Reducing Energy Consumption in Mobile Ad-hoc Sensor Networks

Thesis by
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To sinar, iman, nisa' and arissa...

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Abstract

Recent rapid development of wireless communication technologies and portable mobile devices such as tablets, smartphones and wireless sensors bring the best out of mobile computing, particularly Mobile Ad-hoc Sensor Networks (MASNETs). MASNETs are types of Mobile Ad-hoc Networks (MANETs) that are designed to consider energy in mind because they have severe resource constraints due to their lack of processing power, limited memory, and bandwidth as in Wireless Sensor Networks (WSNs). Hence, they have the characteristics, requirements, and limitations of both MANETs and WSNs. There are many potential applications of MASNETs such as a real-time target tracking and an ocean temperature monitoring. In these applications, mobility is the fundamental characteristic of the sensor nodes, and it poses many challenges to the routing algorithm. One of the greatest challenge is to provide a routing algorithm that is capable of dynamically changing its topology in the mobile environment with minimal consumption of energy. In MASNETs, the main reason of the topology change is because of the movement of mobile sensor nodes and not the node failure due to energy depletion. Since these sensor nodes are limited in power supply and have low radio frequency coverage, they easily lose their connection with neighbours, and face difficulties in updating their routing tables. The switching process from one coverage area to another consumes more energy. This network must be able to adaptively alter the routing paths to minimize the effects of variable wireless link quality, topological changes, and transmission power levels on energy consumption of the network. Hence, nodes prefer to use as little transmission power as necessary and transmit control packets as infrequently as possible in energy constrained MASNETs. Therefore, in this thesis we propose a new dynamic energy-aware routing algorithm based on the transmission power control (TPC). This method effectively decreases the average percentage of packet loss and reduces the average total energy consumption which indirectly prolong the network lifetime of MASNETs. To validate the proposed protocol, we ran the simulation on the Avrora simulator and varied speed, density, and route update interval of mobile nodes. Finally, the performance of the proposed routing algorithm was measured and compared against the basic Ad-hoc On-demand Distance Vector (AODV) routing algorithm in MASNETs.

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Chapter 1

Introduction

1.1 Overview

The rapid development of wireless communication technologies and portable mobile devices such as laptops, PDAs, smartphones and wireless sensors brings the best out of mobile computing particularly mobile ad-hoc and sensor networks. Mobile computing can be defined as the use of portable mobile devices in conjunction with mobile communications technologies that allows transmission of data, via mobile devices, without having to be connected to a fixed physical link [4] as in Mobile Ad-hoc Networks (MANETs) [5] and Wireless Sensor Networks (WSNs) [6].

MANETs are temporary self-configuring multi-hop networks of wireless mobile nodes that dynamically establish their own networks when needed, without relying on any preexisting infrastructure or pre-defined topology. These networks are generally formed in environments where it is difficult to find or settle down a network infrastructure [5]. On the other hand, the WSN is a wireless network consisting of spatially distributed autonomous sensor nodes which are either static or mobile that cooperatively monitor physical or environmental conditions such as temperature, sound, and vibration over short-range wireless interfaces and multiple hops to central locations called sinks [6, 7] (Figure 1.1). WSNs are particular type of ad hoc networks, in which the nodes are sensors equipped with wireless transmission capability. Hence, they have the characteristics, requirements, and limitations of MANETs [5]. Unlike MANETs, the nodes in WSNs have severe resource constraints due to their lack of processing power, limited memory, and bandwidth.

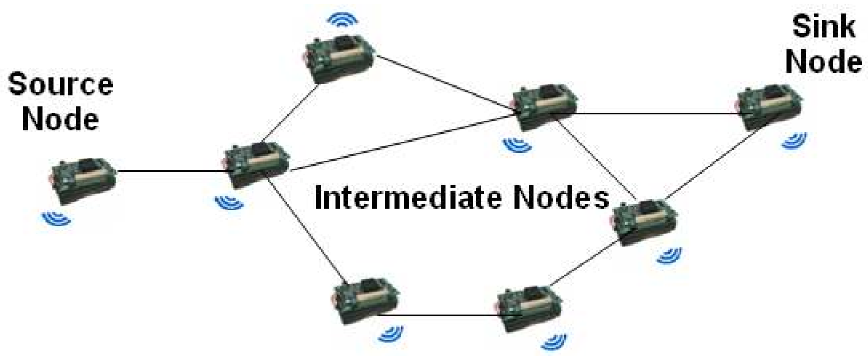

Figure 1.1: Basic structure of WSNs with source, intermediate and sink nodes

The design of routing protocols for both types of networks, which can be called as Mobile Ad-hoc Sensor Networks (MASNETs), is a complex issue because of the diversity of their potential applications, ranging from small, static networks that are constrained by power sources, to large scale highly dynamic mobile networks. Regardless of the application, MASNETs need an efficient and energy-aware routing algorithm to determine viable routing paths and deliver packets in a highly dynamic and frequent topology change network environment. While the shortest path based on a hop count from a source to a destination in a static network is usually the optimal route, this idea is not easily extended to MASNETs because the nodes are mobile and the network topology may change rapidly over time in energy-constrained networks. Factors such as variable wireless link quality, topological changes, and transmission power levels become relevant issues. The network should be able to adaptively alter the routing paths to minimize any of these effects on network energy consumption. Hence, nodes prefer to use as little transmission power as necessary and transmit control packets as infrequently as possible.

1.2 Problem Statement

In several of MASNET applications such as a real-time target tracking [8] and an ocean temperature monitoring [9], some of the sensor nodes are mobile and move in space over time. Some sensor nodes are also mounted on robots, animals, or other moving objects, which can sense and collect relevant information such as body temperature, light intensity, and air humidity. If such information is not properly handled, energy can be wasted due to unpredictable changes in network topology. Therefore, an efficient and energy-aware routing algorithm is needed to reduce energy consumption and reliably transmit data to the sink node in the event of frequent topology changes in energy-constrained MASNETs.

Ad hoc on-demand distance vector (AODV) is a routing protocol that is commonly used in MANETs and other wireless ad-hoc networks such as WSNs [10]. Applying this routing protocol in mobile sensor nodes degrades the network performance due to node movement from one vicinity to another. Since the sensors have limited power supply, they have a low radio frequency (RF) coverage. This can be disadvantageous to mobile sensor nodes because they easily lose their connection with neighbours, and have difficulties updating their routing tables. The switching process from one area to another consumes more energy in relation to transmitting and receiving control packets. Furthermore, mobile nodes need to wait for some time to join a new vicinity, and this introduces some delays in the connection set-up time with their neighbours. During this period, mobile nodes are unable to send or receive data until they successfully establish their connections with neighbouring nodes. This creates a delay in data transmission and reception and reduces throughput degradation which are caused by long switching. Therefore, in this thesis, we target reduction of energy consumption in MASNETs by proposing a new energy-aware routing algorithm which helps to reduce the average percentage of packet loss and minimize the average total energy consumption.

1.3 Research Aims and Objectives

The main aim of this research is to reduce the energy consumption of MASNETs as much as possible in mobile environment by proposing a new energy-aware routing algorithm which helps to decrease the average percentage of packet loss and to minimize the average total energy consumption. In this thesis, the routing technique based on transmission power control (TPC) approach is proposed to achieve the research aim. In our approach, the changing in transmission power is done dynamically in a real time based on RSSI values from neighbour nodes. The following objectives are outlined to achieve the research aims.

- To investigate the impact of mobility on MASNETs through extensive simulation using the selected simulation tool.

- To propose an energy-aware routing algorithm for MASNETs based on TPC approach that can reduce energy consumption in mobility environment.
- To evaluate and compare the performance of the proposed algorithm with the basic AODV in MASNETs.

1.4 Main Contributions

The main contributions of this thesis can be summarized as follows:

- We have evaluated the performance of AODV routing protocol in MASNETs in order to demonstrate the impact of mobile nodes on the performance metrics of MASNETs using the suitable simulation tool. This performance evaluation are conducted in terms of the average percentage of packet loss and the average total energy consumption with various speed, density, and route update interval (RUI) of mobile nodes.
- In order to effectively minimize the percentage of packet loss and reduce energy consumption in MASNETs, we have proposed a new dynamic energy-aware (DEA-AODV) routing algorithm for MASNETs based on the Received Strength Signal Indicator (RSSI) and TPC.

1.5 Motivation and Significance

MASNETs are a fascinating area due to their extensive potential that makes research in this field demanding. However, there are still many research challenges need to be solved to gain their full potential such as:

- Limited energy, power, bandwidth, size and memory that make programming the nodes more difficult.
- MASNETs are dynamic as in mobile environment where the link between two neighbour nodes maybe broken or created that make communication in MASNETs inherently unreliable.

- MASNETs are data or application oriented where the unique context of each application scenario requires its own specifications and requirements, and what applies to certain application may not necessary apply to another.

In MASNETs, the communication between mobile nodes consumes energy related to transmitting and receiving packets. Since this communication is the most energy-consuming activity in these types of networks, the power use for transmission or reception of packets should be controlled as much as possible. Therefore, the proposed energy-aware routing algorithm for MASNETs based on TPC can effectively reduce energy consumption by adaptive control of the transmission power for communication based on the estimated distance between nodes, which is determined by RSSI values. The use of ideal transmission power for communication and transmit control packets as infrequently as possible will indirectly prolong the network lifetime and the reliable communication of MASNETs in mobile environment.

1.6 Thesis Publication

Most of the material in this thesis includes several research works which are relevant or are closely related to as well as peer-reviewed publications which have been written or co-written by the author as listed below. For example, the material in Chapter 5 has been published in [11] and [12]. While, the material in Chapter 4 has been published in [13] and the material in Chapter 3 has been published in [14]. Other publications are referenced appropriately in this thesis.

- [11] M. N. Jambli, H. Lenando, K. Zen, S. M. Suhaili, and A. Tully . The Effects of Transmission Power Control in Mobile Ad-Hoc Sensor Networks. Procedia Engineering, 41(0):1244 1252, 2012. International Symposium on Robotics and Intelligent Sensors 2012 (IRIS 2012).

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1.7 Thesis Outline

This thesis consists of six chapters. Chapter 1 is an introduction to the research work including the research overview, problem statement, aims, objectives, main contributions, motivation, significance, and publication related to the thesis. The rest of the thesis is organized as follows:

In Chapter 2, the background of the research is explained by introducing the overview of MASNETs covering the characteristics, applications and research challenges of MASNETs. The energy consumption, AODV routing protocol and TPC for MASNETs are also described in this chapter.

In Chapter 3, we identify the most suitable simulation tool for MASNETs by conducting a comparative study on the commonly used simulation tools to simulate and evaluate the performance of MASNETs in Chapter 4 and Chapter 5. We also review the existing mobility models in order to choose the appropriate mobility model for simulate mobile sensor nodes in MASNETs.

In Chapter 4, we discuss the impact of mobile nodes on the performance metrics of MASNETs in terms of the average percentage of packet loss and the average total energy consumption through extensive simulation by using selected simulation tool identified in Chapter 3. The AODV routing protocol is used as a benchmark the evaluate the performance of MASNETs.

In Chapter 5, the existing TPC techniques are reviewed and investigated on different possibilities of how TPC can be implemented in routing protocols for MASNETs. We also propose an energy-aware routing algorithm which is based on TPC and RSSI in this chapter. The performance of the proposed algorithm is evaluated and compared with the basic AODV in MASNETs.

In Chapter 6, we conclude the thesis by summarizing our contributions and outline potential further work in MASNETs which may become the direction of our future research. Following the chapters is a reference section.

Chapter 2

Literature Review

2.1 Introduction

In last few years, various research has been conducted on MASNETs due to their wide range of potential applications ranging from environmental monitoring to critical military surveillance and healthcare applications [17]. In most of these applications, sensor nodes remain stationary after their initial deployment. Recently, there has been a demand to deploy sensor nodes mounted on robots, animals or other moving objects, which can sense and collect relevant information. For example, in a real-time target tracking application [8], mobile nodes can be used to avoid holes in the coverage area where sensor nodes cannot be manually deployed or air-dropped. Another example is an ocean temperature monitoring [9] where the sensor nodes are deployed on the surface of the ocean to monitor the water temperature and they are moved around by ocean currents. The operations of a MASNETs now depends not only on the initial network configurations, but also on the mobility characteristic of the sensor nodes.

MASNETs are extremely valuable in such situations where traditional deployment mechanisms fail or are not suitable. This unique characteristic of MASNETs opens up other potential sensor network applications in mobile environment. The enormous potential of MASNETs' applications is the main motivation for the success of these networks. However, sensor nodes in MASNETs are energy constrained where it is difficult to renew especially if they are deployed in a hostile and remote area. Therefore, saving energy to maximize network lifetime is one of the main challenges in MASNETs. Thus, the routing algorithms for such networks should be energy efficient in order to improve the network lifetime of MASNETs.

In this chapter, we start present an overview of MASNETs covering the characteristics, applications and research challenges of MASNETs. Then, we present the energy consumption in MASNETs including operation mode of sensor node, source of energy dissipation, energy efficient techniques and routing protocols. Next, we review the AODV routing protocol and describe the integration of transmission power control (TPC) technique in this protocol. Lastly, we summarize the whole chapter in the summary section.

2.2 Overview of MASNETs

The concept of MASNETs has emerged in recent years because more complex applications require sensor nodes to be mobile rather than static, such as in smart transport systems, security systems and social interaction [18]. In such applications, the mobile sensor nodes have the ability to sense, compute, and communicate like static sensor nodes. However, mobile nodes have the ability to cooperatively interact, reposition and organize itself in the network. MASNETs can start off with some initial deployment and nodes can then spread out to gather information. Information gathered by a mobile node can be communicated to another mobile node when they are within range of each other. In this section, MASNETs are reviewed in terms of their characteristics, current applications and research challenges.

2.2.1 Characteristics of MASNETs

Most of the main characteristics of MASNETs are the same as that of normal static sensor networks. However, there are some major differences that distinguish MASNETs from other networks which can be described in terms of the following aspects [18, 19]:

- **Frequent Topology Change**: Due to their mobility, MASNETs have a much more frequent topology change compared to static sensor networks. This change in topology of MASNETs makes data become outdated quickly. Therefore, a new dynamic routing protocols are needed in such mobile environment.

- Broken communication links: Due to the frequent topology change of MASNETs, the links for communication between different nodes often become unstable and unreliable especially in hostile environments and remote areas. The failure in packet transmission due to broken links requires further research on QoS of MASNETs.

- **Precise localization**: The estimation of position and location of sensor nodes are very important in mobile environment. Thus, it is very critical to have an accurate knowledge of the location of the sink or node for packet transmission. The mobile sink can sense and collect more data from wider area due to the mobility of the sink.

- **High energy usage**: The mobile sensor nodes in MASNETs require additional power to perform mobility compared to static sensor nodes. The frequent topology change due to mobility also consumes energy for establish communication.

- **Dynamic routing protocols**: The increased mobility in the case of MASNETs imposes some restrictions on the existing routing protocols for sensor networks. Most of the efficient protocols in static sensor networks perform poorly in mobile environment. Thus, the efficient dynamic routing protocols are needed for MASNETs.

Most of the aspects described show the effects of mobility on the mobile nodes in MASNETs. However, there are some advantages of mobile nodes that make them better than the static nodes as follows [18, 19]citegetsy2013:

- **Reorganize network**: The mobile nodes can be used to reorganize the network with a proper setting of mobility model. The static nodes can only turn into disconnected sub-network due to energy depletion or hardware failure.

- **Reduce communication gap**: The mobile nodes can be relocated after the initial deployment to reduce the communication gap between different nodes in the network. The static nodes can only use the default transmission range to communicate with their neighbouring nodes.

- **Efficient energy usage**: The mobile nodes can be used to reduce energy consumption during communication in the network by reducing the gap between different nodes when they are relocated near to sink. The base stations or sensor nodes can also move and the energy dissipation is more efficient. The static nodes near the gateway will die sooner due to the many-to-one hop-by-hop communication pattern.

- **Better data fidelity**: The mobility of nodes can reduce the number of hops, and then decrease the probability of errors during transmission.
- **Better targeting**: As mobile sensor nodes are generally deployed randomly instead of precisely, nodes are required to move for better sight or closer proximity.

With the advantages of mobile nodes in MASNETS, various potential applications of MASNETs can be deployed in a real world. Since MASNETs are new type of networks, its specific unique applications areas are yet to be clearly defined. Most of their application scenarios are the same as that of static sensor networks. The only difference is the mobility of sink or sensor nodes existed in different applications of MASNETs. In the next subsection, some of the current applications of MASNETs are described in details.

2.2.2 Applications of MASNETs

The applications of MASNETs can be classified into two categories which are monitoring and tracking as classified in [7]. The example of monitoring applications include environmental monitoring, health monitoring, power monitoring and inventory location monitoring. While tracking applications include tracking objects, animals, humans, and vehicles. Some of these applications might have mobile sensor nodes that cooperatively working with other static sensor nodes in the network. With mobile sensor nodes, they can move to areas of events after deployment to provide the required coverage such as in the environmental monitoring in disaster areas, where manual deployment might not be possible. In military tracking, mobile sensor nodes can collaborate and make decisions based on the target to achieve a higher degree of coverage and connectivity compared to static sensor nodes. In the presence of obstacles in the field, mobile sensor nodes can plan ahead and move appropriately to obstructed regions to increase target exposure. Table 2.1 describes a few real applications that have been deployed and tested in the different mobile environment. These MASNETs applications can be divided into two parts according to the main purpose of applications either as monitoring or tracking based applications.

Area	Applications
Environmental Monitoring	Underwater Monitoring [20], Ocean Monitoring [21]
Habitat Monitoring	ZebraNet [22], Cattle [23]
Health Monitoring	FireLine [24], LISTSENse [24]
Search and Rescue	CenWits [25]
Military	PinPtr [26]

Table 2.1: Some applications of MASNETs in different areas

2.2.2.1 Monitoring

There are several applications of MASNETS that can be classified as monitoring based application include the underwater monitoring [20], ocean monitoring [21], FireLine [24] and LISTSENse [24]. Most of these applications used mobile sensor nodes to sense and collect relevant data for monitoring purpose.

The underwater monitoring study in [20], is developed a platform for underwater sensor networks to be used for long-term monitoring of coral reefs and fisheries. As for ocean monitoring [21], the sensor nodes are deployed on the surface of the ocean to monitor the water temperature and they are moved around by ocean currents. They have a variety of sensing devices, including temperature and pressure sensing devices and cameras. Both applications use the collaboration between the mobile and static nodes to collect data and perform network maintenance functions for deployment, relocation, and recovery of monitoring application.

Another application for monitoring is used in the medical field. FireLine [24] is a wireless heart rate sensing system that is used to monitor a fire fighter's heart rate in real-time to detect any abnormality and stress during the save and rescue operation. This system consists of a Tmote, a custom made heart rate sensor board, and three re-usable electrodes. All these components are embedded into a shirt that a fire fighter will wear underneath all his protective gears. The readings are taken from the T-mote is then transferred to another T-mote connected to the base station. If the fire fighter's heart rate is increasing too high, an alert is sent. This system is very useful in the case of emergency to monitor and alert the conditions of the fire fighter during the mission.

Another application of health monitoring is LISTSENse [24] that enables the hearing impaired to be informed of the audible information in their environment. A user carries the base station T-mote with him. The base station T-mote consists of a vibrator and

LEDs. Transmitter motes are place near objects such as smoke alarm and doorbell that can be heard. They periodically sample the microphone signal at a rate of 20 Hz. If the signal is greater than the reference signal, an encrypted activation message is sent to the user. The base station T-mote receiving the message activates the vibrator and its LED lights to warn the user. The user must press the acknowledgement button to deactivate the alert.

2.2.2.2 Tracking

The example of tracking based applications of MASNETs are ZebraNet [22], Cattle [23], CenWits [25] and PinPtr [26]. Most of these applications used mobile sensor nodes to collect position, location and movement data for tracking purpose.

The ZebraNet [22] system is a mobile wireless sensor network used to track animal migrations. ZebraNet is composed of sensor nodes built into the zebra's collar. Positional readings are taken using the GPS and sent as multi-hop communication transmission across zebras to the base station. The goal is to accurately log each zebra's position and use them for analysis. A set of movement data was also collected during this study. From the data, the biologists can better understand the zebra movements during the day and night. Another application for habitat monitoring is Cattle [23], where sensors are attached to cattle as in ZebraNet [22]. Both applications are hardware-based implementation of mobile sensor nodes, whose objective is to adopt mobility of nodes to increase the effectiveness of data collection and improve research results.

CenWits [25] is a search-and-rescue system designed, implemented, and evaluated using Berkeley MICA2 sensor motes. It is a connection-less sensor-based tracking system using witness that comprises of mobile sensors worn by people. The access points collect information from these sensors and GPS receivers. The location points provide location information to the sensors. The people will use the GPS receivers and location points to determine its current location. The key concept is the use of witnesses to convey a subject's movement and location information to the outside world. The goal of this application is to determine an approximate small area where search-and-rescue efforts can be concentrated.

PinPtr [26] is an experimental counter-sniper system developed to detect and locate shooters. The system utilizes a dense deployment of sensors to detect and measure the time of arrival of muzzle blasts and shock waves from a shot. Sensors route their measurements to a base station to compute the shooter's location. Sensors in the PinPtr system are second-generation MICA2 motes connected to a multi-purpose acoustic sensor board. Each multi-purpose acoustic sensor board is designed with three acoustic channels and a Xilinx Spartan II FPGA.

These are the examples of the current applications of MASNETs that have been deployed in a real world. There are more potential and interesting applications of MASNETs will be deployed in the future because MASNETs are new type of networks. The integration between the mobile and static nodes in such application poses some challenges that need to be solved first for the smooth deployment of these applications. These challenges of MASNETs will be described in the next subsection.

2.2.3 Research Challenges of MASNETs

In order to focus on the mobility aspect of MASNETs, it is important to first understand the main challenges of statically deployed sensor networks when mobile entities are introduced. The research challenges in MASNETs can be analysed and discussed in terms of the following aspects; dynamic topology control, power consumption, localization, coverage, target tracking, network sink [6]. This section addresses these challenges when MASNETs are deployed in mobile environment.

2.2.3.1 Dynamic Topology Control

Topology control is the problem of assigning transmission powers to every node in order to maintain connectivity while minimizing the energy consumption of the whole network. Traditional sensor network routing protocols [27], which describe how to pass messages through the network so they will most likely reach their destination, typically rely on routing tables or recent route histories. In dynamic topologies, table data become outdated quickly, and route discovery must repeatedly be performed at a substantial cost in terms of power, time, and bandwidth. There is considerable theoretical attention about topology control in static sensor networks [28]. In MASNETs where sensors are generally mobile, the setting of transmission powers, which are strongly related to connectivity and energy efficiency, is more significant.

2.2.3.2 Energy Consumption

Energy consumption models [29] differ greatly between sensor networks and MASNETs. For both types of networks, wireless communication incurs a significant energy cost and must be used efficiently. However, mobile entities require additional power for mobility, and are often equipped with a much larger energy reserve, or have self-charging capability that enables them to plug into the power grid to recharge their batteries.

2.2.3.3 Localization

In statically deployed networks, node position can be determined once during initialization. However, those nodes that are mobile must continuously obtain their position as they traverse the sensing region. For example, the applications of sensor networks such as target tracking and animal monitoring need sensors to be aware of the position of the nodes in order to make sense of data and perform further navigation tasks. This requires additional time and energy, as well as the availability of a rapid localization service. Hence, localization in MASNETs is more difficult because of the mobility which increases the uncertainty of nodes.

2.2.3.4 Coverage

One of the most basic and significant factors in the design and application of MASNETs (e.g., target tracking) is sensor coverage measured by the overall area that a sensor network is currently monitoring. Sensor coverage is closely related to the quality of service that the network can provide, and it will decrease due to undesirable sensor deployment and sensor failures. Critical application scenarios (e.g., battlefields) will make the initial deployment obviously far from having the desirable features of full coverage. Moreover, natural limitations (e.g., battery depletions) and external harsh environments (e.g., fire) will also strongly affect the lifetime of sensors. During such conditions, sensors should have the ability to preserve the coverage.

2.2.3.5 Network Sink

In centralized sensor network applications, sensor data is forwarded to a base station, where it can be processed using resource-intensive methods. Data routing and aggregation can incur a significant overhead. Some MASNETs use mobile base stations (sinks)

[30], which traverse the sensing region to collect data, or position themselves so that the number of transmission hops is minimized for the sensor nodes.

In this subsection we have described the characteristics, applications and challenges in the deployment of MASNETs. It is clear that, MASNETs have many unique characteristics and potential applications. But, they also have many challenging problems awaiting for solutions. However, the most vital challenge in MASNETs is energy consumption as in sensor networks. This is because energy consumption is the most important factor in determining the network lifetime of MASNETs as the sensor nodes in the network are all battery-powered. The limited low energy resources affect the data sensing, processing and communications in MASNETs. Therefore, energy optimization approach such as TPC must be used to preserve energy in order to prolong the network lifetime. This can be done by considering energy awareness issues in every aspect of design and operation of each sensor node.

2.3 Energy Consumption in MASNETs

MASNETs typically consist of a number of collaborative mobile and static sensor nodes that capable of performing some processing, gathering sensory information and communicating with other connected nodes in the network. Normally, these sensor nodes are battery-operated and operate in remote and hostile environments such as in a battle field and ocean. Therefore, they must sustain their energy source as long as possible. But, sometime there are several aspects put a limit to their energy source such as inefficient operation mode, inactive communication and energy dissipation. Thus, in this section we describe different operation mode of sensor node, the source of energy dissipation and energy-aware routing protocols in order to understand the aspects that affect the network lifetime of MASNETs.

2.3.1 Operation mode of sensor node

A wireless sensor node can work in one of the following four main operation modes; transmit, receive, idle and sleep. Each mode corresponds to a different power consumption as reported in [1, 2] on the nominal current consumption of the ATmega128L microcontroller that normally use in MICA2 sensor mote (Table 2.2). The following is the detail operation of each mode:

Power Mode	Current (mA)
Transmit (Tx)	8.5
Receive (Rx)	7.0
Idle	3.2
Sleep	0.1

Table 2.2: Current draw of the main power modes for MICA2 sensor mote [1, 2]

- Transmit: A sensor node (sender) is transmitting packets to the next-hop node with the specified transmission power level;
- Receive: A sensor node (receiver) is receiving packets from its neighbouring node with the specified reception power level;
- Idle (listening): A sensor node is stay idle and keep listening to its neighbouring nodes to detect any signals even when no packets are being transmitted over the network;
- Sleep: A sensor node's radio communication is turned off and it is not capable of detecting signals and no communication is possible.

Based on Table 2.2, it shows that most of the energy is consumed through data communication either in transmitting mode or receiving mode. Although in transmit mode, the energy consumption is more than in Receive mode, but it depends on the transmit power level set on the sensor node which can range from 0 to 25 dBm. The lower the power level set on the sensor node, the lower the current consumption that will be used for communication. On the other hand, the least consuming mode is during the sleep mode. It means that, a significant amount of energy can be saved by turning off the transceiver to a sleep mode whenever the sensor node does not need to transmit or receive any data. However, the transition between the sleep mode and active (transmit or receive) modes also consume some additional energy. In addition to that, the energy also consumed when the transceiver switches from transmit mode to receive mode. Therefore, careful consideration need be taken when implement the transition between different mode of sensor node in any routing protocols to avoid extra energy consumption in the network.

2.3.2 Source of energy dissipation

In MASNETs, sensor nodes normally use most of their energy for transmitting and receiving messages in order to disseminate sensing data to the sink. Such usage of energy is necessary to ensure the smooth operation of MASNETs. But, sometime there is a some amount of energy is wasted during some part of the operation mode due to inefficient activities from the application point of view as follows:

- **Idle listening**: In sensor nodes communication, since a node does not know when it will receive a message it must permanently listen to the medium and so it remains in the idle mode. As we can notice in Table 2.2, the idle mode also consume significant amount of energy.
- **Overhearing**: Due to the shared nature of wireless medium, when a sender transmits one packet to next hop, all neighbours of the source receive this packet even if it is intended to only one of them. Thus, the energy will be dissipated when the node is an one-hop neighbour of the sender and is not the destination.
- **Interference**: Each node situated between transmitter range and interference range receives this packet but it cannot decode it.
- **collision**: When a collision occurs, the energy dissipated for the transmission and for the reception of colliding packets is wasted.

The effects of different sources of energy dissipation can be minimized through the proper implementation of the energy efficient routing protocols. The energy constrained nature of MASNETs requires the use of the energy efficient strategies to minimize the energy wasted in these mobile environment and indirectly maximize the network lifetime of MASNETs. In the next section, we describe and classify works aimed at minimizing energy consumption and improving network lifetime.

2.3.3 Energy efficient techniques and routing protocols

With the energy-constrained nature of wireless networks, it is very important to use energy efficient techniques in the design of routing protocol to maximize the network lifetime of MASNETs. These techniques can be classified as follows:

- **Energy efficient routing**: The goal of this technique is to minimize the energy consumed by the end-to-end transmission of a packet to avoid nodes with a low residual energy and reduce the number of unsuccessful transmissions as studied in [31, 32].
- **Node activity scheduling**: The idea of scheduling node activity is to alternate node states between sleeping and active to minimize energy consumption while ensuring the network and application functionalities as reported in [33, 34].
- **Reducing the volume of information transferred**: These strategies is aggregating information with the use of clusters as in [35, 36].
- **Topology control by tuning node transmission power**: These strategies find the optimum node transmission power that minimizes energy consumption, while keeping network connectivity as in [37, 38].

There are also various energy-aware routing protocols have been designed and proposed by several researchers in MASNETs such as in [39, 40, 41]. Most of them aim to minimize the energy consumption in communication. These routing protocols can be classified based on their network structure, state of information, energy efficiency techniques and mobility as classified in [41]. Such energy-aware routing protocols and techniques also need to be addressed for collective groups of communicating sensor nodes in order to have better overall performance and improved energy efficiency in the entire MASNETs. The energy efficient technique that we used is related to topology control by tuning node transmission power which is based on TPC that can be integrated into the existing routing protocol of MASNETs. We believe, it is possible to reduce energy consumption in the network by using the ideal transmission power level for communication in mobile environment.

The lifetime of a sensor network also can be increased significantly if the operating system, the application layer, and the network protocols are designed to be energy aware. The power consumed by the sensor nodes can be reduced by developing design methodologies and strategies that support lower energy wastage. Power management in radios is also a very important issue because radio communication consumes a lot of energy during operation in comparison to the overall energy consumption of each node in MASNETs as a whole. Fortunately, there is an active area of research dedicated to routing in mobile ad-hoc networks (MANETs) [42] from which MASNETs can benefit. One of the well known and the most popular reactive routing protocols of MANETS is Ad-Hoc On-Demand Distance Vector (AODV) [10]. Further investigation needs to be done in order to successfully integrate AODV routing protocol in MASNETs. In the next section we describe the AODV routing protocol in details and how TPC technique can be integrated into this protocol to overcome some of the challenges in MASNETs.

2.4 Ad Hoc On-Demand Distance Vector (AODV)

The AODV routing protocol is designed for use in ad-hoc mobile networks. This routing protocol is one of the most popular reactive routing protocols of WSN. Being a reactive routing protocol, the routes of AODV are created only when they are needed and it uses traditional routing tables, one entry per destination; and destination sequence numbers are used to determine whether routing information is up-to-date and to prevent routing loops [10]. This will greatly increase the efficiency of routing processes. AODV consist of two routing phases such as discovery and maintenance. Various types of control packets are used in the routing process of AODV. The following control packets are used: routing request message (RREQ) is broadcast by a node requiring a route to another node; routing reply message (RREP) is unicast back to the source of RREQ; and route error message (RERR) is sent to notify other nodes of the loss of the link. HELLO messages are used for detecting and monitoring links to neighbours [43].

AODV [10] stands for ad hoc on-demand distance vector protocol because route discovery in AODV is 'on-demand'. This AODV protocol initiates a route discovery process only when it has data packets to send and it does not know any route to the destination node. It combines the use of destination sequence numbers in Destination Sequenced Distance Vector (DSDV) routing with the on demand route discovery technique in Dynamic Source Routing (DSR) protocols to determine the freshness of routing information and formulate a loop-free, on-demand, single path, distance vector protocol. This will greatly increase the efficiency of routing processes. Unlike DSR, which uses source routing, AODV is based on multi-hop routing approach. AODV is designed to improve upon the performance characteristics of DSDV in the creation and maintenance of routes. The primary objectives of the AODV protocol are:

- To broadcast discovery packets only when necessary;

- To distinguish between local connectivity management (neighbourhood detection) and general topology maintenance;
- To disseminate information about changes in local connectivity to those neighbouring mobile nodes which are likely to need the information.

AODV consists of two basic routing operations such as route discovery and route maintenance. There are also various types of control messages used in the routing process of AODV [43] as explained further below.

2.4.1 Control Messages

Route Request (RREQ) message, Route Reply (RREP) message, Route Error (RERR) message and HELLO messages are the control messages used for the discovery and breakage of route. The RREQ message is broadcast by a node requiring a route to another node, RREP message is unicast back to the source of RREQ message, RERR message is sent to notify other nodes of the loss of the link. HELLO messages are used for detecting and monitoring links to neighbours.

2.4.2 Route Discovery

Route discovery is initiated when a source node wants to find a route to a new destination or when the lifetime of an existing route to a destination has expired. During a route discovery process, the source node broadcasts a RREQ message to its neighbours. If any of the neighbours has a route to the destination, it replies to the query with a RREP message; otherwise, the neighbours rebroadcast the RREQ message until the sought route as shown in Figure 2.1. Figure 2.2 shows the flowchart to illustrate this process. This is possible because each node receiving the RREQ message caches the route back to the originator of RREQ message. A route is said to be fresh enough when the Destination Sequence Number (DSN) of the sought route in the recipient nodes routing table is greater than the DSN in the RREQ packet itself. A flag is set in the RREQ for establishing a reverse route between destination node and source node.

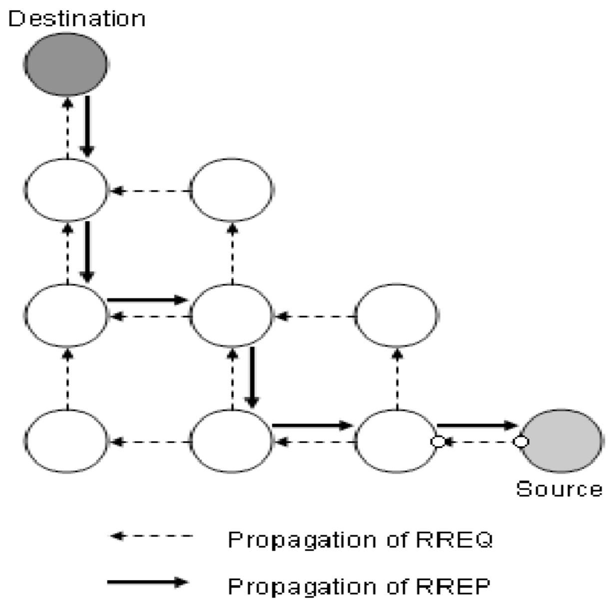

Figure 2.1: AODV Route Discovery

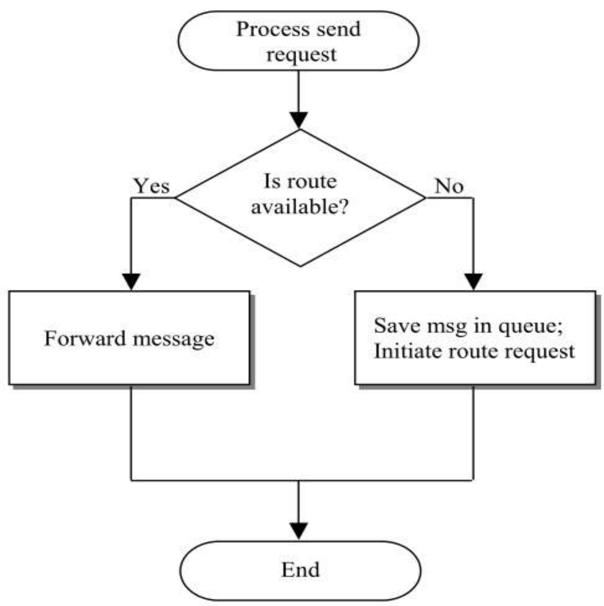

Figure 2.2: Flowchart of a source node broadcasting a RREQ message

2.4.3 Route Maintenance

To handle the case in which a route does not exist or the query or reply packets are lost, the source node rebroadcasts the query packet if no reply is received by the source after a time-out. A path maintenance process is used by AODV to monitor the operation of a route being used. If a source node receives the notification of a broken link, it can re-initiate the route discovery processes to find a new route to the destination. If a destination or an intermediate node detects a broken link, it can choose to repair the link locally or send an RERR packet to notify its upstream nodes. An RERR message contains the list of those destinations which are not reachable due the loss of connectivity. Whenever an end point receives RERR message it removes all the routes information of bad end point from its routing table. AODV only keeps the records of next hop instead of the whole route. The following Figure 2.3 displays a flowchart which summarizes the action of a node when processing an incoming message.

AODV is a method of routing messages between mobile nodes. It allows these mobile nodes to pass messages through their neighbours to nodes with which they cannot directly communicate. AODV does this by discovering the routes along which messages can be passed. AODV makes sure that these routes do not contain loops and tries to find the shortest route possible. AODV is also able to handle changes in routes and can create new routes if there is an error. By understanding how AODV works, hopefully it is much easier to integrate and enhance this routing protocol to support mobile applications in MASNETs.

2.4.4 Related Work

This section reviews the recent related work which directly or indirectly aims at evaluating performance of the existing AODV routing protocol. Most of the previous works on performance evaluation of AODV focused on MANETs as in [44, 45, 46]. However, not many papers in its literature evaluate the performance of AODV in MASNETs especially in mobile environment.

Some work on performance evaluation of AODV in sensor networks assumed sensor nodes as either static or only sink nodes are mobile. For instance, the authors of [47] studied the performance of AODV family of protocols in static environment. They assumed that the sensor network is static, where all the sensor nodes that have the

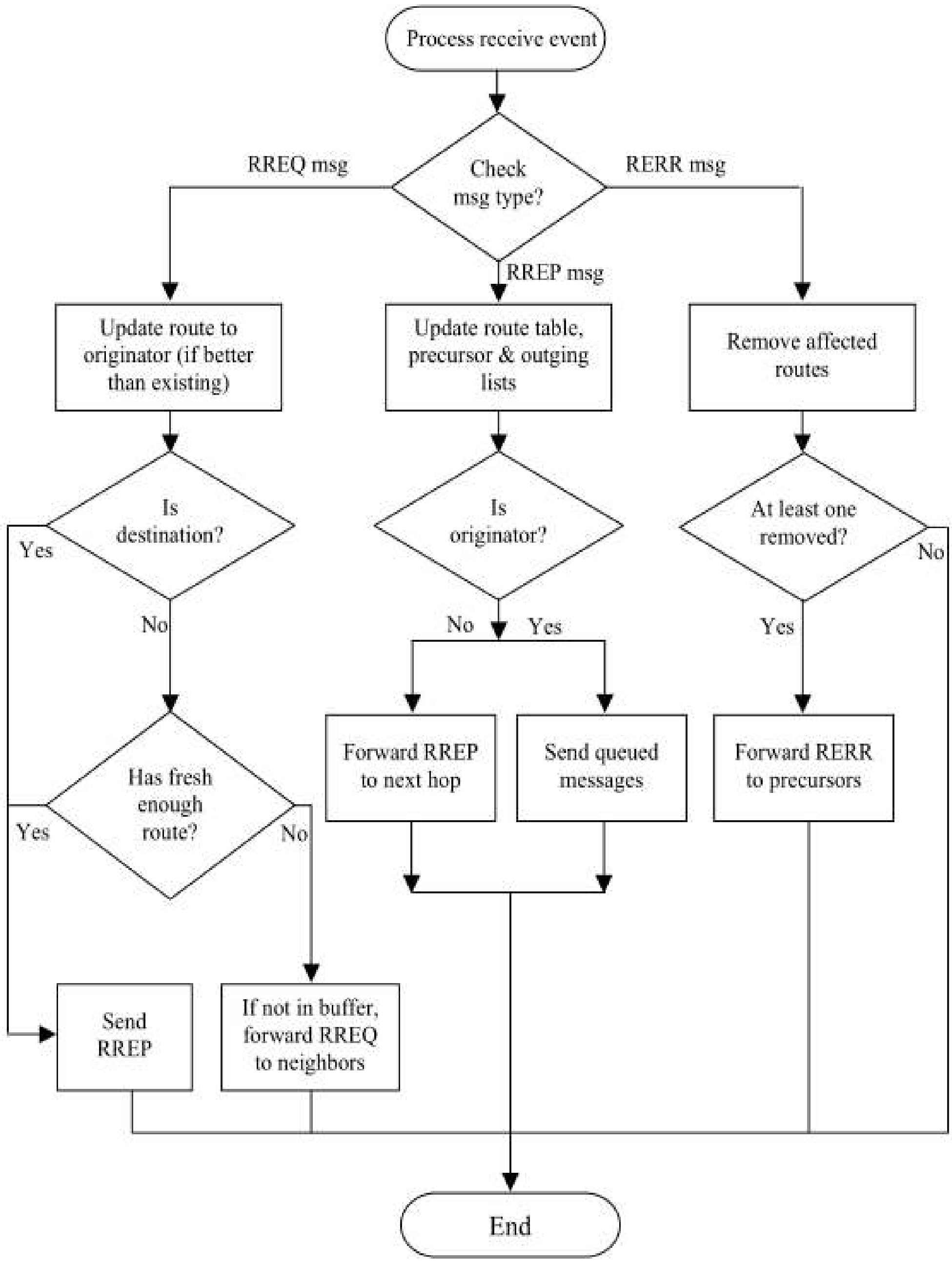

Figure 2.3: Flowchart of a node processing an incoming message

same radio range and energy are uniformly distributed among all sensor nodes. In this paper, various performance metrics like packet delivery ratio, average network delay, network throughput and normalized routing load were investigated. However, energy consumption is not taken into account as one of the metrics in evaluating the performance of AODV in sensor networks.

The authors of [48] have evaluated the performance of AODV over IEEE 802.15.4 in sensor networks with mobile sinks through extensive ns-2 simulations. In their simulation, they investigated the fundamental problems of AODV, and analysed the influence of incorporating multiple mobile sinks. However, they only assumed the sinks are mobile but other sensor nodes are static. Although they have studied the performance of energy, packet loss ratio and delay with different sink velocity, they did not investigate the performance of protocols under high mobility and larger density of mobile nodes in the network, which may lead to network congestion.

2.5 Transmission Power Control for MASNETs

Reducing energy consumption has always been a main focus of MASNETs research. TPC is one of the approaches to conserve energy by adaptively controlling the transmission power of the radio. In this section, we describe the concept of TPC and some of research works related to TPC to identify the best way to integrate TPC into AODV routing protocol in order to improve the network lifetime of MASNETs.

2.5.1 TPC Concept

In this subsection, we describe how TPC can improve energy efficiency in AODV routing protocol for MASNETs. In terms of energy efficiency, Table 2.3 indicates that controlling the transmission power level can decrease the radio's current consumption by up to 51% for the popular CC2420 radio [3]. The received signal strength indicator (RSSI) provided by CC2420 radio is a useful link quality estimation value because it is the measured signal power of a received radio signal of each incoming packet. The RSSI value to estimate the distance between nodes because it would be good indicator of distance as supported by previous research [49].

In our work, we consider the energy consumed based on transmission power that is currently used by each node to transmit each packet towards sink. An optimization

Power Level	Output Power (dBm)	Current Consumption [mA]
31	0	17.4
27	-1	16.5
23	-3	15.2
19	-5	13.9
15	-7	12.5
11	-10	11.2
7	-15	9.9
3	-25	8.5

Table 2.3: Transmission power and typical current consumption for CC2420 radio [3]

function considers the estimated distance between nodes based on RSSI values received from neighbour nodes to decide the ideal transmission power for packet transmission towards sink. The term 'ideal transmission power' can be defined as the lowest power level possible to successfully transmit packets from one node to another, either as a source node or intermediate nodes. As shown in Figure 2.4, if node A (source) wants to transmit packets to nodes D, E, F, and G, it can do that with maximum power of P2 (Ie. 31 as in Table 2.3). It is also possible for node A to transmit packets to nodes B and C with the same power of P2, but this fixed setting of maximum power for all nodes consumes more energy which is not practical for energy-constrained MASNETs.

Moreover, some of mobile nodes might be moving nearer to node A just like in the positions of nodes B and C in Figure 2.4, which require only low transmission power of P1 (Ie. 15 as in Table 2.3) for node A to reach these nodes. Therefore, to minimize energy consumption, node A must be able to select the ideal transmission power level in every packet transmission. This can be done if node A has some knowledge about the power output needed for every packet transmission based on the estimated distance between node A and its neighbours. In our work, we propose the use of RSSI values to estimate the distance between nodes to determine the ideal transmission power to be implemented in AODV routing protocol for MASNETs.

2.5.2 Related Work

There are many research works on mobile ad-hoc and sensor networks that use TPC as a way to reduce energy consumption in the network. However, most of proposed TPC techniques to determine the transmission power for mobile devices in mobile ad-

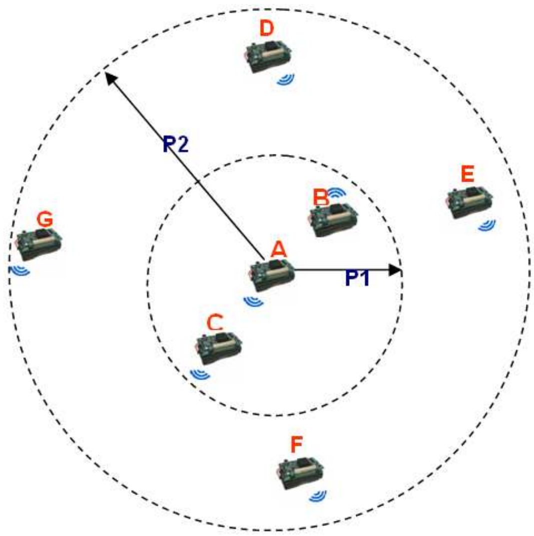

Figure 2.4: Ideal transmission power selection based on estimated distance between nodes

hoc networks (MANETs) [50, 51] are not applicable to MASNETs because of limited resources in MASNETs. These techniques mostly use signal strength related metrics such as signal to noise ratio (SNR) or signal to interference ratio (SIR) computed over incoming packets and compare the resulting values to static or dynamic thresholds to determine a mobile node's transmission power. While some existing TPC related work in sensor networks only focus on the transmission power of resource constrained motes for static nodes [52, 53], their proposed techniques cannot be applied to MASNETs, because they rely on gathering extensive information about the channel environment prior to deciding the transmission power. These are not possible in MASNETs, as the channel conditions for mobile nodes change frequently. In [52], the transmission powers for stationary nodes are determined by instantaneous link quality indicators such as RSSI which have one-to-one correlation with the packet reception ratio (PRR). While the technique we propose also used RSSI values to estimate the distance between nodes in order to determine the ideal transmission power, our work focuses on both static and mobile sensor networks not just on static networks as in [52, 53].

There are only a few literature studied TPC in mobile environment as in [38, 54]. In [54], they have investigated the impact of TPC on mobile nodes for ad-hoc networks by using NS-2 simulator in terms of packet delivery ratio in scenarios with low traffic load, limited node mobility, low initial node energy, and low node spatial density. However, in [38], they studied TPC through test-bed experiments. But, we are focused more on the impact of TPC on the total energy consumption and the percentage of packet loss of MASNETs based on simulation as investigated in [11, 12].

2.6 Summary

As a summary, in order to provide a background to the performance analysis of MASNETs, this chapter has overviewed MASNETs, including their characteristics, applications and research challenges. The energy consumption, AODV and TPC in MASNETs is also reviewed to further understand how to integrate and enhance this routing algorithm for MASNETs. By understanding how AODV and TPC works, hopefully it is much easier to integrate and enhance this routing protocol to support mobile applications and indirectly improve the network lifetime of MASNETs.

Chapter 3

Simulation Tools and Mobility Models

3.1 Introduction

Mobile ad-hoc sensor networks (MASNETs) have recently become an important area of research for the researchers. The increasing capabilities and the decreasing costs of mobile sensors make MASNETs' applications such as Ocean Monitoring [21], Cattle [23], LISTSENse [24], CenWits [25] and PinPtr [26] become possible and practical to be implemented in real mobile environment. In this type of network, mobility plays a key role in the deployment of these applications. Furthermore, recent studies show that many researchers have proposed mobility-based routing protocols [40, 41] for MASNETs to support mobile applications. Most of these protocols are compared and evaluated through simulation because it is very difficult to duplicate the real world scenario. Furthermore, the use of real-world evaluation is costly and not practical for the investigation purpose. Therefore, it is more economical and practical to use simulation tools to create a mobile environment to study MASNETs and to create a statistically significant amount of test runs. It is also a commonly used option to study the behaviour of the protocols in a simulated environment [55]. For these reasons, we decided to use a network simulation tool for comparing and evaluating routing protocols for MASNETs in our research work. Thus, there is a need to review and identify the suitable simulation tool and mobility model for MASNETs.

3.2 Simulation Tools

There are several network simulation tools available that can be used for studying MASNETs including GloMoSim, OPNET, EmStar, SensorSim, ns-2, and many others [56]. In order to compare these simulation tools, several criteria for comparison need to be identified and defined properly in order to get a better comparison result of different simulation tools for MASNETs. In this chapter, a comparison study of different simulation tools that is based on their capabilities and components that can support the evaluation of MASNETs is conducted to identify the most appropriate simulation tool for our research work.

3.2.1 Overview of Simulation Tools

In order to identify the most appropriate simulation tool for our research work, fifteen existing simulation tools have been selected for comparison including NS-2 [57], OPNET Modeller [58], GloMoSim [59], QualNet [60], J-Sim [61], OMNeT++ [62], Castalia [63], SENS[64], SENSE [65], Shawn [66], Avrora[67], TOSSIM [68], ATEMU [69], EmStar [70] and COOJA [71]. The selection of these simulation tools are based on their popularity, interesting characteristics and key features in simulating MASNETs. The brief descriptions of these tools are as follows:

- NS-2 (network simulator version two) [57, 72] is a discrete event network simulator targeted at networking research. It provides substantial support for simulation of TCP, routing protocols, and multicast protocols over wired and wireless networks especially in ad-hoc networking research. It was built in C++ and provides a simulation interface through OTcl (an object oriented version of Tcl). It is an open source and is licensed for use under version 2 of the GNU General Public License.

- OPNET (Optimized Network Engineering Tools) Modeller [58, 73] is a commercialized software tool for network modelling, simulating, analysing and designing communication networks, devices, protocols, applications. The users can analyse simulated networks to compare the impact of different technology designs on end-to-end behaviour The modeller (wireless suite) provides high fidelity modelling, simulation, and analysis of a broad range of wireless networks. It also supports any network with mobile devices, mobile ad hoc, wireless LAN, personal area networks and satellite.

- GloMoSim (Global Mobile Information System Simulator) [59, 74] is a scalable network protocol simulation software that simulates wireless and wired network systems. It is designed using the parallel discrete event simulation capability provided by Parsec, a parallel programming language. It currently supports protocols for a purely wireless network. It uses the Parsec compiler to compile the simulation protocols. It is built using a layered approach to allow the rapid integration of models developed at different layers by different people.

- QualNet [60, 75] is a commercial version of GloMoSim simulator used by Scalable Network Technologies (SNT) for their defence projects. It can predict wireless, wired and mixed platform network and networking device performance. It also can explore and analyse early-stage device designs and application code in closed, synthetic networks at real time speed or faster. It allows users to set up, develop, and run custom network models. A feature-rich visual development environment allows users to set quick and efficient code protocols models; and then run models that present real-time statistics and helpful packet-level debugging insight. It can also support over thousands of network nodes.

- J-Sim [61] is a discrete event, platform-independent, extensible and reusable Java-based simulation environment for building quantitative numeric models and analysing them with respect to experimental reference data. It provides GUI library, which facilitates users to model or compile the Mathematical Modelling Language, a text-based language written to J-Sim models. J-Sim provides open source models and online documents. In addition, it also can simulate real-time processes.

- OMNeT++ [62] is an extensible, modular, component-based C++, and open-architecture discrete event simulation framework. The most common use of OMNeT++ is for simulation of computer networks, but it is also used for queuing network simulations, and other areas as well. Instead of containing explicit and hard-wired support for computer networks or other areas, it provides the infrastructure for writing such simulations. Specific application areas are catered by various simulation models and frameworks, most of them open source. These models are developed completely independent of OMNeT++, and follow their own release cycles. The review in [76] has described in details the operation of this simulator.

- Castalia [63] is a simulator for sensor network, body area network and generally networks of low-power embedded devices. It is based on the OMNeT++ platform and can be used by researchers and developers to test their distributed algorithms and protocols in realistic wireless channels and radio models, with a realistic node behaviour especially relating to access of the radio. It can also be used to evaluate different platform characteristics for specific applications, since it is highly parametric, and can simulate a wide range of platforms.

- SENS [64] is a customizable sensor network simulator, consisting of interchangeable and extensible components for applications, network communication, and the physical environment. It enables realistic simulations, by using values from real sensors to represent the behaviour of component implementation. It allows users to execute the same source code on simulated sensor nodes as deployed on actual sensor nodes, enabling application portability.

- SENSE (Sensor Network Simulator and Emulator) [65] is a component-based sensor network simulator written in C++ and developed on top of COST, a general purpose discrete event simulator. It implements sensors as a collection of static components. Connections between each component are in the format of in ports and out ports. This allows for independence between components and enables straightforward extensibility and re-usability Traversing the ports are packets. Each packet is composed of different layers for each layer in the sensor. The designers try to improve scalability by having all sensors use the same packet in memory, assuming that the packet does not have to be modified.

- Shawn [66] is a customizable sensor network simulator based on an algorithmic approach that is designed to support large-scale network simulation. The primary design goals of Shawn include to simulate the effect caused by a phenomenon, scalability, and support for extremely large networks and free choice of the implementation model. Instead of simulating the effects of a phenomenon, Shawn simulates only the causal effects. It is claimed to provide the highest abstract level, and supports larger networks.

- Avrora [67, 77] is an open-source cycle- accurate simulation and analysis tool for embedded sensing programs written for the AVR microcontroller produced by Atmel and the MICA2 sensor nodes. It contains a flexible framework for simulating and analysing assembly programs, providing a clean Java API and infrastructure for experimentation, profiling, and analysis. It provides a framework for program analysis, allowing static checking of embedded software and an infrastructure for future program analysis research. It simulates a network of motes, runs the actual microcontroller programs (rather than models of the software), and runs accurate simulations of the devices and the radio communication.

- TOSSIM [68] is a discrete event simulator for TinyOS sensor networks that is part of the official TinyOS package developed at UC Berkeley. It captures the behaviour and interactions of networks, not on the packet level but at network bit granularity. It is designed specifically for TinyOS applications to be run on MICA Motes. It simulates entire TinyOS applications by replacing components with simulation implementations. To compile TinyOS code, no additional modifications have to be made to the source code, instead just another make target has to be defined. After successful testing the implementation can be deployed directly to a real TinyOS-based sensor node without any modifications.

- ATEMU [69] is an emulator of an AVR processor used in the MICA platform for sensor network which is developed in C programming language. It provides GUI to run codes on sensor nodes, debug codes, and monitor program executions. It is a specific emulator for sensor network that can support users to run TinyOS on MICA2 hardware. It can also emulate not only the communication among the sensors, but also every instruction implemented in each sensor. This emulator provides open sources and online documents.

- EmStar [70] is an emulator specifically designed for sensor network built in C programming language, and it was first developed at the University of California, Los Angeles. It provides a flexible environment for transitioning between simulation and deployment for iPAQ-class sensor nodes running Linux. Users have three options: i) running many virtual nodes on a single host with a simulated network; ii) running many virtual nodes on a single host with each virtual node bridged to a real-world one for networking; iii) and running a single real node on a host with a network interface.

- COOJA [71, 78] COOJA is a simulator for the Contiki sensor node operating system. It was originally developed for Cygwin/Windows and Linux platform, but was ported to MacOS. It combines low-level simulation of sensor node hardware and simulation of high-level behaviour in a single simulation. A simulated Contiki Mote in this simulator is an actual compiled and executable Contiki system which is controlled and analysed by COOJA. This can be done by compiling Contiki for the native platform as a shared library, and loading the library into Java using Java Native Interfaces (JNI).

3.2.2 Comparison Study of Simulation Tools

There are many different possible platforms for simulating and evaluating routing protocols for MASNETs. Several studies have been done in comparing different simulators for sensor networks as in [56, 79, 80, 81, 82, 83]. However, most of these studies do not focus on simulation tools for MASNETs where mobility is one of the important factors that needs to be considered. This comparison study is more focused on these types of networks where criteria such as mobility, energy consumption and sensor network simulation are important. In this section, the existing simulation tools listed in the previous subsection are reviewed and compared in order to identify the most suitable simulation tool for the evaluation of MASNETs. The comparison study will be done based on the mandatory and optional criteria identified. The sources of information for this comparison study are basically from scientific papers, vendor web sites and available documentation.

3.2.3 Criteria for Comparison

The criteria for comparing different simulation tools are based on different sets of criteria in evaluation of routing protocols for MASNETs. They can be classified into mandatory and optional criteria based on the requirement priority. The mandatory criteria are the main requirements of simulation tools, and it is better if the simulation tools can also satisfied the optional criteria.

The mandatory criteria are the main requirements that are essential for any simulation tools to be able to simulate MASNETs. These criteria are evaluated on a yes (✓) or no (✗) basis. Simulation tools that fail to meet all the required criteria are given no further consideration. The major MASNETs mandatory evaluation criteria are designed so that these criteria are easy to determine. There are three mandatory criteria identified for the best selection of MASNETs simulation tools, which are as follows:

- *Sensor network simulation.* The selected simulation tool should also be designed to simulate sensor network applications and not just as a general purpose tool. If the tool is not able to support sensor network simulation, it might not be able to offer the desired unique characteristics of MASNETs which are needed to accurately simulate the real sensor network environment.

- *Energy model.* The selected simulation tool need to provide some sort of energy model that is able to examine the energy consumption of sensor nodes and the whole network when simulating any routing protocols for static or mobile sensor nodes in MASNETs.

- *Mobility model.* The selected simulation tool must support some type of mobility models such as Random Way Point, Manhattan, and Gauss Markov [84] and allow user to modify network topology when simulating MASNETs. It should also be able to examine the accuracy of simulation results when the network topology has been changed in mobile environment.

On the other hand, the optional criteria are the extra requirements for any simulation tool for MASNETs. These criteria are also evaluated on a yes (✓) or no (✗) basis as in mandatory criteria. It is better for any simulation tool to satisfy most of these extra criteria for ease of use and to get more accurate experimental results for MASNETs. The following are six optional criteria that have been identified.

- *Free license.* There are various software licenses for simulation tools ranging from very restrictive proprietary licenses to free or open-source licenses. Ideally, the simulation tool must be free, so that it can be easily obtained, used and extended.

- *Bridging of code.* The simulation tool must bridge the gap between algorithm conception and actual field implementation. It should allow developers to test and verify the code that will run on real hardware with minimum changes. It is even better if it can use the same code in simulation as in real sensor node. For example, it should be able to simulate the MASNETs directly from TinyOS code.

- *Scalability.* The simulation tool should be extremely scalable and run efficiently in handling large networks (Ie. more than 1000 nodes) in a wide range of configurations.

- *Protocols support.* The simulation tool must be able to examine separately each important layer or segment sensor network including radio propagation, physical (PHY) layer, medium access control (MAC) layer, network layer, transport layer and sensing. The lack of available protocol models in this tool will cause the increase in development time.

- *Technical support.* The simulation tool must provide sufficient technical support (Ie. help, documentation, tutorials and maintenance) to help shorten the learning curve and accelerate development process.

- *GUI support.* Graphical User Interface (GUI) support for simulation can be used as a debugging aid, and a visualization and composition tool to view debugging errors or results; and to facilitate the design of small experiments or the composition of basic modules.

3.2.3.1 Comparison Study

In this subsection, all the fifteen selected simulation tools described in Section 3.2.2 are reviewed and compared based on the predefined mandatory criteria only. These mandatory criteria are very important in order to get more accurate and reliable experimental results for MASNETs evaluation study. Table 3.2 shows the comparison study of the selected simulation tools for MASNETs based on these criteria.

Based on this table, there are only five simulation tools that can be considered for further evaluation because of their capability to simulate specific WSN applications and ability to provide energy and mobility models. They are SENSE [65], Avrora[67], TOSSIM [68], EmStar [70] and COOJA [71] simulation tools. Furthermore, these top

Simulation Tool	Latest Version	Sensor Network Simulation	Energy Model	Mobility Model
NS-2 [57]	2.35 (Nov 2011)	✗	✓	✓
OPNET Modeller[58]	17.1 (Dec 2010)	✗	✓	✓
GloMoSim [59]	2.0 (Dec 2000)	✗	✓	✓
QualNet [60]	5.0 (Nov 2009)	✗	✓	✓
J-Sim [61]	2.06 (Feb 2012)	✗	✓	✓
OMNeT++ [62]	4.0 (Mar 2009)	✗	✓	✓
Castalia [63]	3.2 (Mar 2011)	✓	✓	✓
SENS[64]	jan31-2005b (Jan 2005)	✓	✓	✗
SENSE [65]	3.1 (Nov 2008)	✓	✓	✓
Shawn [66]	SVN (May 2010)	✓	✗	✗
Avrora [67]	Beta-1.7.106 (Aug 2008)	✓	✓	✓
TOSSIM [68]	2.1.1 (Apr 2010)	✓	✓	✓
ATEMU [69]	0.4 (Jan 2004)	✓	✓	✗
EmStar [70]	2.5 (Oct 2005)	✓	✓	✓
COOJA [78]	2.4 (July 2010)	✓	✓	✓

Table 3.2: Comparison study of simulation tools based on mandatory criteria

five simulation tools are reviewed and compared again based on the predefined mandatory and optional criteria. Before conducting further studies, each of these simulation tools are described in detail in terms of their advantages and disadvantages, and are described below:

- *SENSE* [65, 85]. One of the advantages of SENSE is its balanced consideration of modelling methodology and simulation efficiency. It is a user-friendly simulator that is also very fast. Unlike object-oriented network simulators, it is based on a novel component-oriented simulation methodology that promotes extensibility and re-usability to the maximum degree. At the same time, the simulation efficiency and the issue of scalability was considered. It also supports a sufficient energy model and parallelism for WSNs. It provides different battery models, application, network, MAC and physical layer functionalities. It also integrates G-Sense tool to improve on its ease of use through graphical input of simulation parameters, save and load simulation features, and simulation results management with plot view [86]. Although the core of the simulator has been gradually stabilized, SENSE is still in its active development phase. At the moment, it still lacks a comprehensive set of models and a wide variety of configuration templates for WSNs.

- *Avrora* [67**?**]. One of the main advantages of Avrora is that it is an accurate and scalable simulator for the actual hardware platform on which sensor programs run. It provides a framework for program analysis, allowing static checking of embedded software and an infrastructure for future program analysis research. It is also capable of running a complete sensor network simulation with full timing accuracy, allowing programs to communicate via the radio using the software stack provided in TinyOS [87]. In addition, it has an extension point that allows users to create a new simulation type and choose the type of simulation to perform, depending on the number and orientation of the nodes. It is language and operating system independent where it can simulate any platforms like MICA2 and MICAZ, and run AVR elf-binary or assembly codes for both platforms. Unlike TOSSIM [88], it is implemented in Java, which helps flexibility and portability where it can simulates each node as its own thread while still running actual MICA code. It can simulate different programming code projects, but TOSSIM can only support TinyOS simulation. It also enables developers to test and evaluate experiments for time-critical application scenarios in large scale sensor networks. It also has an extension point that allows users to create a new simulation type and choose the type of simulation to perform, depending on the number and orientation of the nodes. It can provides a wide range of tools that can be used in simulating WSNs such as control flow graph generation, energy analysis, and the distance-attenuation, and the random waypoint mobility model. Since, it runs code instruction by instruction and avoids synchronizing all nodes after every instruction to achieve better scalability and speed. It enables the simulator to conduct simulation experiments with sensor networks of up to 10,000 nodes and performs as much as 20 times faster than previous simulators with equivalent accuracy [89]. Open source code and online documentation provided improve the ease of use of this simulator for simulating WSNs. Although Avrora has many advantages, it also has some drawbacks. One of them is that it does not model clock drift, a phenomenon where nodes may run at slightly different clock frequencies over time due to manufacturing tolerances, temperature, and battery performance. It is also does not provide a GUI and is fifty percent slower than TOSSIM [88].

- TOSSIM [88, 90]. TOSSIM simulates the TinyOS [87] network stack at the bit level, allowing experimentation with low-level protocols in addition to top-level application systems. The simulation provides several mechanisms for interacting with the network, packet traffic can be monitored and packets can be statically or dynamically injected into the network. It can support thousands of nodes simulation and provide more precise simulation result at component levels because of direct compilation to native codes. This is a very good feature, as it can simulate the real world situation more accurately. It can be run on Linux or on Cygwin for Windows. It also has a GUI, TinyViz [88], which is very convenient for the user to interact with electronic devices because it provides images instead of text commands. It also has an add-on PowerTOSSIMz [91] that can be used to measure energy consumption in WSNs. Open source code and online documentation are also provided for user references. On the other hand, TOSSIM also has some disadvantages. Firstly, it is designed to simulate behaviours and applications of TinyOS, and not to simulate the performance metrics of other new protocols. Therefore, it cannot correctly simulate issues of the energy consumption in WSNs. Secondly, every node has to run on NesC code, a programming language that is event-driven, component-based and implemented on TinyOS. Hence, it can only emulate homogeneous applications. Thirdly, because it is specifically designed for WSN simulation, mote-like nodes are the only thing that it can simulate. Lastly, since interrupts are discrete events, it does not model pre-emption and the resulting possible TinyOS data races.

- *EmStar* [70, 92] EmStar allows the users to run each module separately without sacrificing the re-usability of the software due to its modular programming model. It has a robust feature that it can mitigate faults among the sensors, and it provides many modes, making debugging and evaluation much easier. There is a flexible environment in EmStar that users can freely change between deployment and simulation among sensors. Also with a standard interfaces, each service can easily be interconnected. It also has a GUI, which is very helpful for users to control electronic devices. When using EmStar, every execution platform is written by the same codes, which will decrease bugs when repeating the separate modes. In addition, it provides many online documents to facilitate the wide use of this emulator. However, this emulator contains some disadvantages. For example, it cannot support large numbers of sensor simulation and it can only run in a real time simulation. Moreover, it can only apply to iPAQ-class sensor nodes and MICA2 motes. All these disadvantages limit the use of this emulator.

- COOJA [71, 93]. COOJA is primarily a code level simulator for networks consisting of nodes running Contiki OS. Nodes with different simulated hardware and different on-board software may co-exist in the same simulation. It is flexible and extensible in that all levels of the system can be changed or replaced: sensor node platforms, operating system software, radio transceivers, and radio propagation models. Moreover, it also supports adding and using different radio mediums. Code level simulation is achieved by compiling Contiki core, user processes and special simulation glue drivers into object code native to the simulator platform, and then executing this object code from COOJA [94]. It can execute the Contiki programs in two different ways: either by compiling the program code directly on

Evaluation Metric	SENSE [65]	Avrora [67]	TOSSIM [89]	EmStar [70]	COOJA [71]
WSN Simulation	✓	✓	✓	✓	✓
Energy model	✓	✓	✓	✓	✓
Mobility model	✓	✓	✓	✓	✓
Free license	✓	✓	✓	✓	✓
Bridging of code	✗	✓	✓	✓	✓
Scalability	✓	✓	✓	✗	✗
Protocols support	✓	✓	✓	✓	✓
Technical support	✓	✓	✓	✓	✓
GUI support	✗	✗	✗	✓	✗

Table 3.3: Comparison study of selected simulation tools for MASNETs

the host CPU, or compiling it for the MSP430 hardware. It can simulate sensor networks simultaneously at different levels, including the operating system level and the network application level. However, due to its extendibility, the simulator has relatively low efficiency. Simulating many nodes with several interfaces each requires a lot of calculations. This simulator also can only support a limited number of simultaneous node types. The simulator has to be restarted once and a while if the number of nodes exceed the allowable limit. A test interface GUI is absent, thus making extensive and time-dependent simulations difficult.

Based on the review of these simulation tools, they are compared in terms of both mandatory and optional criteria that have been defined earlier as shown in Table 3.3. From this table, it can be seen that the main contenders for simulating MASNETs appeared to be Avrora and TOSSIM because the two simulators can simulate mobile environment and at the same time are capable of bridging TinyOS codes into hardware implementation. In addition, these tools also provide different models to support sensor network implementation and can support large number of sensors simulation in comparison to other simulation tools. Although, these simulators lack in GUI, but the technical and protocols support provided by these tools can help users to use them effectively.

Using Avrora with TinyOS [87] provides a high quality simulation of the actual code that runs on a MICAZ node. This allows for more in-depth testing and debugging of sensor network applications. Avrora is also more flexible and portable than TOSSIM where it can simulate each node as its own thread while still running actual sensor node code. Moreover, Avrora can simulate different programming code projects, but TOSSIM can only support TinyOS simulation. From the comparison study, we have identified that Avrora is the most suitable simulation tool for our research works because most of the criteria that we defined for simulating MASNETs can be provided by Avrora.

3.3 Mobility Models

In order to simulate and evaluate routing protocol in MASNETs, it is necessary to choose the appropriate mobility model to describe the location, velocity and movement pattern of mobile nodes. Since mobility patterns may play a significant role in determining the performance of MASNETs, it is desirable for mobility models to emulate the movement pattern of targeted real life applications in a reasonable way and be able to examine the accuracy of simulation results in a mobile environment. Otherwise, the observations made and the conclusions drawn from the simulation studies may be misleading. Hence, when evaluating MASNETs routing protocols, it is necessary to choose the ideal mobility model. For example, the nodes in Random Waypoint (RWP) model behave quite differently as compared to nodes moving in groups as in Reference Point Group (RPG) model [95]. It is not appropriate to evaluate the applications where nodes tend to move together using RWP model. Therefore, in this section the existing mobility models are reviewed to identify the most appropriate model for our research work.

3.3.1 Existing Mobility Models

In this subsection, we briefly describe several existing mobility models that represent mobile nodes that can be used in the simulation of MASNETs. The following are the most relevant and popular mobility models used in ad-hoc and sensor network research as studied in [84, 95, 96]:

- *Random Walk Model.* This is the simplest mobility model which is also known as Brownian motion. It is a widely used model to represent purely random movements of the entities of a system in various disciplines. In this model, the position of a node at a given time step depends on the node position at the previous step.

In particular, no explicit modelling of movement direction and velocity is used in this model. However, it cannot be considered as a suitable model to simulate wireless environments, since sensor node movements do not present the continuous changes of direction that characterize this mobility model.

- *Random Waypoint (RWP) Model.* This model is the most commonly used mobility model for ad-hoc network. It is an extension of Random walk. This model introduces a pause time at each interval time, where nodes stay at a location for a certain time (pause). Before the node moves to a new location, a new random direction or destination is given at a speed uniformly distributed between [minSpeed, maxSpeed]. The RWP model has been deeply studied in the literature and it has also been generalized to be slightly more realistic, though still simple model.

- *Random Direction Model.* This model quite similar to RWP model where the random direction model resembles individual, obstacle-free movement. This model is designed to maintain a uniform node spatial distribution during the simulation time. This can avoid the border effects as in RWP model. In this model, any node chooses a direction uniformly at random in the interval [0, 2π], and a random velocity in the interval [υ_{min},υ_{max}]. Then, it starts moving in the selected direction with the chosen velocity. When the node reaches the boundary of R, it chooses a new direction and velocity, and so on.

- *Manhattan Model.* This mobility model is a popular, special case of a geographic restriction model. In this model, the map is predefined in the simulation field and utilizes a random graph to model the map of the city. Initially the nodes are placed randomly on the edges of the graph. Then for each node a destination is randomly chosen and the node moves toward this destination through the shortest path along the edges. Upon arrival, the node pauses for a short time and again chooses a new destination for the next movement. This procedure is repeated until the end of the simulation. Unlike the RWP model, where the nodes can move freely, the mobile nodes in this model are only allowed to travel on the pathways. However, since the destination of each action phase is randomly chosen, a certain level of randomness still exists for this model and the movement of a mobile node is also restricted to the pathways in the simulation field.

- *Gauss-Markov Mode*l. This model is designed to adapt to different levels of randomness via tuning parameters. Initially each mobile node is assigned a current speed and direction. At each fixed intervals of time n a movement occurs by updating the speed and direction of each mobile node. Specifically, the value of speed and direction at the nth instance is calculated based on the basis of the value of speed and direction at the $(n-1)$st instance and a random variable. When the node is going to travel beyond the boundaries of the simulation field, the direction of movement is forced to flip 180 degree. This way, the nodes remain away from the boundary of simulation field.

- *Reference Point Group (RPG) model.* This model can be used to simulate the movement of a number of soldiers that move together in a group or platoon or simulate a situation where various rescue crews form different groups and work cooperatively during the disaster relief. In this model, each group has a centre, which is either a logical centre or a group leader node. Thus, each group is composed of one leader and a number of members. The movement of group leader at time t, define the motion of group leader and the general motion trend of the whole group. This means, the movement of group members is significantly affected by the movement of its group leader. For each node, mobility is assigned with a reference point that follows the group movement. Upon this predefined reference point, each mobile node could be randomly placed in the neighbourhood

Among the mobility models described above, the most popular and widely used model is RWP model. This is because RWP is a simple model that is applicable to many scenarios and is already implemented in popular network simulation tools including Avrora [89], GloMosim [74] and Ns2[72]. This model also has been the subject of many studies and a number of them claim that their results show that this mobility model is a good approximation for simulating the motion of wireless mobile nodes as in [97, 98, 99, 100]. For all of these reasons, it is therefore appropriate for us to use RWP model in this research work to simulate the movement of sensor nodes in MASNETs with Avrora simulation tool.

3.3.2 RWP Mobility Model in Avrora

Based on comparison study in Section 3.2.2, we have identified Avrora simulation tool as the most appropriate tool to simulate MASNETs. Therefore, in this section the implementation of RWP mobility model in Avrora is described in detail.

At the beginning of simulation, a starting topology of nodes can be given as for static topology. When doing so, the minimum or maximum coordinates are automatically adjusted so that they at least cover all nodes. By default, the ranges are negative which will lead to an error when no start topology and no min/max settings are given. Then, each mobile node randomly selects one location in the simulation field as the destination. All nodes given by the mobile-nodes list will travel towards this destination with constant speed chosen uniformly and randomly between mobility-minvel and mobility maxvel. The mobility-minvel is the minimum allowable speed whereas the mobility maxvel is the maximum allowable velocity for every mobile node. The speed and direction of a node are chosen independently of other nodes. Upon reaching the destination, they will wait a random time between zero and mobility-maxwait before they select a new destination. If mobility-maxwait equals zero, this leads to continuous mobility. After this duration, it again chooses another random destination in the simulation field and moves towards it. The whole process is repeated again and again until the simulation ends. The positions of nth nodes are update with the given granularity. Note that a finer granularity will result in higher computational effort and therefore higher simulation time. As an example, the movement trace of a mobile node is shown in Figure 3.1 with the mobility setting parameters in Table 3.4.

3.4 Summary

In this chapter, we have provided a comparative study of a number of different commonly used simulation tools for MASNETs and present the pros and cons of the selected simulation tools. In addition, short descriptions of fifteen selected simulation tools are also provided. The tools are then compared based on predefined mandatory and optional criteria for simulating MASNETs. In the beginning part, this study illustrates why we need the right simulation tools and what mandatory and optional criteria should be considered when simulating MASNETs. Then, this study analyses fifteen chosen simulation tools to get a short list of tools appropriate for MASNETs based on

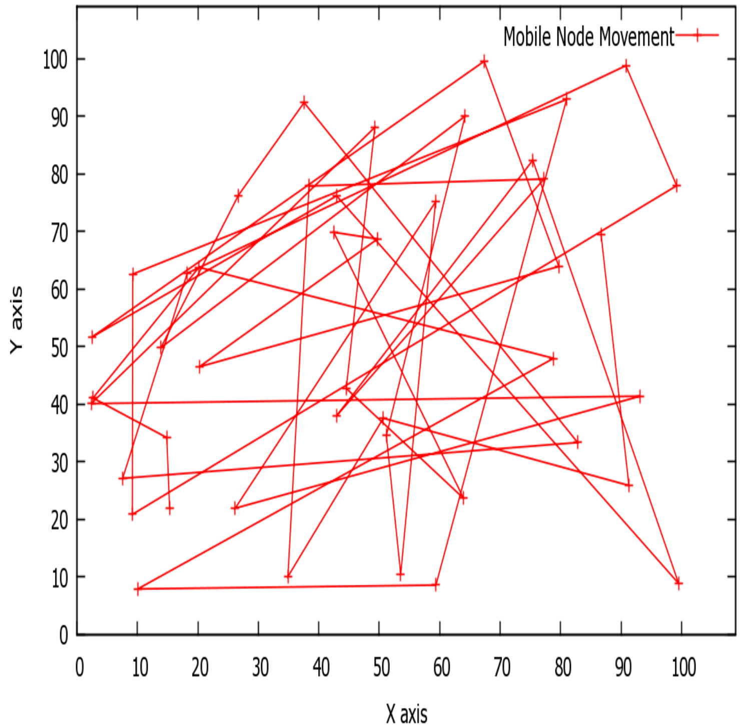

Figure 3.1: The example of mobile node movement in RWP mobility model with Avrora

Parameters	Value
Simulation Tool	Avrora-Beta 1.7.114
Routing Protocol	AODV
Mobility model	Random Waypoint
Simulation duration	500 seconds
Simulation area	100 m x 100 m
Number of nodes	9
Number of mobile node	1
Mobility-minvel	5 m/s
Mobility-maxvel	10 m/s
Mobility-maxwait	10 sec

Table 3.4: Mobility setting parameters in mobile nodes simulation

the mandatory criteria. Only five tools including SENSE, Avrora, TOSSIM, EmStar and COOJA are shortlisted and further compared their advantages and disadvantages based on the optional criteria. Lastly we have reviewed different mobility models for MASNETs and identified the appropriate mobility model to simulate the mobile nodes in our research work.

From the comparison study, we have identified Avrora as the most appropriate simulation tool for our research works because most of the criteria that we defined for simulating MASNETs is provided by Avrora. However, some of the simulation tools outweigh others in terms of different evaluation metrics or criteria. Since most of the work in the thesis centre on new enhancements to the basic AODV protocol, this is of considerable convenience in enabling us to provide an accurate assessment of the performance gain and to evaluate various enhancements on AODV. Moreover, based on the review of existing mobility models, we have decided to use RWP model to be integrated with Avrora to simulate a sensor node movement. Although, no other models have been developed on Avrora due to the limitation of this simulator, we believe the use of RWP model is sufficient and appropriate enough for our study. This is because of its simplicity and applicability to many mobile applications or scenarios. In addition, this model is already included in Avrora latest version (Avrora-Beta 1.7.115). In the next chapter, the chosen simulation tool and mobility model are used to evaluate the performance of AODV in MASNETs. As a summary, the identification and selection of the right simulation tool and mobility model are very important because the performance of MASNETs in our research work is totally based on simulation in the mobile environment.

Chapter 4

Performance Evaluation of AODV in MASNETs

4.1 Introduction

MASNETs has certain characteristic, which imposes new demands on the routing protocol. The most important characteristic is the dynamic topology, which is a consequence of the mobile nodes. A mobile node can change position quite frequently, which means that we need a routing protocol that quickly adapts to topology changes. In designing such routing protocol we have to consider the constraints of the nodes in MASNETs that are often very limited in resources such as processing capacity, storage, battery power and bandwidth [17]. Since the nodes are forwarding packets for each other towards sink, some sort of efficient routing protocol is necessary to make better routing decisions with less energy consumption in mobile environment. Before designing a better routing protocol for MASNETs, there is a need to identify the effects of node mobility on a routing protocol for such mobile networks.

In this chapter, the performance of a well-known AODV [43] routing protocol as described in Chapter 2 is evaluated to demonstrate the impact of mobile nodes on performance metrics of MASNETs. We present the analysis of the impact of mobile nodes on performance metrics of MASNETs routing protocol through a simulation. Here we give the emphasis for the evaluation of performance of AODV routing protocol for MASNETs in terms of performance metrics such as the average percentage of packet loss and the average total energy consumption with different speed, density and route update interval (RUI) of mobile nodes. The simulations are performed using Avrora network simulation tool, which is the most appropriate simulation tool for evaluating MASNETs as shown in the comprehensive simulation study conducted on different popular simulation tools for WSNs as described in Chapter 3. We also presented several simulation results on Castalia [63] simulator in order to validate the accuracy of Avrora simulation results. Lastly, the experimental results and findings from both simulation tools are discussed in details.

4.2 Performance Evaluation

In this section, through extensive simulation we evaluate the capability of AODV routing protocol on how far it can react to network topology change in MASNETs. Firstly, we outline the performance metrics for evaluating the performance of AODV in mobile environment. Then, we describe the general simulation set-up used in the experiments. Next, we present the experimental results and findings of AODV in terms of the effects of mobile node speed, density and RUI on AODV. Lastly, we show the different combination of experimental results of AODV on the speed, density and RUI of mobile nodes.

4.2.1 Performance Metrics

In order to evaluate the capability of AODV routing protocol on how it reacts to network topology change in MASNETs, we focused on two performance metrics as follows:

- *Average percentage of packet loss*: Average percentage of packet loss can be defined as the average percentage of packets sent by the source and the packets dropped (loss) before being received by the base station (sink). The average percentage of packet loss, $\bar{X}_{PL}$, is determined by calculating the average ratio of packets unsuccessfully delivered to the sink, N_L, to the total number of packets sent by any node, N_S, as given below:

$$\bar{X}_{PL} = \frac{N_L}{N_s} * 100 \tag{4.1}$$

- *Average total energy consumption*: Average total energy consumption is defined as the average amount of energy consumed by nodes in the network through

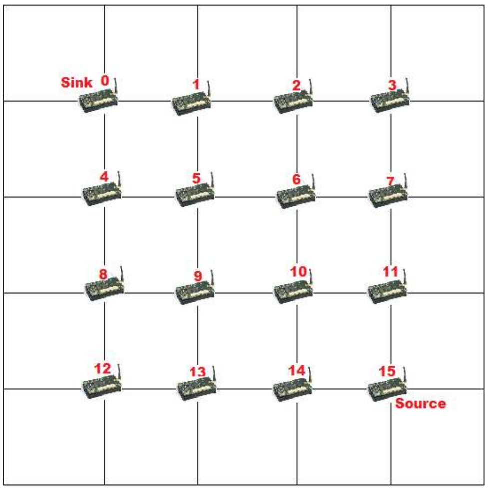

Figure 4.1: Initial grid topology set-up for AODV Simulation

radio communication and processing. So, this metric, given as $\bar{X}_{PE}$, can be calculated by adding all energy consumed by each nodes, n, for transmitting (TX), receiving (RX) and processing throughout the simulation time. The equation for the average total energy consumption is written as below where this equation calculate the average of total energy consumed in all nodes when they send and receive the association and data packets.

$$\bar{X}_{PE} = \sum_{i=1}^{n} (E^i_{Tx} + E^i_{Rx}) \tag{4.2}$$

4.2.2 Simulation Set-up

We considered a network of sensor nodes placed initially in a grid topology set-up as shown in Figure 4.1. In this topology, sixteen sensor nodes are initially allocated within 75 m x 75 m simulation area with the distance of fifteen meters between each node. This distance is equivalence to maximum communication range that has has been set-up for the simulation purpose. Such set-up is important to ensure each of mobile node in the simulation area is able to establish communication with each other and they only drop the packets if they send or forward packets towards sink on a broken route due to mobility. Hence, the performance of AODV was evaluated by keeping the mobility area and pause time of RWP mobility model constant and varying the speed, density and RUI of mobile nodes with 10 simulation seeds for different experiment settings. For each experiments, the statistical analysis is done on the simulation data gathered by using the Excel Data Analysis Tool (Descriptive Statistics) to get the average, standard deviation and confidence interval. This statistical analysis is important to support the simulation results of each experiments.

4.2.3 Effect of mobile node speed

The objective of this experiment was to observe the packet loss when mobile nodes are moving at different speed. In order to study the effect of different mobile nodes' speed on the AODV performance, the mobile nodes were set to move constantly according to RWP mobility model in each experiment. In this experiment, we have selected eight nodes in the middle of the simulation area as a mobile node which are node 2, node 3, node 6, node 7, node 8, node 9, node 12 and node 13 as shown in Figure 4.1. Such setting is important to ensure the occurrence of broken links when these nodes are moving within the simulation area. By increase the speed of mobile nodes in the simulation, the effect of mobility on AODV would also increase. The different levels of speed which increased from 2 m/s to 10 m/s in step of 2 were configured with the experiment setting as in Table 4.1.

The statistical analysis in Table 4.2 and the simulation result in Figure 4.2 show the average percentage of packet loss increased gradually from 51.13% to 86.84% as the speed of mobile nodes increase, from minimum speed of 2 m/s to the speed of 10 m/s. This indicates that AODV dropped a high number of packets when the mobility increased, and higher speed contributes to higher average percentage of packet loss. The main reasons for dropping packets are that the protocol is sending packets on a broken route that it assumed was still valid and that the packet in the buffers are dropped because of congestion and timeout

When we analysed the total communication time during the transmission and reception of each packets throughout the simulation time of 1000 seconds, the percentage of route unavailability is increased gradually from 21.0% to 83.2% as the speed of mobile node increase as in Table 4.3. In relation to the average percentage of packet loss, the more longer the route availability for communication between nodes the less packet will loss in the network. This shows that it is important for each of the sensor node to ensure the availability and the validity of route before they can transmit any packet

Parameters	Value
Simulator	AVRora-Beta 1.7.115
Protocol	AODV
Simulation duration	1000 seconds
Simulation area	75 m x 75 m
Number of nodes	16 nodes
Number of mobile nodes	8 nodes
Mobility model	Random Waypoint
Pause time	5 sec
Maximum Speed	2, 4, 6, 8, 10 m/s
Data Rate	1 packet / sec

Table 4.1: Parameters used in the mobile node speed experiment

Speed	Average Packet Loss (%)	Standard Deviation	95% C. I.
2	51.13	19.26	13.78
4	61.40	22.51	16.10
6	69.22	10.51	7.52
8	78.87	16.86	12.06
10	86.84	11.54	8.26

Table 4.2: The statistical analysis of different speed of mobile nodes

in order to minimize the percentage of packet loss in mobile environment such as in MASNETs.

4.2.4 Effect of mobile node density

The objective of the second experiment experiment was to observe the packet loss when the density of mobile node are changing when different number of mobile nodes exists in the network. This experiment showed the effect of change in mobile node density

Speed	Communication Time	Route Availability (%)	Route Unavailability (%)
2	790	79.0	21.0
4	657	65.7	34.3
6	496	49.6	50.4
8	387	38.7	61.3
10	168	16.8	83.2

Table 4.3: The percentage of time a route is available and unavailable for the mobile node speed experiment

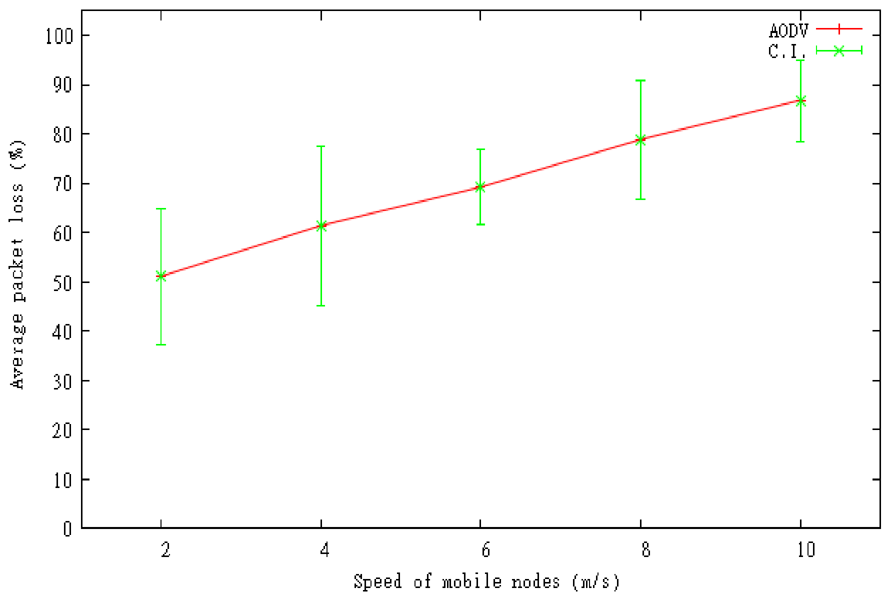

Figure 4.2: The average percentage of packet loss caused by the increasing speed of mobile nodes

on the average percentage of packet loss as in the first experiment. In order to study the effect of different mobile nodes' density on the AODV performance, the different number of mobile nodes were set to move constantly according to RWP mobility model in each experiment. In this experiment different number of nodes in the middle of the simulation area were set as mobile, which increased from 2 mobile nodes to 10 mobile nodes in step of 2 except for the sink and source. Such setting is important to ensure the occurrence of broken links when different number of mobile nodes moving within the simulation area. These mobile nodes are numbered 3, 12 (2 nodes); 3, 6, 9, 12 (4 nodes); 2, 3, 6, 7, 9, 12 (6 nodes); 2, 3, 6, 7, 8, 9, 12, 13 (8 nodes) and 2, 3, 5, 6, 7, 8, 9, 10, 12, 13 (10 nodes) accordingly. By increase the density of mobile nodes in the simulation, more mobile nodes exist in the network and this increase the effect of mobility on AODV. All mobile nodes are moved constantly with maximum speed of 2 m/s within 75 m x 75 m simulation area and configured with the simulation parameters as in Table 4.4.

Based on the statistical analysis in Table 4.5 and Figure 4.3, there was almost zero average percentage of packet loss when there is only 2 mobile nodes in the network. This is due to less existence of mobile nodes in the network and no occurrence of broken link

Parameters	Value
Simulator	AVRora-Beta 1.7.115
Protocol	AODV
Simulation duration	1000 seconds
Simulation area	75 m x 75 m
Number of nodes	16 nodes
Number of mobile nodes	2, 4, 6, 8, 10 nodes
Mobility model	Random Waypoint
Pause time	5 sec
Maximum Speed	2 m/s
Data Rate	1 packet / sec

Table 4.4: Parameters used in the mobile node density experiment

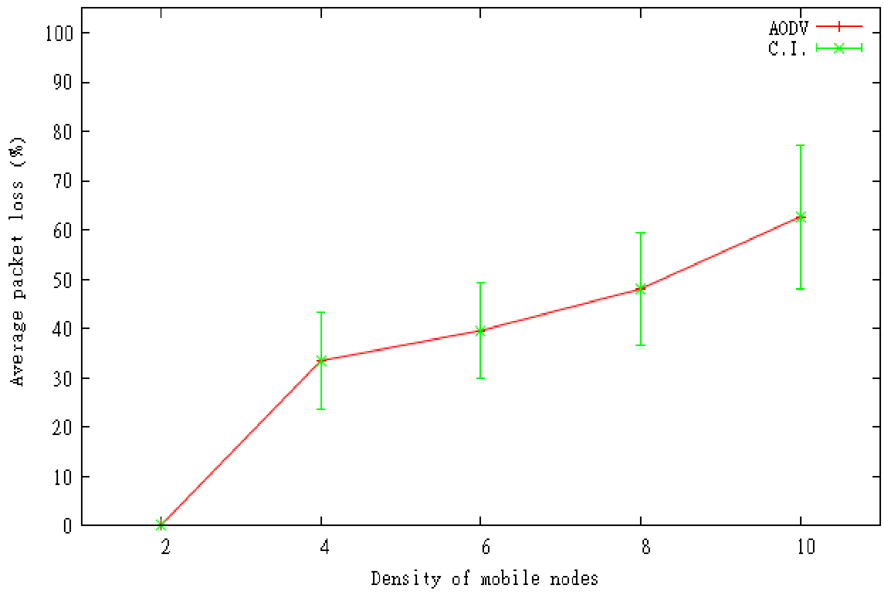

Figure 4.3: The average percentage of packet loss caused by the increasing density of mobile node

Density	Average Packet Loss (%)	Standard Deviation	95% C. I.
2	0.03	0.05	0.03
4	33.42	13.74	9.83
6	39.54	13.57	9.71
8	48.01	16.14	11.54
10	62.64	20.48	14.65

Table 4.5: The statistical analysis of different density of mobile node

Density	Communication Time	Route Availability (%)	Route Unavailability (%)
2	996	99.6	0.4
4	781	78.1	21.9
6	659	65.9	34.1
8	578	57.8	42.2
10	417	41.7	58.3

Table 4.6: The percentage of time a route is available and unavailable for the mobile node density experiment

because the source node is able to find another route to sink for packet transmission. Moreover, the movement of the selected mobile nodes in the network not have much effect on the network topology. But, the average percentage of packet loss increased dramatically from 0.03% to 33.42% when there are 2 to 4 mobile nodes in the network. Then, the average percentage of packet loss increased gradually from 33.42% to 62.64% as the density of mobile nodes increase, from 4 to 10 density of mobile nodes. This indicates that more packets are lost when more nodes become mobile because AODV dropped more packets when the number of mobile nodes increased due to frequent broken links. However, this high average percentage of packets loss is not acceptable and the reason for these losses is because of the packets were sent on a broken route before the routing tables have had enough time to converge, and therefore, the packets are dropped.

When we looked into the total communication time during the transmission and reception of each packets throughout the simulation time, the percentage of route availability is decreased gradually from 99.6% to 41.7% as the density of mobile node increase as shown in Table 4.6. This show that the higher percentage of route availability, the less packet will loss in the network. Therefore, the less number of mobile node in the network can improve the percentage of route availability and minimize the percentage of packet loss in MASNETs.

4.2.5 Effect of route update interval

The third experiment study the effect of change in RUI on both performance metrics for AODV which are the average percentage of packet loss and the average total energy consumption. This experiment is different from the previous two experiments because we investigate the effect of changing the frequency of updating the routing table of

Parameters	Value
Simulator	AVRora-Beta 1.7.115
Protocol	AODV
Simulation duration	1000 seconds
Simulation area	75 m x 75 m
Number of nodes	16 nodes
Number of mobile nodes	8 nodes
Mobility model	Random Waypoint
Pause time	5 sec
Maximum Speed	2 m/s
Data Rate	1 packet / sec
Route Update Interval	10, 20, 30, 40, 50, 60 sec

Table 4.7: Parameters used in the RUI experiment

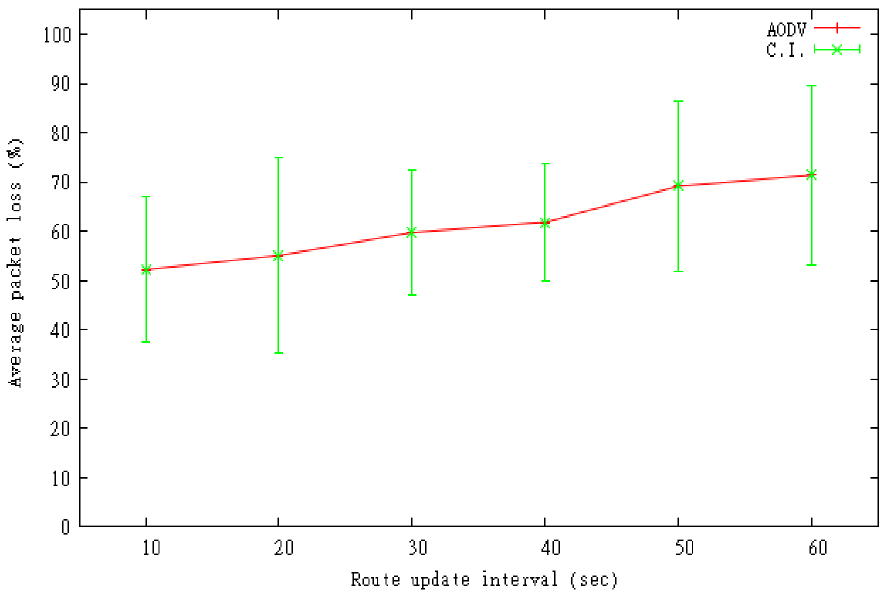

Figure 4.4: The average percentage of packet loss versus RUI

RUI	Average Packet Loss (%)	Standard Deviation	95% C. I.
10	52.19	20.63	14.76
20	55.05	27.73	19.83
30	59.71	17.75	12.70
40	61.81	16.83	12.04
50	69.14	24.10	17.24
60	71.36	25.40	18.17

Table 4.8: The average percentage of packet loss and statistical analysis of different RUI

nodes in the network in relation to optimum speed and density of mobile nodes. In order to study the effect of different RUI on the AODV performance, each node is set to update constantly their routing table according to different RUI which increased from 10 seconds to 60 seconds in step of 10 seconds including the sink and source. Such setting is important to increase the number of broken links in the network and to allow the packet to be forwarded on the invalid route to destination. By increase the RUI of mobile nodes in the simulation, more broken links exist in the network and this increase the topology change in the network. There are eight mobile nodes are moved constantly with maximum speed of 2 m/s within 75 m x 75 m simulation area and configured with the simulation parameters as in Table 4.7.

Figure 4.4 and the statistical analysis in Table 4.8 show the average percentage of packet loss increased gradually from 52.19% to 71.36% as the RUI increase, from minimum 10 seconds to 60 seconds. This indicates that AODV dropped a high number of packets when the RUI increased, and higher RUI contributes to higher average percentage of packet loss. This is because the increase of RUI reduce the frequency for the nodes to update their routing tables which force their next route to sink to become invalid and unreliable. But, by increasing the RUI, the energy consumed by the mobile nodes was reduced because less packets were transmitted to establish the connection and update their routing tables. This is shown in Figure 4.5 and Table 4.9 where the average total energy consumption reduced significantly from 224,379 joule to 138,782 joule as the RUI increase from minimum 10 seconds to 60 seconds. The reduction of energy consumption through by optimizing the route update frequency can minimize the overall energy consumption in the network.

As refer to the total communication time during the transmission and reception of each packets throughout the simulation time of 1000 seconds, the percentage of route unavailability is increased significantly from 0.4 % to 58.3% as the RUI increase from minimum 10 seconds to 60 seconds as shown in Table 4.10. The decrease in the communication time is due to the increase in RUI that affect the accuracy of next-hop node selection in the routing table. When the selection of the next-hop node is inaccurate, this contribute to the increase of broken links and indirectly increase the average percentage of packet loss in the network. Although the average of energy consumption can be reduced by maximize the RUI, but the optimum frequency of

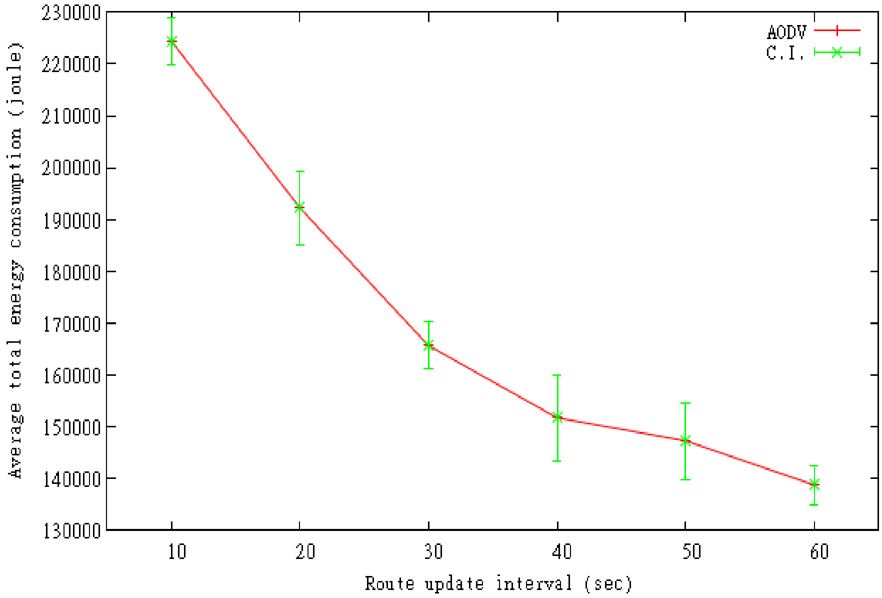

Figure 4.5: The average total energy consumption versus RUI

RUI	Average Total Energy Consumption	Standard Deviation	95% C. I.
10	224379.76	6367.84	4555.28
20	192213.56	10047.75	7187.72
30	165652.21	6336.23	4532.66
50	151719.58	11625.49	8316.38
50	147293.55	10345.67	7400.84
60	138782.46	5303.41	3793.83

Table 4.9: The average total energy consumption and statistical analysis of different RUI

route update need to be considered in order to minimize the effect of mobility on the performance of AODV.

Furthermore, when we analyse the experimental results of the average percentage of packet loss and the average total energy consumption in relation to the effects of RUI, we found that there is indirect relation between these two performance metrics of AODV. This is shown in Figure 4.6 and Table 4.11 where the average percentage of packet loss is decreased gradually from 71.36% to 52.19% as the average of total energy consumption increased from 138,782 joule to 224,380 joule. This show that when more energy is consumed by nodes for updating their routing tables, the less percentage of packet will be lost. On the other hand, when less energy is consumed for route update,

RUI	Communication Time	Route Availability (%)	Route Unavailability (%)
10	996	99.6	0.4
20	781	78.1	21.9
30	659	65.9	34.1
40	578	57.8	42.2
50	417	41.7	58.3
60	417	41.7	58.3

Table 4.10: The percentage of time a route is available and unavailable for the RUI experiment

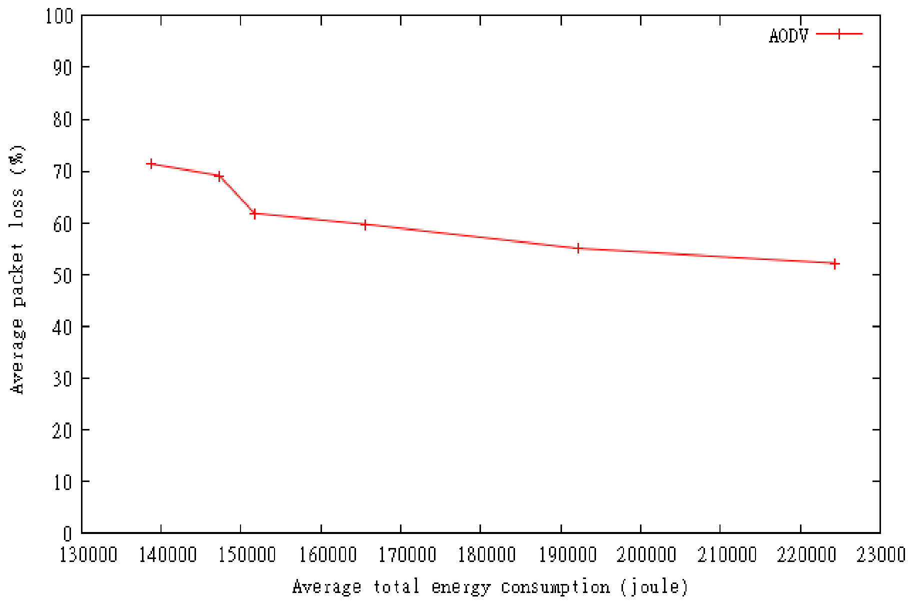

Figure 4.6: The average packet loss versus the average total energy consumption

the average percentage of packet loss will be higher. This is because of the next route to sink is unreliable when there is a low frequency of route update.

4.2.6 Combination of Simulation Results

In this subsection, when we combine the experimental results of the effects of speed and density of mobile nodes on the average percentage of packet loss, we found that there is a direct relationship between these two properties of mobility. This is shown in Figure 4.7 and Table 4.12 where the average percentage of packet loss for both speed and density of mobile nodes increased gradually from 2 to 10 m/s and from 2 to 10 mobile nodes respectively. This indicates that if more number of mobile nodes with

Average Total Energy Consumed	Average Packet Loss (%)
138782	71.36
147294	69.14
151720	61.81
165652	59.71
192214	55.05
224380	52.19

Table 4.11: The average total energy consumed versus the average packet loss

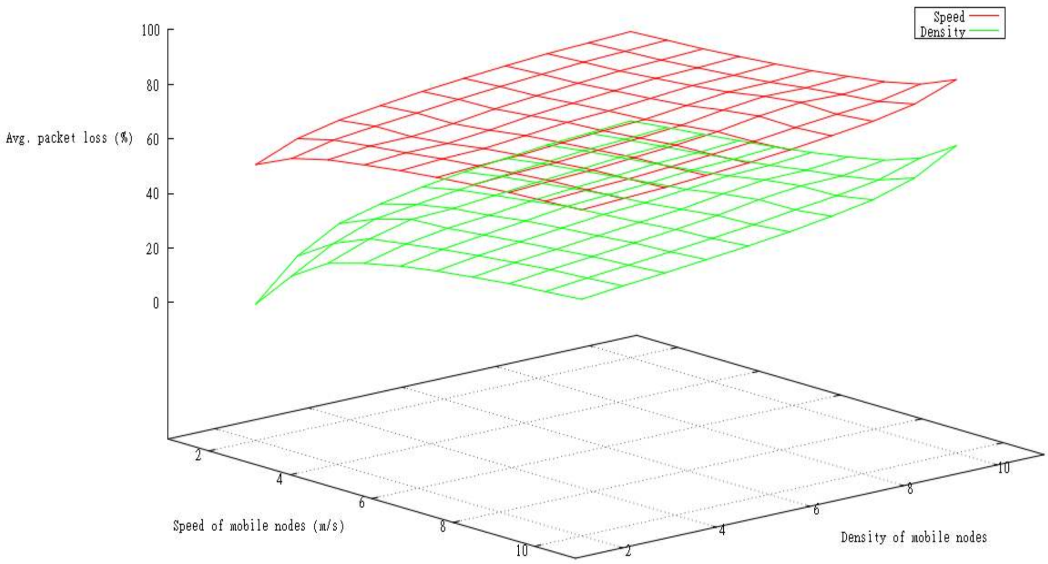

Figure 4.7: The 3D graph between speed and density of mobile nodes

high speed mobility in the network, the average percentage of packet will be higher. This is may due to the fact that the combination of mobility properties might double up the impact of mobility on AODV in mobile environment although the impact of speed is more than density of mobile nodes as in this 3D graph.

Furthermore, when we combine different experimental results of the effects of speed of mobile nodes and RUI on the average percentage of packet loss, we found that there is also a direct relationship between these two results. This is shown in Figure 4.8 and Table 4.13 where the average percentage of packet loss for both speed of mobile nodes and RUI increased gradually from 2 to 10 m/s and from 10 to 50 seconds respectively although the impact of speed is also more than RUI in this 3D graph. This indicates that if the node is moving in higher speed with longer RUI in the network, the occurrence of

Speed (m/s)	Avg. Packet Loss (%)	Density (mobile nodes)	Avg. Packet Loss (%)
2	51.13	2	0.03
4	61.40	4	33.42
6	69.22	6	39.54
8	78.87	8	48.01
10	86.84	10	62.64

Table 4.12: The average packet loss for speed and density of mobile nodes

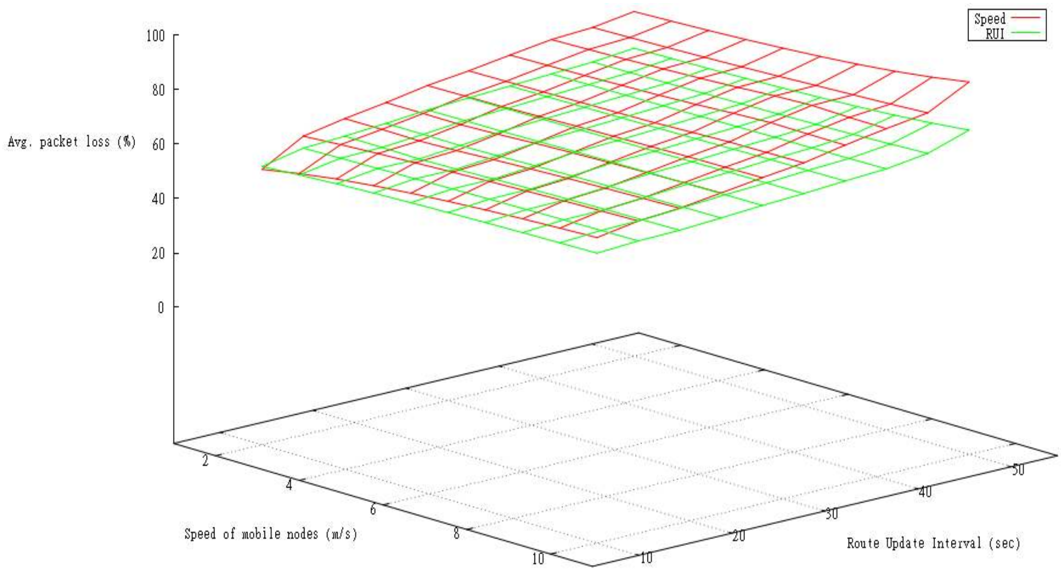

Figure 4.8: The 3D graph between speed of mobile nodes and RUI

broken links is much more higher than the mobile nodes with high speed and density but with more frequent route update.

4.3 Validation of Simulation Results

In the previous section, all the experiments are conducted on Avrora simulation tool. Avrora can simulate as closely as possible the reality of network of sensor nodes in MASNETs because it runs the actual microcontroller programs rather than models of the software. It also capable of simulate accurate simulations of the devices and the radio communication of sensor nodes. But, for the purpose of validation of Avrora simulation results and due to the significant divergences existed between different simulation tools studied in [101], we have simulated the mobile node speed and density

Speed	Avg. Packet Loss (%)	RUI	Avg. Packet Loss (%)
2	51.13	10	52.19
4	61.40	20	55.05
6	69.22	30	59.71
8	78.87	40	61.81
10	86.84	50	69.14

Table 4.13: The average packet loss for speed of mobile nodes and RUI

experiments in subsection 4.2.3 and subsection 4.2.4 respectively on another simulation tool which is Castalia [102]. In order to show the accuracy of the simulation results conducted on Avrora, the simulation results of Castalia are compared to the simulation results of Avrora for these two experiments.

In the first experiment, we have conducted the experiments of speed of mobile nodes on Castalia with similar configuration and parameters that have been used in Avrora as in Table 4.1. The statistical analysis in Table 4.14 and the simulation result in Figure 4.9 compare the average percentage of packet loss of different speed of mobile nodes on Avrora and Castalia. As shown in Figure 4.9, the average percentage of packet loss for Avrora increased gradually from 51.13% to 86.84% as the speed of mobile nodes increase from speed of 2 m/s to 10 m/s. When we compare the simulation results of Avrora to Castalia, the average percentage of packet loss also increase from 86.38% to 90.36% with a slow rate as the speed of mobile nodes increase. This indicates that the pattern of simulation results on Avrora is more or less the same as compared to the pattern of simulation results on Castalia.

Speed	Average Packet Loss (%)		Standard Deviation		95% Confidence Interval	
	Avrora	Castalia	Avrora	Castalia	Avrora	Castalia
2	51.13	86.38	19.26	1.07	13.78	2.67
4	61.40	86.80	22.51	0.55	16.10	1.37
6	69.22	86.15	10.51	1.64	7.52	4.07
8	78.87	87.68	16.86	1.22	12.06	3.02
10	86.84	90.36	11.54	3.24	8.26	8.04

Table 4.14: The average percentage of packet loss and statistical analysis of different speed of mobile nodes on Avrora and Castalia

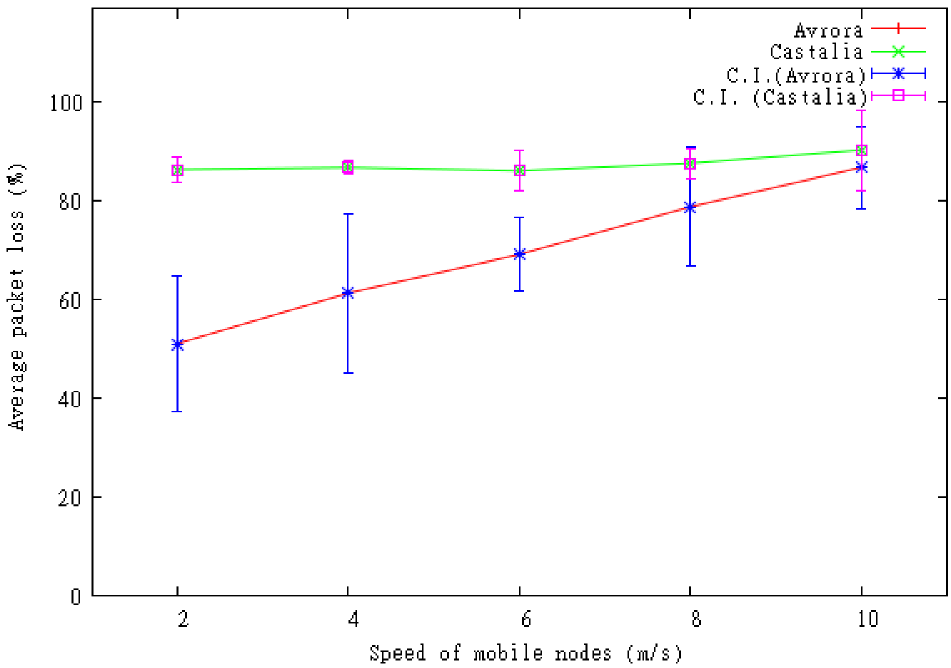

Figure 4.9: Average Percentage Packet Loss in different speed of mobile nodes for Avrora and Castalia

Density	Average Packet Loss (%)		Standard Deviation		95% Confidence Interval	
	Avrora	Castalia	Avrora	Castalia	Avrora	Castalia
2	0.03	81.47	0.05	0.13	0.03	0.32
4	33.42	85.53	13.57	3.79	9.71	9.41
6	39.54	88.72	13.74	1.20	9.83	2.98
8	48.01	88.64	16.14	1.26	11.54	3.12
10	62.64	89.09	20.48	1.89	14.65	4.70

Table 4.15: Average percentage of packet loss with different density of mobile nodes on Avrora and Castalia

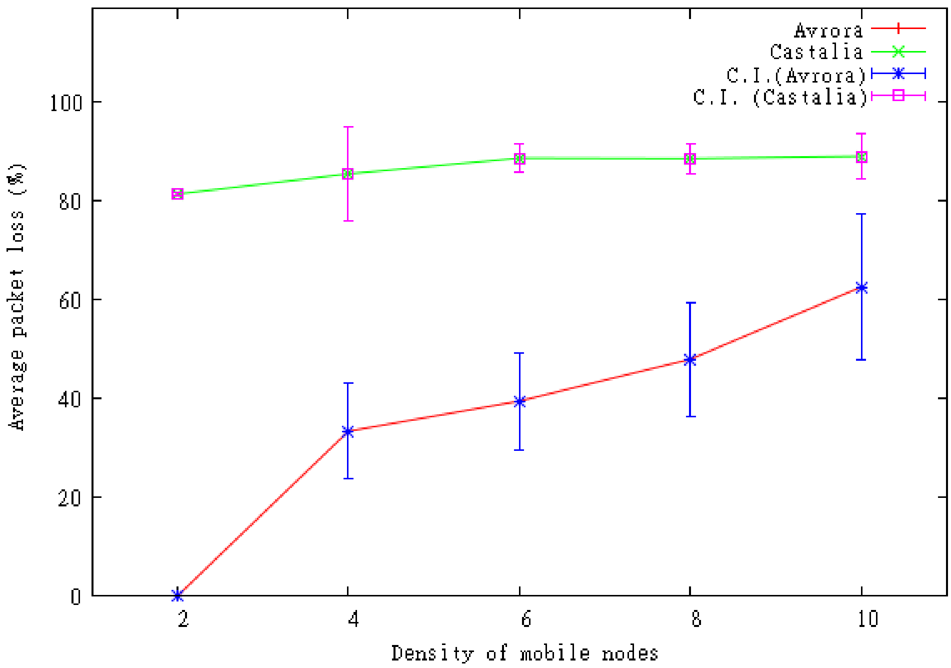

Figure 4.10: Average Percentage Packet Loss in different density of mobile nodes for Avrora and Castalia

In the second experiment, we have conducted the experiments of density of mobile nodes on Castalia with similar configuration and parameters that have been used in Avrora as in Table 4.4. The statistical analysis in Table 4.15 and the simulation result in Figure 4.10 compare the average percentage of packet loss of different density of mobile nodes on Avrora and Castalia. The average percentage of packet loss increased sharply from 0.03% to 33.42% when there are 2 to 4 mobile nodes and it increased gradually from 33.42% to 62.64% as the density of mobile nodes increase from 4 to 10 density of mobile nodes as shown in Figure 4.10. But, when we compare the simulation results of Avrora to Castalia, the average percentage of packet loss only increase slowly from 81.47% to 89.09% as the density of mobile nodes increase. This indicates that the pattern of simulation results on Avrora is almost the same as compared to the pattern of simulation results on Castalia.

Based on these simulation results, there is some differences between the simulation results of Avrora and Castalia. One of the reasons is due to the use of different programming language to implement AODV in these two simulators. In Avrora, AODV is implemented using NesC, which is based on C programming language whereas Castalia is used C++ programming language. The different implementation of AODV might have different complexity of source code, where C++ in Castalia is an object-oriented programming language and more complex in comparing to C programming language in Avrora. Another reason is the different implementation of RWP mobility model in these simulation tools. The implementation of RWP mobility model in Castalia is more complex than Avrora because it is integrated with OMNET++ mobility models. In Avrora, the implementation of RWP mobility model is within the simulator itself that make it more simple. Although, the functions of AODV routing protocol and RWP mobility model in each simulator is similar and the simulation set-up on each experiments is also the same, the different implementation of source codes and complexity of mobility model affects the simulation results on Avrora and Castalia.

However, from the simulation results the simulation pattern for both simulation tools show increasing in the average percentage of packet loss in different speed and density of mobile nodes. The simulation pattern of both simulation tools also show that speed and density of mobile nodes have a negative impact on AODV, where the higher speed and the increase number of mobile nodes in the network contribute to the higher average percentage of packet loss. With these similar pattern of simulation results on both Avrora and Castalia, we can show that the simulation results conducted on Avrora are valid and acceptable.

4.4 Summary

In this chapter, we have evaluated the performance of a AODV routing protocol in MASNETs to demonstrate the impact of mobile nodes on performance metrics of MAS-

NETs routing protocol through Avrora simulation tool. Several experiments have been conducted to evaluate AODV in terms of the average of percentage of packet loss and the average of total energy consumption with various speed, density, and RUI of mobile nodes. It can be clearly seen from the experimental results that AODV routing protocol cannot perform in MASNETs as good as in static sensor networks when there is a high topology change in MASNETs due to increase in the speed and density of mobile nodes. The reasons are that AODV does not successfully find a new route for those packets; and since broken links are not detected fast enough, the mobile nodes keep sending packets on a broken link believing that it is still working properly. AODV performance in mobile environment is not only affected by the speed and density of mobile nodes but also the length of RUI and is therefore not suitable for MASNETs. From the results of our studies, we also found out there is no direct relation between mobility and energy consumption. However, there exists indirect relation in terms of RUI where the less frequent the nodes update their routing table the less energy will be consumed with the drawback of increasing of packet loss.

From the simulation results, we can conclude that AODV protocol was not able to detect broken routes and react to topology change fast enough in mobile environment. However, in low speed and density of mobile nodes, the percentage of packet loss is still acceptable for certain application of MASNETs. In this case, we believe that there is still some room for improvement of performance of AODV in terms of minimizing packet loss and reducing energy consumption in MASNETs. In order to successfully implement AODV in a mobile environment, some sort of support from the lower layer and the use of low power technique might become a potential solution to improve the performance of AODV in MASNETs. Therefore, in the next chapter a dynamic energy-aware routing algorithm based on the controlling of transmission power is proposed to enhance the performance of MASNETs in a dynamic mobile environment.

Chapter 5

Enhancement of AODV for MASNETs

5.1 Introduction

The design and development of routing protocols in sensor networks is very challenging due to several characteristics that distinguish them from contemporary communication and wireless ad hoc networks [27]. One of the unique characteristics is that the sensor nodes in sensor networks are tightly constrained in terms of transmission power, on-board energy, processing capacity and storage. Hence, careful resource management is essential to save energy as much as possible in designing any routing protocol for this type of networks. It is even more difficult to design routing protocol in mobile ad-hoc sensor networks (MASNETs) because when some of the sensor nodes are mobile, it is not easy to detect any broken routes and react in a faster manner to topology change. The increase of mobility in sensor nodes also affects the connection to their neighbours and the routing table update as evaluated in our work in [13]. Moreover, the communication process between sensor nodes also consumes more energy related to transmitting and receiving control packets when the nodes are moving from one area to another.

Since the communication is the most energy-consuming activities in sensor networks, when designing any routing protocol for MASNETs the power use for the transmission or reception of packet should be controlled as much as possible. The adjustment of transmission power through dynamic transmission power control (TPC) protocols is one of the techniques to effectively reduce energy consumption in sensor networks [37]. In the IEEE802.15.4 MAC protocol [103], each node transmits packets at the same power level which is normally the maximum possible power level. However, if a node transmits packets at high power level, it may generate too much interference to the network and consume more energy than necessary. In the case when two node pairs are close to each other, a low transmission power is sufficient to communicate with each other. Therefore, in this research work we wanted to address how to determine an appropriate transmission power for transmitting each packet to minimize energy consumption in MASNET applications. The power level should be high enough to guarantee the transmission, but low enough to save energy in a mobile environment.

In this chapter, we study the possible enhancements and limitations of dynamic TPC on multi-hop MASNETs in the following steps. A new dynamic energy-aware routing algorithm based on Received Signal Strength Indicator (RSSI) and transmission power level provided by CC2420 radio [3] is proposed. The proposed algorithm is evaluated in terms of the average percentage of packet loss and the average total energy consumption through simulation of mobile nodes in MASNETs. Ad hoc on-demand distance vector (AODV) routing protocol is used as a medium of communication to assist the evaluation of proposed TPC technique. Lastly, the experimental results and findings from simulation of proposed technique are discussed in details.

5.2 Proposed Dynamic Energy-Aware (DEA-AODV) Routing Algorithm

The transmission energy consumption can be significantly reduced with the TPC algorithm. A good TPC algorithm for MASNETs should provide an energy-aware mechanism to support dynamic topology changes in energy-constrained networks. In order, to achieve the best performance in MASNETs, the radio transmission power needs to be set to the right level. The radio transmission power of each sensor node can be set to fixed value or it can be adjusted dynamically based on the estimated distance between nodes. In our work, we propose a dynamic energy-aware (DEA-AODV) routing algorithm that specifies the transmission power level during runtime based on RSSI values provided by CC2420 radio.

The proposed DEA-AODV algorithm attempts to reduce the percentage of packet loss and total energy consumption of multi-hop AODV in MASNETs. There are three important design goals for the proposed algorithm as follows:

- design a simple TPC algorithm that can be easily integrated into any routing protocol
- identify the optimal transmission power level effectively without the initialization phase
- adjust dynamically transmission power level over time for each node and minimize the average percentage of packet loss without additional packet overhead

We consider the transmission energy consumption based on transmission power level that is currently used by each node to transmit or forward each packet towards sink. An optimization function considers the estimated distance between nodes based on RSSI values received from neighbour nodes within communication range to decide the ideal transmission power level for transmit packets.

In the proposed algorithm, when a source node has a data packet to be sent to sink, first it looks at whether there is any existing optimal transmission power level in the routing table. If it exists, the node uses that optimal transmission power level for packet transmission. Otherwise, it broadcasts a BEACON message periodically to its neighbour nodes with the maximum transmission power level, $TxPL_{max}$. When a node (either neighbour nodes or sink within broadcast range) receives a BEACON message, it sends ECHO message as a response. When a source node receives the ECHO message, it stores the required received information from these ECHO messages in its routing table including RSSI values. The source records and calculates RSSI values corresponding to the data packet and roughly estimates the ideal transmission power level, $TxPL_{ideal}$, according to the measured RSSI.

The ideal transmission power level for each neighbour nodes will be updated periodically based on the frequency of data rate. This is very essential in MASNETs because of the frequent change in the network topology. The RSSI values and the corresponding ideal transmission power level can be easily retrieved for each packet transmission to sink. The algorithms for retrieved RSSI values, mapping RSSI values to the ideal transmission power level, and setting transmission power level based on RSSI values retrieved can be illustrated in Function 1, Function 2 and Function 3 respectively.

Function 1 Get RSSI value for node n

Node n received packet from node z
Extract RSSI value from packet z
Store extracted value of RSSI[z]

Function 2 Map RSSI values to ideal transmission power level

```
Get the node x RSSI value
if RSSI of node x greater than estDistance1 then
    TxPowerLevel = minLevelTxPower
else if RSSI of node x greater than estDistance2 then
    TxPowerLevel = 1stLevelTxPower
else if RSSI of node x greater than estDistance3 then
    TxPowerLevel = 2ndLevelTxPower
else if RSSI of node x greater than estDistance4 then
    TxPowerLevel = 3rdLevelTxPower
else
    TxPowerLevel = maxLevelTxPower
end if
```

Function 3 Set TxPower level based on RSSI values received for node n

Get current RSSI value of node n using Algorithm 1
Map current RSSI value with ideal TxPower Level using Algorithm 2
Set transmission power = TxPower Level

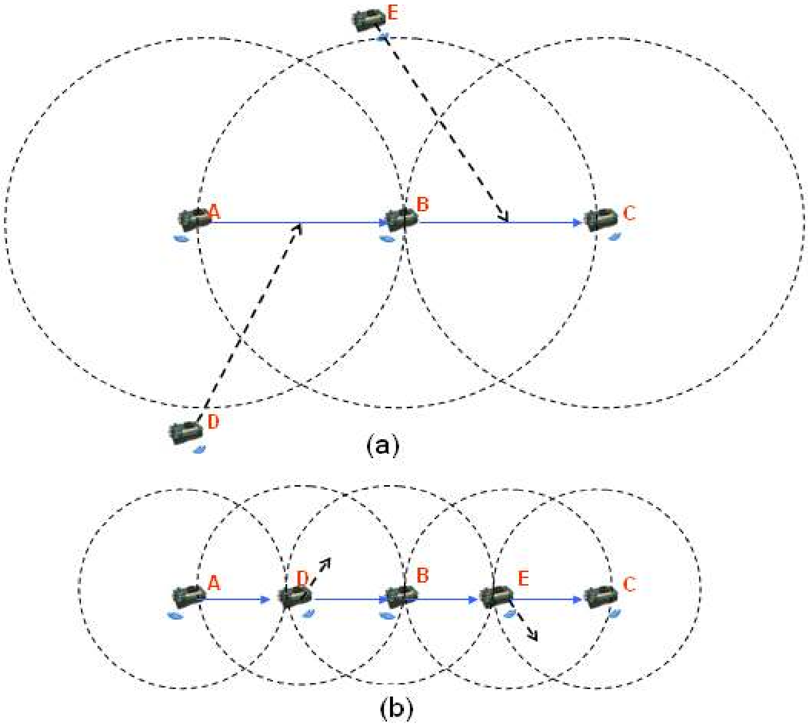

Figure 5.1: (a)2 hops communication (b)4 hops communication when mobile nodes exist

5.3 Experimental Evaluation

In this section, we present the analysis of the efficiency of proposed dynamic TPC approach implemented on AODV routing protocol for MASNET applications through a simulation. The relationship between the number of hops and transmission energy consumption and the correlation between the transmission power level and RSSI in multi-hop network are also investigated here. We give the emphasis for the evaluation of performance of AODV routing protocol for MASNETs in terms of the average percentage of packet loss and the average total energy consumption as in previous chapter. All of the experiments are performed using the selected Avrora network simulation tool as validated in section 4.3 and justified in the comprehensive simulation study conducted in Chapter 3.

5.3.1 Relationship between Number of Hops and Transmission Energy Consumption

In this subsection, the relationship between the number of hops and transmission energy consumption in multi-hop AODV routing protocol is investigated through simulation. The implementation of AODV routing protocol for these experiments are coded in NesC (Networked embedded system C) programming language. In our experiments, we simulated five MICAZ motes with Avrora where one as static source node, one as static intermediate node, one as static sink node and another two as mobile nodes as shown in Figure 5.1. In part (a) of Figure 5.1, the source node (node A) transmitted around 300 packets within 300 seconds of simulation time. The intermediate node (node B) then forwarded the packets received from the source node to the sink node (node C). At this stage, the two mobiles nodes (node D and node E) were not within the communication range of other static nodes. Therefore, the node A required maximum transmission power level (Ie. 31) in order to reach node B, which also used maximum power level of 31 to forward the received packets from node A to the sink node. But, as mobile nodes within the range of static nodes as shown in part (b) of Figure 5.1, the transmission power level for every nodes can be adjusted to as minimum as possible (Ie. 15) when forwarding the packets from source node to sink nodes within 4 hops of communication.

The energy consumed by source node within multi-hop communication of different number of hops is recorded while increasing the number of nodes involved to route the packets from source node to sink node. The transmission energy consumption of source node can be defined as follows:

- *Transmission energy consumption*: This metric is an amount of energy consumed by source nodes in the network through radio communication. Hence, the transmission energy consumption, given as P_E, can be calculated by adding all energy consumed only by source nodes (transmitter), n, throughout the simulation time. The equation for total energy consumption is written as below where this equation totals up the energy consumed in all source nodes when they transmit data packets, as given below:

$$P_E = \sum_{i=1}^{n} E_{Tx}^{i} \tag{5.1}$$

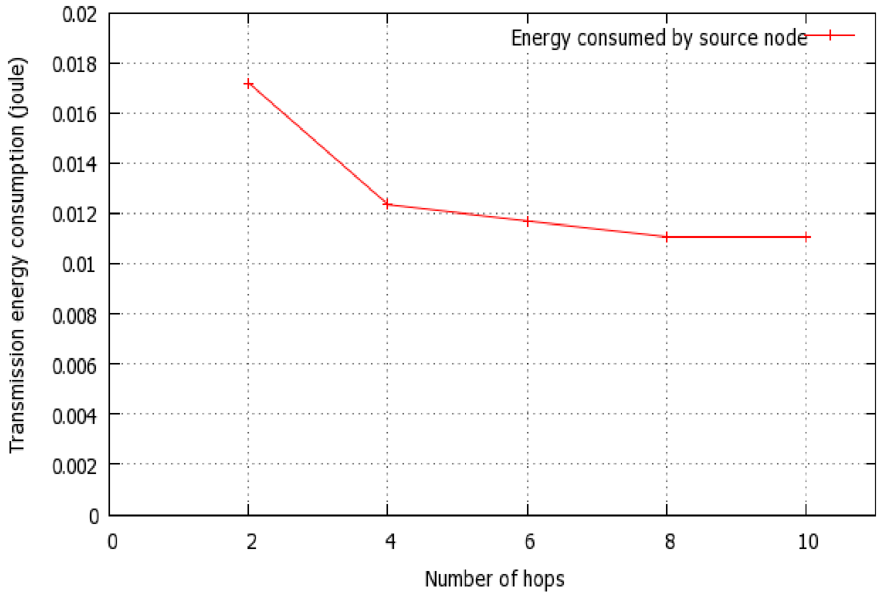

Figure 5.2: Transmission energy consumption by source node with different number of hops

Number of hops	Transmission energy consumption (joule)
2	0.017198848
4	0.012355494
6	0.011701345
8	0.011054663
10	0.011054663

Table 5.1: Transmission energy consumption with different number of hops

As expected, the transmission energy consumed by source node is reduced as the number of hops increased especially from 2 hops to 4 hops as shown in Figure 5.2 and Table 5.1. This is because of change in transmission power levels and distance between nodes when there is an intermediate node within a range that can forward the packets towards the sink node. As can be seen in Figure 5.3, after 8 hops there appears to be a gradual decline in the transmission energy consumption. Therefore, the total number of hops should be in range of 4 and 8 where the most transmission energy consumption can be reduced within the communication of multi-hop communication in AODV.

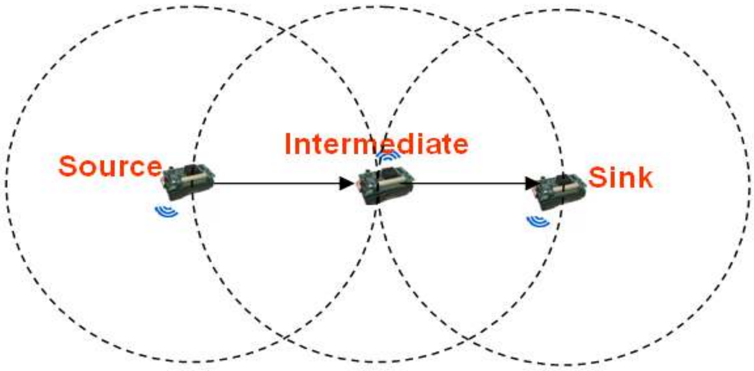

Figure 5.3: Multi-hop communication between source, intermediate and sink nodes

5.3.2 Correlation between Transmission Power Level and RSSI

This subsection outlines the simulation experiments conducted to investigate the correlation between the transmission power level and link qualities based on RSSI in multi-hop AODV routing under MICAZ platform. We simulated three MICAZ sensor nodes in our experiments where one is simulated as the source node, one as the intermediate node and the last one as the sink node as shown in Figure 5.3. The source node sent out 100 packets at each transmission power level. The intermediate node forwarded the packets received from the source node to the sink node, which recorded the RSSI values and the number of packets received at each transmission power level. The distance between these nodes we varied from 2 to 16 meters.

Figure 5.4 and Table 5.2 show our experimental data obtained from three sensor nodes in static environment. Each curve demonstrated the correlation between the transmission power level and RSSI at different distance of that pair of nodes. It is clearly shown that there is an approximate linear and strong relationship between transmission power level and RSSI. Moreover, this result shows that the TPC can be adapted to MICAZ platform. Thus, it can be reasoned out that when the transmitted power level is known, the appropriate transmission power level can be roughly estimated based on the RSSI. From the results of the experiment, it can be seen that although the RSSI with specified transmission power and distance varies in a very small range, we still be able to identify the ideal transmission power level that the source node should use to send packets toward sink in order to preserve energy as much as possible.

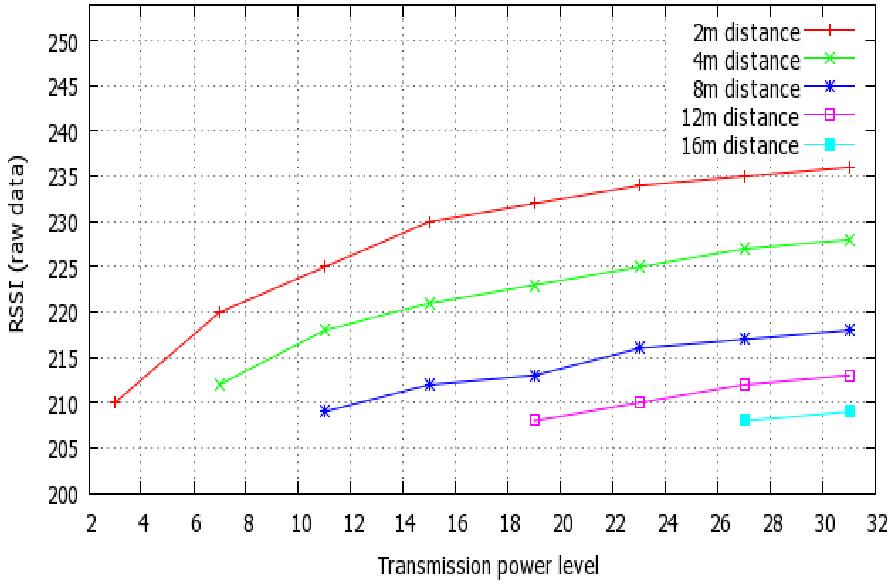

Figure 5.4: Transmission power level versus RSSI at different distance

Transmission Power Level	RSSI (raw data)				
	2 m	4 m	8 m	12 m	16 m
3	210	x	x	x	x
7	220	212	x	x	x
11	225	218	209	x	x
15	230	221	212	x	x
19	232	223	213	208	x
23	234	225	216	210	x
27	235	227	217	212	208
31	236	228	218	213	209

Table 5.2: RSSI raw data at different transmission power level and distance

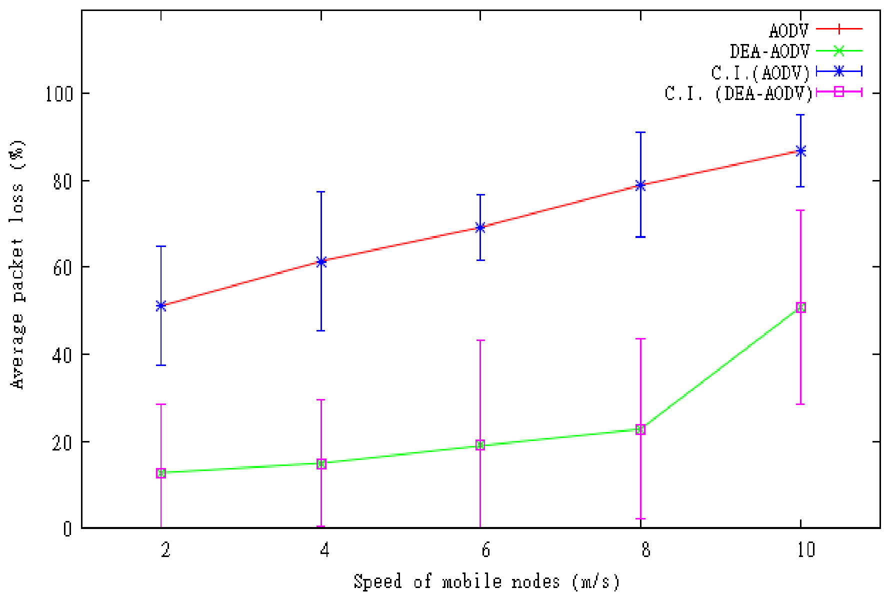

Figure 5.5: The average percentage of packet loss caused by the increasing speed of mobile nodes for DEA-AODV and AODV

5.3.3 Effect of mobile node speed on the performance of DEA-AODV

The objective of this experiment is to study the effect of different mobile nodes' speed on the proposed DEA-AODV performance. Therefore, we have conducted the experiments of speed of mobile nodes on Avrora with similar configuration set-up as in Figure 4.1 and simulation parameters as in Table 4.1 with transmission power level of 31. We chose this value since it is the highest transmission power of the CC2420 radio, and thus must yield the best communication in terms of link quality and number of packet delivered. Then, we compare the experimental results of the proposed DEA-AODV with the basic AODV that presented in subsection 4.2.3.

The simulation result in Figure 5.5 and the statistical analysis in Table 5.3 compare the average percentage of packet loss caused by different speed of mobile nodes of AODV with DEA-AODV. As shown in Figure 5.5, the average percentage of packet loss of both DEA-AODV and AODV increase significantly as the speed of mobile nodes increase, from speed of 2 m/s to 10 m/s. But, the average percentage of packet loss of DEA-AODV is much more lower than AODV with the different of 36% to 56%. This indicates that the proposed DEA-AODV can perform better than the basic AODV in terms of the average percentage of packet loss when the speed of mobile nodes increase.

Speed	Average Packet Loss (%)		Standard Deviation		95% Confidence Interval	
	AODV	DEA-AODV	AODV	DEA-AODV	AODV	DEA-AODV
2	51.13	12.81	19.26	22.08	13.78	15.80
4	61.40	15.00	22.51	20.24	16.10	14.48
6	69.22	19.00	10.51	34.14	7.52	24.42
8	78.87	22.83	16.86	28.83	12.06	20.62
10	86.84	50.83	11.54	31.04	8.26	22.21

Table 5.3: The average percentage of packet loss and statistical analysis with different speed of mobile nodes for DEA-AODV and AODV

5.3.4 Effect of mobile node density on the performance of DEA-AODV

The objective of this experiment is to study the effect of different mobile nodes' density on the proposed DEA-AODV performance. Therefore, we have conducted the density of mobile nodes experiment on Avrora with similar configuration set-up as in Figure 4.1 and simulation parameters as in Table 4.4 with transmission power level of 31. Then, we compare the experimental results of the proposed DEA-AODV with the basic AODV that presented in subsection 4.2.4.

The simulation result in Figure 5.6 and the statistical analysis in Table 5.4 compare the average percentage of packet loss caused by different density of mobile nodes of AODV with DEA-AODV. The average percentage of packet loss of both DEA-AODV and AODV increase gradually as the number of mobile nodes in the network increase, from density of 2 mobile nodes to 10 mobile nodes (Figure 5.6). But, the average percentage of packet loss of DEA-AODV is lower than AODV when the density of mobile nodes increase from 4 mobile nodes to 10 mobile nodes in the network with the different of 30% to 48%. This indicates that the proposed DEA-AODV can minimize the effects of mobility in terms of the average percentage of packet loss when the density of mobile nodes increase. This is because the broken links can be minimized through the integration of TPC approach on DEA-AODV which can control the use of ideal transmission power to transmit packet but at the same time ensure the power level use is good enough to sustain the communication link.

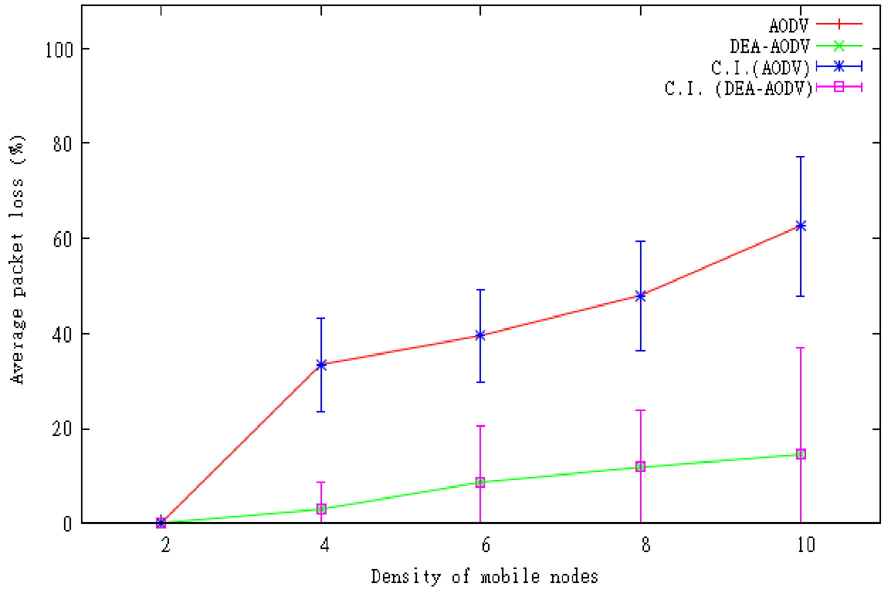

Figure 5.6: The average percentage of packet loss caused by the increasing density of mobile node for DEA-AODV and AODV

Density	Average Packet Loss (%)		Standard Deviation		95% Confidence Interval	
	AODV	DEA-AODV	AODV	DEA-AODV	AODV	DEA-AODV
2	0.03	0.06	0.05	0.20	0.03	0.14
4	33.42	3.00	13.74	7.89	9.83	5.64
6	39.54	8.67	13.57	16.42	9.71	11.75
8	48.01	11.83	16.14	16.81	11.54	12.03
10	62.64	14.50	20.48	31.49	14.65	22.52

Table 5.4: The average percentage of packet loss and statistical analysis with different density of mobile nodes for DEA-AODV and AODV

RUI	Average Packet Loss (%)		Standard Deviation		95% Confidence Interval	
	AODV	DEA-AODV	AODV	DEA-AODV	AODV	DEA-AODV
10	52.19	18.93	20.63	24.27	14.76	17.36
20	55.05	22.33	27.73	33.70	19.83	24.11
30	59.71	25.83	17.75	35.24	12.70	25.21
40	61.81	33.67	16.83	34.98	12.04	25.02
50	69.14	38.33	24.10	33.61	17.24	24.04
60	71.36	39.17	25.40	40.45	18.17	28.94

Table 5.5: The average percentage of packet loss and statistical analysis with different RUI for AODV and DEA-AODV

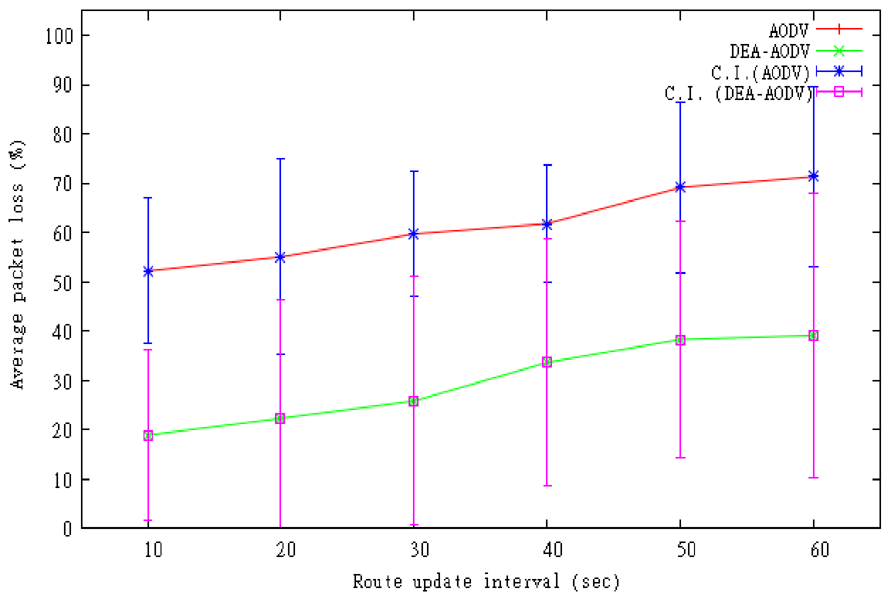

Figure 5.7: The average percentage of packet loss versus RUI for AODV and DEA-AODV

5.3.5 Effect of route update interval on the performance of DEA-AODV

The objective of this experiment is to study the effect of different route update interval (RUI) on the proposed DEA-AODV performance. Therefore, we have conducted the RUI experiment on Avrora with similar configuration set-up as in Figure 4.1 and simulation parameters as in Table 4.7 with transmission power level of 31. Then, we compare the experimental results of the proposed DEA-AODV with the basic AODV that presented in subsection 4.2.5.

The statistical analysis in Table 5.5 and the simulation result in Figure 5.7 compare the average percentage of packet loss caused by different values of RUI of AODV with DEA-AODV. The average percentage of packet loss of both DEA-AODV and AODV increase gradually as the RUI increase, from 10 seconds to 60 seconds as shown in Figure 5.7. But, the average percentage of packet loss of DEA-AODV is much more lower than AODV with the average different of 32%. This indicates that the proposed DEA-AODV can minimize the effects of mobility in terms of the average percentage of packet loss when the frequency of route update may need to be compromised to conserve energy.

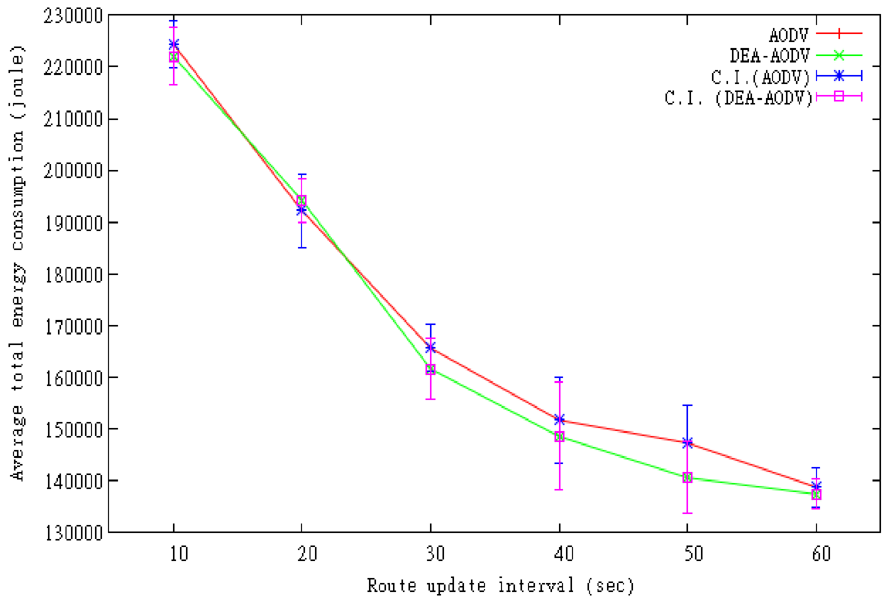

Figure 5.8: The average total energy consumption with different RUI for AODV and DEA-AODV

RUI	Avg. T. Energy Consumption		Standard Deviation		95% Confidence Interval	
	AODV	DEA-AODV	AODV	DEA-AODV	AODV	DEA-AODV
10	224379.76	222044.43	6367.84	7783.33	4555.28	5567.86
20	192213.56	194197.40	10047.75	6020.95	7187.72	4307.13
30	165652.21	161652.46	6336.23	8085.41	4532.66	5783.95
40	151719.58	148567.31	11625.49	14589.26	8316.38	10436.53
50	147293.55	140589.86	10345.67	9682.36	7400.84	6926.34
60	138782.46	137421.58	5303.41	4097.63	3793.83	2931.27

Table 5.6: The average total energy consumption and statistical analysis with different RUI for AODV and DEA-AODV

Average Total Energy Consumed		Average Packet Loss (%)	
AODV	DEA-AODV	AODV	DEA-AODV
138782	137422	71.36	39.17
147294	140590	69.14	38.33
151720	148567	61.81	33.67
165652	161652	59.71	25.83
192214	194197	55.05	22.33
224380	222044	52.19	18.93

Table 5.7: The average total energy consumed versus the average packet loss for AODV and DEA-AODV

The simulation result in Figure 5.8 and the statistical analysis in Table 5.6 compare the average total energy consumption caused by different values of RUI of AODV with DEA-AODV. In Figure 5.8, the average total energy consumption of both DEA-AODV and AODV decrease sharply as the RUI increase, from 10 seconds to 60 seconds. But, the average total energy consumption of DEA-AODV is less than AODV when the RUI increase from 30 seconds to 60 seconds with the different of 1361 joule to 6704 joule of energy. This indicates that the proposed DEA-AODV can save more energy when the frequency of route update may need to be compromised to conserve energy in a mobile environment.

Furthermore, when we analyse the experimental results of the average percentage of packet loss and the average total energy consumption in relation to the effects of RUI, we found that there is indirect relation between these two performance metrics of AODV and DEA-AODV. As shown in Table 5.7 and Figure 5.9, the average percentage of packet loss of both DEA-AODV and AODV decrease gradually as the average total energy consumption decrease. But, the average percentage of packet loss of DEA-AODV is much more lower than AODV with the average different of 2595 joule of energy. This show that when more energy is consumed by nodes for updating their routing tables, the less percentage of packet will be lost. On the other hand, when less energy is consumed for route update, the average percentage of packet loss will be higher. This is because of the next route to sink is unreliable when there is a low frequency of route update. These experimental results also indicate that the performance of DEA-AODV is better than AODV with lower average percentage of packet loss and less average total energy consumption.

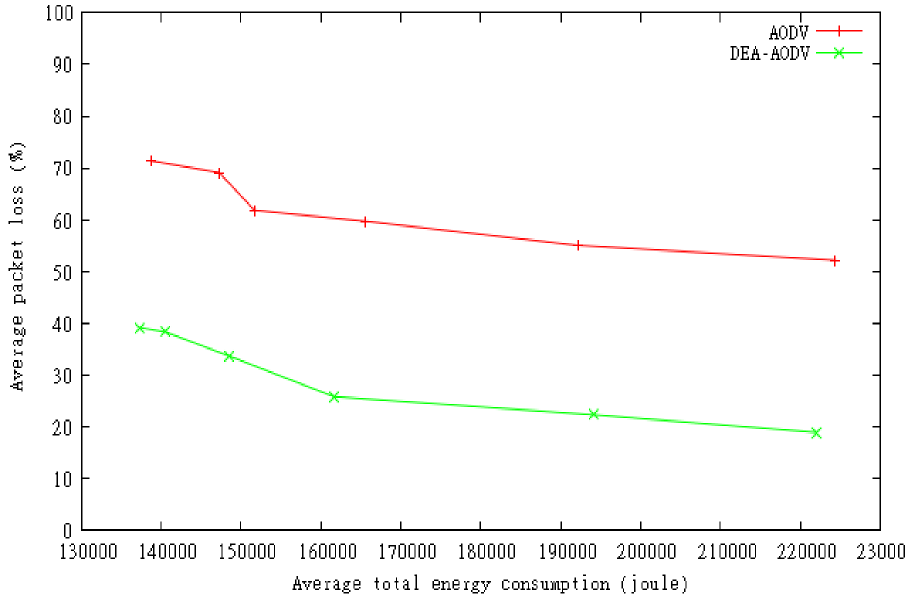

Figure 5.9: The average total energy consumption versus the average packet loss versus for AODV and DEA-AODV

5.4 Summary

We experimentally investigated the effectiveness of TPC integration on AODV routing algorithm in MASNETs. We have proposed DEA-AODV to enhance the performance of AODV. Our enhancement is based on TPC approach that is able to control transmission power level based on the estimated distance. Our approach utilise the existing RSSI provided by CC2420 radio to estimate the distance between nodes in mobile environment. The experimental results show a significant advantage of the proposed DEA-AODV over the basic AODV with respect to the average total energy consumption and the average percentage of packet loss. The proposed DEA-AODV manage to reduce average total energy consumption and decreased the average percentage of packet loss compared to the basic AODV algorithm in MASNETs. DEA-AODV also able to minimize the effects of mobility in terms of the average percentage of packet loss when the speed and density of mobile nodes increase. This is because DEA-AODV can control the use of ideal transmission power to transmit packet and at the same time ensure the power level use is good enough to sustain the communication link. These significant results from the implementation of DEA-AODV in AODV showed that the integration of TPC approach can enhance the performance of AODV in MASNETs.

Chapter 6

Conclusion and Future Work

As stated in Chapter 1, this research work aimed to reduce energy consumption of Mobile Ad-hoc Sensor Networks (MASNETs) as much as possible in mobile environment. In this final chapter, we will conclude by describing the progress made towards this aim in terms of our main contributions to the thesis. We will also suggest some future research directions that could provide the next steps for future studies.

6.1 Summary of Contributions

In this thesis, the focus is on the enhancement of Ad-hoc On-demand Distance Vector (AODV) to reduce energy consumption in MASNETs. The DEA-AODV routing algorithm, a dynamic energy-aware routing algorithm based on transmission power control (TPC) approach is proposed to ensure AODV can perform better in mobile environment. In the proposed routing algorithm, the changing in transmission power is done dynamically in a real time which is based on the estimation of the distance between sensor nodes through the computation of Received Signal Strength Indicator (RSSI) values. The thesis has made two main important contributions as follows:

- In Chapter 4, we have evaluated the performance of AODV routing protocol under various MASNETs' scenarios on different performance metrics including the percentage of packet loss and total energy consumption. We have demonstrated through extensive simulation experiments that the AODV performance in mobile environment is not only affected by the speed and density of mobile nodes but also the length of RUI. We conclude that AODV cannot perform very well in

MASNETs because the protocol is not be able to detect broken routes and react to topology change fast enough in mobile environment.

- In Chapter 5, we have investigated the effectiveness of transmission power control (TPC) for MASNETs in order to enhance the performance of AODV routing protocol in mobile environment. Moreover, we have proposed the DEA-AODV routing algorithm based on TPC and link qualities for controlling transmission power that can reduce energy consumption. Simulation experiments with mobile nodes in mobile environment show that the proposed DEA-AODV routing algorithm can minimize total energy consumption and reduce the average percentage of packet loss better than the existing AODV in MASNETs.

6.2 Future Work

The research work presented in this thesis provides a basis for a number of potential related future works as follows:

- **Hierarchical clustering network**: In this thesis, we only consider the flat network of sensor nodes where each sensor node plays the same role and collaborate together to perform the sensing task. The idea of the proposed energy-aware routing algorithm could be expanded to cover a wider range of MASNETs by considering a hierarchical clustering network for the sensor nodes. In this clustering network, the routing is usually divided in two stages: select cluster heads and routing. By randomized rotation of cluster heads, the energy load can be distributed evenly over sensor nodes. The implementation of the proposed DEA-AODV algorithm in this network can be used to reduce the energy consumption in cluster-head selection and clustered-based routing processes.

- **Deployment in real application**: One of the possible directions for future research would be to implement the proposed routing algorithm on a real practical MASNETs application such as animal monitoring application in order to evaluate the performance and, more importantly, validate the results obtained via the simulation approach. Clearly such an approach would be costly since a hardware-based experiment would need to be set up and tested under laboratory conditions before it can be deployed in the real world. It would also be interesting to use different wireless sensor node platforms such as MICAZ, TelosB, IRIS, Cricket and Lotus in order to see if the resulting algorithms yield further performance enhancement.

- **Cross-layer design**: There could be an investigation to integrate cross-layer design into the proposed DEA-AODV algorithm for MASNETs. For instance, we can let the mobile sink piggybacks its position and energy usage information in AODV control packets, in order for the devices choose more energy-efficient path. It is also necessary to have some sort of feedback from data link layer protocol like IEEE 802.15.4 to improve the discovery process of the neighbours. The integration of cross-layer design in the proposed DEA-AODV algorithm will surely enable MASNETs to support different services required by different applications with minimal energy consumption.

- **Link Quality**: Most of the modifications in this thesis are based on the quality of the link, therefore any improvement for a high quality link with minimum interference will improve all data transmissions and receptions within MASNETs. It is also possible to use another link metric such as Link Quality Estimator (LQI) as the input to the proposed DEA-AODV routing algorithm. The combination of both metrics, RSSI and LQI might provide a more accurate estimated distance between nodes to improve the performance of MASNETs. Further evaluation of the link quality can be investigated in relation to sensor node's speed and density before applying mobility to sensors.

6.3 Summary

In summary, we have proposed DEA-AODV routing algorithm, which is a dynamic energy-aware routing algorithm to support mobility in MASNETs. The simulation results have indicated that the proposed routing algorithm can enhance the performance of MASNETs because it has achieved a significant performance benefits in respect to the average energy consumption and the average percentage of packet loss. Finally, this research work has indicated that the integration of TPC approach on AODV is very critical for the successful implementation of AODV in mobile environment. This thesis has made contributions in making routing protocols in MASNETs energy-aware by reducing energy consumption through the effective implementation of TPC approach in MASNETs.

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