols are zone-based, meaning that the network is partitioned or seen as a number of zones by each node.

In the Zone Routing Protocol (ZRP) [2.73][2.74], the nodes create a routing zone, where nodes can connect to each other proactively. Consequently, the nodes that belong to this routing zone can be connected immediately. For nodes that are outside the routing zone, routes can be reached on-demand, by using any on-demand routing protocol to define a route to the destination node. In this way, these kinds of protocols can reduce the amount of communication overhead compared to proactive protocols. Moreover, it reduces the delays that happened with some reactive protocols such as DSR, by discovering routes faster. This occurs because, in order to define a route to a node outside the routing zone, the routing only has to travel to a node which is on the edge of the routing zone of the destination node, as the node at the boundaries would proactively store routes to the destination. On the other hand, the disadvantage of ZRP protocol is that for large sub-networks of routing zones the protocol behaves like a proactive protocol, while for small part of routing zone it behaves like a reactive protocol.

## 2.11  The Mobility Model

The network size is a factor that provides information regarding the number of nodes that the network consists of, and how this affects the communication between nodes. The AODV protocol uses the flooding method to find a route to destination node. In cases where the number of intermediate nodes between the source and the destination nodes is high, it consumes more energy during the route discovery process because it needs more time to establish the route and vice versa.

In MANETs the mobile nodes usually move from one point to another, which makes it difficult to model these movements. In order to evaluate communication protocols for MANETs, it is important to develop and use mobility models that can depict the movements of mobile nodes.

There are two mobility models that are used for the evaluations of protocols [2.56]:

1.  traces

2.  synthetic models

Traces are mobility patterns that are found in real life systems. They give precise information, and especially when the observed system is populous and take part for a long time. The disadvantage of this model is that it doesn't offer confidentiality of certain data. Furthermore, new systems like MANETs are not easily to be modeled if there are not any pre-existent traces. In this case synthetic models are often used. Synthetic mobility models works like the random waypoint model [2.57] which try to predict the behaviour of mobile nodes without the use of traces. In addition to the random waypoint model, there are many other models which use different approaches to model patterns, such as the community based mobility model [2.58] that can be used to models human mobility within communities and amongst different communities. There are also the Manhattan mobility models [2.60] [2.61] for models vehicular mobility on structured roads in a city, and the Group mobility model for military combat zones.

The random waypoint mobility model [2.57] is one of the most famous mobility models in mobile ad hoc network research and is itself the focal point of most research activity [2.60][2.61]. The model defines a collection of nodes which are placed and move randomly within a specific simulation space. Then a node is assigned to choose a random destination inside the simulation area and moves towards it at a pre-define speed, s. Once it has reached its destination, the node pauses for some time, t, before it selects another random destination and repeats the process. The node speed, s, of each node is defined according to a uniform distribution with s (0...V max), where Vmax is the maximum speed parameter. Pause time is a constant, t, in seconds.

It should be mentioned that the random waypoint mobility model is the most popular mobility models [2.60][2.61], because each node moves independently.

## 2.12   The Simulation Software

The process of simulation has proven to be a precious tool for many researchers where other methods cannot be applied and experimentation isn't attainable. Simulation is used by researchers generally in order to analyze system performance prior to physical design or to compare multiple system conditions. Currently, there are several discrete-event network simulation tools have been used for performance analysis in MANETs [2.62][2.64]. The most commonly used network simulators include NS-2 [2.59], GloMoSim [2.60], QualNet [2.66] and OPNET [2.66].

NS-2 [2.62] is one of the most popular discrete event network simulation tools and it uses an architecture which is organized according to the OSI reference model [2.1]. NS-2 was initially designed for wired networks but has been extended for simulating wireless networks, including wireless LANs, mobile ad hoc networks (MANETs), and wireless sensor networks (WSN). The number of users has increased significantly over the past couple of years [2.64]. This occurred because it is open source software and includes detailed simulation examples of significant operations of such networks [2.59]. The

development efforts of the simulator have been supported by National Science Foundation (NSF) and Defense Advanced Research Projects Agency (DARPA) [2.67].

The NS-2 simulator supports many models such as [2.68] [2.69]:

    a. radio propagation

    b. capture effects

    c. carrier sense

NS-2 simulation software [2.62] uses the IEEE 802.11 standard such as the Distributed Coordination Function (DCF) MAC protocol [2.2]. In this standard, before the transmission of each unicast data packet there is an RTS/CTS control packet which is exchanged between nodes that communicate in order to reduce the probability of collisions because there are hidden terminals [2.71]. Every correctly received unicast data packet should be followed by an Acknowledgment (ACK) to the sender, else the sender re-broadcasts the packet a limited number of times until this ACK is received [2.2]. On the other hand broadcast packets such as the RREQ packets are not preceded by an RTS/CTS exchange nor acknowledged by their recipients, but they are sent only when the transmission medium is sensed as to be idle.

## 2.13   The Research Method

In this research, extensive simulations are conducted in order to explore power consumption issues in MANETs. This section briefly discusses the choice of simulation as the proper method of study for the purpose of this dissertation, justifies the adoption of NS-2 as the preferred simulator, and further provides information on the techniques used to reduce the opportunity of simulation errors.

After some consideration, simulation has been chosen as the method of study in this research. Notably, when this research work was undertaken, analytical models with respect to multi-hop MANETs were considerably coarse in nature [2.70], which made them incompatible for the purpose of studying power consumption with a light accuracy.

Moreover, since this study includes the use of a large scale of MANETs, the deployment of nodes to conduct the experimental tests would have been difficult. For all the above reasons simulation was therefore chosen since it provides balance between the accuracy of observation involved in a test-bed implementation and the flexibility required to study different scenarios.

To conduct performance analysis of the proposed solutions in this thesis, NS-2 version (2.29) simulator [2.62] has been extensively used. NS-2 was chosen at the beginning because it is a proven simulation tool that has been used in many previous studies on MANETs [2.64] and has been validated and verified in [2.64][2.65].

## 2.14   Simulation and Metrics

The following metrics have been used to evaluate the performances of the protocols [2.69]:

- *Number of Packets dropped*: The number of data packets that are not successfully sent to the destination during the transmission.

- *Remaining Battery Power*: this is the average remaining battery power across all the nodes in the network.

- *Consumed Power*: the average consumed battery power across all the nodes in the network.

- *Throughput*: it is the number of packet arriving at the sink per millisecond.

- *MAC Load*: this is the ratio of the number of MAC layer messages generated by every node in the network to the total number of data packets successfully delivered to all destination nodes.

- *Dropped Packets*: this is the number of nodes in the network versus agent level total dropped packet.

- ***Dropped Bytes***: This is the number of nodes in the network versus agent level total dropped bytes.

## 2.15　Summary

In this chapter, the characteristics of MANETs and their implementation based on the OSI reference model, focusing in first four layers, the physical, data link, network and transport is discussed. The chapter has reviewed various broadcast algorithms that have been proposed for MANETs including simple flooding as well as probabilistic, counter-based, knowledge based, distance based and location based methods.

The chapter has also provided background information on AODV, DSR, DSDV, TORA and OLSR which are used in the dissertation in order to evaluate the power consumption of these protocols in various scenarios. The justification for selecting NS-2 as a simulation platform has been given and the advantage of using a simulator instead of a real experimental system has also been widely described.

The next chapter will described in details the AODV routing protocol. Justification for the decision to develop a new algorithm that reduces the energy consumption in AODV routing protocol will be given.

## 2.16　References

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# CHAPTER 3
# PRINCIPLES OF AODV PROTOCOL

*Abstract: This chapter describes the AODV protocol and the effects of flooding mechanism on its performance. Justification for the decision to develop a new algorithm that reduces the energy consumption in networks using this algorithm is provided.*

## 3.1    Justification for the decision to develop a new algorithm

AODV and most of the on-demand ad hoc routing protocols [3.1] employ a broadcast scheme referred to as "simple flooding" whereby a route request packet originating from a source node is blindly disseminated to the rest of the network nodes. This leads to excessive redundant re-transmissions, causing high channel contention and packet collisions in the network, a phenomenon called broadcast storm. Thus leads to high power consumption with limited effectiveness. Reducing the flooding will reduce the protocol overhead and routing load and therefore the power consumption.

## 3.2    AODV Protocol

AODV [3.2], as briefly presented in chapter 2, is a reactive routing protocol that establishes a route to a destination on-demand. That is, a route is established only when it is required by a source node for transmitting data packets. This is beneficial in mobile ad hoc networks since maintaining up-to-date knowledge of all routes for every node implies large communication overhead. The routing mechanism of AODV consists of two processes:

   a.     Route discovery

   b.     Route maintenance

When the source node wants to send information to a destination node and there is no valid route, it starts the process to discover the route by sending the route request packet to all nodes using simple flooding technique [3.3] as shown in figure 3.2.

## 3.3    Route Request Mechanism (RREQ)

In AODV [3.4] the messages that are broadcasted include Route Request (RREQ), Route Reply (RREP), and Route Error (RERR). These are saved in routing table entries in the form of concrete status information for destinations of interest.

The RREQ packet has the following main parts:

1. Source identifier,
2. Destination identifier
3. Source sequence number
4. Destination sequence number
5. Broadcast identifier (Request ID)
6. Time-to-live

Each entry in the routing table has the latest information such as sequential serial number for the destination. The specific number is called destination sequence number which is updated when a node receives new information from RREQ, RREP, or RERR messages about the destination. If each node in the network is denoted by N and there are m nodes in the network then $sq(N_i)$ is the sequential number of node i.

A destination node increases the sequence number in the following cases:

- Before it starts the search process for new route, it increases its sequence number. In this way, it protects against possible conflicts with previously defined routes to the source.

$$sq(N_i) = sq(N_i) + 1 \hspace{4cm} (3.1)$$

- When it intends to start sending a RREP, it has to renew its own sequence number to the maximum of its current sequence number $sq(N_i)$ and the destination sequence number $sq(N_j)$ in the RREQ packet.

if $sq(N_i) \le sq(N_j)$ then

$$sq(N_i) = sq(N_j) \quad i,j=1....m \tag{3.2}$$

if $sq(N_j) \le sq(N_i)$ then

$$sq(N_j) = sq(N_i) \quad i,j=1....m \tag{3.3}$$

A destination node can increment the sequence number $sq(N_j)$ by one if one of the three following statements is true:

$$sq(N_j) = sq(N_j) + 1 \begin{cases} N_i \ne N_j \\ New\ sq(N_j) \\ No\ valid\ path \end{cases} \tag{3.4}$$

## 3.4    The routing table entries and lists of adjacent nodes

When a node receives a control packet (routing packet) from its neighbour, or creates, or renews a path to a particular destination or subnet, it searches in its routing table for a valid entry for this destination. If there is no record in the table it creates a new one. The sequence number is defined by the information contained in the control packet.

The sequential number is updated in the following cases:

- When the value is higher than that in the routing table, that is

  if $sq(N_i)$ is sequence number of node i in the routing table, if it receives a new number

  $$sq(N_i)' > sq(N_i) \quad \text{then } sq(N_i)' = sq(N_i) \tag{3.5}$$

- When the value is the same as in the table, but the sum of the required steps (number of hops) is smaller than that in the table, that is:

$$\sum_{j=i+1}^{k} hopC(N_i, N_j) < \sum_{j=i+1}^{l} hopC(N_i, N_j), k \le l \le m \tag{3.6}$$

where $\sum_{j=i+1}^{l} hop(N_i, N_j) = n + 1$ is the number of hopes from node $N_i$ to node $N_j$ that is currently stored in the table and $\sum_{j=i+1}^{k} hopC(N_i, N_j) = n$ is the updated number of hops from node $N_i$ to node $N_j$

- When the sequential number is unknown, then

$$sq(N_i) = sq(N_i) + 1 \tag{3.7}$$

For each valid route maintained in a routing table, a list of precursors is also maintained, i.e. intermediate nodes that can forward packets along the route. The precursors are notified by the node if it loses a link route.

## 3.5    Route Request Query

A node distributes a RREQ packet if there is a route request to a destination. This can happen if the destination is not known in advance or if a path was invalid or becomes inactive. The value of the destination sequential number that is copied to a routing table is contained in the packet and is associated with the last number received. The exact number is increased when a priority RREQs messages is sent.

If $sq(N_j)$ is the sequence number to the destination node j, then:

$$sq(N_j) = sq(N_j) + n_{priority} \tag{3.8}$$

where $n_{priority}$ is the priority number of the received RREQ message.

The $RREQ_{ID}$ field is increased from a value of 1 except the last $RREQ_{ID}$ that is used by the current node. Each node maintains only one $RREQ_{ID}$ and the source node uses the $RREQ_{ID}$ and the IP address of the source of RREQ for PATH_DISCOVERY_TIME. PATH_DISCOVERY_TIME procedure of the RREQ mechanism, that is used to prevent nodes from responding to the same RREQ message it has already processed.

If $(RREQ_{ID})_i = 1$ then

$$(RREQ_{ID})_{n+1} = (RREQ_{ID})_n + 1, \text{n=i,..1, } 1 \leq n \tag{3.9}$$

where i is the number of current node and $RREQ_{ID}$ field is to be used by the current node.

The communication between a source and a destination is duplex. That means that the destination has to have a route to the source. To achieve this efficiently, the creation of a RREP by an intermediate node is accompanied by information about the route to the source.

The RREP packet has the following main parts as shown in figure 3.1:

| Source Identifier | Destination Number* (Destination IP Address) | Destination Sequence Number | Hop Count | Lifetime |
|---|---|---|---|---|
|  |  |  |  |  |

Figure 3.1: Sample of RREP packet.

*Destination Number is the same as the Destination IP address
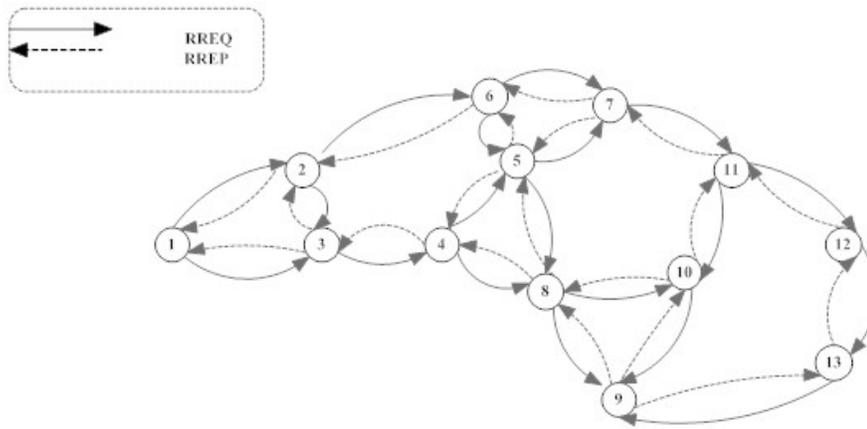


Figure 3.2: A typical AODV network of nodes

Every intermediate node that forwards a RREQ packet creates a reverse route back to the source node by imprinting the next hop information in its routing table. When the RREQ packet finds the destination node or an intermediate node with a valid route, the node responds by sending a route reply (RREP) packet to the source using the reverse route. The validity of a route at the intermediate nodes is determined by comparing its sequence number with the destination sequence number. Each node that takes part in forwarding RREP packets back to the source creates a forward route to the destination by saving the next hop information in the routing table. Nodes along the path from source to destination are not required to have knowledge of all nodes other than the next hop node to the source and destination.

In addition AODV also has a route maintenance process. After the route discovery process and the discovered route is in use, the intermediate nodes together with the active route maintain an up-to-date list of their one-hop neighbours using a periodic exchange of "hello" packets. If the route becomes inactive, e.g. no battery life, a timer is activated to inform the network about the expiration of this route. When the routing agent of a node becomes aware of a link breakage for an active route, a Route Error (RERR) packet is generated and disseminated to the appropriate nodes participating in the route's formation. When the RERR packet reaches the source node a new route discovery is initiated.

AODV uses a simple flooding method for route discovery where a source node transmits to all nodes in the vicinity. Each node checks whether it has received this message before. If it had, then the message will be dropped, if not then the message is re-transmitted to all neighbouring nodes. This process continues until all nodes get the message. However, this method increases the network traffic and depletes battery power.

A probabilistic message forwarding scheme (a forwarding scheme that uses a probability to choose the number of nodes to forward the messages) could be used that will reduce the routing message overhead and hence power consumption of AODV. This can be achieved by reducing any redundant broadcasting from the nodes with a predetermined probability. The most important factor in this scheme is the forwarding probability.

## 3.6    Flooding on AODV protocol

Flooding [3.5] or blind flooding is the mechanism that the protocol uses in order to discover a route from a sender to a destination node. This is achieved through broadcasting the RREQ packet from the source node to all one-hop nodes. When the destination node is found then it transmits the RREP packet using the reverse route in order to verify the destination node and the shortest route to it. If a route is not found then a RRER packet is transmitted in order to inform the source node that there is no valid route to the destination node. All the three packets are called control packets. The flooding procedure causes [3.6] overhead due to constant re-broadcast of control packets which results in network congestion and increased energy consumption.

There have been many research studies [3.6]-[3.9] to alleviate the problems that are caused by the flooding procedure. All these research studies have been focused on developing mechanisms that choose a set of nodes with low forwarding overhead.

The (Enhanced Ad hoc On demand Distance Vector routing) EAODV in [3.6] proposed by Shobha and Rajanikanth who uses two mobility conditions and provides the possibility that nodes that are moving quick will have better recent routes compared to those that are moving slowly. Using this approach it avoids the use of flooding mechanism because it uses the adjacent nodes to transmit the RREQ according to their mobility rate and recent participation.

In [3.7], the authors propose an efficient on demand routing approach with directional flooding (DF), which is suitable for MANETs. This approach intervenes in the route discovery process and reduces the number of route request (RREQ) packets broadcast by using a restricted directional flooding technique.

Another approach to efficient flooding has been proposed by Karthikeyan et al in [3.8] which is a density based flooding mechanism that ensures delivery of control packets from a source node to all the nodes of the network with the minimum MAC load, overhead and power consumption.

Karthikeyan et al. [3.9] also proposed a cluster based algorithm which tries to reduce the complexity of the flooding broadcasting problem. The algorithm adapts itself dynamically to the topology and informs nodes about the shortest time for every transmission. It guarantees to transfer the messages within a specific time. The algorithm uses information regarding the multiple nodes located at the same point and tries to fix any delay latencies and therefore avoiding the side effects of the flooding.

## 3.7    Summary

This chapter has described the reason for choosing the AODV routing protocol instead of other existing protocols for further development. Moreover, it has presented, in details, how the AODV routing protocols works and how the flooding mechanism affects overhead,

routing load, MAC load and energy consumption. The following chapters will describe the two proposed algorithms, the AODV_EXT and AODV_EXT_BP.

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# CHAPTER 4

# PROPOSED ALGORITHMS: AODV_EXT AND AODV_EXT_BP

*Abstract: This chapter describes the two proposed AODV_EXT and AODV_EXT_BP protocols.*

## 4.1 AODV_EXT protocol

Standard AODV protocol routing process broadcasts route request to all nodes. In the proposed scheme, a table of nodes in a given neighbourhood (one-hop nodes) is maintained. When a message is transmitted, only a subset of nodes in each neighbourhood is allowed to transmit. The number of selected nodes can be varied dynamically depending on the application and required quality of service. In this proposed scheme, the parameters that are used are defined in Table 4.1. Each node in the network will forward a route request message if and only if a condition based on its neighbourhood density at that instance is satisfied. The proposed scheme minimizes network congestion due to redundant transmission.

Table 4.1: Definition of AODV_EXT Parameters

| | |
|---|---|
| $n$ | The total nodes in the network |
| $F_i$ | Any node $F_i$, i = 1,2,…n that receives the RREQ message |
| $P_i$ | Packet forwarding probability derived from neighbourhood node count. |
| $\beta_i$ | The number of nodes neighbouring node $F_i$. |
| $d*$ | Minimum number of neighbouring nodes - if the number of neighbours at a forwarding node, $F_i$, is less than or equal to $d$, then that node will forward the RREQ message to avoid path failure or network partitioning. |
| $C_f$ | It is a control factor which can be used to adjust the probability $P_i$ according to the application or average expected node density of the network,$(0 < C_f \leq 1)$. |
| $R**$ | Random number (between 0 and 100). This is used to generate varying conditions in the network. |

* In this proposed algorithm d = 5, and defines a minimum condition which provides greater certainty of successfully packets routing but minimizes redundant transmissions. Moreover this means that if there are five nodes or less in the whole network then the algorithm chooses the flooding method that the original version of AODV uses in order to broadcast the RREQ packets.

** A random number generator is used to generate a sequence of numbers between 0 and 100 [4.1]. Using a random number generator reduces the chance of using the same intermediate nodes between the source and the destination node. In this proposed algorithm it generates random numbers between 0 and 100.

If the RREQ is received from an intermediate node then there will be at least one possible path which includes that node in its path list. Therefore, if only selected nodes are allowed to forward the RREQ packet, then only these nodes will be included in the path list. In this proposed scheme, the neighbourhood density of an intermediate node is considered as a criterion in RREQ forwarding decision at intermediate node. It means that if the number of nodes in the neighbourhood is high, then the probability of any node transmitting will decrease and hence reduces the transmission overhead. Random selection of nodes from the neighbourhood set increases the chance of full network coverage. Greater energy savings could be achieve by using a distance dependent technique, a technique that counts the minimum number of nodes on the shortest routing path in order to estimate the distance between two nodes[4.2].

**PROPOSED ALGORITHM**

Any node $F_i$, i = 1,2,…n  receiving the RREQ message will process the packet as follows :

For RREQ message originating from $S$ destined for node $D$ that is received by node $F_i$ process it if $F_i \neq S$ and $F_i \neq D$ (i.e. $F_i$ is an intermediate node) as follows:

Node $F_i$ resolves its neighbourhood density $\beta_i$

If $\beta_i \leq d$ then

Forward the RREQ message

Else

Calculate message forwarding probability $P_i$ at node $F_i$

$$P_i = \frac{100}{\beta_i} * (d * C_f) \text{ for } 0 < C_f \leq 1$$

 If $R < P_i$  then

    Forward the RREQ message

Else

    Ignore and Drop the RREQ message

End

End

## 4.2   Bayesian probability theory

The Bayesian probability theory [4.2] is a conditional probability theory. The joint probability of two events, A and B, can be expressed as:

$$P(AB) = P(A/B) * P(B) \text{ or } P(B/A) * P(A) \tag{4.1}$$

In Bayesian probability theory one of these events is called hypothesis and denoted with H and the other is called data and denoted with D. The Bayesian probability theory can be used to assess the probability of the observed data D resulting from hypothesis H.

$$P(H/D) = \frac{P(D/H)*P(H)}{P(D)} = \frac{P(D/H)*P(H)}{\sum_i P(H_i)*P(D/H_i)} \qquad (4.2)$$

The term $P(H)$ is called the prior because it reflects prior knowledge before the data is considered. The term $P(D)$ or the denominator of the second fraction $(\sum_i P(H_i) * P(D/H_i))$ is the total probability of all the pathways that lead to D. Finally, the term $P(H/D)$ is known as a posterior (posterior probability) and reflects the probability of the hypothesis after consideration of the data.

## 4.3    AODV_EXT_BP protocol

There have been many efforts to use the Bayesian probability in order to alleviate the flooding problem in AODV. Rusheel Jain et al [4.4] proposed a heuristic algorithm with a route establishment technique using Bayesian approach. This algorithm improves the performance of route discovery by ameliorating the cost of route establishment using a history based Bayesian method together with the relative region information of the destination node.

Massimiliano de Leoni et al [4.5] has also used the Bayesian probability theory in order to predict the loss of connection that may occur in MANETs. The proposed approach in this thesis uses the Bayesian probability theory in RREQ broadcasting mechanism in order to reduce and alleviate the flooding problem. How this is accomplished through the modification of AODV is described in this chapter.

Assume a node, D broadcasts messages to many nodes $D_i$ $(i = 1, 2 ..., n)$. Then if the probability of the message being forwarded by each node is $P_i$, $P_{(D/D_i)}$ can be computed as follows:

$$P_{(D/D_i)} = \frac{P_{(D/D_i)}*P_{(i)}}{P_{(D_1/D)}*P_{(D_1)} + P_{(D_2/D)}*P_{(D_2)} + \cdots \cdots + P_{(D_n/D)}*P_{(D_n)}} \qquad (4.3)$$

In this equation we made an assumption made that the posterior probability $P_i = 1$ which is the forward probability of 5 nodes if $d = 5$ (number of nodes) then the algorithm chooses to use the flooding method in order to disseminate the RREQ packet)

So if there are 9 nodes between the source and the destination node, and the posterior probability $P_i$ which is the forward probability of 5 nodes is 1 then

$$P_{(D/Di)} = \frac{\frac{1}{2}*1}{\frac{1}{2}*\frac{1}{2}+\frac{1}{2}*\frac{1}{2}+\frac{1}{2}*\frac{1}{2}+\frac{1}{2}*\frac{1}{2}+\frac{1}{2}*\frac{1}{2}+\frac{1}{2}*\frac{1}{2}+\frac{1}{2}*\frac{1}{2}+\frac{1}{2}*\frac{1}{2}+\frac{1}{2}*\frac{1}{2}} = \frac{\frac{1}{2}*1}{\frac{9}{4}} = \frac{4}{18} = 0.22.$$ This means that the RREQ packets will be received only from the 22% of the 9 nodes.

The forward probability depends on the posterior probability $P_i$, so if we forward the message with probability 55% ($P_i = 0.55$) then the 12.2 % ($P_{(D/Di)} = 0.122$) of the nodes will receive the message. Where $P(D_1 / D) = P(D_1) = \frac{1}{2}$ which is an independent probability that explains that the node will receive the message with 50 % probability. In table 4.2 are the results of the forward probability implemented the Bayesian theory and the number of nodes.

Table 4.2 Forwarding Probability results implemented the Bayesian

| Number of Nodes | Posterior Probability | Forward Probability |
|---|---|---|
| 5 |  | 1 |
| 6 | 1 | $\frac{1}{3}$ |
| 7 | 1 | $\frac{2}{7}$ |
| 8 | 1 | $\frac{1}{4}$ |
| 9 | 1 | $\frac{2}{9}$ |
| 10 | 1 | $\frac{1}{5}$ |
| 11 | 1 | $\frac{2}{11}$ |

| | | |
|---|---|---|
| 12 | 1 | $\frac{1}{6}$ |
| 13 | 1 | $\frac{2}{13}$ |
| 14 | 1 | $\frac{1}{7}$ |
| 15 | 1 | $\frac{2}{15}$ |
| 16 | 1 | $\frac{1}{8}$ |
| 17 | 1 | $\frac{2}{17}$ |
| 18 | 1 | $\frac{1}{9}$ |
| 19 | 1 | $\frac{2}{19}$ |
| 20 | 1 | $\frac{1}{10}$ |
| 21 | 1 | $\frac{2}{21}$ |
| 22 | 1 | $\frac{1}{11}$ |
| 23 | 1 | $\frac{2}{23}$ |

Table 4.3: Definition of AODV_EXT_BP Parameters

| | |
|---|---|
| $n$ | The total nodes in the network |
| $F_i$ | Any node $F_i, i = 1, 2 \dots, n$ that receives the RREQ message |
| $P_i$ | Packet forwarding probability derived from neighbour node count. |
| $d$ | Minimum number of neighbouring nodes - if the number of neighbours at a forwarding node, $F_i$, is less than or equal to $d$, then that node will forward the |

| | RREQ message to avoid path failure or network partitioning. Here $d = 5$. |
|---|---|
| $R$ | Random number (between 0 and 1). This is used to generate varying conditions in the network. |

In the following table is presented the proposed algorithm based on Bayesian theory.

---

**PROPOSED AODV_EXT_BP ALGORITHM**

➢ Any node $F_i, i = 1, 2 \ldots, n$ receiving the RREQ message will process the packet as follows :

➢ If the RREQ message is originated from the node $S_i$ or received at destination node $D_i$ just process it in the normal way. If $F_i$ is not the $S_i$ or $D_i$ then it will be an intermediate node :

➢ The node $F_i$ will resolve the neighbourhood density $D_i$

The Bayesian Probability $P_i$ is :

$$* P_{(D/D_i)} = \frac{P_{(D/D_i)} * P_{(i)}}{P_{(D_1/D)} * P_{(D_1)} + P_{(D_2/D)} * P_{(D_2)} + \cdots \cdots + P_{(D_n/D)} * P_{(D_n)}} * \frac{1}{2} * \left(\frac{n}{d}\right)$$

➢ If $P_i < R$ then

Just forward the RREQ message

    Else

        Just ignore and Drop the RREQ message

   End

(Here $R$ is a random number between 0 and 1)

---

\*The Bayesian Probability $P_i$ has been modified in order to resolve the neighbourhood density

## 4.4　Summary

This chapter has presented two novel algorithms AODV_EXT and AODV_EXT_BP that has been proposed to reduce the flooding phenomenon in RREQ mechanism that consequently reduces the power consumption. Using the two algorithms that have been implemented as extensions of the AODV routing protocol, the simulation results are presented in chapter 6 of this dissertation. The following chapter presents the simulation methodology that has been used in this research.

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# CHAPTER 5

# SIMULATIONS

*Abstract: This chapter describes the simulations conducted and the methodology used in order to evaluate existing and proposed (new) ad hoc routing protocols in terms of power consumption.*

## 5.1 Introduction

A simulation platform was selected for this research because:

- hardware systems can be complex and costly (e.g: space simulations, flight simulations);

- it can be used to quickly evaluate design alternatives (e.g: different system settings);

- it can be used to evaluate complex functions for which closed form formulas or numerical techniques are not available.

In the course of this research many simulations have been conducted in order to evaluate the followings:

- how the NS-2 works;

- how each protocol behaves in terms of power consumption;

- how to develop a new algorithm and implement it in NS-2;

NS-2 [5.1] is based on Tool Command Language (TCL) [5.2] programming language which is based on C++. NS-2 is an open source simulation programme which is free and is supported by many fora and user communities. There are many other free and open source simulation softwares like Glomosim [5.3] and Omnet++ [5.4] but the communities that support such programs are too small. Moreover many studies have been conducted using NS-2 resulting in its measured reliability. For all the above reasons in this research NS-2 has been chosen.

## 5.2    Defining Parameters on NS-2

The NS-2 works only in Linux environment. In order to install it on a "Windows platform" a virtual machine or similar e.g. Cygwin running Linux OS has to be used. After the installation of the Cygwin [5.5], the next step was to install NS-2. The suitable version of NS-2 that supports the TORA routing protocol was the 2.28. In order to simulate TORA protocol a special patch/modification was required [5.6]. In addition, DSR, AODV, DSDV, TORA routing protocols the Communication Management Unit's (CMU's) wireless extension had to be implemented [5.7][5.8].

This allowed comparison to protocols such as AODV, DSDV, TORA, DSR and OLSR in different scenarios and network densities to be studied. The first step was to compare ad hoc routing protocols (AODV, DSDV, TORA) in terms of power.

In the following section the energy model [5.9] that NS-2 is presented and has been used to compare protocols in terms of power.

The basic energy model is very simple and is defined by class Energy Model and it shows that there is only a single class variable energy which represents the level of energy in the node at any given time. The constructor Energy Model $P_{total}$ (1) requires the initial energy $P_{init}$ to be passed along as a parameter. The other class methods are used to decrease the energy level of the node for every packet transmitted ($t_{tx} * P_{tx}$) and every packet received ($t_{rx} * P_{rx}$) by the node. $P_{tx}$ and $P_{rx}$ are the transmitting and receiving power (respectively) required by the node's interface or PHY. At the beginning of simulation, energy_ is set to initial Energy $P_{init}$ and then decremented for every transmission and reception of packets at the node. When the energy level at the node goes down to zero, no more packets can be received or transmitted by the node. The following equation describes the Energy Model that the NS-2 uses in order to calculate the power consumption on each node.

$$P_{total} = P_{init} - (t_{tx} * P_{tx}) - (t_{rx} * P_{rx}) \tag{5.1}$$

where

$\boldsymbol{P_{total}}$ is the energy level that a node has at any time

$P_{init}$ is the energy level that a node initially has

$P_{tx}$ is the power that consumes a node when it transmits a packet

$P_{rx}$ is the power that consumes a node when it receives a packet

$t_{tx}$ is the time that a packet need to be transmitted

$t_{rx}$ is the time that a packet need to be received

The parameteres that can be changed in the generation of the scenario on NS-2 are the following [5.10]:

1. Simulation time (sec);
2. Minimum speed (m/s);
3. Maximum speed (m/s);
4. Pause time (sec);
5. Dimension space (square meters).

All the above parameters are concerned with node movement and topology.

In addition there are parameters that can be changed in traffic pattern. Random traffic connections of TCP and Constant Bit Rate (CBR) can be setup between mobile nodes using a traffic-scenario generator script. In order to generate a traffic-connection file, the following parameters have to be defined [5.11]-[5.14]:

1. Traffic type connection (CBR,TCP);
2. Number of nodes;
3. Maximum number of connections;
4. Random seed (is used to create random numbers of source-destination pair);
5. Rate [Interval time between the CBR packets (only for CBR)];

As we already know, UDP does not require a bidirectional link because there is no need of acknowledgement, in contrast with TCP. The Constant Bit Rate (CBR) when is used in telecommunications, relates to the quality of service, and specific at the stability of data flow during the transmission or reception process. The CBR can be used as bandwidth-

allocation service, on Asynchronous Transfer Mode (ATM), in cases where the there is a need of a fixed bandwidth, especially at the time the connection is set up so that the data can be sent in a steady stream. In codecs, CBR encoding means that the rate of the consumed output data is constant. CBR is useful for streaming multimedia content such the MPEG 4 video format, on limited capacity channels because it uses the maximum bit rate and not the average [5.15][5.16].

Except the CBR there is the Variable bitrate (VBR) another traffic profile that can be used in telecommunications and computing. VBR usually produces smaller file sizes, but the encoding time takes much longer. Also VBR provides a higher bitrate than the CBR and therefore needs more storage space to be allocated. VBR is useful for streaming multimedia content such MPEG-2 MPEG-4 part 10 [5.15][5.16].

All the scenarios that have been simulated in NS-2 had the following settings:

- Over time duration of 100 sec;
- Minimum and maximum speed which is varied and depended on the scenario;
- Pause time of 0.1 sec;
- Transport/Traffic Type was the CBR over UDP.

To assess the performance of the protocol developed in this research, a mobile scenario was elected and simulated. This scenario was the monitoring of vehicles with an airport setting.

There are various validation techniques that can be used, in this dissertation the degeneracy validation method is the one that has been chosen to validate the simulation model. This method the model's behaviour is tested by selecting appropriate input values of parameters [5.17][5.18]. This process is repeated until the simulation model provides sufficient data. In this research 10 iterations have been used.

The time duration of 100 seconds, has been determined for all simulation scenarios to be a sufficient time, because each scenario needed more than 72 hours to be run on a PC, due to the complexity of the variables (high speed of the nodes, node density) and the type of the pc (how fast pc was) that has been used. Moreover after 45 seconds the network started to behave as the time it started. Also this time was sufficient in order to get results that could be compared to similar studies that have been conducted.

The CBR settings that have been used in all simulation scenarios are the following Table 5.1:

Table 5.1: CBR settings of simulation scenarios

| Parameters | Value | Description |
|---|---|---|
| Time interval | 0.1 Second | Every 0.1 second it will transmit 512 Bytes[1] |
| Maximum number of Bytes per packet Agent (UDP) | 1000 Bytes | Maximum segment size[2] |
| Packet Size | 512 Bytes | |

[1]This means that in 1 second it will be transmitted 10 packets.

[2]This means that when the size of the packet exceeds the 1000 Bytes it will be split.

The three most important protocols in the transport layer are:

a) Transmission Control Protocol (TCP) [2.20]

b) User Datagram Protocol (UDP) [2.21].

c) Stream Control Transmission Protocol (SCTP) [2.23]

TCP [2.20][2.22] offers reliability in data transmission/reception making it suitable for applications like file transfer protocol (FTP) and email. The protocol is optimized for reliable delivery rather than fast delivery. Therefore TCP can sometimes cause notable delays while waiting for non-delivered data or retransmissions of lost data packets, and it is not particularly adequate for real time applications such as video casting.

The main features of the TCP protocol are as follows [5.19][5.20]:

- put datagrams back in order when coming from the IP protocol
- enables the data flow to be monitored so as to avoid network saturation
- allows data to be formed in variable length segments
- can multiplex data, so that information coming from distinct sources on the same line can be circulated simultaneously
- allows communication to be kindly started and ended

During a communication using the TCP protocol, the two machines must establish a connection. The destination machine is called the client, while the recipient machine is called the server. So it is said that we are in a Client-Server environment and the communication takes place in both directions [5.19].

When the communication process starts, that means that data is encapsulated and a header is added to data packets which will enable the transmissions to be synchronized and ensure their reception. TCP can control the data speed using its capability to issue variably sized messages; these messages are called segments [5.20].

| URG ACK PSH RST SYN FIN | | | |
|---|---|---|---|
| 0-15 (Ports) | | 16-31 (Ports) | |
| Source Port | | Destination Port | |
| Sequence number | | | |
| Acknowledgement number | | | |
| Data Offset | Reserved | Window | |
| Checksum | | Urgent pointer | |
| Options | | Padding | |
| Data | | | |

Figure 5.1: The TCP header

Explanation of TCP header parts.

- **Flags** (6x1 bit): The flags represent additional information:
- **URG**: if this flag is set to 1 the packet must be processed urgently
- **ACK**: if this flag is set to 1 the packet is an acknowledgement.
- **PSH** (PUSH): if this flag is set to 1 the packet operates according to the PUSH method.
- **RST**: if this flag is set to 1 the connection is reset.
- **SYN**: The TCP SYN flag indicates a request to establish a connection.
- **FIN**: if this flag is set to 1 the connection is interrupted.
- **Source port** (16 bits): Port related to the application in progress on the source machine
- **Destination port** (16 bits): Port related to the application in progress on the destination machine
- **Sequence number** (32 bits): When the SYN flag is set to 0, the sequence number is that of the first word of the current segment. When SYN is set to 1, the sequence

number is equal to the initial sequence number used to synchronize the sequence numbers (ISN)

- **Acknowledgement number** (32 bits): The acknowledgement number, also called the acquittal number relates to the (sequence) number of the last segment expected and not the number of the last segment received.
- **Data offset** (4 bits): This makes it possible to locate the start of the data in the packet. Here, the offset is vital because the option field is a variable size
- **Reserved** (6 bits): A currently unused field but provided for future use
- **Window** (16 bits): Field making it possible to know the number of bytes that the recipient wants to receive without acknowledgement
- **Checksum** (CRC): The checksum is conducted by taking the sum of the header data field, so as to be able to check the integrity of the header
- **Urgent pointer** (16 bits): Indicates the sequence number after which information becomes urgent
- **Options** (variable size): Various options
- **Padding**: Space remaining after the options is padded with zeros to have a length which is a multiple of 32 bits

UDP [2.21] enables communicating nodes to receive/transmit short messages, also known as datagrams. This protocol does not ensure delivery reliability as the TCP does. Data may arrive out of order, be duplicated or lost without notice. Avoiding the overhead of checking if every packet actually arrives makes UDP faster and more efficient, at least for applications that do not require guaranteed delivery, such as broadcasting, video streaming and VoIP. UDP is more suitable to transmit voice data over a VoIP network, as there is no requirement for the transmitter to keep sent packets.

Many of the features of the TCP and UDP can also be found in the (SCTP) [2.23] which has been standardized as RFC 2960 in 2000 [2.24]. It provides acknowledged error-free non-duplicated transfer of data. SCTP provides reliability in flow control mechanisms but can also like the UDP can support unreliable transmission [2.25]. SCTP can provide multi-stream and multi-homing services for a single connection.

The CBR is part of the Application Layer of the TCP/IP model. (Table 5.1) [5.24]

Table 5.2: The TCP/IP model

| Application Layer | CBR, FTP, Telnet |
|---|---|
| Transport Layer | SCTP,TCP,UDP |
| Network Layer | Rtproto * |
| Data Link Layer | Transmission mode<br>Simplex mode<br>Duplex mode |
| Physical Layer | |

*Is a dynamic routing strategy, in which during the send/receive process it computes the routes in the topology according to number of messages that have been exchanged.

In all simulation scenarios it has been used drop-tail as an interface queue type instead of Random Early Detection (RED) because research that have been conducted by Ghansyam et al in [5.25] showed that the RED queue type is suitable for high speed packet switch networks and also has lower throughput compared to drop-tail.

The Transport Layer uses two protocols, UDP and TCP. UDP does not guarantee packet delivery and applications which use this must provide their own means of verifying delivery, while TCP does guarantee delivery of packets.

## 5.3   Evaluating NS-2 and routing protocols in terms of power consumption

Initial research was to compare the ad hoc routing protocols (AODV, DSR, DSDV, TORA) in terms of power consumption. The following parameters given in Table 5.2 were used to evaluate 2 networks of different sizes: 30 nodes and 100 nodes. The scenario with 30 nodes that has been simulated had the following characteristics:

Figure 5.2 shows that the consumed power of networks using AODV and DSR decreases significantly when the number of nodes exceeds 20. On the contrary, the consumed power of a network using the TORA protocol increases rapidly whilst that of DSDV based network shows a steady increase with number of nodes.

Fig. 5.2, Fig. 5.3a and 5.3b show the results of power analysis.

Table 5.3: Parameters of the Simulation of AODV, DSR, DSDV, TORA (30 nodes)

| | |
|---|---|
| Channel type | WirelessChannel |
| Radio-propagation model | TwoRayGround |
| Antenna type | OmniAntenna |
| Interface queue type | DropTail/PriQueue |
| Maximum packet in Queue | 50 |
| Network interface type | Phy/WirelessPhy |
| MAC type | 802_11 |
| Topographical Area | 500 x 300 sq.m |
| txPower | 0.5W |
| rxPower | 0.1W |
| idlePower | 0.01W |
| Initial energy of a Node | 1000.0 Joules |
| Routing protocols | AODV/DSDV/DSR/TORA |
| Number of mobile nodes | 10,20,30 |
| Mobility | 0 to 20m/s |

The simulation set up assumes the use of 802.11 standards based on the two ray propagation model [5.27] described by equation (5.2).

$$P_r = P_t G_t G_r (\frac{h_t h_r \lambda}{4\pi R^2})^2 \qquad (5.2)$$

Where $P_r$ and $P_t$ are the received and transmitted power; $G_r$ and $G_t$ are the gains of the receiving and transmitting antennas; $h_r$ and $h_t$ are the heights of the transmitting and receiving antennas; is the wavelength of the signal and R is the distance between the transmitting and receiving nodes. This model assumes free-space. However, in reality the propagation conditions are usually more complex and often exhibit time and spatial variations resulting in shorter network life span than predicted by simulation. The recommended safe Equivalent Isotropically Radiated Power (EIRP) for Europe is 100 mW and for USA 125 mW [5.28].

Also the simulation setup takes into consideration that the maximum number of packets in queue is 50. This number is selected due to the hardware limitation that the wireless ad hoc nodes have, and they cannot use the same capacity for queued packets as the 802.11 wireless routers can offer (more than 350 packets) [5.29].
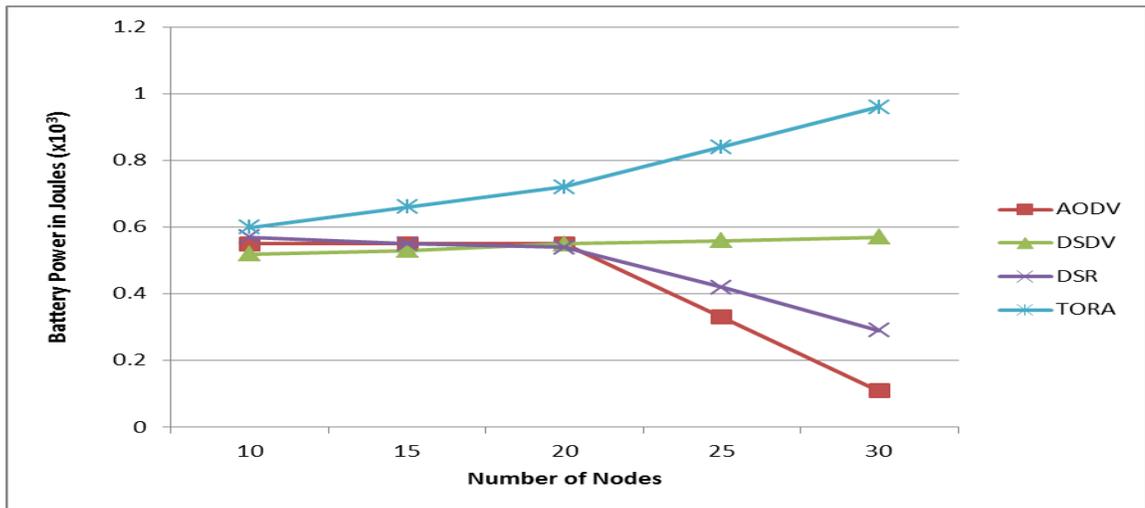


Figure 5.2: The average consumed power versus the number of nodes (10, 20, 30)

The second scenario that has been simulated had the following characteristics (Table 5.3) which is different from the previous scenario only in the number of nodes:

Table 5.4: Parameters of the Simulation of AODV, DSR, DSDV, TORA (100 nodes)

| Channel type | WirelessChannel |
|---|---|
| Radio-propagation model | TwoRayGround |
| Antenna type | OmniAntenna |
| Interface queue type | DropTail/PriQueue |
| Maximum packet in Queue | 50 |
| Network interface type | Phy/WirelessPhy |
| MAC type | 802_11 |
| Topographical Area | 500 x 300 sq.m |
| txPower | 0.5W |

| | |
|---|---|
| rxPower | 0.1W |
| idlePower | 0.01W |
| Initial energy of a Node | 1000.0 Joules |
| Routing protocols | AODV/DSDV/DSR/TORA |
| Number of mobile nodes | 10,20,30,40,50,60,70,80,90,100 |
| Mobility | 0 to 20m/s |

Figure 5.3a shows that the consumed power of networks is very different from the graph in Figure 5.2. DSR protocol consumes more energy when the number of nodes is 20, which happens due to increased node mobility and hence causing inconsistencies to the route reconstruction procedure and therefore increases the routing overhead which is reduced when the number of nodes is 30. One the other hand the other three protocols are very stable in terms of consumed power. Figure 5.3b shows behavior of the network when the number of nodes is between 15 and 24 in terms of power consumption. This figure depicts the difference in power consumption between the three protocols AODV, TORA, DSDV and DSR which is huge and has been thoroughly explained on Figure 5.3a.

Studies have also been conducted to compare the Ad hoc routing protocols (AODV, DSR, DSDV, OLSR) in terms of power consumption. In order to evaluate them we used the parameters that the following table has in the NS-2 and we simulate a scenario using 70 nodes. The results are presented at the followed graphs.
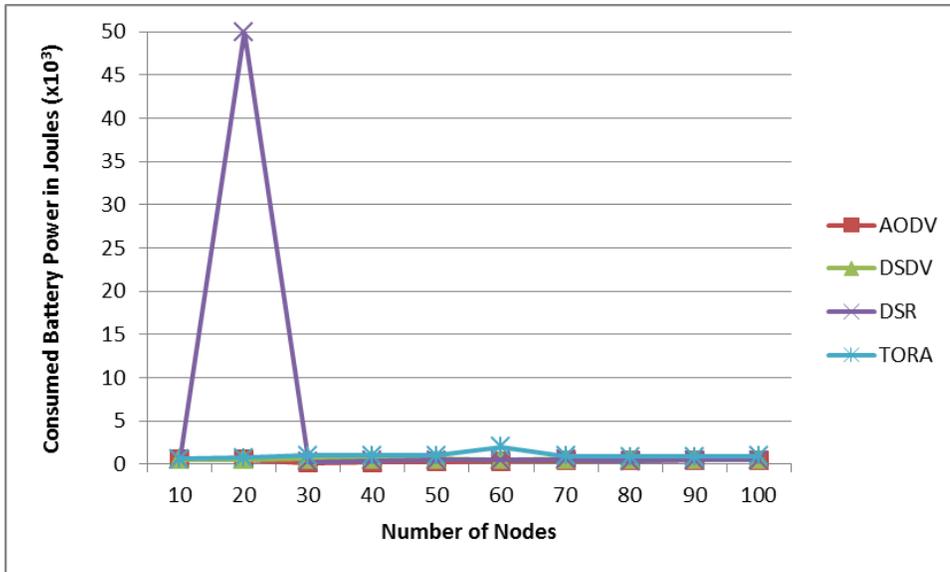
Figure 5.3a: The average consumed power versus the number of nodes (100)
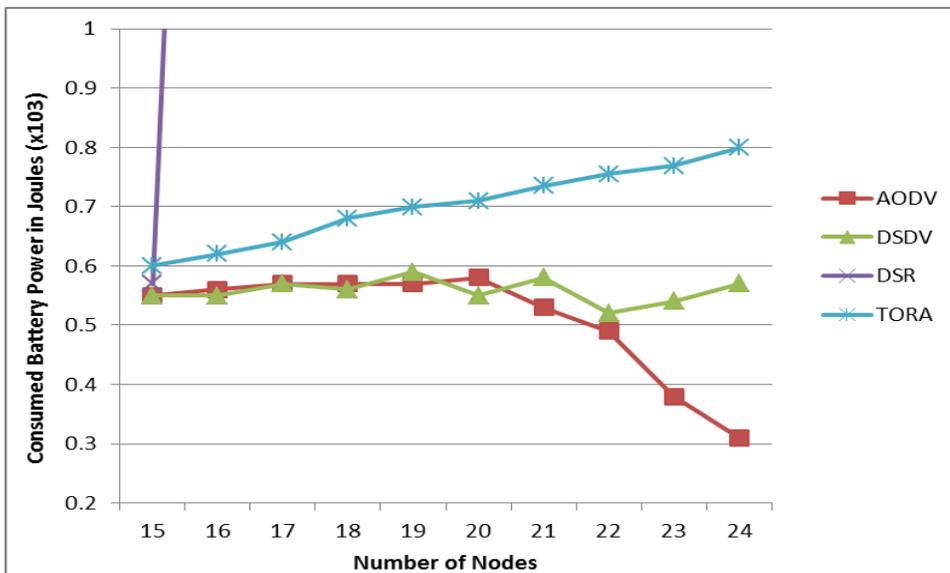


Figure 5.3b: The average consumed power versus the number of nodes (15-24)

Table 5.5: Parameters of the Simulation of AODV, DSR, DSDV, OLSR (70 nodes)

| Channel type | WirelessChannel |
|---|---|
| Radio-propagation model | TwoRayGround |

| | |
|---|---|
| Antenna type | OmniAntenna |
| Interface queue type | DropTail/PriQueue |
| Maximum packet in Queue | 50 |
| Network interface type | Phy/WirelessPhy |
| MAC type | 802_11 |
| Topographical Area | 500 x 300 sq.m |
| txPower | 0.5W |
| rxPower | 0.1W |
| idlePower | 0.01W |
| Initial energy of a Node | 1000.0 Joules |
| Routing protocols | AODV/DSDV/DSR/OLSR |
| Number of mobile nodes | 10,20,30,40,50,60,70 |
| Mobility | 0 to 20m/s |

Figure 5.4 shows that the consumed power of the network using OLSR increases rapidly when the number of nodes exceeds 20. This is because the OLSR protocol floods the network with information updates when the topology changes. On the contrary, the consumed power of a network using DSR and AODV decreases depending on the number of nodes that is within the neighbourhood. Both of these protocols use methods to find valid routes by following complete different methods of that the OLSR which causes flooding into whole network. The DSDV protocol presents a stability at the power consumption as it has a mechanism of finding a valid route be using a technique which exchanges routing messages between nearby mobile nodes, hence consumes almost the same energy in every scale of the network.
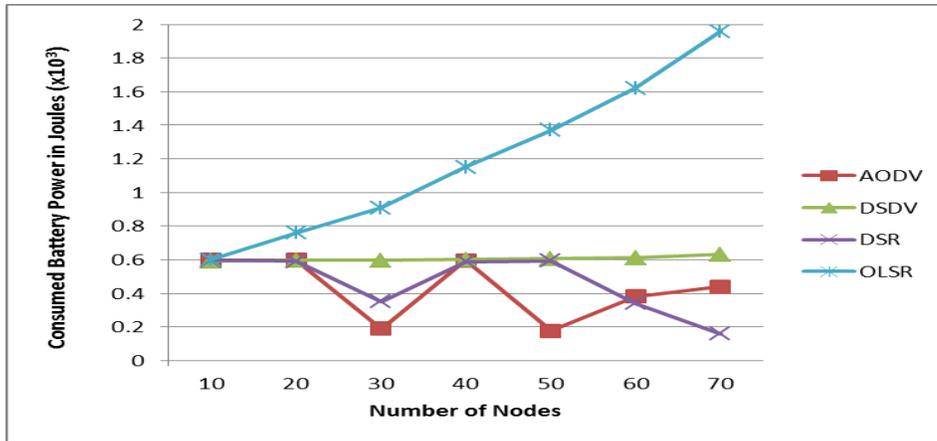
Figure 5.4: The average consumed power versus number of nodes (70)

## 5.4 Implementing different probability on RREQ mechanism of AODV protocol

A probabilistic technique has been used to implement the RREQ mechanism in AODV. In the following lines is going to be presented the modification that has been on the RREQ mechanism in AODV.

- Assume that there are N nodes in the network and n is the number of nodes in the neighbourhood of a transmitting node;

- In normal AODV route message forwarding, if a node is forwarding a packet then all the n neighbours will try to forward the message again. If $P_{rx}$ is the energy consumed when receiving a route control message and $P_{tx}$ is the energy consumed when forwarding a route control message, then all n nodes will spend $P_s$,

$$P_s = (P_{rx} + P_{tx}) * m \tag{5.3}$$

Where $m = n * P_{(i)}$, $P_{(i)}$ is the probability to use the $n$ nodes from the neighbourhood

- If $P_{init}$ is the sum of total initial power of the n neighbouring nodes, then the total remaining power of the neighbouring node is $P_{total}$, $P_{total} = P_{init} - P_s$ $\qquad$ (5.4)

- If probabilistic route message forwarding scheme is used, for example, assume that only 50 % of the nodes are allowed to forward the message at any instance by assigning a probability of 0.5 to each node, this means that only $\frac{n}{2}$ nodes will receive and forward the message. This means that the network residual power will be

$$P_{total} = (P_{init} - \frac{P_S}{2})$$

(5.5)

- If we compare equations (5.4) and (5.5), the latter will preserve the battery power and double the lifetime of the network.

- Studies have also been carried out to modify AODV to use density based probabilistic route message forwarding with dynamic probability so that only a certain percentage of the n neighbours will forward the message based on the density of its neighbours. And if the density is high then $P_{total}$ is expected to be much higher than that of equation (5.5).

Table 5.6: Description of variables of the proposed modification of AODV Routing Protocol

| Field | Description |
|---|---|
| $P_{tx}$ | Power consumed during transmitting a route control message |
| $P_{rx}$ | Power consumed during receiving a route control message |
| $P_{total}$ | The sum of total remaining power of the adjacent nodes |
| $P_{init}$ | The sum of total initial power of the $n$ nodes |
| $P_s$ | The total power of all nodes |
| $n$ | Number of nodes in the neighbourhood |
| m | Percentage of $n$ nodes |
| $P_{(i)}$ | Probality (0.1….1.0) |
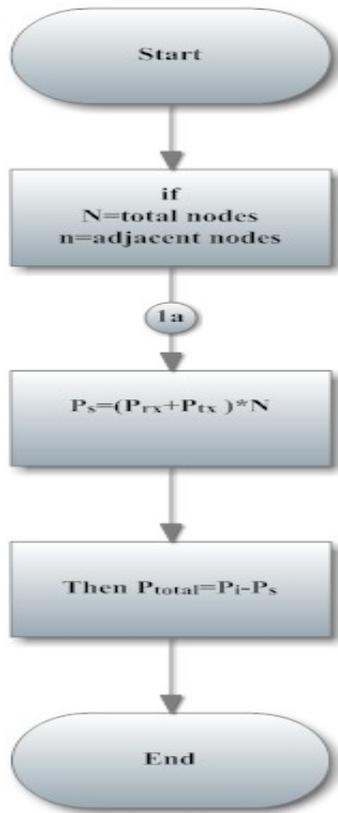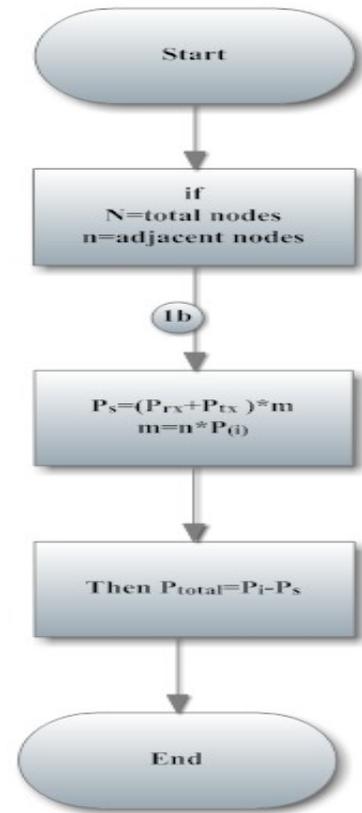
Figure 5.5: Flow chart of the standard AODV and the modified AODV Routing Protocol

**1a**: is the step when the flooding mechanism starts and the RREQ packets are broadcasting in to the whole network so the $P_{(i)} = 1$

**1b**: is the step when the RREQ broadcasting mechanism starts but is broadcasting these packets only to a part of the network so the $P_{(i)}$ is less than 1.

Table 5.7: Parameters of the Simulation of AODV in different probabilities 0,25 0,5 0,75 1,0 (50 nodes)

| AODV Modified | AODV in different probabilities |
|---|---|
| Topographical Area | 600m x 600m |
| Number of Nodes | 20, 30, 40, 50 |
| Mobility | 0 - 20m/s |

| Probability | 0.25, 0.5, 0.75, 1.0 |
|---|---|
| Radio-propagation model | TwoRayGround |
| Network interface type | WirelessPhy |
| MAC type | 802_11 |
| Interface queue type | DropTail/PriQueue |
| Antenna model | OmniAntenna |
| Total Simulation Time | 100sec |
| Transport /Traffic Type | CBR over UDP |

Figure 5.6 shows that the consumed power of networks using 0.5 probability of forwarding each message received achieves very good results by consuming less energy compared to a probability of 1.0 which is the traditional AODV protocol.
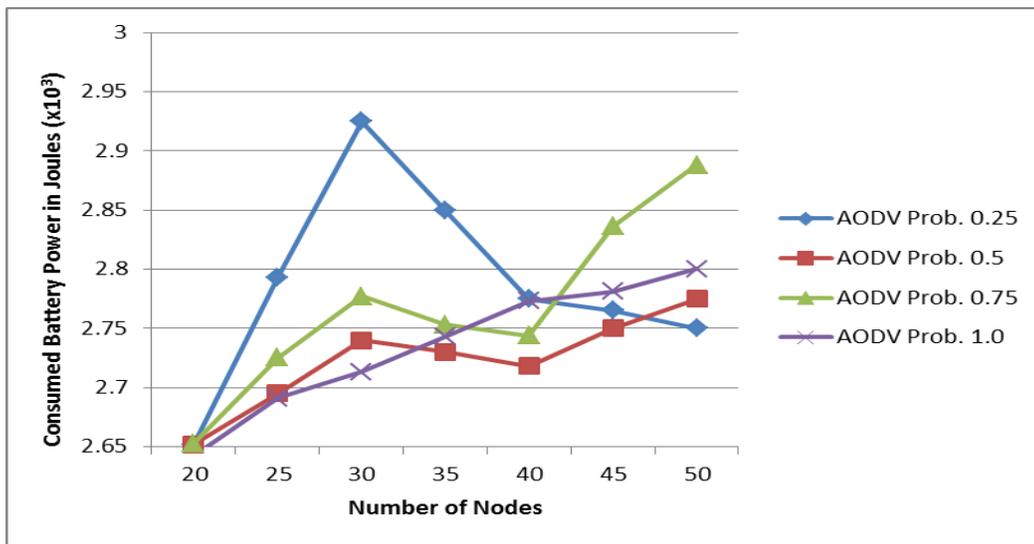


Figure 5.6: The average consumed power versus the number of 50 nodes

The percentage (%) of Communicating Nodes at any given time is 50% (25 % of the nodes will randomly send CBR traffic to another 25% of the Nodes in the network. In the 100 seconds of the simulation, the 25% of the nodes will randomly start the traffic and try to send the at least 5 packets to another 25% of the nodes at an instance and stop the traffic after one second. This will be repeated at least 4 times during the simulation.

Since the mobility is 20 m/s, the chances for link breakage is high and hence the nodes will try to find other route by using route request messages. This has been implemented to frequently which allows the overhead due the control message propagation of AODV to be measured. That is why the CBR is stopped and started at uniform intervals over time.

Table 5.8: Parameters of the Simulation of AODV with different message forwarding probabilities 0,1-1,0  (100 nodes)

| The Protocol | Probabilistic RREQ Message Forwarding Protocol |
| --- | --- |
| Topographical Area | 600m x 600m |
| Number of Nodes | 10, 20, 30, 40, 50, 60,70, 80, 90, 100 |
| Mobility | 1 m/s |
| Probability | 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 1.0 |
| Radio-propagation model | TwoRayGround |
| Network interface type | WirelessPhy |
| MAC type | 802_11 |
| Interface queue type | DropTail/PriQueue |
| Antenna model | OmniAntenna |
| Total Simulation Time | 100sec |
| Transport /Traffic Type | CBR over UDP |

Figure 5.7 shows that the consumed power of networks using 0.5 and 0.8 probability in order to forward the messages has very good results by consuming less energy than using 1.0 probability which is the traditional AODV protocol. However very good results can also be achieved by using 0.2 probability but only in networks with 20 nodes. The 1.0 and 0.5 probability consume the same energy. By using 0.5 probability, the algorithm uses only 50 % of the intermediate nodes in order to reach the destination node, while 1.0 probability uses 100 % of the intermediate nodes but it will need less or none re-transmissions in order the source node to find the destination node, instead of the 0.5 probability that might use more than one re-transmission in order the source node to find the destination node and that means almost the same energy consumption with that of 1.0 probability.
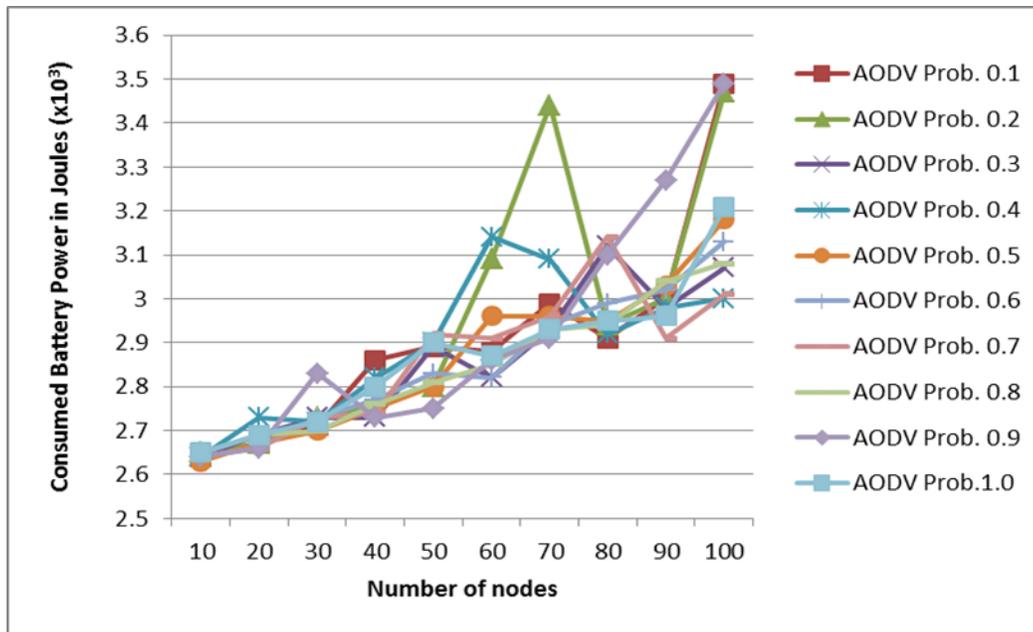
Figure 5.7: The average consumed power versus the number of 100 nodes

## 5.5 Dynamically change the probability on RREQ mechanism of AODV (AODV_EXT)

In this aspect a new algorithm that dynamically changes the probability of the RREQ mechanism according to density of the network has been delivered and implemented.

Table 5.9 presents the parameters used to implement the simulations.

Figure 5.8 shows that AODV_EXT consumes less power than OLSR and DSDV protocols. For AODV protocol it has almost the same behavior with AODV_EXT until the density of the network increases to more than 40 nodes where it consumes more energy than the AODV_EXT. The DSR protocol consumes more energy comparing to AODV and AODV_EXT but shows better performance when the density of the network is medium (30 nodes). On the contrary, the power consumption in networks using DSDV and OLSR rises steadily with that of DSR showing a slower rate of nodes. OLSR protocol uses a mechanism that constantly updates information regarding nodes in the neighbourhood and therefore consumes more energy than the other three protocols.

Table 5.9: Parameters of the Simulation of AODV, AODV_EXT, OLSR, DSDV, DSR (50 nodes)

| | |
|---|---|
| Routing Protocols | AODV/ AODV_EXT/OLSR/DSDV/DSR |
| Topographical Area | 800m x 800m |
| Number of Nodes | 10, 20, 30, 40, 50 |
| Mobility | 1m/s to 40m/s |
| Channel type | Wireless Channel |
| Radio-propagation model | TwoRayGround |
| Network interface type | WirelessPhy |
| MAC type | 802_11 |
| Interface queue type | DropTail/PriQueue |
| Antenna model | OmniAntenna |
| Max packet in Queue | 50 |
| Transport /Traffic Type | CBR over UDP |



Figure 5.8: The average consumed power in network of 50 nodes

Table 5.10: Parameters of the Simulation of AODV, AODV_EXT, OLSR, DSDV, DSR (100 nodes)

| Routing Protocols | AODV/ AODV_EXT/OLSR/DSDV/DSR |
|---|---|
| Topographical Area | 800m x 800m |
| Number of Nodes | 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 |
| Mobility | 1m/s to 40m/s |
| Channel type | Wireless Channel |
| Radio-propagation model | TwoRayGround |
| Network interface type | WirelessPhy |
| MAC type | 802_11 |
| Interface queue type | DropTail/PriQueue |
| Antenna model | OmniAntenna |
| Max packet in Queue | 50 |
| Transport /Traffic Type | CBR over UDP |

Figure 5.9 shows that on average AODV_EXT consumes less power than the other four protocol. The power consumption decreases notably when the number of nodes in the network is between 40 and 75. For AODV protocol it has almost the same behaviour with AODV_EXT until the number of nodes in the network is more than 40 where it starts to consumes more energy than AODV_EXT. The DSR protocol consumes more energy compared to AODV and AODV_EXT but shows better performance when the density of the network is near 30 nodes. On the contrary, the power consumption in networks using OLSR rises steadily whilst that of a DSR shows a slower increase with increasing number of nodes. OLSR protocol uses a mechanism that constantly updates information of nodes in the neighbourhood and therefore consumes more energy than the other three protocols.
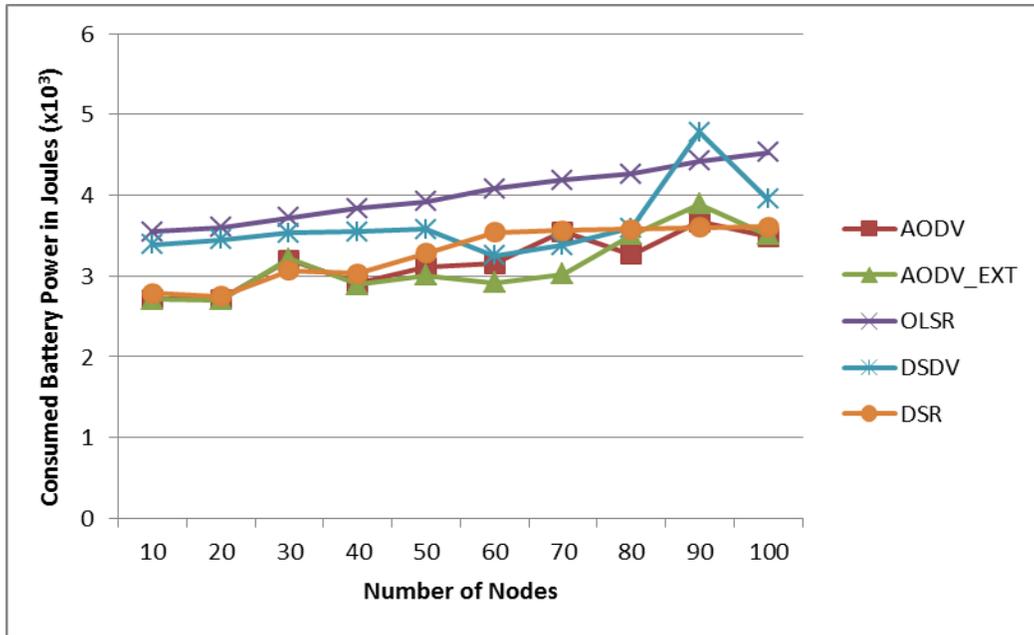
Figure 5.9: The average consumed power in network of 100 nodes

## 5.6 Dynamically changing the probability of RREQ mechanism of AODV_EXT using Bayesian probability AODV_EXT_BP

For each routing protocol, in order to discover a route to a destination node, uses different algorithms and mechanisms. All the on-demand routing protocols implement a broadcast layout referred to as simple flooding in which a route request packet (RREQ) is broadcasted from a source node and spread to every node in the network. This situation can lead to unnecessary retransmissions, causing high congestion and packet collisions in the network, a phenomenon called a broadcast storm [5.24]- [5.26].

The RREQ message forwarding scheme for AODV the AODV_EXT which reduces some of the overheads in routing has already been presented in this thesis. In order to find out whether the change of probability on the RREQ mechanism reduces the energy consumption using a probability scheme, a Bayesian theory based probability [5.23] has been implemented call AODV_EXT_BP. The performances of these new two protocols and four other routing protocols AODV, DSDV, DSR and OLSR have been studied to evaluate their route discovery mechanisms.

The simulation parameters and the results of the new algorithm will be presented in this chapter.

Table 5.11: Parameters of the Simulation of AODV, AODV_EXT, AODV_EXT_BP, OLSR, DSDV, DSR (50 nodes)

| Routing Protocols | AODV/AODV_EXT/AODV_EXT_BP/OLSR/DSDV/DSR |
|---|---|
| Topographical Area | 800m x 800m |
| Number of Nodes | 10, 20, 30, 40, 50 |
| Mobility | 1m/s to 40m/s |
| Channel type | Wireless Channel |
| Radio-propagation model | TwoRayGround |
| Network interface type | WirelessPhy |
| MAC type | 802_11 |
| Interface queue type | DropTail/PriQueue |
| Antenna model | OmniAntenna |
| Max packet in Queue | 50 |
| Transport /Traffic Type | CBR over UDP |

Figure 5.10 shows that AODV_EXT_BP consumes less or the same power as AODV_EXT. The power consumption is significantly smaller when the number of nodes in the network is 10 and 40. AODV protocol it has almost the same behaviour as AODV_EXT until the density of the network is more than 40 nodes then it consumes more energy than the AODV_EXT. The DSR protocol consumes more energy compared to AODV and AODV_EXT but shows better performance when the density of the network is close to 30 nodes. On the contrary, the power consumption in networks using DSDV and OLSR rises at faster rate compared to that of a DSDV which shows a slow steady increase with increasing number of nodes.
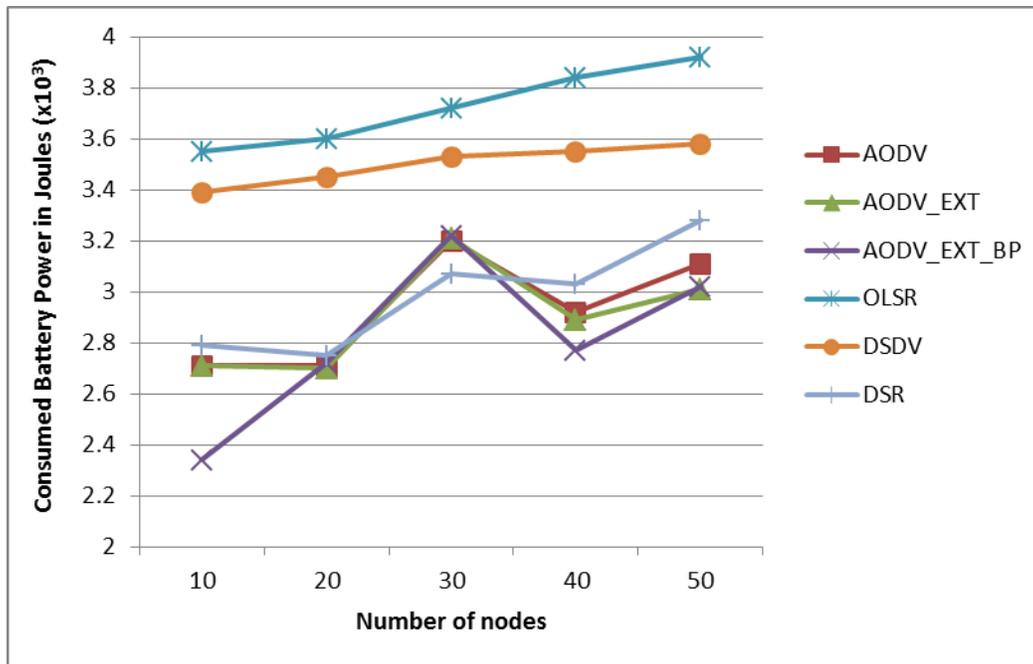
Figure 5.10: The average consumed power in network of 50 nodes

## 5.7 Summary

In this chapter, the characteristics of NS-2 simulation program are discussed together with the parameters that have been chosen for evaluating the modified protocols. The modifications that have been made to AODV implement in the NS-2 for comparison with other routing protocols (AODV, DSDV, DSR, OLSR, and TORA) in terms of power consumption have been also presented.

In addition, it has been shown the use of probability in the RREQ mechanism of the AODV protocol changes the behavior of the protocol in terms of energy consumption. The chapter has presented results of how a dynamically changed probability algorithm in AODV_EXT achieves good result in terms of power consumption.

Last the chapter has described a second algorithm the AODV_EXT_BP which implements the Bayesian probability theory which offers an improvement on the performance of AODV_EXT in terms of power consumption.

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# CHAPTER 6

# SIMULATION RESULTS

*Abstract: This Chapter describes the results from the simulations that have been conducted in order to compare and evaluate existing and designed (new) ad hoc routing protocols in terms of power consumption.*

## 6.1    Introduction

This chapter presents the simulation results that compare existing ad hoc routing protocols and the two new proposed algorithms that have been presented in chapters 4 and 5. During this research many scenarios have been studied in order to evaluate ad hoc routing protocols in term of power consumption. This chapter presents comparisons of AODV, DSR, DSDV, OLSR and TORA in varied scenarios and node density networks. Comparisons are also made between the performances of the two proposed algorithms AODV_EXT and AODV_EXT_BP against the original AODV, DSDV, DSR and OLSR in terms of power consumption, routing overhead, network throughput and MAC Load.

## 6.2    Comparison of AODV, DSDV, DSR, TORA

In this section comparisons are made between AODV, DSDV, DSR and TORA in terms of dropped packets, network throughput and MAC Load.

Figure 6.1 shows that the routing efficiency of AODV protocol in terms of time is greater than 80 Kbps and DSDV which is least efficient of the four protocols. In AODV protocol there, are receptions or transmissions each time a connection needs to be established between two nodes. This ensures that unnecessary transmission in route discovery is avoided. TORA and DSR result trends are similar to that of DSDV. TORA protocol's mechanism that keeps information regarding adjacent nodes gives it an advantage over DSR and DSDV routing protocol because it can forward messages faster. The efficiency of AODV protocol to route data packets is the key to its energy efficiency.

Table 6.1: Parameters of the Simulation of AODV, DSR, DSDV, TORA (30 nodes)

| Channel type | WirelessChannel |
|---|---|
| Radio-propagation model | TwoRayGround |
| Antenna type | OmniAntenna |
| Interface queue type | DropTail/PriQueue |
| Maximum packet in Queue | 50 |
| Network interface type | Phy/WirelessPhy |
| MAC type | 802_11 |
| Topographical Area | 500 x 300 sq.m |
| txPower | 0.5W |
| rxPower | 0.1W |
| idlePower | 0.01W |
| Initial energy of a Node | 1000.0 Joules |
| Routing protocols | AODV/DSDV/DSR/TORA |
| Number of mobile nodes | 10,20,30 |
| Mobility | 0 - 20m/s |



Figure 6.1: Packet throughput versus time

Figure 6.2 shows that the throughput of AODV protocol becomes stable when the number of nodes exceeds 20, and that happened due to low overhead that the AODV routing protocol presents. The high overhead depends on the high MAC Load and large dropped packets which are showed in the following graphs (Figure 6.3 & 6.4) that

AODV presents very good results in those two terms. The DSR routing protocol reaches a maximum and starts to fall. On the other hand the throughput of TORA and DSDV increases steadily until the number of nodes reaches 20 and then slowly with further increases in the number of nodes.
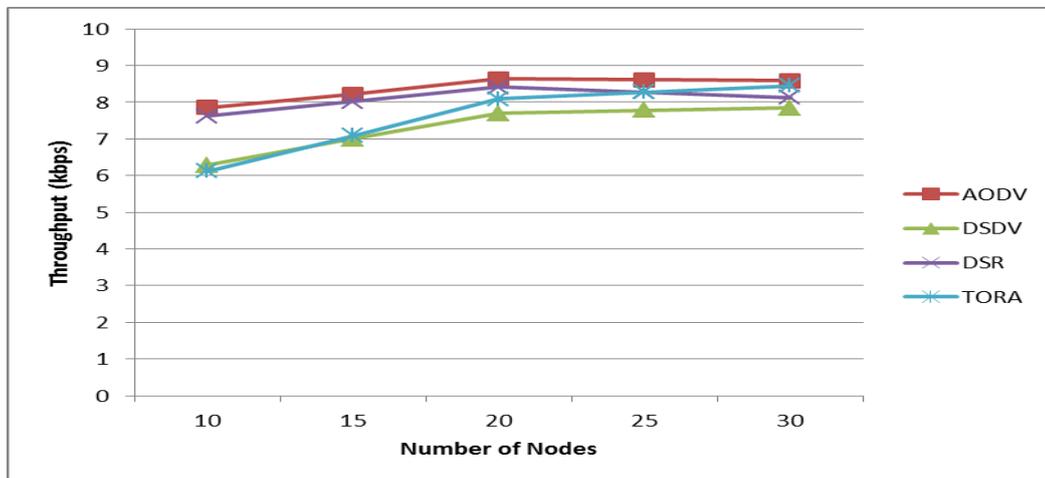


Figure 6.2: Throughput versus the number of nodes

Figure 6.3 shows that the MAC Load increases rapidly when the number of nodes exceeds 20 for TORA protocol. For the other three protocols the MAC Load is stable and remains low. The routing mechanism of TORA protocol uses the "link reversal" algorithm in which every node keeps information about the adjacent nodes, meaning that in order to forward a packet to a destination node, it also passes information about the other nodes and this keeps the MAC Load constantly high. On the other hand the other three protocols establish communication only on "demand" and in this way keep the MAC Load low.

Figures 6.4 shows that when the number of nodes exceeds 20 the performance of a network based on TORA deteriorates significantly resulting in maximum loss of information (dropped packets). AODV and DSR protocols have minimum loss of information of all the 4 protocols. From Figure 6.3, since TORA protocol has a high MAC Load, longer delays (more re-transmissions) are experienced when sending

packets to target nodes and which leads to more packets being lost during those re-transmissions. This is made worse by node mobility.
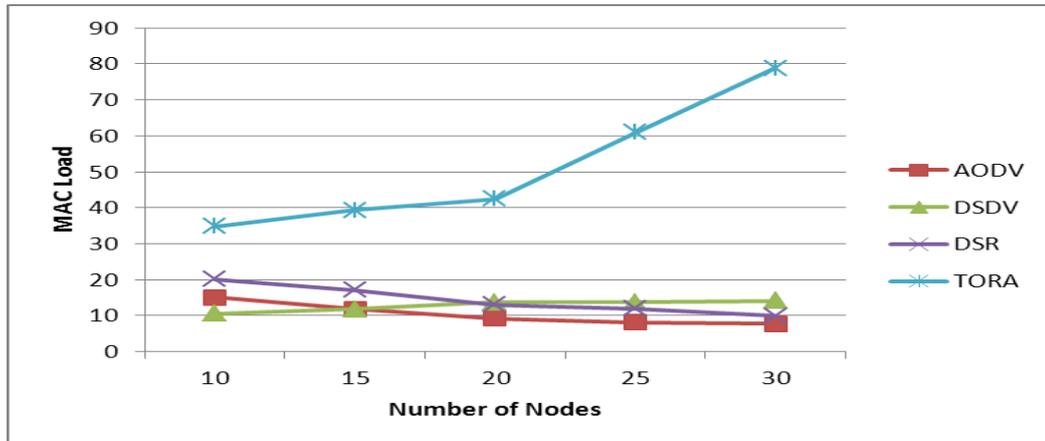


Figure 6.3: The MAC Load versus the number of nodes

## 6.3    Comparison of AODV, DSDV, DSR and OLSR protocols.

In this section comparisons are made between AODV, DSDV, DSR and OLSR in terms of number of packets dropped, remaining battery power, throughput, MAC Load, dropped packets and dropped bytes.
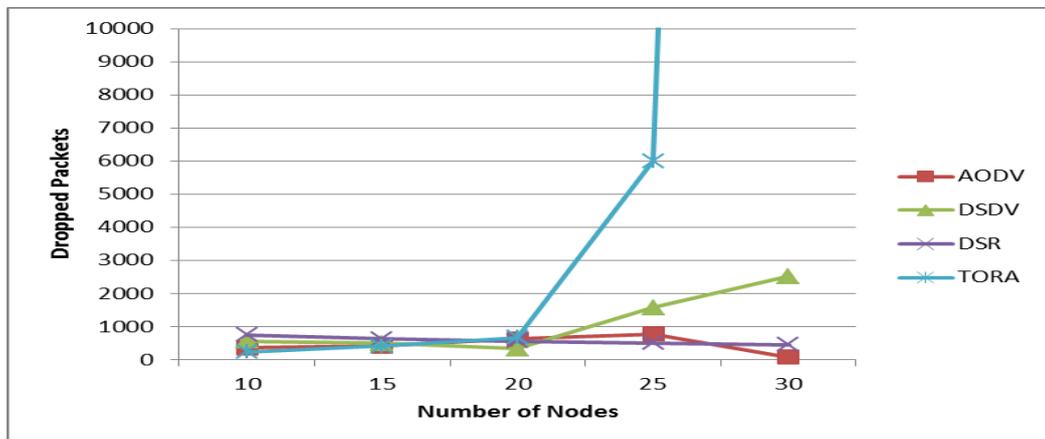


Figure 6.4: Number of dropped packets against number of nodes

Figure 6.5 shows that the energy efficiency of networks using AODV and DSR increases when the number of nodes exceeds 20, this is due to the fact that the nodes

will transmit a packet in every 0.1 second and will try to send at least 200 packets each and 50% of the nodes are transmitting and 50 % of the nodes are receiving during the simulation as the whole network runs for 100 sec. The DSDV protocol presents almost a stable consumption of power in every scale of the network. On the contrary, the energy efficiency of a network using the OLSR protocol drops sharply, especially when the network has more than 30 nodes. This happens due to the MPR mechanism that the OLSR protocol uses in order to inform adjacent nodes of one-hop nearby nodes. The lifetime of the nodes using OLSR protocols in this simulated scenario, is 830 minutes which is very short compared to the lifetime of networks using AODV, DSR, or DSDV.

Table 6.2: Parameters of the Simulation of AODV, DSR, DSDV, OLSR (50 nodes)

| | |
|---|---|
| Channel type | WirelessChannel |
| Radio-propagation model | TwoRayGround |
| Antenna type | OmniAntenna |
| Interface queue type | DropTail/PriQueue |
| Maximum packet in Queue | 50 |
| Network interface type | Phy/WirelessPhy |
| MAC type | 802_11 |
| Topographical Area | 500 x 300 sq.m |
| txPower | 0.5W |
| rxPower | 0.1W |
| idlePower | 0.01W |
| Initial energy of a Node | 1000.0 Joules |
| Routing protocols | AODV/DSDV/DSR/OLSR |
| Number of mobile nodes | 10,20,30,40,50,60,70 |
| Mobility | 0 - 20m/s |

Figure 6.5: Remaining Battery Power versus the number of nodes

Figure 6.6 shows that the throughput of AODV and DSR protocols presents a relatively very stable behaviour in every scale of the network. DSDV data throughput is worst for number of nodes greater than 10. OLSR has the lowest throughput when the network has less than 10 nodes. This happens due to the MPR mechanism that the OLSR protocol uses in order to inform adjacent nodes of one-hop nearby nodes using hello messages. When the number of adjacent nodes is increased then the network overhead is also increased.
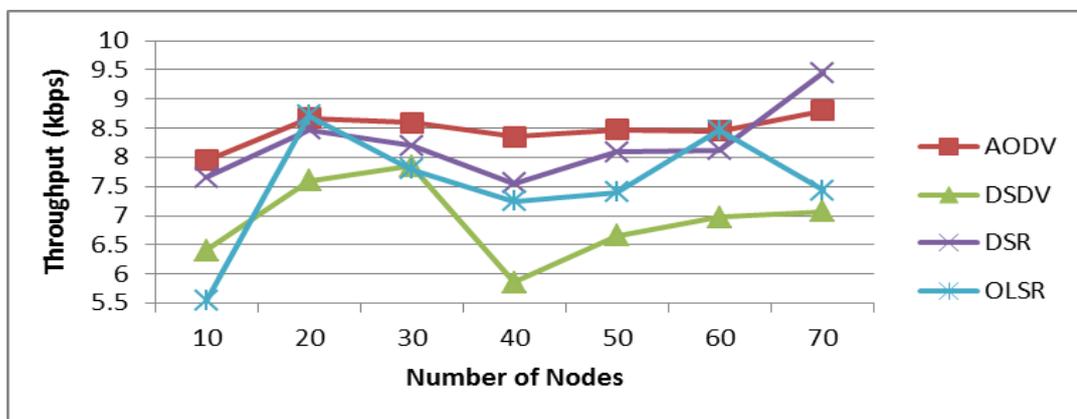


Figure 6.6: Data throughput versus the number of nodes

Figure 6.7 shows that the MAC Load (number of MAC messages generated to each data packet successfully delivered to the destination) increases rapidly when the number of

nodes exceeds 30 for OLSR protocol. This behaviour is due to the flooding mechanism that the protocol uses for route discovery. The DSDV protocol presents a very low MAC Load when the network consists of less than 30 nodes and increases when the number of nodes exceeds 30 which is consistent with the number of nodes that need to exchange topology information. The DSR routing protocol presents almost the same behaviour trend as DSDV when the number of nodes is up to 50 but the MAC Load decreases until the number of nodes is 70. In high density networks the DSR routing protocol shows low MAC Load because there are more nodes that contain information about the network topology. Compared to the others, the MAC Load of the AODV protocol remains consistently low in every scale of the network due to the RREQ mechanism that the protocol uses in order to discover routes.

Figure 6.8 shows the relationship between the number of nodes and the dropped packets. This figure shows that the AODV, DSDV and the OLSR protocols become inefficient when the network consists of more than 50 nodes for high density network. This is the results of increasing the number of re-transmissions in order to reach the destination node. On the contrary the DSR protocol presents a very good behaviour in small and large networks in terms of dropped packets. This occurred because in DSR protocol, every packet that is transmitted contains ordered information in its header about all the nodes through which it should be routed, and in this way it eliminates periodic route advertisement and neighbour detection packets that are used in other protocols.
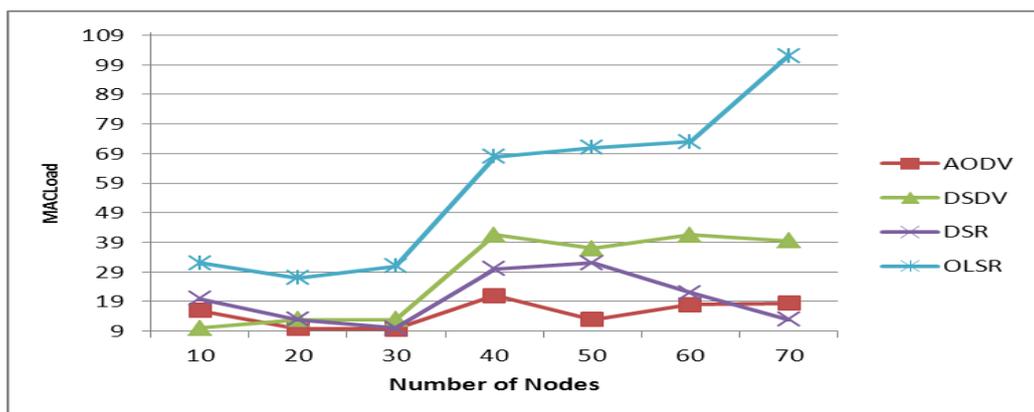
Figure 6.7: MAC Load versus the number of nodes
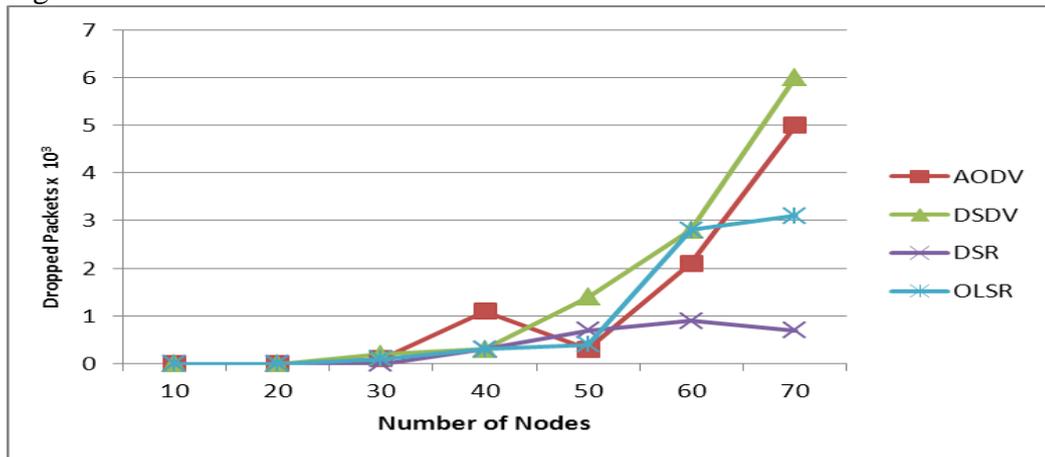


Figure 6.8: The Dropped Packets versus the number of nodes

Figure 6.9 shows how the number of nodes affects the total number of control message broadcasts sent per node or received by a node for all the four protocols. This figure shows that AODV and DSR send more messages than OLSR and DSDV protocols. This also means that the network load of AODV and DSR is high especially when the number of nodes is between 40 and 60. DSDV and OLSR present good results in all network sizes and show low number of total control message broadcast.
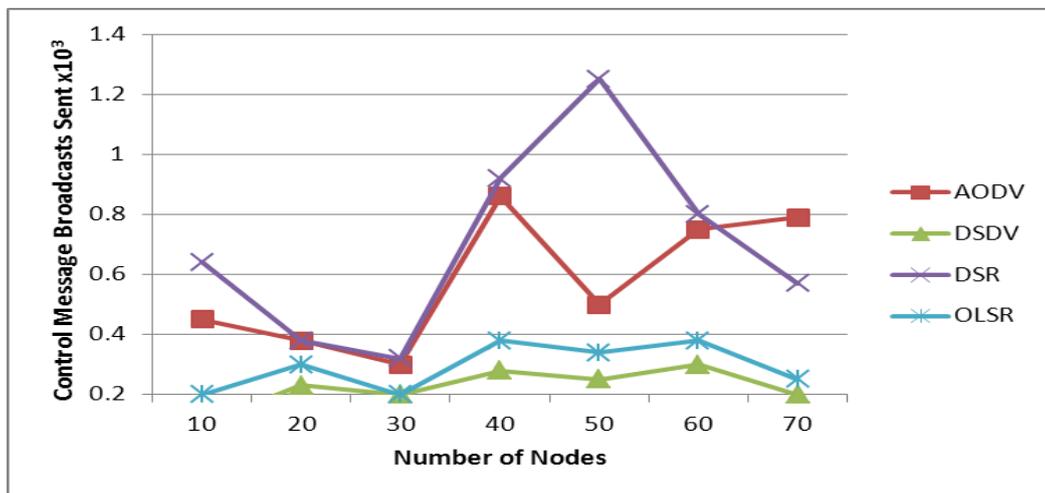


Figure 6.9: Total Control Message Broadcasts Sent per second against the Number of nodes

All the above results confirm that the use of simple flooding mechanism lead to excessive redundant re-transmissions, causing high channel contention (Figure 6.8 & 6.9) and packet collisions in the network (broadcast storm). Therefore by reducing flooding we will reduce the overhead, routing load and therefore power consumption. The convergence time, can be used as to measures how quick and reliable information exchange between the nodes are. However this metric has not been used in this research. The following sections show that using less RREQ packets can significantly reduce overhead and routing load.

## 6.4 The impact of varying the probability of the RREQ mechanism of AODV

In this section, the impact of varying the probability of the RREQ forwarding mechanism of AODV is presented in terms of the number of packets dropped, remaining battery power, throughput, MAC Load, dropped packets, dropped bytes and network load. The results are presented for all probabilities of forwarding the RREQ from 0.1 to 1.0 for network sizes from 10 to 100 nodes. It is worth nothing that the average parameter values given in each Figures 6.10 to 6.14 inclusive are for probabilities 0.1 to 1.0 and not for the network size.

Table 6.3: Simulation Parameters of AODV to evaluate different RREQ message forwarding probabilities (100 nodes)

| The Protocol | Probabilistic RREQ Message Forwarding Protocol |
|---|---|
| Topographical Area | 600m x 600m |
| Number of Nodes | 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 |
| Mobility | 1 m/s |
| Probability | 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 1.0 |
| Radio-propagation model | TwoRayGround |
| Network interface type | WirelessPhy |
| MAC type | 802_11 |
| Interface queue type | DropTail/PriQueue |
| Antenna model | OmniAntenna |
| Total Simulation Time | 100sec |
| Transport /Traffic Type | CBR over UDP |

Figure 6.10 shows that in small and medium size networks, RREQ forwarding probability of 0.1 performs even better than networks in which all nodes broadcast the

RREQ (probability of 1.0). For large networks and all network sizes, RREQ forwarding probability of 0.8 provides, on average, the best performance with a throughput of 5.405 kbps. This is followed by a network with a RREQ forwarding probability of 0.4 which achieves an average throughput of 5.248 kbps. This shows that network performance is not adversely affected by reducing the number of nodes that rebroadcast messages.

Figure 6.11 shows that the MAC Load presents very good results (is low) in small and medium size networks when the RREQ forwarding probability is 0.3 and 0.5 respectively, while for probabilities of 0.7 and 0.9 the MAC Load is very low in large scale networks. For small networks and all network sizes, RREQ forwarding probability of 0.3 provides, on average, the best performance with a MAC Load of 63.63.

| | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|
| AODV Prob. 0.1 | 1.37 | 2.16 | 3.55 | 4.07 | 4.75 | 5.65 | 7.04 | 7.22 | 7.97 | 7.5 |
| AODV Prob. 0.2 | 1.36 | 1.93 | 2.63 | 3.83 | 4.84 | 5.28 | 5.82 | 7.36 | 8.93 | 7.28 |
| AODV Prob. 0.3 | 1.37 | 2.2 | 3.27 | 4.45 | 4.86 | 5.64 | 6.93 | 6.4 | 8.94 | 8.3 |
| AODV Prob. 0.4 | 1.37 | 2.13 | 3.21 | 4.14 | 5.04 | 5.7 | 6.47 | 7.25 | 8.72 | 8.45 |
| AODV Prob. 0.5 | 1.37 | 2.15 | 3.15 | 4.14 | 4.84 | 5.81 | 6.39 | 7.47 | 8.88 | 8.15 |
| AODV Prob. 0.6 | 1.37 | 2.05 | 3.38 | 4.37 | 4.84 | 5.33 | 6.43 | 7.7 | 8.35 | 7.27 |
| AODV Prob. 0.7 | 1.37 | 2.28 | 3.38 | 3.83 | 5.26 | 5.25 | 6.95 | 7.21 | 8.12 | 7.8 |
| AODV Prob. 0.8 | 1.36 | 2.09 | 3.35 | 4.45 | 5.03 | 6.3 | 6.92 | 7.54 | 8.82 | 8.19 |
| AODV Prob. 0.9 | 1.37 | 2.28 | 3.44 | 4.33 | 5.43 | 5.67 | 7.16 | 5.91 | 7.36 | 7.43 |
| AODV Prob.1.0 | 1.36 | 2.28 | 3.46 | 4.03 | 4.96 | 5.62 | 6.5 | 7.81 | 8.77 | 7.55 |
| Avg. Throughput for Prob. from 0.1 to 1 | 5.128 | 4.926 | 5.236 | 5.248 | 5.235 | 5.109 | 5.145 | 5.405 | 5.038 | 5.234 |

Figure 6.10: Average network throughput against the number of nodes for different RREQ Forwarding Probability

| Number of nodes | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|
| AODV Prob. 0.1 | 14.75 | 35.34 | 36.62 | 44.59 | 72.94 | 74.94 | 61.95 | 98.26 | 103.05 | 131.35 |
| AODV Prob. 0.2 | 13.17 | 38.91 | 49.98 | 48.97 | 63.86 | 72.82 | 74.31 | 89.59 | 88.71 | 131.38 |
| AODV Prob. 0.3 | 13.17 | 35 | 39.1 | 41.8 | 65.64 | 65.95 | 72.51 | 91.7 | 92.49 | 118.94 |
| AODV Prob. 0.4 | 13.29 | 38 | 44.89 | 46.67 | 63.37 | 61.77 | 75.9 | 95.8 | 101.88 | 121.87 |
| AODV Prob. 0.5 | 13.17 | 37.74 | 42.62 | 46.74 | 63.86 | 67.68 | 74.85 | 87.65 | 90.28 | 116.57 |
| AODV Prob. 0.6 | 14.08 | 37.72 | 39.48 | 42.5 | 65.45 | 75.17 | 85.26 | 90.19 | 101.45 | 128.67 |
| AODV Prob. 0.7 | 13.08 | 34.77 | 40.05 | 48.71 | 58.27 | 74.88 | 69.09 | 84.5 | 93.2 | 132.48 |
| AODV Prob. 0.8 | 13.38 | 36.95 | 42.44 | 42.15 | 64.99 | 61.82 | 78.84 | 80.66 | 89.29 | 131.16 |
| AODV Prob. 0.9 | 13.38 | 33.45 | 41.4 | 42.91 | 60.35 | 72 | 71.47 | 103.29 | 100.25 | 108.37 |
| AODV Prob.1.0 | 13.96 | 34.45 | 40.08 | 45.05 | 69.58 | 71.42 | 82.88 | 85.03 | 95.6 | 136.81 |
| Avg. MACLoad for Prob. 0.1 to 1 | 67.379 | 67.17 | 63.63 | 66.344 | 64.116 | 67.997 | 64.903 | 64.168 | 64.687 | 67.486 |

Figure 6.11: Average MAC Load against the number of nodes for different RREQ Forwarding Probability.

Figure 6.12 shows that using 0.3 and 0.5 RREQ forwarding probability in small and medium scale networks the number of dropped packets is small. Meanwhile in large scale network, the number is small for probabilities of 0.7 and 0.9. For small networks and all network sizes, RREQ forwarding probability of 0.3 provides, on average, the best performance with the number of dropped packets as low as 70847.1.

Figure 6.13 confirms that when the RREQ forwarding probability is 0.3, 0.5 and 0.8 the network traffic is reduced, while when the probability is 0.1, 0.2, 0.6 and 1.0 the network traffic is increased. The best performance, on average, is obtained when the RREQ forwarding probability is 0.3 which has an average network load of 41.024.
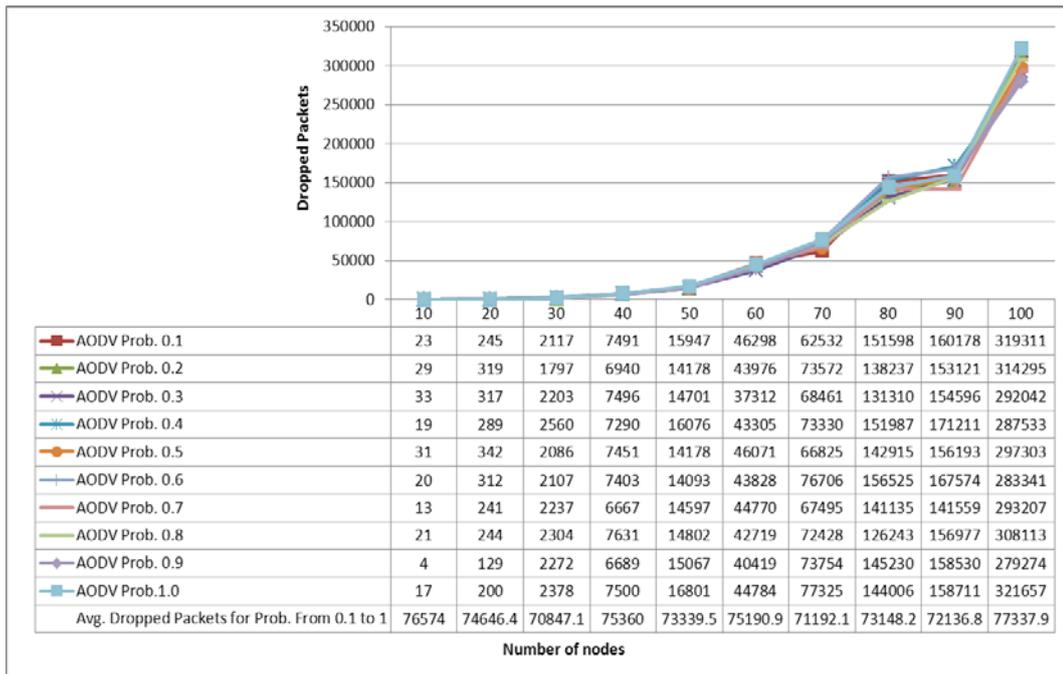
Figure 6.12: Average dropped packets against the number of nodes for different RREQ Forwarding Probability.

Figure 6.14 shows that when the RREQ forwarding probability is 0.3 and 0.5 in small size networks, the number of control messages that sent is small. Very few control messages are sent in large scale networks when the RREQ forwarding probability is 0.9. The best performance, on average, is obtained when the RREQ forwarding probability is 0.3.

| | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|
| AODV Prob. 0.1 | 5.17 | 11.26 | 16.89 | 26.08 | 41.98 | 48.97 | 41.9 | 72.35 | 75.89 | 102.37 |
| AODV Prob. 0.2 | 5.17 | 12.97 | 22.57 | 28.63 | 37.86 | 45.46 | 53.35 | 65.61 | 64.66 | 100.28 |
| AODV Prob. 0.3 | 5.17 | 11.08 | 19.17 | 24.41 | 40.14 | 40.29 | 50.24 | 64.77 | 65.04 | 89.93 |
| AODV Prob. 0.4 | 5.08 | 12.47 | 20.53 | 25.68 | 37.85 | 40.98 | 53.02 | 71.35 | 73.42 | 91.1 |
| AODV Prob. 0.5 | 5.17 | 11.84 | 19.23 | 25.07 | 37.86 | 43.06 | 51.45 | 64.86 | 65.04 | 89.21 |
| AODV Prob. 0.6 | 5.17 | 11.81 | 18.93 | 24.04 | 37.84 | 48.09 | 60.34 | 67.1 | 74.77 | 100.33 |
| AODV Prob. 0.7 | 5.17 | 9.87 | 19.23 | 26 | 34.59 | 48.82 | 49.85 | 61.57 | 68.26 | 99.9 |
| AODV Prob. 0.8 | 5.17 | 10.81 | 19.8 | 23.56 | 38.09 | 39.89 | 54.26 | 57.51 | 65.54 | 98.56 |
| AODV Prob. 0.9 | 5.17 | 9.7 | 18.92 | 24.42 | 36.32 | 45.05 | 50.61 | 78.06 | 71.86 | 82.81 |
| AODV Prob.1.0 | 5.58 | 10.2 | 18.69 | 25.27 | 40.13 | 46.72 | 58.92 | 62.54 | 69.88 | 104.87 |
| Avg. Network Load for Prob. from 0.1 to 1 | 44.286 | 43.656 | 41.024 | 43.148 | 41.279 | 44.842 | 42.326 | 41.319 | 42.292 | 44.28 |

Figure 6.13: Average network load against the number of nodes for different RREQ Forwarding Probability.



| | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|
| AODV Prob. 0.1 | 124 | 428 | 1064 | 1982 | 3610 | 5044 | 5657 | 9406 | 11232 | 15355 |
| AODV Prob. 0.2 | 124 | 441 | 1061 | 1947 | 3294 | 4773 | 6935 | 8858 | 10799 | 15443 |
| AODV Prob. 0.3 | 124 | 432 | 1112 | 1928 | 3532 | 4110 | 6431 | 8291 | 10797 | 14299 |
| AODV Prob. 0.4 | 122 | 474 | 1170 | 1952 | 3520 | 4754 | 6733 | 9490 | 11821 | 14211 |
| AODV Prob. 0.5 | 124 | 450 | 1077 | 1855 | 3294 | 4737 | 6225 | 8950 | 10861 | 14541 |
| AODV Prob. 0.6 | 124 | 425 | 1136 | 1875 | 3292 | 4617 | 7120 | 9663 | 11814 | 14147 |
| AODV Prob. 0.7 | 124 | 395 | 1154 | 1768 | 3355 | 4736 | 6481 | 8866 | 10102 | 14486 |
| AODV Prob. 0.8 | 124 | 400 | 1168 | 1861 | 3428 | 4547 | 6891 | 8052 | 11010 | 15375 |
| AODV Prob. 0.9 | 124 | 388 | 1192 | 1880 | 3487 | 4595 | 6731 | 9055 | 11066 | 13746 |
| AODV Prob.1.0 | 134 | 408 | 1140 | 1845 | 3652 | 4812 | 7070 | 9069 | 11251 | 15836 |
| Avg. Tot. Con. Mes. Br. Sent for Prob. From 0.1 to 1 | 5390.2 | 5367.5 | 5105.6 | 5424.7 | 5211.4 | 5421.3 | 5146.7 | 5285.6 | 5226.4 | 5521.7 |

Figure 6.14: Average Total Control Message Broadcasts Sent against the number of nodes for different RREQ Forwarding Probability.

## 6.5 Results of the proposed algorithm AODV_EXT against the traditional AODV, DSDV, DSR, OLSR

The results of a comparison between the proposed algorithm, AODV_EXT, which implements dynamic probability as a part of the RREQ mechanism and the traditional AODV, DSDV, DSR, OLSR is presented in this section in terms of the number of packets dropped, remaining battery power, throughput, routing load, MAC Load, dropped packets, transmitted control messages, received control messages as shown in Table 6.4.

Table 6.4: Simulation parameters settings (50 nodes)

| Routing Protocols | AODV, AODV_EXT, OLSR, DSDV, DSR |
|---|---|
| Topographical Area | 800m x 800m |
| Number of Nodes | 10, 20, 30, 40, 50 |
| Mobility | 1m/s to 40m/s |
| Channel type | Wireless Channel |
| Radio-propagation model | TwoRayGround |
| Network interface type | WirelessPhy |
| MAC type | 802_11 |
| Interface queue type | DropTail/PriQueue |
| Antenna model | OmniAntenna |
| Max packet in Queue | 50 |
| Transport /Traffic Type | CBR over UDP |
| TxPower of the nodes | 0.1819 watts |
| RxPower of the nodes | 0.0501 watts |
| IdlePower of the nodes | 0.0350 watts |
| Initial energy of the nodes | 1000.0 Joules |

Figure 6.15 shows that AODV_EXT has slightly more remaining battery power than the other four protocols when the number of nodes is 50. Most importantly the remaining battery power of AODV_EXT is more in comparison to that of standard AODV as the number of nodes in the network increases beyond 30. The two protocols perform equally in small size networks. DSR protocol based networks uses more power compared to AODV and AODV_EXT but shows better performance when the number of nodes in the network is up to 30 nodes. On the contrary, the power consumption of

networks using DSDV and OLSR increases steadily, thus decreasing remaining power, with the network size. With increasing number of nodes, the battery power of OLSR based networks decrease faster than those for the other protocols. OLSR protocol uses a mechanism that constantly updates information about nodes in the neighbourhood. As the number of nodes in the network increases, more updates are required and hence proactive protocols perform poorly, especially when the network is subject to changes e.g. in mobile environment.
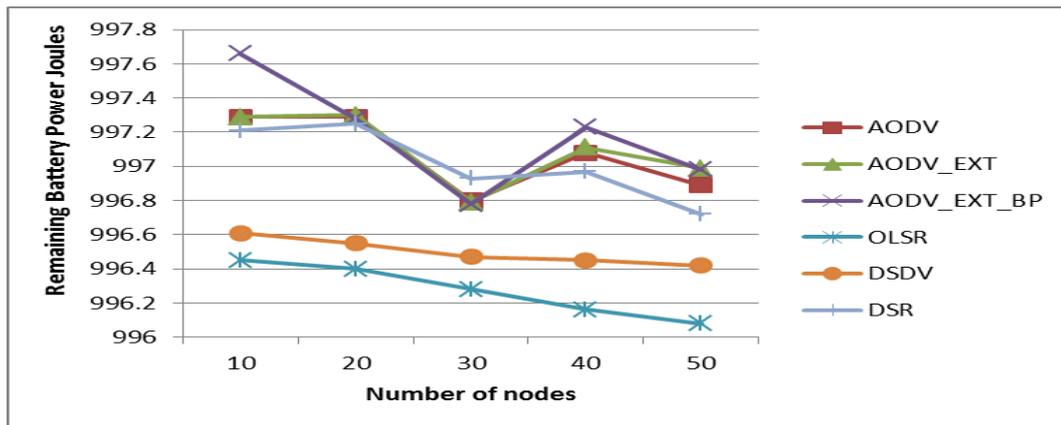


Figure 6.15: The average remaining battery power

Figure 6.16 shows the performance of the protocols based on data throughput. It shows that AODV and DSR achieve comparable performance. However, AODV_EXT shows superior performance in larger networks. With AODV_EXT and AODV protocol, every node does not need to keep information regarding the route between two nodes. This reduces the amount of signaling required for route discovery and maintenance. OLSR and DSDV both show poor performances compared to the other three protocols. This is because both are proactive protocols and table updates generate relatively high messaging overhead that can cause collision in large networks, especially in mobile networks, and reduces data rate performance of the network. However, these protocols are better suited to low data rate transmission because their self-updating scheme ensures connectivity rather than the availability of bandwidth for application data.

Figure 6.17 shows the routing control message overheads. In the case of AODV_EXT, it is lower than that of standard AODV protocol. DSR and DSDV show better performances due to the fact that they transmit and receive the least number of control messages. OLSR protocol has the worst performance of all the protocols and this degrades significantly as the number of nodes exceeds 20.
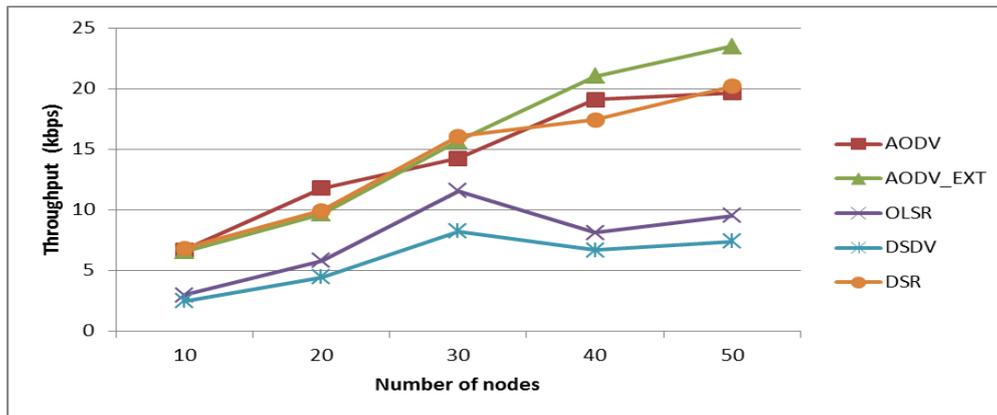


Figure 6.16: Comparison of data throughput for various network sizes (number of nodes)
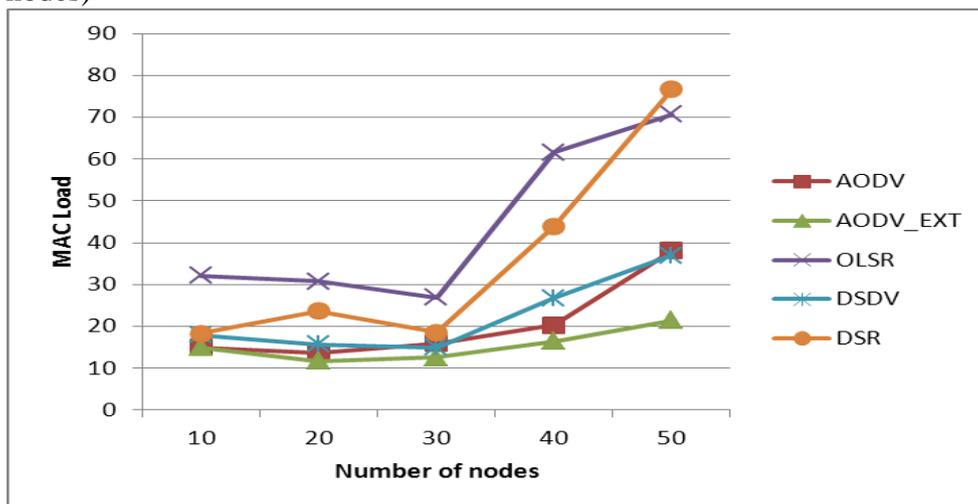


Figure 6.17: MAC Load against the number of nodes

Figure 6.18 shows that DSDV drops the least number of packets with standard AODV dropping the most for networks with more than 20 nodes. However, compared to standard AODV, AODV_EXT performance is a factor 4 better.

Figure 6.19 shows that DSR and AODV_EXT have the least routing load compared to the traditional AODV and DSDV. OLSR presents a very high routing load especially when the number of nodes increases beyond 30 nodes.
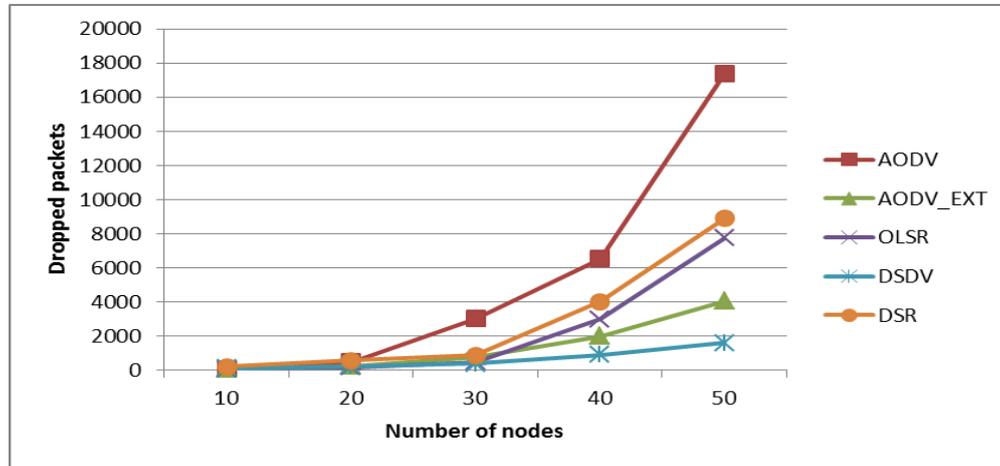


Figure 6.18: Dropped Packets against the number of nodes
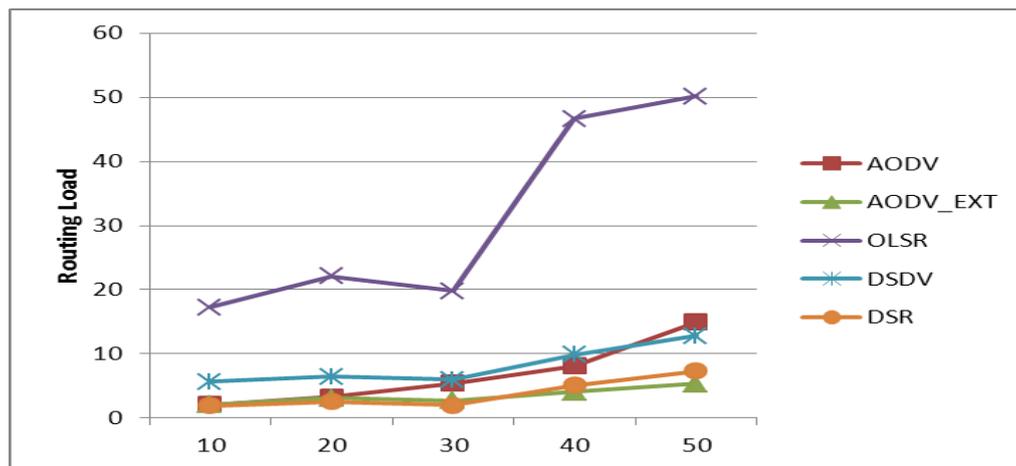


Figure 6.19: Routing Load against the number of nodes

Figure 6.20 shows that DSDV and AODV_EXT transmit less control messages compared to the other three protocols for networks with 30 or more nodes. AODV_EXT performs much better in terms of total transmitted control messages in large size networks (40 & 50 nodes) when compared to standard AODV. OLSR protocol shows a very high number of transmitted control messages in networks of all sizes.
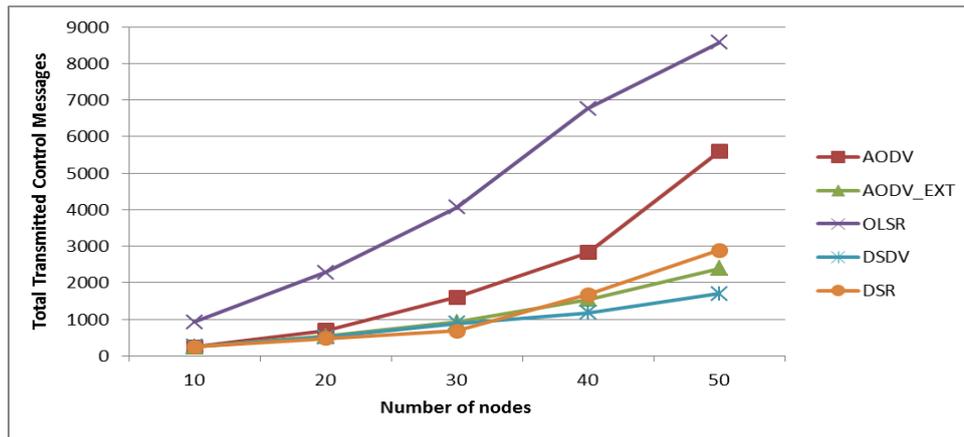
Figure 6.20: Total Transmitted Control Messages against the number of nodes

## 6.6 Comparison of AODV_EXT_BP against AODV_EXT, AODV, DSDV, DSR, OLSR

AODV_EXT_BP uses Bayesian theory as a part of the RREQ mechanism and its performance and the results of comparison to other protocols is presented in this section. The parameter values for the simulation carried out are presented in table 6.5.

Table 6.5: Simulation parameters settings (50 nodes)

| Routing Protocols | AODV/ AODV_EXT/ AODV_EXT_BP / OLSR/DSDV/DSR |
|---|---|
| Topographical Area | 800m x 800m |
| Number of Nodes | 10, 20, 30, 40, 50 |
| Mobility | 1m/s to 40m/s |
| Channel type | Wireless Channel |
| Radio-propagation model | TwoRayGround |
| Network interface type | WirelessPhy |
| MAC type | 802_11 |
| Interface queue type | DropTail/PriQueue |
| Antenna model | OmniAntenna |
| Max packet in Queue | 50 |
| Transport /Traffic Type | CBR over UDP |
| TxPower of the nodes | 0.1819 watts |
| RxPower of the nodes | 0.0501 watts |
| IdlePower of the nodes | 0.0350 watts |
| Initial energy of the nodes | 1000.0 Joules |
| TxPower of the nodes | 0.1819 watts |

Figure 6.21 shows that, on average, AODV_EXT_BP has more remaining battery power than the other five protocols for most network sizes. Most importantly, AODV_EXT_BP based network is more energy efficient in comparison to the other proposed probabilistic algorithm, AODV_EXT. The AODV_EXT_BP protocol based network use less battery power especially in small size networks. The battery power of nodes using DSDV and OLSR protocols decreases steadily starting from fairly high levels. With increasing number of nodes, the battery power of OLSR based networks decrease faster than those for the other protocols.
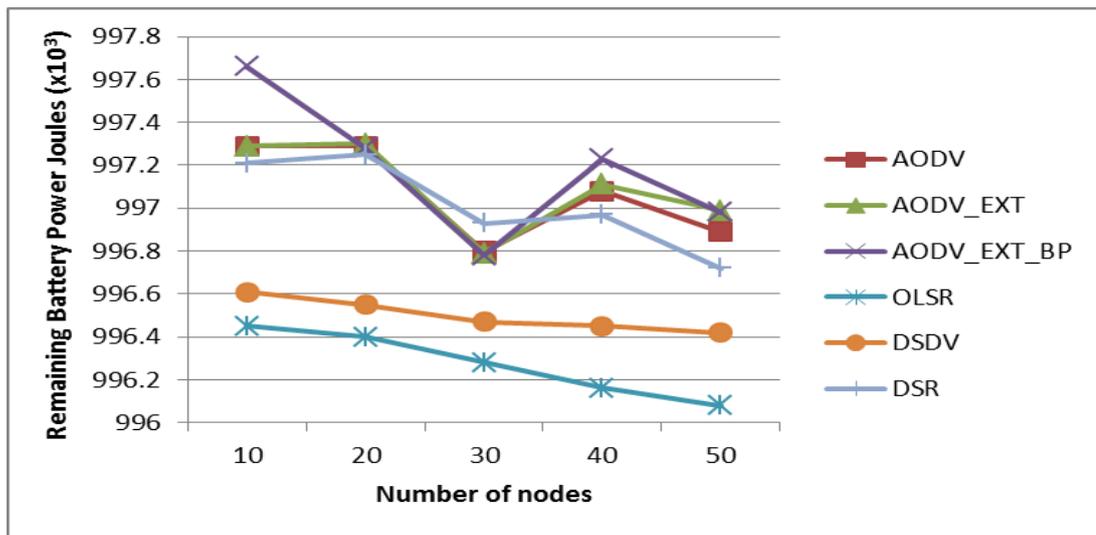


Figure 6.21: The average remaining battery power

Figure 6.22 shows the performance of the protocols based on data throughput. It shows that AODV_EXT_BP, AODV_EXT, AODV and DSR achieve comparable performance for network sizes greater than 10 nodes. However, AODV_EXT shows superior performance in larger networks. In AODV_EXT_BP, AODV_EXT and AODV protocols, every node does not need to keep information regarding the route between two nodes. This reduces the amount of signaling required for route discovery and maintenance. OLSR and DSDV both show poor performances compared to the other three protocols. This is because both are proactive protocols and require table updates that generate relatively high messaging overhead that can cause collision in large

networks, especially in mobile networks, and reduces data rate performance of the network. However, these protocols are better suited to low data rate transmissions because their self-updating scheme ensures connectivity rather than the availability of bandwidth for application data.
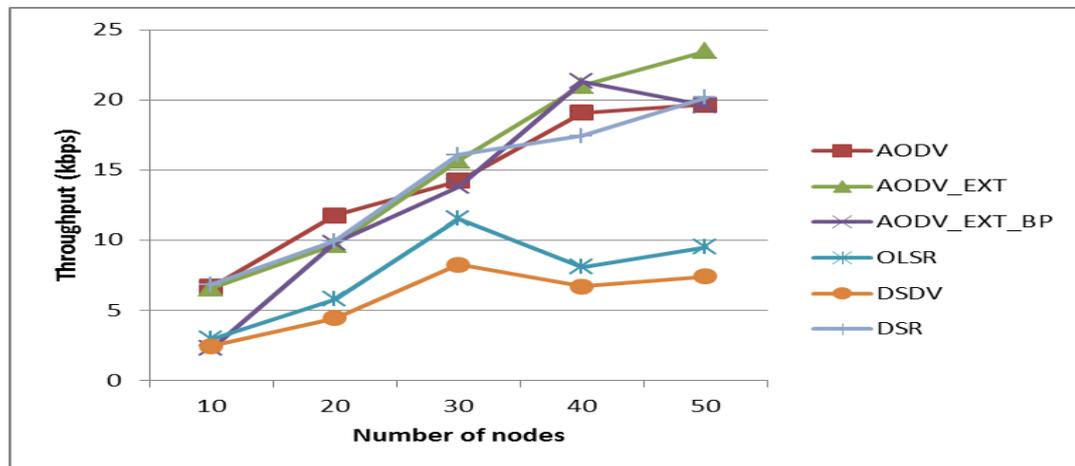


Figure 6.22: Comparison of data throughput for various network sizes (number of nodes)

Figure 6.23 shows the MAC Load. In the case of AODV_EXT_BP, it is lower than that of the other proposed AODV_EXT protocol. DSDV and AODV show better performances due to the fact that they transmit and receive the least number of control messages. OLSR and DSR protocols performances are poor and degrade significantly as the number of nodes exceeds 30.
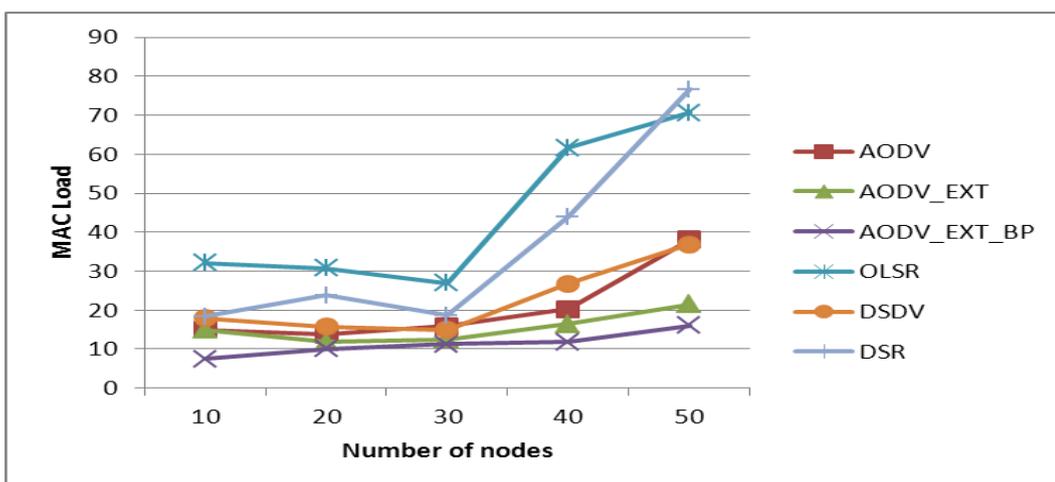


Figure 6.23: Comparison of MAC Load for various network sizes (number of nodes)

Figure 6.24 shows that AODV_EXT_BP and DSDV drop the least number of packets, whilst the traditional AODV drops the most for network sizes up to 50 nodes.
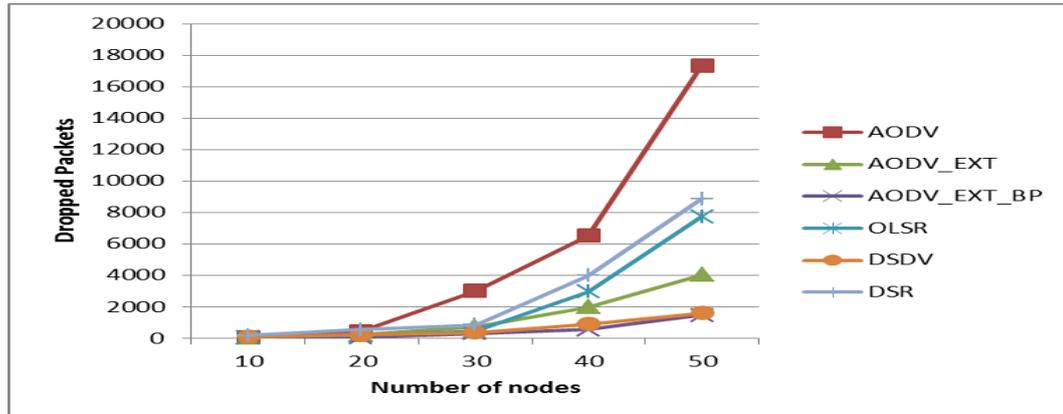


Figure 6.24: Dropped Packets against the number of nodes

Figure 6.25 shows that AODV_EXT_BP and AODV_EXT has the least routing load. On the other hand the OLSR protocol presents poor performance with high routing load especially when the number of nodes exceeds 30 nodes.
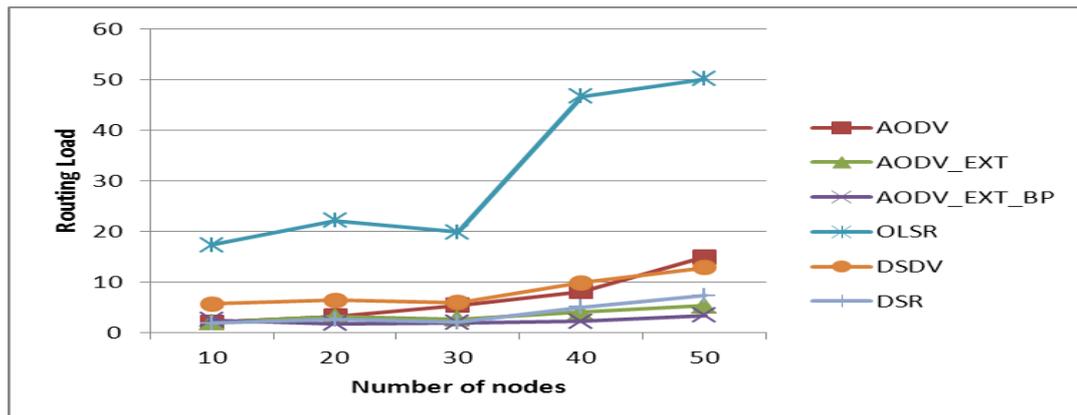


Figure 6.25: Routing Load against the number of nodes

Figure 6.26 shows that the AODV_EXT_BP transmits the least number of control messages compared to the other protocols. Since AODV_EXT_BP protocol transmits the least number of control messages, it follows that a network using this protocol will receive the least number of control messages compared to the other protocols. OLSR protocol transmits a very high number of control messages in all network sizes.
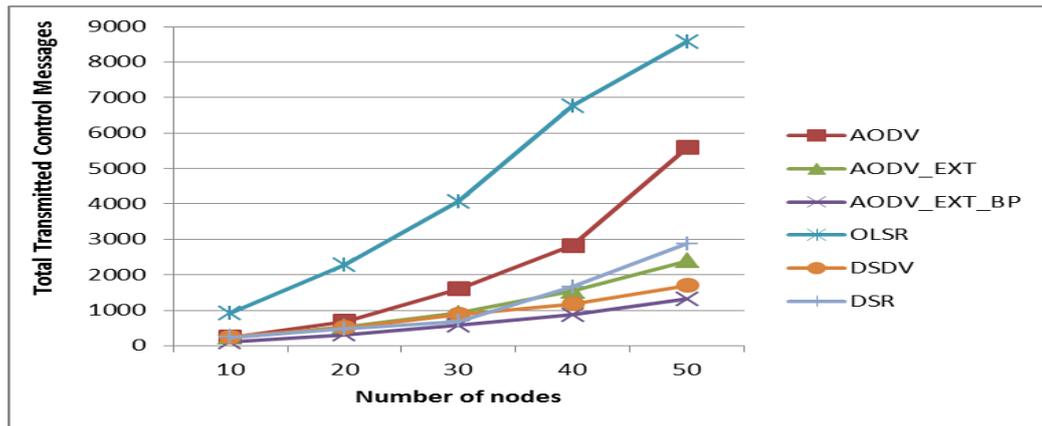
Figure 6.26: Total Transmitted Control Messages against the number of nodes

## 6.7 Summary

This chapter has presented the simulation results and comparison of existing Ad Hoc routing protocols (AODV, DSDV, OLSR, DSR, TORA) with the two newly proposed protocols AODV_EXT and AODV_EXT_BP. All the results have been presented in terms of the number of packets dropped, remaining battery power, consumed power, throughput, routing load, MAC Load, dropped packets and transmitted control messages. The two proposed protocols have been evaluated and compared with existing protocols and found to perform consistently better than the other protocols.

Table 6.6 shows the total performance of the new proposed protocols compared to the original AODV.

Table 6.6: Performance comparison of AODV_EXT and AODV_EXT_BP to standard AODV

| Metrics | AODV | Improved Performance of AODV_EXT | Improved Performance of AODV_EXT_BP |
|---|---|---|---|
| Average Remaining Battery Power (Joules) | 3.8 | 3.0 % | 3.3 % |
| Average Throughput (Kbps) | 14.294 | -2.5 % | 3.5 % |
| Average Dropped Packets | 5487.8 | 25.9 % | 89.5 % |
| Average MAC Load | 20.59 | 25.1 % | 44.9 % |
| Average Total Transmitting Control Messages | 2189.4 | 49.6 % | 71.8 % |

The Table 6.6 shows that the two proposed protocols AODV_EXT and AODV_EXT_BP presents better efficiency, especially in terms of power, instead the

original AODV which is due to the overhead that the RREQ broadcasting causes. Moreover the average MAC Load of the two proposed protocol presents very good results, because it reduces the routing load and the overhead. All the above make the two proposed protocols suitable for use in industrial grade networks.

# CHAPTER 7

# CONCLUSIONS AND FUTURE WORK

*Abstract: This Chapter describes the various achievements of the research, especially the author's contributions. Recommendations for further development of different probability schemes and implementation are also discussed.*

## 7.1    Introduction

A combination of centralized and ad hoc networks is envisaged to provide solutions for the provision of ubiquitous communication for a wide range of applications. Whilst centralized communication is well established, ad hoc networking is seen as the way forward for self-organizing and managing networks which eliminates meticulous and expensive planning, high cost, rigidity and vulnerability inherent in fixed centrally managed networks such as wired and wireless networks e.g. Mobile Telecommunications System (UMTS). Ad hoc networks also hold great promise and applications in an extensive number of areas ranging from disaster management to environmental monitoring. Progress in ad hoc networks is also facilitating the application of sensors for process automation in a variety of industries and is enabling progress in sensor fusion. Unpredictable events, e.g. earthquake often serve to illustrate the vulnerability of centrally managed networks and the importance of research and development in ad hoc networks such as Mobile Ad hoc Networks (MANET), for which centralized connectivity is not required. MANET is a wireless network that has mobile nodes with no fixed infrastructure. The main limitation of ad hoc network systems is the availability of power and continuous reduction in the size of devices mean that power limitation cannot simply be ameliorated with large battery packs [7.1]. In addition to running the onboard electronics, power consumption is governed by the number of processes and overheads required to maintain connectivity.

A wide range of techniques have been proposed to address connectivity and power limitation issues in ad hoc networks. These include hardware development, protocols, routing algorithms and battery technology or energy management systems [7.2]. Some researchers have proposed the development of hardware optimized for specific applications based on data rates [7.3]. More detailed studies of energy consumption by hardware have been carried out to evaluate energy consumption when transmitting, receiving, in sleep and idle modes. It has been proposed in [7.4][7.5] that energy management should be tailored to each application where the voltage, and hence processing speed and energy, can be reduced for non-time sensitive applications. This proposed technique benefits from the fact that the speed of microprocessors and energy consumption depend on the voltage that is applied to it. The common goal of energy management techniques proposed for ad hoc networks is to preserve energy and maximize life span of the network. Other proposed methods are aimed at preventing network partitioning by managing energy consumptions of critical link nodes. In this thesis the author proposed a modification of one of the most widely used protocols to improve the energy and data transmission efficiency of the network.

In general, ad hoc wireless networks broadcast packets to the whole network as a means of transmitting information from one node to the other in the network [7.6]. Broadcasting in MANETs is not only a fundamental action for unicast routing protocols in mobile scenarios, but it is also an inextricable part of a number of multicast routing protocols. A variety of unicast, multicast, and geocast protocols utilize broadcasting as a building block, providing important control and route establishing functionality. Broadcasting a packet to the entire network has extensive applications in mobile ad hoc networks. Therefore, improving the broadcasting process will result in savings in several MANET applications.

Flooding is the simplest technique used by source nodes to broadcast packets to neighbouring nodes [7.7]. Each neighbour node receiving the packet for the first time

rebroadcasts it ensuring outward propagation from the source until every node in the network has received and transmitted the broadcast packet exactly once.

Significant research activities have focused on reducing flooding in the network [7.7][7.8]. Any procedure that leads to a reduction in congestion saves energy and prolongs the life span of the network. In general, multi-hop transmissions are less energy efficient because of the startup energy consumption of the transceivers [7.9]. Therefore flooding which results in the reception and retransmission by multiple nodes in a network where path loss is not the dominant energy consumption element is energy inefficient. In high density networks allowing nodes to be turned off or enabling sleep mode and maximizing transmission range can increase energy efficiency. In [7.10] the concept of a minimum range routing where nodes within a specific range of a transmitting node are not allowed to retransmit a packet has been proposed. However, the proposed technique relies on nodes keeping an updated table of information about neighbouring nodes which can be time and energy inefficient in a high mobility environment. Another approach has been proposed in [7.11] where power consumption is distributed amongst the nodes by controlling the transmission and the reception powers. Using this technique, the amount of power consumed for sending one packet to any destination node is the same and determined for each node that is taking part in the routing process.

Broadcast protocols can be broadly divided into two main categories; deterministic and probabilistic. The probabilistic approach usually provide a simple solution in which every node that receives a broadcast packet has a fixed probability of forwarding the message [7.10]. However this approach does not guarantee full network coverage, which also may happen in the two proposed protocols. On the other hand the deterministic approach can provide full coverage and can be further grouped into two categories, location information and neighbour set based.

In MANETs the routing task is delivered through network nodes which act as both routers and end points in the network. In order for a route to a specific destination node

to be discovered, existing on-demand routing protocols use a simple flooding mechanism whereby a Route Request packet (RREQ) originating from a source node is broadcasted without exception to all nodes in the network [7.12]. This can lead to significant redundant retransmissions, causing high channel usage and packet collisions in the network.

The following protocols have been studied and their performances in simulated networks have been analysed; Dynamic Source Routing (DSR), Ad hoc On-Demand Distance Vector Routing (AODV), Destination Sequenced Distance Vector (DSDV) routing and Optimized Link State Routing (OLSR). These protocols have been widely used and cited in literature [7.13].

## 7.2    Summary of the results

The main objectives of this thesis were to evaluate existing protocols and routing algorithms for power efficiency, identify and develop techniques (protocol and/or routing algorithm) that will improve ad hoc network power efficiency. In order to conduct this research, extensive investigations of the advantages and disadvantages of ad hoc protocols were carried out. Different simulation platforms were considered and NS-2 was select for this research because it is cost effective, less demanding on the computer system and has a large user community.

The objectives and the achievements can be summarized as follows:

- Evaluate existing protocols for power efficiency and modify or develop a more efficient power conservation scheme;
    - The performances of the Dynamic Source Routing (DSR), Destination-Sequenced Distance-Vector Routing (DSDV), Temporally Ordered Routing Algorithm (TORA), Optimized Link State Routing (OLSR) and Ad hoc On-Demand Vector (AODV) routing protocols haves been compared in terms of power consumption, routing overhead, network throughput and MAC Load, in order to find out the advantages and

disadvantages of each protocol. AODV has been selected because of its flexibility and good performance in comparison to the other protocols. The Route Request (RREQ) mechanism of AODV has been modified to it was easy to be modified on the RREQ forwarding mechanism, with aim to reduce the flooding, routing overhead and routing load and therefore the power consumption

- Investigate, develop and modify an existing protocol or routing algorithm to improve energy efficiency;

  - Two probability techniques have been implemented in the RREQ forwarding mechanism of AODV to reduce re-transmissions. These are: a dynamic random probability scheme, the AODV_EXT, and an approach based on the Bayesian theory, the AODV_EXT_BP. These proposed algorithms alleviate the storm phenomenon and thus reduce the total network power consumption.

- Test and critically analyse the protocol and the routing algorithm;

  - Test results show that the average MAC Load is reduced by 25.1% and 44.9% using the two new protocols, AODV_EXT and AODV_EXT_BP, respectively, compared to the standard AODV. A 25.9% and 89.5% reduction in dropped packets is also achieved for AODV_EXT and AODV_EXT_BP, respectively. In terms of power consumption AODV_EXT and AODV_EXT_BP based networks show 3.0% and 3.3%, respectively, improvements in remaining battery power compared to standard AODV. However, AODV_EXT achieve a 2.5% poorer performance in data throughput compared to standard AODV but AODV_EXT_BP achieves a 3.5% better performance.

- Evaluate the performance of the modified protocol and routing algorithm in small, medium and large scale networks;

- In small (0-10 nodes), medium (10-30 nodes) and large (more than 30 nodes) scale networks AODV_EXT achieves 1.8%, 5.7% and 1.9%, energy efficiencies, respectively, compared to standard AODV protocol. For the same network sizes, AODV_EXT_BP exhibits 2.2%, 4.3% and 2.8% improvements in power consumption. Overall, the results show that the developed algorithms will improve the network life span by more than 2%.

Most studies that have been conducted on probability based broadcast algorithms proposed in the literature [7.14]-[7.17] have tried to alleviate the broadcast storm problem in simple flooding. But most of them tried to use a combination of probabilistic and counter-based schemes [7.14]. Some other studies have tried to reduce the power consumption in AODV routing protocol, e.g. as in [7.19], by reducing energy consumption through minimizing the listening. In order to do that, the number of listening nodes is randomly selected based on probability, but the results showed that the energy consumption, using this scheme, is much higher than the original AODV consumes. In addition the network size that the results have been taken from was very small (30 nodes).

Another research that has been conducted by Khelifa and Maaza [7.18] proposed the Energy Reversed Ad hoc On-Demand Distance Vector (ER-AODV) routing protocol based on dynamic probabilistic broadcasting. Study by the author showed that it consumes up to 1.7 % more power than AODV_EXT and 2.0 % more power than the AODV_EXT_BP.

In performance analysis, existing implementations of the AODV routing protocol in the NS-2 simulator have been modified in order to design the two proposed algorithm, the AODV_EXT and the AODV_EXT_BP. Extensive simulation analysis has revealed that given a set of system parameters, the performance behaviour of the dynamic probabilistic versions of the two proposed routing protocols, AODV_EXT and AODV_EXT_BP, offers significant improvements over standard AODV especially in

small and large size networks. This study is the first in the literature that conducts a performance analysis of dynamic probabilistic broadcasting algorithm using the Bayesian theory.

The new approach, referred to as AODV_EXT combines the functionalities of the original AODV flooding mechanism in low density networks and the proposed algorithm which significantly reduces re-broadcasts. In the proposed algorithm, a table of nodes in a given neighbourhood (one-hop nodes) is maintained. When a message is transmitted, only a subset of nodes in each neighbourhood is allowed to transmit. The number of selected nodes can be varied dynamically depending on the application and required quality of service. Each node in the network will forward a route request message if and only if a condition based on its neighbourhood density at that instant is satisfied. The proposed scheme minimizes network congestion due to redundant transmissions.

Numerous simulation experiments have been conducted under different network working conditions to compare the performance of the proposed AODV_EXT to that of the traditional AODV and DSDV, DSR, OLSR. Several performance metrics have been considered in the analysis, including Number of Packets dropped, Remaining Battery Power, Consumed Power, Throughput, Mac Load, Dropped Packets, Dropped Bytes, and Control Message Overhead. A wide range of system parameters, including network density and node mobility have been considered. Simulation results have shown that in most cases considered, AODV_EXT exhibits superior performance in terms of power consumption, routing overhead, network throughput and MAC Load compare to the traditional AODV. In the standard AODV, each node forwards a RREQ packet that is received for the first time according to simple flood mechanism. However, the network topology in MANETs is highly dynamic due to the movements of nodes in the network. As a result, the status and the position of each node changes frequently. Therefore, the forwarding probability should be changed dynamically to follow any network changes and reduce redundant retransmissions.

Extensive simulation experiments have been conducted to compare the performance of the new AODV_EXT and AODV_EXT_BP against the standard AODV. The performance impact of different network densities, offered loads and node mobility have been examined in the simulation experiments. The results have revealed that AODV_EXT_BP presents superior performance in terms of power consumption, network throughput and MAC Load compared to AODV_EXT, the standard AODV and some other ad hoc routing protocols (DSDV, DSR, OLSR).

## 7.3    Directions for Future Work

There are a number of issues that require further research. This thesis has presented extensive performance analysis of two dynamic probabilistic broadcasting algorithms which have been implemented as part of AODV reactive routing protocol. It would be an interesting prospect to examine the effects of these dynamic probabilistic broadcasting algorithms on another reactive routing protocol such as DSR [7.20], the routing table advertisements in proactive routing protocols, such as OLSR [7.13] , and hybrid routing protocols, such as ZRP [7.20].

This research has extensively use of random waypoint mobility model [7.21] in order to simulate node mobility and its impact on the performance of the proposed algorithms, AODV_EXT, and AODV_EXT_BP. There are other new models which have recently been proposed [7.21] and which account for different motion patterns. For instance, the Manhattan Grid mobility model [7.21] which models vehicular mobility on structured roads in a city.

This research can be continued by examining the two proposed algorithms AODV_EXT, and AODV_EXT_BP for other mobility models. This thesis has been conducted assuming CBR traffic that relies on UDP. A natural extension of the research work would be to analyse the performance behaviour of the proposed algorithms for other traffic types such as VBR [7.22] and those that rely on TCP.

Simulation has been used as a tool for evaluating the performance of a MANETs, and some assumptions are made in order to keep the complexities of the various models at a stable level. As a result, the model may on occasion, over simplify or make more complexity some scenarios that may not closely follow the real system performance. Until now there has been little activity in the development and performance measurements of real MANET systems. This will be an interesting avenue to explore and develop a testbed to obtain realistic results.

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# Appendix A

## Published Journal Papers

[1]. V. Kanakaris, D. Ndzi, D. Azzi, "Ad-hoc Networks Energy Consumption: A review of the Ad-Hoc Routing Protocols", Journal of Engineering Science and Technology Review Vol.3 Iss. 1, pp.162-167, 2010

[2]. V. Kanakaris, D. Ndzi, K. Ovaliadis, "Improving AODV performance using Dynamic Density Driven Route Request Forwarding", International Journal of Wireless & Mobile Networks, vol. 3, no. 3, June 2011.

[3]. V. Kanakaris, D. Ndzi, K. Ovaliadis, "Applications of MANET Routing Protocols in Sensor Network", International Journal of Research and Reviews in Ad Hoc Networks (IJRRAN), Vol. 1, Iss. 4, 2011.

[4]. V. Kanakaris, D. L. Ndzi, K. Ovaliadis, Y. Yang, "A New RREQ Message Forwarding Technique Based on Bayesian Probability Theory", to appear in EURASIP Journal on Wireless Communications and Networking -Springer

## Published Conference Papers

[5]. V. Kanakaris, D. Ndzi, D. Azzi, "Ad-hoc Networks Energy Consumption: A review of the Ad-Hoc Routing Protocols", 9TH Hellenic European Conference on Computer Mathematics and its Applications (HERCMA 2009), 24-26 September , 2009, Athens, Greece