Energy-aware routing protocols in wireless sensor networks

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by

Hesham Abusaimeh

A Doctoral Thesis

Submitted in partial fulfilment
of the requirements for the award of

Doctor of Philosophy

of

Loughborough University

May 2009

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First and foremost, my deepest gratefulness goes to GOD for all his blessings without which none of my work could have been possible. I would like to express my sincere thanks to my supervisor Professor Shuang-Hua Yang for his time and effort in supervising and guiding this research using all his experience and knowledge. I would like to acknowledge my director of research Dr. Chris Hinde for his guidance. I would also like to thank Loughborough University for the facilities provided to me throughout this research, which have helped me accomplish my achievements. I would definitely acknowledge my sponsor Applied Science University in the Hashemite Kingdom of Jordan for funding my study and living expenses in the UK during my PhD years.

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Thank you all.
Abstract

Saving energy and increasing network lifetime are significant challenges in the field of Wireless Sensor Networks (WSNs). Energy-aware routing protocols have been introduced for WSNs to overcome limitations of WSN including limited power resources and difficulties renewing or recharging sensor nodes batteries. Furthermore, the potentially inhospitable environments of sensor locations, in some applications, such as the bottom of the ocean, or inside tornados also have to be considered. ZigBee is one of the latest communication standards designed for WSNs based on the IEEE 802.15.4 standard. The ZigBee standard supports two routing protocols, the Ad hoc On-demand Distance Vector (AODV), and the cluster-tree routing protocols. These protocols are implemented to establish the network, form clusters, and transfer data between the nodes. The AODV and the cluster-tree routing protocols are two of the most efficient routing protocols in terms of reducing the control message overhead, reducing the bandwidth usage in the network, and reducing the power consumption of wireless sensor nodes compared to other routing protocols. However, neither of these protocols considers the energy level or the energy consumption rate of the wireless sensor nodes during the establishment or routing processes.
This thesis aims to develop a methodology for WSN routing protocols to consider the energy level of sensor nodes through the establishment and routing processes in order to increase the network lifetime and reduce the energy consumption rate of wireless sensor nodes. The contribution of this thesis consists of five parts. Firstly, it develops a novel approach to distribute the responsibility of data routing among most of the wireless sensor nodes in Flat and Hierarchical WSNs. Secondly, another new approach to reduce the transmission and the reception powers is developed to balance the power consumption of nodes. Thirdly, we propose a dynamic mechanism to distribute the role of the cluster-head among some of the nodes in the same cluster in order to distribute the power consumption and increase the WSN lifetime. Fourthly, a new technique is proposed to consider the energy level of the WSN in dividing the network into clusters and choosing the highest energy nodes to be the cluster-heads. Finally, we develop a method for discovering the optimum communication routes based on the energy level of the intermediate sensor nodes, on the route between a source node and a destination node, in a WSN. All the aforementioned approaches contribute in increasing the lifetime of the WSN, and distributing the power consumption among the wireless sensor nodes.

We demonstrate the proposed techniques through simulations accomplished using NS-2 simulator. All the simulation results have verified the remarkable improvement of performance in term of reducing the power consumption rate and increasing the lifetime of the WSN compared with the original AODV and cluster-tree routing protocols.

Publications

Journals' Publications


Conferences’ Publications


* This paper won the best paper prize in the conference
# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ACK</td>
<td>Acknowledgment Packet</td>
</tr>
<tr>
<td>ACQUIRE</td>
<td>Active Query forwarding in the WSNs</td>
</tr>
<tr>
<td>ADC</td>
<td>Analogue to Digital Converter</td>
</tr>
<tr>
<td>ADV</td>
<td>Advertising Packet in SPIN</td>
</tr>
<tr>
<td>AODV</td>
<td>Add hoc On-demand Distance Vector</td>
</tr>
<tr>
<td>APTEEN</td>
<td>Adaptive Threshold sensitive Energy Efficient sensor Network</td>
</tr>
<tr>
<td>CBR</td>
<td>Constant Bit Rate</td>
</tr>
<tr>
<td>CCA</td>
<td>Clear Channel Assessment</td>
</tr>
<tr>
<td>CH</td>
<td>Cluster-Head</td>
</tr>
<tr>
<td>CID</td>
<td>Cluster ID</td>
</tr>
<tr>
<td>CSMA-CA</td>
<td>Carrier Sense Multiple Access with Collision Avoidance</td>
</tr>
<tr>
<td>DD</td>
<td>Designated Device</td>
</tr>
<tr>
<td>ED</td>
<td>Energy Detection</td>
</tr>
<tr>
<td>EMV</td>
<td>Energy Mean Value</td>
</tr>
<tr>
<td>FFD</td>
<td>Full-Function Device</td>
</tr>
<tr>
<td>GAF</td>
<td>Geographic Adaptive Fidelity</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>GEAR</td>
<td>Geographic and Energy-Aware</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GTS</td>
<td>Guaranteed Time Slot</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IOS</td>
<td>International Organisation for Standardisation</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>LEACH</td>
<td>Low Energy Adaptive Clustering Hierarchy</td>
</tr>
<tr>
<td>LLC</td>
<td>Logical Link Control</td>
</tr>
<tr>
<td>LML</td>
<td>Local Markov Loops</td>
</tr>
<tr>
<td>LNCA</td>
<td>Local Negotiated Clustering Algorithm</td>
</tr>
<tr>
<td>LQI</td>
<td>Link Quality Indication</td>
</tr>
<tr>
<td>LR-WPAN</td>
<td>Low Rate-Wireless Personal Area Network</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MAN</td>
<td>Metropolitan Area Network</td>
</tr>
<tr>
<td>MLDE</td>
<td>MAC Layer Data Entity</td>
</tr>
<tr>
<td>MWE</td>
<td>Multiple Winner Algorithm</td>
</tr>
<tr>
<td>NLDE</td>
<td>Network Layer Data Entity</td>
</tr>
<tr>
<td>NLME</td>
<td>Network Layer Management Entity</td>
</tr>
<tr>
<td>NS-2</td>
<td>Network Simulator-2</td>
</tr>
<tr>
<td>OSI</td>
<td>Open Systems Interconnection</td>
</tr>
<tr>
<td>PAN</td>
<td>Personal Area Network</td>
</tr>
<tr>
<td>PDA</td>
<td>Personal Digital Assistants</td>
</tr>
<tr>
<td>PEGASIS</td>
<td>Power Efficient Gathering in Sensor Information Systems</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical Layer</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>REQ</td>
<td>Requesting the data Packet in SPIN</td>
</tr>
<tr>
<td>RERR</td>
<td>Route Error Packet</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>RFD</td>
<td>Reduce-Function Device</td>
</tr>
<tr>
<td>RREP</td>
<td>Route Reply Packet</td>
</tr>
<tr>
<td>RREQ</td>
<td>Route Request Packet</td>
</tr>
<tr>
<td>SAP</td>
<td>Service Access Point</td>
</tr>
<tr>
<td>SAR</td>
<td>Sequential Assignment Routing</td>
</tr>
<tr>
<td>SPIN</td>
<td>Sensor Protocol for Information via Negotiation</td>
</tr>
<tr>
<td>SWE</td>
<td>Single Winner Algorithm</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TEEN</td>
<td>Threshold sensitive Energy Efficient sensor Network</td>
</tr>
<tr>
<td>WAN</td>
<td>Wide Area Network</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>WN</td>
<td>Wireless Network</td>
</tr>
<tr>
<td>WPAN</td>
<td>Wireless Personal Area Network</td>
</tr>
<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
</tr>
</tbody>
</table>
List of Symbols

AODVeng : The new AODV with the Energy efficient discovery process
AODVeng+dist: The hybrid AODV with the Energy efficient discovery process and the technique of distributing the role of routing among the nodes
CN : The number of clusters
ConsRate : The rate of the energy consumption for the node
d : The transmission distance
EstRouteCost : The energy cost of establishing route
FullEng : The full energy of the WSN
G : The number of nodes that did not act as cluster-head
Gr : The antenna gain for the receiver
Gt : The antenna gain for the transmitter
H : The number of hops from the source to this node
HopsNo : The number of hops between the source and the destination
hr : The height of the receiver antenna
ht : The height of the transmitter antenna
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>InitEng</td>
<td>The initial energy level of the node</td>
</tr>
<tr>
<td>L</td>
<td>The system loss</td>
</tr>
<tr>
<td>LifeTime</td>
<td>The period of time for which the node can be kept running before dying or stopping transmitting and receiving signals</td>
</tr>
<tr>
<td>LN</td>
<td>A set including all the leaf nodes in the cluster</td>
</tr>
<tr>
<td>MaxCons</td>
<td>The maximum energy consumption</td>
</tr>
<tr>
<td>MinCons</td>
<td>The Minimum energy consumption</td>
</tr>
<tr>
<td>NewCN</td>
<td>the new number of clusters</td>
</tr>
<tr>
<td>NN</td>
<td>The number of the neighbour nodes</td>
</tr>
<tr>
<td>Node_Eng</td>
<td>The energy of the node</td>
</tr>
<tr>
<td>NoHops</td>
<td>The number of hops between the furthest node in the network and the coordinator</td>
</tr>
<tr>
<td>P</td>
<td>A group of nodes choose themselves to act as cluster-heads</td>
</tr>
<tr>
<td>Pf</td>
<td>The full power</td>
</tr>
<tr>
<td>PktNo</td>
<td>The Number of packets transferred</td>
</tr>
<tr>
<td>PktR</td>
<td>The number of packets received by the node</td>
</tr>
<tr>
<td>PktT</td>
<td>The number of packets transmitted by the node</td>
</tr>
<tr>
<td>Pr</td>
<td>The reception power</td>
</tr>
<tr>
<td>Pres</td>
<td>The residual power</td>
</tr>
<tr>
<td>PrInit</td>
<td>The initial reception power</td>
</tr>
<tr>
<td>Pt</td>
<td>The transmission power</td>
</tr>
<tr>
<td>PtInit</td>
<td>The initial transmission power</td>
</tr>
<tr>
<td>r</td>
<td>Random number between 0 and 1</td>
</tr>
<tr>
<td>RemainTime</td>
<td>The period left for a node to keep running and serving the route</td>
</tr>
<tr>
<td>RemEng</td>
<td>The Current (Remaining) energy level of the node</td>
</tr>
</tbody>
</table>
RemEngRatio : The ratio of the remaining energy of the node
REng : The energy consumed by receiving one packet
RoutEng : The Route Energy which is the energy of the nodes on that route
rxPower : the reception power of each packet
rxTime : The time required to receive each packet
T (n) : Threshold Value of the node (n)
TEng : The transmission energy required to transmit each packet
TimePeriod : The period of time that the node takes to consume the energy
txPower : The transmission power of each packet
txTime : The time required to transmit each packet
W : The weight of the node to be a cluster-head
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Table 6-1 Simulation Parameters Values

Table 7-1 Simulation Parameters

Table 8-1 Simulation Parameters

Table 9-1 Simulation Parameters
Chapter 1
Introduction

1.1 Wireless Sensor Network Background

Nowadays, organisations use networks in their work to be able distribute and share information throughout the entire company. Networks make all programs, equipment, and especially data available to anyone on the network, regardless of the physical location of the resources and the users. Computer networks are divided into many types such as LAN (Local Area Network), MAN (Metropolitan Area Network), WAN (Wide Area Network), and WN (Wireless Network). LANs are used to connect computers in one building or number of buildings in a small area. While the network that connects computers inside a city or town is called MAN. A WAN connects many numbers of computers in a large area such as country or continent. The last type, WN, connects any devices or computers using radio waves, infrared, or any other wireless media. It can cover a large area, in which case it will be called Wireless WAN. Alternatively, it can cover a small area or a building, in which case it will be called a Wireless LAN. Alternatively, it can connect the components of a computer, in which case it will be called a system interconnection (Tanenbaum, 2003).

Wireless local area networks (WLANs) are becoming more widely distributed among companies, organizations, and individuals. Airports, hotels, and
shopping centres around the world are offering WLAN service for their customers and visitors (Eren, 2006). Transferring data between a sender and a receiver via radio or microwave signals is known as wireless communication (Shorey et al., 2006).

Technological developments such as mobile devices and notebook computers has led to the need to keep these devices connected to the internet or exchange information with each other without being limited by the devices' physical locations. Wireless networks were introduced to allow mobile devices or notebook computers to be connected to any required network, regardless of their geographic location. Wireless technologies have many forms of devices, standards, and protocols, starting from notebook computers, personal digital assistants (PDAs), mobile devices, ending with very small devices called wireless sensors. Although, wireless technologies are very popular now, the wireless market still lacks many support technologies such as communications standard and routing protocols (Shorey et al., 2006).

### 1.2 Wireless Sensor Network

![Figure 1-1 Wireless Sensor Network](image)

Advance research and development in wireless technology and digital electronic devices has led to the creation of low-cost, low power, multifunctional, small, and with limited communication distance, devices called wireless sensors (Akyildiz et al., 2002). Large number of sensing nodes, which have the ability to
communicate wirelessly and limited computation form what are called Wireless Sensor Networks (WSNs) (Romer et al., 2002). The WSN can be connected to a base station or any other type of network device through a gateway device as shown in Figure 1-1. Specific functionality can be obtained through cooperation between these nodes; functions such as sensing, tracking, monitoring, and alerting (Shorey et al., 2006). These functions make these wireless sensors very useful for monitoring natural phenomena, environmental changes, controlling security, estimating traffic flows, monitoring military applications, and tracking friendly forces in the battlefields (Romer et al., 2002).

Wireless sensor nodes contain a battery as a power source, a memory unit, transceiver unit, and computational unit. These components allow the wireless sensor nodes to have the facility to send and receive signals. Wireless sensors are made from materials such as metals, polymers and plastics, ceramics and glass, biological materials, semiconductors, and mixtures between two or more of these materials (Eren, 2006). They can execute many functions based on their types.

1.2.1 Types of Wireless Sensors

There are many types of wireless sensors depending on the type of sensing. There are sensors for sensing (Lewis, 2004), (Akyildiz et al., 2002):

- Temperature
- Humidity
- Acoustic waves
- Vehicular movement
- Lighting condition
- Pressure
- Soil makeup
- Noise levels
- The presence or absence of certain kinds of objects
- Mechanical stress levels on attached objects
The current characteristics such as rate, direction, and size of an object

Moreover, there are many functions for the wireless sensor nodes, such as the following (Akyildiz et al., 2002):

- Continues sensing
- Event detection
- Event ID
- Location sensing
- Local control

1.2.2 Wireless Sensor Applications

The numerous types and specifications of the wireless sensor nodes have led these sensors to work in many fields and applications. Therefore, wireless sensors can be the integral part of many practical applications such as (Akyildiz et al., 2002):

- Military applications, such as monitoring friendly forces by leaders, checking the equipment status, or detecting any nuclear, biological, and chemical attack.
- Environmental applications, such as sensing any strange chemical materials in air or water, detecting forest fire, or tracking the movements of animals.
- Health applications, for example, doctors monitoring the physiological data of patients remotely without agitating them.
- Home automation applications, such as managing home devices remotely.
- Commercial applications, such as, tracking vehicles and objects, managing inventories, controlling robots, monitoring products, and detecting car thefts.

Wireless sensors can be used to measure natural phenomena. In various applications, wireless sensor nodes can work inside or very close to the natural phenomenon. These applications include sensors working in the interior of large machinery, at the bottom of an ocean or on the surface of an ocean during a tornado. However, there are other types of sensors that can be applied in biologically or
chemically contaminated fields, in a battlefield beyond the enemy lines, in a large building, in a large warehouse, attached to animals, attached to fast moving vehicles, and in a drain or river moving with the current. These areas, which wireless sensor can be applied to, give a clear illustration that wireless sensors can work under pressure, hard conditions, and in critical applications, which means that these sensors need a very powerful and stable architecture designs and protocols (Akyildiz et al., 2002).

Obviously, WSNs are used in critical application areas and real time systems. Therefore, they need to be stable in design and structuring to transfer data among the wireless sensors safely and without any problem. Designing WSN is much more difficult than any other computer networks, because of the limitation of the power resource, computation unit, and memory size.

1.2.3 Architecture of Wireless Sensors

As shown in Figure 1-2, each sensor node should consist of at least four basic components, which are (Akyildiz et al., 2002):
1. The sensing unit; this consists of two components, the sensor unit that produces the analogue signal after sensing any phenomena, and the analogue to digital converter (ADC) unit that converts analogue signals to digital signals.

2. The processing unit; this has a simple processor, which processes the input data and send the required information to a responding node. This processor also manages the collaboration among the sensor nodes. The processing unit incorporates a small storage unit to store the classes and the headers of the communication protocol.

3. The transceiver unit; this is responsible for connecting the sensor to the WSN by controlling the transmission and reception operations.

4. The power unit; this provides energy for the sensor node. It may also be connected to another power supply unit or power generator such as solar cells.

In order to compare WSNs with the other wireless network, we will discuss the main differences between the nodes in both the WSN and Mobile Ad hoc Network (MANET). MANET is a self-configuring wireless network that has the ability to keep updating the network configuration based on information from the mobile nodes. These differences can be summarized as following (Akyildiz et al., 2002):

- The number of nodes in WSNs can be much higher than the number of the nodes in a MANET, which means that the WSN has a very high density of nodes.
- The nodes in a MANET are much more scattered than in a WSN.
- The wireless sensor nodes may have more nodes failing than in a MANET.
- Any node failure in the WSN frequently causes many changes in the network topology.
- The wireless sensor nodes use broadcast communication more than point-to-point communication, which is the base of a MANET.
Chapter 1 Introduction

- The wireless sensor nodes have many constraints such as limitation in power, computation unit, and memory size.
- The wireless sensor nodes may not have identification number because of the large number of sensors.
- WSNs aim to reduce the power consumption, while other networks aim to reach high quality of service (QoS).

Many factors may affect the design of the WSNs; these factors should be covered during the design stage of the WSN or the design of the routing protocol. These factors include the following (Akyildiz et al., 2002):

- Reliability or Fault tolerance; which means, that the failure of any wireless sensor node should not affect the functionality of the WSN.
- Scalability, the deployment of these sensors may reach thousands of sensor nodes. Consequently, the design of the WSN must have the ability to work with numerous nodes and a high-density environment of sensor nodes.
- Production cost of each wireless sensor has to be low as possible, because the sensor network consists of a large number of sensor nodes, otherwise deploying traditional sensors will be more cost effective.
- Hardware constraints: the sensor nodes must consume very low power in order to live as long as possible, and they may use solar cells to generate power or harvest more energy to recharge the sensors. Therefore, designing any WSN should consider the limitation of the hardware's resources.
- WSN topology must be chosen carefully, because this topology may deal with a huge number of nodes.
- Harsh environment: the wireless sensor nodes must be designed to work under harsh conditions, such as high pressure at the bottom of the ocean, high temperature in the nozzle of aircraft, and hostile environment in a battlefield.
- Transmission of communicating nodes is by wireless transmission, and this wireless communication can be created from radio, infrared or optical media.
Data communication and data processing are the main events for consuming power in a wireless sensor node. Therefore, the consideration of the energy consumption is very important in designing any communication protocol in the WSNs.

1.2.4 Wireless Sensors Stack

As shown in Figure 1-3, the wireless sensor stack is a part of the standard Open Systems Interconnection (OSI) reference model proposed by the International Organisation for Standardisation (IOS). The OSI consists of seven layers, namely, the physical layer, data link layer, network layer, transport layer, session layer, presentation layer, and the application layer. Control is passed from one layer to the next, starting at the application layer in one station, and proceeding to the bottom layer over the channel to the next station then back up along the hierarchy as shown in Figure 1-4. The OSI reference model was never implemented in reality, because it had too many layers, which made this model too complex and difficult to implement efficiently (Aschenberner, 1986).

Each layer in the model is assigned specific tasks. The first and lowest layer is the physical layer. It may need to adapt to rapid changes in wireless links characteristics and mobility. The physical layer deals with raw bits. It is responsible for bit encoding, determining the voltage to be used for transmitting the bit stream.
over the physical medium and the time duration of each bit. It is also concerned with the physical specifications of the devices such as connectors and cables.

![Figure 1-4 The communication between node A and node D](image)

The second layer is the data link layer (also known as the Medium Access Control 'MAC' and Logical Link Control 'LLC'). The main functions of the data link layer are to coordinate the access of multiple nodes to a shared (wireless) medium, to ensure error-free transmission of data over a physical link, and to take into account the requirement of time synchronization. The data link layer is also responsible for minimizing collisions arising due to simultaneous transmissions by multiple nodes, maximizing throughput, allowing fair access, and the use of directional antennas. In addition, the data link layer has to solve the problems of hidden and exposed terminals (Zhong et al., 2001).

The third layer is the network layer, where this research is concentrated. It is responsible for routing data packets from a source node to a destination node. Therefore, the network layer has to determine and distribute information, which is used to setup routes between sources and destinations in a way that maintains efficiency while links change frequently. The network layer needs to provide IP addresses to end hosts, to minimise signalling overhead of the control packets required for route establishment and setup routes that support requested QoS and scalability.
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The fourth layer is the transport layer. The main objectives of the transport layer's protocols include handling delay and packet loss statistics that are very different from wired networks, segmentation, and reassembly of packets, setting up and maintaining end-to-end connections, reliable end-to-end delivery of data packets, end-to-end error recovery, and congestion control and flow control.

In some networks, there are session and presentation layers above the transport layer. Although, these layers are responsible for defining the lifetime of the network and the format of the data type sent over the network, they are not required in all networks.

Finally, the application layer enables the user to access the network. The main role of this layer is to handle frequent disconnection and reconnection with peer applications, and to support data transmission and services between users such as electronic mail, and remote file access and transfer (Murthy & Manoj, 2004).

1.2.5 Wireless Network Standard

Recently, advanced research and interest in time critical, low cost, long battery life, and low data rate wireless applications has led to work on LR-WPAN (Low Rate-Wireless Personal Area Network). LR-WPANs are designed to work in applications with restricted power, reliable data transfer, short range communication, and reasonable low cost such as industrial monitoring and control, home automation and security, and automotive sensing applications.

The first wireless communication standard designed for low data rate applications was Bluetooth. Bluetooth has a good capability to enable it to transfer large data packets such as audio, images, and video files. However, it has many problems with connecting a large number of devices. Therefore, Bluetooth cannot cover more than eight devices (ZigBee tutorial, 2004). In addition, the need for regular charging any Bluetooth device's battery is a major drawback. Therefore, the ability to provide the battery life required by the Bluetooth devices may not be available, when limited power consumption is required. Moreover, Bluetooth may not be suitable for real time critical applications, because Bluetooth devices need several seconds to join the network.
Wi-Fi is also used to transfer audio and video data in LR-WPAN. However, it also cannot work with a large number of devices, not more than 32 devices (ZigBee tutorial, 2004). A Wi-Fi device battery cannot work more than a couple of hours without requiring charging. Additionally, Wi-Fi has a high data rate. Therefore, it is unlikely that Wi-Fi would be chosen for use in industrial automation, or critical applications.

These restrictions of the above standards have encouraged IEEE (Institute of Electrical and Electronics Engineers) to work on producing new standard for medium access control and physical layers. The IEEE 802.15.4 standard has emerged as the IEEE low data rate proposal. This standard is suitable for LR-WPAN such as WSN. After the initial introduction of this standard, additional requirements such as network configuration, application programs, and security features led a group of semiconductor manufactures and technology provider companies to produce an extended standard called ZigBee. ZigBee is a standard for the network, security, and the application layer based on the IEEE 802.15.4, which is a standard for the Medium Access Control (MAC) and the Physical (PHY) layers. ZigBee and IEEE 802.15.4 can be combined together to form a full layers standard for low cost, low power, and low data rate WSNs (ZigBee tutorial, 2004).
IEEE 802.15.4

IEEE 802.15.4 is a standard defining the PHY and MAC layers to satisfy the market needs for low cost, low power, and low data rate WSN. IEEE 802.15.4 supports three types of network topologies, which are the star, mesh, and cluster tree topologies. Only the star topology can be really implemented based on the IEEE 802.15.4, because the network architecture is designed by the network layer, which does not exist as a part of an IEEE 802.15.4 stack as shown in Figure 1-5. The 64 bit IEEE address combined with the 16 bit short address of the IEEE 802.15.4 can theoretically serve up to \(2^{16} = 65,000\) devices. The IEEE 802.15.4 can define two types of PHY layers, one can operate at 2.4GHz bandwidth with 250 kbps data bit rate, and the other can operate at 868/915 MHz bandwidth with 20 or 40 kbps data bit rate (Kaiser et al., 2004).

Two types of devices can be supported by the IEEE 802.15.4, one is the Full-Function Device (FFD), and the other is the Reduced-Function Device (RFD). The RFD is a very simple device; it is used to forward data into the FFD. Each network may have any number of RFDs, which can only talk to the FFD, while it
should have at least one FFD, which can talk to other FFDs or RFDs. This FFD acts as the Wireless Personal Area Network (WPAN) coordinator (IEEE, 2003).

Data can be transferred in one of three ways of communication in the WSN; the first way is from a device to a coordinator, the second way is from a coordinator to a device, and the third way is from one peer device to another device in peer-to-peer network. Data transmission can be classified in terms of its low power consumption as three types: direct data transmission, indirect data transmission, and Guaranteed Time Slot (GTS) data transmission. Each layer in the IEEE 802.15.4 standard has many functions to execute such as giving details about the type of devices, determining the structure of frame and super frame, deciding the mode of data transfer, controlling robustness, and considering low power consumption and security (Zheng & Lee, 2006).

The IEEE 802.15.4 physical layer supports many functions such as activating and deactivating the radio transceiver, receiver Energy Detection (ED), Link Quality Indication (LQI), channel frequency selection, data transmission and reception, and Clear Channel Assessment (CCA) which make switching between channels possible (Le, 2004, Zheng & Lee, 2006). While the IEEE 802.15.4 MAC layer also has many functions, such as generating the network beacons from the coordinator to the devices, synchronizing the beacon from the device side, and self-configuring association and disassociation. In addition, the MAC layer is responsible for applying the carrier sense multiple access with collision avoidance CSMA-CA mechanism for channel access, using the guaranteed time slot (GTS) mechanism, and providing an unfailing link between two peer Mac layers (Zheng & Lee, 2006).
As shown in Figures 1-5 and 1-6, the ZigBee standard has added three extra layers to the Medium Access Control (MAC) and the Physical (PHY) layers of the IEEE 802.15.4 standard. These layers are the network layer, the application layer, and the security layer. A related specification for different applications can be defined in the application layer. The network layer supports three network topologies: star, tree and mesh topologies. The network layer is also responsible for the network establishment, maintenance, and the network routing protocols. The ZigBee standard uses a combination technique of two routing protocols in its routing table: the Cluster-Tree and Ad hoc On-demand Distance Vector (AODV)
routing protocols. These routing protocols cooperate in order to establish the network and send data between the wireless sensor devices in the network. Inside the ZigBee stack, there are few interfaces between the layers to transfer data and control packets as shown in Figure 1-5 such as Network Layer Data Entity (NLDE), MAC Layer Data Entity (MLDE), Network Layer Management Entity (NLME), and the Service access point (SAP) (ZigBee Alliance, 2005).

Each ZigBee network should have a coordinator. This coordinator must be an IEEE 802.15.4 FFD. This coordinator is responsible for connecting and disconnecting nodes to the WSN. Moreover, the ZigBee coordinator is responsible for establishing the network, and providing secure and stable links between the network devices. The ZigBee network can have devices acting as ZigBee routers. These routers are any other FFDs in the network, which is not the ZigBee coordinator. The routers participate in the routing process, and supporting association in the network. The IEEE 802.15.4 RFDs may participate in the ZigBee network acting as end devices. These end devices sense the surrounding phenomena, and then they send the data packets back to the coordinator directly or through other router devices. These end devices are optional, but they can perform very low power operations (Liang et al., 2006).

1.3 Problem Description and the Research Objectives

One of the most challenging and interesting research areas in WSN is energy-aware routing. Since routing is a demanding task and is an essential requirement for all other research areas in WSNs, it has received considerable attention from researchers. Moreover, consuming less energy and increasing the lifetime of the wireless sensor nodes based on routing protocols are primary objectives in designing WSNs, because of the limitation of the power resources and the difficulties of replacing the batteries of the wireless sensor nodes. These difficulties result from the installation of the wireless sensor nodes in critical locations as diverse and inhospitable as the bottom of the oceans or inside tornados (Akyildiz et al., 2002). There are three possible solutions in order to reduce the power consumption of the wireless sensor nodes: enhance the storage systems energy density, create a technique to distribute the power among the nodes, and
produce a mechanism to make the nodes scavenge for their own power (Roundy, S. et al., 2004)

The key functions of routing protocols include finding a feasible path for a data packet transferring from source node to destination node. They also include determining and exchanging the routing information required for establishing the routing path, detecting any path breaks, re-establishing or repairing the broken paths and minimizing bandwidth utilization. All these functions have to be performed without generating unnecessary overhead control messages. Control messages must be generated only when absolutely necessary. These control messages have to be exploited efficiently to deliver data packets. Reducing control message overhead and the effect of flooding reflect the efficiency of routing protocols in terms of bandwidth and energy consumption.

Routing protocols designed for traditional wired networks cannot be directly applied to WSNs due to the unique characteristics of these networks. These characteristics include low power supply, bandwidth constraint, and limited memory and computation capacity. Consequently, designing efficient routing protocols is a fundamental challenge and many different routing protocols have been developed for WSN over the past several years (Alkaraki & Kamal, 2004). Designing a protocol for these unusual constraints in wireless sensors is very difficult (Zorzi, 2004).

It is necessary to investigate the applicability of existing wireless sensor routing protocols and to determine which ones are suitable for any given application. It is important to determine how to select the appropriate routing protocols for such applications due to the very diverse requirements of the applications and the unpredictable nature of WSNs. This has led to the development of many different routing protocols for WSNs. Each proposed protocol claims that the proposed strategy provides an improvement over a number of different strategies considered in the literature for a given network scenario. Therefore, it is quite difficult to determine which protocols may really perform better under a number of different network scenarios, such as increasing node density and traffic.
The performance of WSNs is related to the efficiency of the routing protocol. The rate of link failure and the activation of broken links will increase, when the use of sensor nodes and the number of sensors are increased. Therefore, the number of control messages and backlogs, which are required to maintain routes, will increase. Thus in order to achieve adaptive routing responsiveness and efficiency, one of the main aims of designing any routing protocol has to be the efficient creation of the new routes in order to deal with sudden failure node (McDonald and Znati, 1999). In addition, considering the energy level of the wireless sensor nodes in establishing or recovering any routes failure is the main objective to design the WSNs' routing protocol. The research in this thesis concentrates on designing novel energy-aware routing techniques in the WSNs. In detail:

- Research the current relevant literature to obtain a better understanding of the topic.
- Propose several approaches in order to increase the lifetime of the WSN based on routing technique and network topology.
- Build a simulator for modelling the proposed approaches.
- Use the simulator to evaluate and compare the performance of the proposed approaches and routing strategies.

1.4 Area of Contributions made in the thesis

The first contribution in this research is the proposal of an approach to balance the energy consumption rate across the wireless sensor nodes, and make them participate in the routing process. This proposed approach is an improvement over the AODV routing protocol, which can increase the lifetime of the whole network. The second contribution is related to decreasing the transmission and receptions powers of the wireless sensor nodes in order to increase the lifetime of the wireless sensor nodes and the WSN. An approach to balance the consuming energy of the cluster-heads in the cluster-tree WSN is the third contribution in this thesis. The fourth contribution is proposing a new method to define the number of clusters and the cluster-head nodes in the WSN based on the level of the remaining energy in the sensor nodes. The fifth contribution is to discover the routes between
the source and the destination nodes based on the energy level of the wireless sensor nodes over the AODV routing protocol. All these contributions aim to reduce the energy consumption rate of the wireless sensor nodes and increase the lifetime of the WSN.

1.5 Thesis organisation

In Chapter 2, we present related research about WSNs routing protocols. These routing protocols are classified based on two main categories, which are network structure and protocol operations. The routing protocols, which are based on network structure, include three sub-categories, which are flat network, hierarchical network, and location-based network routing protocols. The sub-categories of the routing protocols based on the network operations include query-based, negotiation-based, multipath-based, QoS-based, and coherent-based routing protocols.

Chapter 3 reviews the routing techniques that are used in one of the most recent WSN technologies, the "ZigBee standard". ZigBee include two routing protocols in its routing layer. These protocols are the AODV and the cluster-tree routing protocols.

In Chapter 4, a new approach, to balance the energy consumption among the wireless sensor nodes and increase the lifetime of the flat WSN, has been proposed. This approach distributes the role of routing data between most of the wireless sensor nodes based on the AODV routing protocol in the flat WSN.

Chapter 5 contains the implementation of the new approach proposed in Chapter 4 over a hierarchical WSN. This also allows most of the nodes in the hierarchical network to participate in the routing process and share the energy consumption based on the AODV routing protocol.

Chapter 6 proposes a new approach for reducing the transmission and the reception powers during the routing process based on the AODV routing protocol in order to increase the lifetime of the WSN.
In Chapter 7, we have proposed a new approach to distribute the role of cluster-heads inside each cluster based on the energy level of the wireless sensor nodes. This approach has better performance comparing with the existing cluster-tree routing protocol.

In Chapter 8, a new approach has been proposed to define the number of clusters required in the network based on the network energy level, and to define the cluster-head node in each cluster based on the remaining energy level of the wireless sensor nodes. This approach is compared with the cluster-tree routing protocol as well.

Chapter 9 proposes a new approach for considering the energy level of the wireless sensor nodes in the route discovery process of the AODV in order to increase the lifetime of the WSN and select the route of the highest energy. This approach and a hybrid approach with the one introduced in Chapter 4 have been compared with the original AODV routing protocol.

All the Simulation models and results of performance in terms of increasing the network lifetime and reducing the consumption rate of the sensor nodes, are given for each approach respectively in Chapters 4-9 with all the details of the simulation parameters, conditions, and variables.

Proposals for future work and a summary of the whole thesis form the conclusion presented in Chapter 10.
Chapter 2
Existing WSN Routing Techniques

2.1 What the literature says about this problem

The main function of the wireless sensor nodes is to quantify the environmental phenomena surrounding them. These wireless sensors convert these
Chapter 2 Existing WSN Routing Techniques

phenomena into digital signals. These signals are processed to get the required data for some applications. Subsequently, the sensors send the data back to the sink node as shown in Figure 2-1. Broadcasting data efficiently among the wireless sensor nodes is very difficult to achieve, because of many constraints that distinguish this type of network from other types of networks. Routing techniques in the WSN are different from network routing techniques used in the other wireless communication, because the architecture and the structure of the WSNs are different from that of any other network, and because WSNs can be applied in different types of applications (Al-Karaki & Kamal, 2004).

Some of the constraints that must be taken into account and overcome before designing efficient routing protocol in WSNs, can be described as follows (Al-Karaki & Kamal, 2004).

- Firstly, the main objective of the routing protocol in a WSN is preserving energy and reducing the power consumption rate. In other networks, the routing protocols are designed to achieve high Quality of Service (QoS) during data transferring.

- Secondly, the architecture of wireless sensor nodes has many limitations such as a limited power supply, memory size, computation capability, and bandwidth of the wireless channels between the wireless sensors.

- Thirdly, each WSN potentially contains a large number of sensor nodes, which may reach thousands. Consequently, using global identification addresses to access each individual node may not be feasible.

- Fourthly, a WSN is designed for specific applications requirements. Hence, the design of the WSN is changeable depending on the application. Therefore, the routing protocol should work in different network topologies.

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- Fifthly, the routing protocol should eliminate the redundancy of the sensed data, which is arised from the common environmental phenomena sensed by many wireless sensor nodes at the same time.

- Sixthly, frequent wireless sensor nodes failures may cause many changes in the network topology. Therefore, the routing protocol must be fault tolerant. Fault tolerant means that the routing protocol should have the ability to cover any failure in the network by maintaining a new route to transmit data.

### 2.2 Classification of the Existing Routing Techniques in WSN

![Classification of the existing routing techniques in WSN](image)

As shown in Figure 2-2, WSN routing protocols can be classified into two main categories. These categories are those routing protocols, which are based on the network structure, and those, which are based on protocol operations, which can be further classified into different sub-categories. In term of network structure, there are three sub-categories: Flat, Hierarchical, and Location-based routing protocols. In
term of protocol operations, there are five sub-categories: Query-based, Negotiation-based, Multipath-based, Quality of Service (QoS)-based, and Coherent-based routing (Al-Karaki & Kamal, 2004), (Vidhyapriya & Vanathi, 2007), and (Akkaya & Younis, 2005). These categories and sub-categories are not mutually exclusive since some routing protocols could be classified under more than one category and sub-categories.

2.3 Routing Protocol based on the network structure

The structure of WSNs can be classified into three main categories, which are flat, hierarchical, and location-based structures. Therefore, routing protocols groups, as mentioned earlier, can be classified based on the network structure to three categories, which are Flat, Hierarchical, and Location-based routing protocols. In Flat routing protocols, all the wireless sensor nodes have the same level of functionality and responsibility. All the wireless sensor nodes forward the data to all the neighbour nodes without any attention to the network topology. On the other hand, Hierarchical routing protocols have different roles of functionality distributed among the wireless sensor nodes. Location-based routing protocols depend on the physical location of the wireless sensor nodes in order to send the data back to the sink node (Vidhyapriya & Vanathi, 2007), (Jolly & Latifi, 2006), and (Al-Karaki & Kamal, 2004).

2.3.1 Flat Routing Protocols

Flat routing protocols use the data centric routing protocols for transferring data, where there is a base station responsible for sending requests and queries to other nodes and waiting for their responses. Data elimination and a negotiation system can be used to save more energy in the network (Al-Karaki & Kamal, 2004). A route discovery process can be initiated by flooding or broadcasting data to all the neighbour nodes without paying attention to any updates, occurred for the topology. This section will discuss the most popular Flat routing protocols. There are more
protocols dealing with flat architecture and data centric routing techniques. More details can be found in (Al-Karaki & Kamal, 2004), and (Jolly & Latifi, 2006) reviews.

Flooding

The Flooding protocol is a most basic Flat routing protocol that can be easily implemented over the WSNs. There is no need for any complex algorithm programming. The Flooding protocol simply broadcasts the data to all the neighbour nodes without considering the topology or the structure of the network (Jolly & Latifi, 2006). Then the data can be delivered to the destination node by repeating the same process of broadcasting as shown in Figure 2-3. Although, this protocol is simple and easy to implement, it has some critical problems. One of these problems is the generation of a large number of duplicate messages by many nodes. Another problem is called “Implosion”. The implosion occurs when a certain node receives the same data twice, because each node is sending the received data to its neighbours without knowing whether the neighbour nodes have received these data before or not.

![Figure 2-3 Flooding routing Protocol with implosion problem](image-url)
Chapter 2 Existing WSN Routing Techniques

The Flooding protocol can be used in some applications such as in military applications, when the sending station needs to send the data to all other stations in any direction, and to update these stations' database immediately regardless of any other factors such as energy consumption (Tanenbaum, 2003).

**SPIN**

Sensor Protocol for Information via Negotiation (SPIN) is another Flat routing protocol. SPIN is similar to Flooding in that it works by sending the data to all the neighbour nodes in the network assuming that all nodes are base stations. However, this protocol preserves more energy by sending only the sensed data. In addition, SPIN's negotiation solves the problem of flooding by creating a negotiation system. This negotiation system consists of three types of packets, which are advertising the data (ADV), requesting the data (REQ), and sending the data (DATA) packets (Al-Karaki & Kamal, 2004).

A sensor node, which has data, sends an advertisement packet (ADV) to all the neighbour nodes. This ADV includes information about the sensed data. If one of the nodes, which received this ADV, has already received this data before, it will ignore the ADV packet. While the other nodes, which do not have these data, will send the request packet (REQ) back to the source node. Then, the source node will send the data to these nodes by sending the data packet (DATA). This routing protocol is an attempt to solve the problems of the duplicate data packets and the implosion problem. There are many versions to enhance the work of SPIN protocol such as SPIN-1, SPIN-2, SPIN-BC, SPIN-RL, SPIN-PP, and SPIN-EC (Jolly & Latifi, 2006).

Lower energy consumption can be achieved by SPIN than by flooding. However, the data distribution rates are the same, or sometimes faster than with flooding. SPIN also does not use the distance information between the neighbours to reduce the energy consumption (Jolly & Latifi, 2006). SPIN's negotiation system
reduces the redundant data produced by half. Sometimes the destination nodes are located faraway from the source node, and the nodes near to the source node may not be interested in these data. Therefore, the advertisement packet (ADV) cannot guarantee the delivery of the data to the far away interested nodes in the WSN (Al-Karaki & Kamal, 2004).

**Directed Diffusion**

![Directed Diffusion Diagram](image)

Figure 2-4 Reinforce the path in Directed Diffusion

Directed Diffusion is another data centric routing protocol, which is used in the Flat network architecture. In the Directed Diffusion routing protocol, the process of collecting data is initialized by a base station. This process happens in three steps as follow (Al-Karaki & Kamal, 2004), and (Jolly & Latifi, 2006):

- Step1: the base station broadcasts an interest packet to all the neighbour nodes, and these neighbours will broadcast this interest packet to all their neighbours until the interest message reaches the source node that has this type of data. The interest message includes gradient value, which includes attributes value and direction.
Step2: the source node, which has the requested data, sends the data packet to the base station using multi paths depending on the gradient.

Step3: the best paths are reinforced by the base station as shown in Figure 2-4. Selecting the best path based on the gradient value is dependent on the application, for example, some applications need the shortest path, and other applications need the lowest energy consumption path.

The Directed Diffusion is different from the SPIN or the Flooding routing protocol. Data request packet in the Directed Diffusion are always issued from the base station to the wireless sensor nodes, while in SPIN the wireless sensor nodes advertise that they have data to send, and allow the interested nodes to request it. On the other hand, all the transactions in the Directed Diffusion are neighbour-to-neighbour communications, and all the nodes have the ability to make data aggregation and caching. Directed Diffusion routing protocol does not require a certain network topology such as SPIN. However, Directed Diffusion may not be acceptable for application in environmental cases that need continuous data delivery (Al-Karaki & Kamal, 2004), and (Jolly & Latifi, 2006).

**ACQUIRE**

Active Query forwarding in the WSNs (ACQUIRE) is another data centric routing protocol. It is similar to Directed Diffusion. However, ACQUIRE can be used with complex queries. Directed Diffusion uses flooding to send the query, while ACQUIRE sends an active query to all the sensor nodes. When this query is resolved, the response will be sent directly back to the querying node (Jolly & Latifi, 2006).

If the number of hops between the source and the destination nodes is equal to the network diameter, ACQUIRE performance will be similar to Flooding performance (Jolly & Latifi, 2006). In addition, ACQUIRE can, in general, reduce
the power consumption compared with Directed Diffusion by around 60% (Jolly & Latifi, 2006).

**COUGAR**

COUGAR is another data centric Flat routing protocol, which is also similar to Directed Diffusion. The principle of COUGAR is to have an additional query layer. This layer lies between the application and the network layers. Data aggregation is also used to save energy, and remove redundant data (Al-Karaki & Kamal, 2004, Jolly & Latifi, 2006). COUGAR has a database approach in addition to Directed Diffusion. This database approach has a relational table. This relational table contains sensor node details and information collected from the node, to summarize the information in the WSN (Jolly & Latifi, 2006).

There are three disadvantages of using COUGAR. First, the additional query layer will add extra overhead in terms of the power consumption, and memory size. Second, it needs high-level synchronisation between the wireless sensor nodes (Al-Karaki & Kamal, 2004), and (Jolly & Latifi, 2006). Leader nodes are required to aggregate data and to send information to the base station, and these leaders should be dynamically selected to prevent nodes from being failure hops (Al-Karaki & Kamal, 2004).

**Rumor**

Rumor routing is the last data centric Flat routing protocol that will be discussed in this chapter. Rumor's base station sends a query directly to the wireless sensor node that detects any event without flooding the query to the entire network as in Directed Diffusion (Al-Karaki & Kamal, 2004), and (Jolly & Latifi, 2006). When the sensor node detects an event, it adds this event to an event table, and generates an agent. This agent travels to all nodes giving information about the event. Nodes, which know the routs and receive the agent, will answer the query of
Chapter 2 Existing WSN Routing Techniques

the base station. Rumor can handle node failure and save more energy compared with Flooding and Directed Diffusion. Rumor works most efficiency with a few events applications, but when there are a large number of events, the generation of an event tables and agents will cause extra overhead on the network resources such as memory capacity, and computation operations (Jolly & Latifi, 2006).

2.3.2 Hierarchical Routings Protocols

Hierarchical routing was originally proposed to route data in wired networks. However, it is also suitable for routing data in wireless networks with some enhancement related to the network scalability and the efficiency of communication. The main concept of the Hierarchical routing protocols depends on dividing the job among the wireless sensor nodes into more than one level. Most Hierarchical routing protocols consist of two routing layers, the first one is responsible for selecting the cluster-heads, and the second is related to routing decisions. For example, Hierarchical routing protocols, that need to achieve very low power consumption, can divide the task depending on the energy level. The nodes with a high energy level can be assigned to process and transmit data, while the nodes with a low energy level can be assigned to only sense events. The formation of clusters within the network nodes can improve the efficiency and the scalability of the sensor nodes (Al-Karaki & Kamal, 2004), and (Jolly & Latifi, 2006). There are many Hierarchical routing protocols. This section will evaluate and discuss only some of the available protocols.

LEACH

Low Energy Adaptive Clustering Hierarchy (LEACH) concentrates on saving energy and reducing the communication power consumption. In LEACH, a few wireless sensor nodes are selected randomly to act as cluster-heads. By repeating this cluster-head selection process, the wireless sensor nodes will share the energy consumption. If the cluster-heads are fixed, then they will die quickly as
they consume more energy than ordinary nodes, which will prevent the other linked nodes from joining the network (Jolly & Latifi, 2006). LEACH works in two discrete phases. The first phase is the setup phase, which includes defining the cluster-heads. The second phase is the steady state phase, which includes transferring the data. In the setup phase, a group of nodes (P) choose themselves to act as cluster-heads. These nodes should select a random number r between zero and one. If this random number is greater than threshold value $T(n)$, then the node $n$ cannot act as a cluster-head. The threshold $T(n)$ is calculated below, where $G$ is the number of nodes that did not act as a cluster-head in the last rotation ($1/P$) (Al-Karaki & Kamal, 2004).

$$T(n) = \frac{P}{1 - P(r \mod(1/P))} \quad \text{If } n \in G$$  \hspace{1cm} (2-1)

All the designated cluster-heads send an advertisement to all non cluster-head nodes to join them as shown in Figure 2-5. After receiving this advertisement, the non cluster-head nodes will take a decision to which cluster-head they want to join. This decision is mainly based on the signal strength of the cluster-heads that reach these nodes. Therefore, the non cluster-head will choose the cluster-head that requires lowest communication energy. After that, the non-cluster nodes will report the decision about the choice of the cluster-head to other cluster-heads (Al-Karaki & Kamal, 2004). This report will be sent by using Carrier Sense Multiple Access (CSMA) MAC protocol (Jolly & Latifi, 2006).
Each cluster-head will build a Time Division Multiple Access (TDMA) schedule for all the nodes within the cluster. Each node will transfer the data to the cluster-head according to the time schedule. The cluster-head aggregates the data in order to reduce the data size. At the end, the aggregated data will be sent to the base station. There is no way in LEACH to distribute the cluster-head role on the sensor nodes inside the network systematically. Moreover, LEACH assumes that all the energy levels on the network are the same. LEACH also assumes that each node has data to send at a certain time (Al-Karaki & Kamal, 2004), and (Jolly & Latifi, 2006).

PEGASIS

In (Lindsey & Raghavendra, 2002) Power Efficient Gathering in Sensor Information Systems (PEGASIS) was suggested as an enhancement to LEACH. Nodes in PEGASIS can only talk to their neighbours. Therefore, PEGASIS will increase the network lifetime, and decrease the bandwidth consumption in the network. Each node in the PEGASIS routing protocol communicates directly with the base station respectively. When all the nodes have finished communicating with the base station, a new round of communication will start.
Figure 2-6 Sensor nodes can link to base station in PEGASIS

In (Heinzelman et al., 2000) every node in PEGASIS, which linked directly to the base station, eliminates the overhead of forming clusters. It also shortens the distance between the non cluster-head nodes and the cluster-heads. PEGASIS will allow only one time of communication for each sensor per round, which will reduce the number of transmission in the network.

On the other hand, PEGASIS expects that each node has the ability to link directly to the base station without any other hops as shown in Figure 2-6. It also assumes that each sensor node has a database to save the location of the neighbours, which add extra overhead to the network (Lindsey & Raghavendra, 2002).

**TEEN**

Threshold sensitive Energy Efficient sensor Network (TEEN) protocol is another Hierarchical routing protocol. TEEN is useful for physical phenomena applications such as sensing temperature, and pressure. TEEN is also suitable for real time applications such as fire alarms. The sensing process in TEEN happens instantaneously, while the data sending process happens periodically. TEEN uses cluster formation for sending data. Two thresholds value will be sent by the cluster-head to the non cluster-head nodes inside the cluster. One is called the hard
threshold, which contains the old value of sensed attribute. The other is called the soft threshold, which contains the value of the sensed attribute with small modification that triggers the node to switch on its transmitter and transmit. Moreover, the sensor nodes just transmit when the sensed attribute in the scope of their interest (Manjeshware & Agrawal, 2001).

An enhancement version of TEEN, called APTEEN has been proposed. In (Manjeshware & Agrawal, 2002) The Adaptive Threshold sensitive Energy Efficient sensor Network routing protocol (APTEEN) aims to concentrate on intermittent data collection and fast response to time critical actions depending on the applications. The cluster-heads broadcast the hard and soft threshold, and schedule the transmission time to all the wireless sensor nodes within the cluster. These nodes are allowed to transmit the sensed data when the data values are above the hard threshold. The wireless sensor node will transmit the data when the attribute value is changed by an amount equal to or greater than the soft threshold. The maximum period between two successive reports for each node is called the count time. This count time is used to assign certain time for each node to send the sensed data. If the sensor node does not transmit any data during the count time, TDMA schedule will be used to assign time slot for each node.

The performance of TEEN and APTEEN is better than LEACH in terms of increasing the network lifetime and saving energy. On the other hand, the extra overhead for forming a cluster still exists for both protocols. The threshold functions and determination of the count time increase the complexity of implementation and overhead inside the network (Manjeshware & Agrawal, 2002).

**Self-Organizing Protocol**

The Self-Organizing protocol is the last Hierarchical routing protocol that will be discussed in this chapter. The Self-Organizing protocol has the ability to self-configure the network and arrange the wireless sensor nodes based on the
applications. It supports variety of types of sensors that can be either portable or fixed. As shown in Figure 2-7, a group of wireless sensor nodes sense the environmental events and transmit these events as data to another group of chosen nodes, which perform as routers. These routers have a fixed location and forward the sensed data to sink nodes. These sink nodes have the highest energy in the network. Local Markov Loops (LML) algorithm is used in self-organizing protocol to achieve fault tolerance amongst the sensors (Subramanian & Katz, 2000).

Figure 2-7 Self-Organizing Protocol Process

In (Subramanian & Katz, 2000), the self-organizing protocol is described in four phases as follows:

- The first phase is the discovery phase, where each node discovers the related neighbours.
- Secondly, the association phase, where a hierarchy is formed based on the groups of sensors. In this phase, each node allocates an address depending on its place in the hierarchy.
- The third phase is the Maintenance phase, where nodes inform their neighbours their energy levels and routing tables. Updating on the routing table or the energy level is done during this stage.
Self-reorganization phase is the last phase in the self-organizing algorithm, where any node failure will be overcome.

Al-Karaki and Kamal (2004) indicated that broadcasting messages by this protocol consumes less power than SPIN protocol. In contrast, the organization phase needs extra overhead.

2.3.3 Location-Based Routings Protocols

The third category of the WSNs routing protocols based on the network structure is the Location-Based routings protocols. The main idea of routing protocols in this category is to utilize the advantage of the locations of the wireless sensor nodes in the routing of the data. The address of each node is determined based on its physical location. The location of each node may be determined by satellite through the Global Positioning System (GPS) Technique or other positioning techniques (Al-Karaki & Kamal, 2004). The distance between neighbours can be calculated depending on the signal strength. In order to save energy some nodes may be set to a sleep mode (Jolly & Latifi, 2006). Some of the Location-Based routing protocols will be described in this section. More detail and more Location-Based routing protocols can be found in the survey by Al-Karaki (Al-Karaki & Kamal, 2004).

**GAF**

Geographic Adaptive Fidelity (GAF) is concerned primarily with energy awareness. GAF was originally designed for wireless ad hoc networks, but it is also suitable for WSNs. GAF saves energy without any effect on the routing dependability. The main principle of GAF is dividing the sensors field into fixed virtual grid zones. The cost of routing for each node in the same zone will be symmetric. Therefore, some of these nodes in the same zone can be ignored by
Chapter 2 Existing WSN Routing Techniques

putting them into the sleep mode, thus saving more power. GPS can be used to determine the position of each node in the same zone (Xu & Heidemann, 2001).

There are three stages in GAF, the discovery stage, the active stage, and the sleep stage. The discovery stage includes discovering the neighbours of each node within the grid. In the active stage, nodes participate in routing data. The sleep stage consists of turning off the radio of the node and setting the node to the sleep mode (Xu & Heidemann, 2001). It is obvious that this routing protocol depends on the GPS technique to determine the positions of the wireless sensor nodes, which is not always available especially for indoor applications. Moreover, this routing protocol places extra overhead on the memory unit in order to save the neighbours addresses for each node.

GEAR

Yu et al., 2001 discussed how to use the geographical information to distribute queries to a certain area in the network, especially when most of the data queries contain a geographic attribute. Routing data to a destination in the Geographic and Energy-Aware Routing protocol (GEAR) depends on energy and geographically information about the neighbours. The main idea of GEAR is to reduce the number of interests in Direct Diffusion by only sending the interest packets to certain regions or direction in the network. This will preserve more energy than Directed Diffusion.

Each node in GEAR keeps two values an estimated cost and a learned cost. The estimated cost is the combination of distance to the sink node and the remaining energy. When a node does not have any other nearby nodes except itself on a route to the destination area, a network hole will be created. The modification of the estimated cost that accounts for routing around the network holes is the learned cost. The estimated cost will be equal to the learned cost, if there are no holes in the network. The learned cost will be transmitted back one hop every time the data
packet reaches the sink node. Therefore, the route setup for the next data packet can be adapted (Yu et al., 2001).

There are two phases in the GEAR algorithm. The first phase is the forwarding of the packets towards the target region. The second phase is the forwarding of the packet within the same region. In the first phase, the wireless sensor node, that received the data, makes sure that there is at least one neighbour node closer to the destination area. If there is more than one neighbour node, then the sensor node will choose the one nearest to the destination area. If there are no neighbours on the way to the destination area, then this node is marked as a network hole. In the second phase, after the data packet has reached the destination region. It can be distributed by restricted flooding or recursive geographic forwarding. In high-density networks recursive geographic flooding is more energy efficient than restricted flooding (Yu et al., 2001).

**EAGR**

Energy Aware Greedy Routing (EAGR) has been introduced in WSN as a location based protocol that works on geographical information of the node as well as the energy level available in the sensor node. In most of the greedy routing algorithms, only shortest path is considered. All the nodes present in most of the shortest paths will lose its energy very quickly. Therefore, creates a hole in that area and results in dropping of packets. EAGR combines the location information and energy level of nodes so beautifully that the workload is evenly distributed amongst the alive nodes (Razia et al., 2007).

EAGR assumes that all the nodes have the same energy level and a threshold energy level is set. Node having less than that energy level is considered dead. Then, it finds out the location of each node. All the nodes should have energy level greater than their locations energy cost (Razia et al., 2007).
NHRPA

Novel Hierarchical Routing Protocol Algorithm (NHRPA) selects the topology of the network based on the distance of the nodes to the based station, density of the nodes, and the remaining energy of the sensor nodes. This protocol has better performance than Direction Diffusion routing protocol in term of energy usage, packet latency, and security in the presence of node compromise attacks (Cheng et al., 2008).

One main drawback of NHRPA is the complexity of the computation cost due to the need of initializing the network, forming the topology and calculating the distance to the base station, which will increase the overhead inside the WSN.

2.4 Routing Protocol based on protocol operations

The second category of the wireless sensor routing protocols is based on protocol operations. Any routing protocol can execute many operations such as asking question, starting negotiations, covering up any failure, measuring quality of service attribute like energy and bandwidth, and processing data. The routing protocols, as mentioned earlier, can be classified based on these protocol operations into five main sub-categories, Query-based, Negotiation-based, Multipath-based, Quality of Service (QOS)-based, and Coherent-based routing protocols (Al-Karaki & Kamal, 2004). In the following sections, a description of each category will be discussed.

2.4.1 Query-Based Routing

Query-Based routing protocols consist of all the routing protocols that are based on distribution queries. In this category, the destination nodes spread a query among the whole network nodes. The nodes, that have the data, which satisfy this query, will send these data back to the destination nodes. Natural language or high-
level query language can be used to describe the queries. Directed Diffusion is an example for this type of query-based routing protocols (Al-Karaki & Kamal, 2004).

### 2.4.2 Negotiation-Based Routing

In (Al-Karaki & Kamal, 2004), and (Jolly & Latifi, 2006), Negotiation-Based routing protocols use high-level data descriptors or labels to aggregate and eliminate redundant data. Transmitting the negotiation packets among the nodes is dependent on the resources available in the network. The key point of the Negotiation-Based routing protocols is to exchange a sequence of the negotiation packets before transmitting the real data. SPIN family protocols are examples of this type of routing protocol.

### 2.4.3 Multipath-Based Routing

Multipath-Based routing protocols deal with routing protocols that utilise multiple paths for routing data in order to provide fault tolerance. If the main path fails, an alternative path can be used. The alternative path can be kept alive by sending periodic messages. Multipath-based routing protocols can increase the network trustworthiness. SPIN and Directed Diffusion are examples of multipath-based routing algorithms (Al-Karaki & Kamal, 2004).

### 2.4.4 QoS-Based Routing

Quality of Service (QoS)-based Routing protocols concentrate on routing data with better service of information flows. Balance between energy consumption and data quality should determine the performance of sensors. QoS measurements include latency, power, and bandwidth. Sequential Assignment Routing (SAR) is an example of QoS-based routing protocols. SAR concentrates on three factors including energy resources, QoS on each path, and the priority level of each path. SAR contains the Multipath approach and location-based approach. SAR is Multipath approach guaranteed, which ensures fault tolerance and simple recovery.
(Jolly & Latifi, 2006). On the other hand, SAR has high overhead in order to maintain tables and states at each sensor node (Akkaya & Younis, 2005).

JAM (Jammed-Area Mapped) is another QoS-Based routing protocol that deals with denial of services attacks prevention strategies in the WSN environments. JAM implementations use a jamming detection module and a mapping module. When a node detects that it is jammed, it announces its neighbours, using a power management or a carrier sense strategies to temporary override the jamming (Wood & Stankovic, 2008).

2.4.5 Coherent-Based Routing

Sensor nodes make collaborative efforts to process the data in the WSN. Data processing is the main idea of WSN operations. A routing technique, which deals with data processing, is suggested in (Sohrabi et al., 2000). This routing technique includes two categories.

- Coherent Data Processing Based Routing: in this category, sensor nodes execute only minimum processing operations such as time stamping, and duplicate suppression. After that, the data is forwarded to other nodes called aggregators.

- Non-Coherent Data Processing Based Routing: in this category, sensor nodes will process the data locally before sending the processed data to the aggregators to execute further processing.

Coherent data processing is normally more energy efficient. On the other hand, non-coherent data processing goes through three stages. Target detection, data collection, and pre-processing as a first phase, the second phase is the membership declaration, which includes a certain node declaring its intent to collaborate in a cooperative function, and the third phase is a central node election where a central
node is chosen to execute complex information processing (Al-Karaki & Kamal, 2004).

Single Winner algorithm (SWE) and Multiple Winner algorithm (MWE) are two examples of coherent-based routing. In SWE, a single aggregator is selected to execute complex processing. The selection of nodes is based on the nodes energy levels available. At the end of SWE, a minimum-hop spanning tree completely covers the network. MWE limits the number of nodes that can send data to the central node in order to reduce the energy consumption (Sohrabi et al., 2000).

2.5 Conclusion

Routing protocols are the protocols that deal with finding a feasible path between two nodes in order to transfer data and communicate between them. There are many classifications for the routing techniques especially for those designed for WSN. There are many constraints in the WSN, which limit the ability of the routing techniques and reduce their efficiencies. These routing protocols can be classified into two main categories, the network structure based routing technique, and protocol operations based routing techniques. In term of network structure, there are three sub-categories. These sub-categories are Flat, Hierarchical, and Location-based routing protocols. In term of protocol operations, there are five sub-categories: Query-based, Negotiation-based, Multipath-based, Quality of Service (QoS)-based, and Coherent-based routing. There are many other routing protocols that are classified under these sub-categories, the most popular and important ones have been reviewed in this chapter.

All of these routing protocols are not mutual exclusive, as some of them may be classified under more than one category. These routing protocols have many methods for increasing WSN efficiency in terms of reducing the network bandwidth, the control messages overhead, and energy consumption. For example, SPIN creates a negotiation system to reduce the overhead of flooding, and LEACH
applies a clustering technique in order to group the wireless sensor nodes and increase the lifetime. However, none of them is efficient enough and can achieve all of the performance various methods.

There are other routing techniques supported in the routing layer of the ZigBee stack in order to establish the WSN, and transfer data among the sensor nodes in the WSN. These routing protocols are reviewed in the following chapter.
Chapter 3
ZigBee Routing Techniques

3.1 ZigBee Routing Layer

The routing layer provided by ZigBee is based on the combination of two efficient routing protocols. These routing protocols are the Ad hoc On-demand Distance Vector (AODV), and Motorola’s Cluster-Tree algorithm (Lee et al., 2006). These two routing protocols can be categorized under more than one of the previous categories in Chapter 2. Consequently, AODV and Cluster-Tree can be categorized to be Negotiation-Based, Multipath-Based, Query-Based, and Hierarchical-Based routing protocol. However, due to the implementation of these two routing protocol inside the ZigBee stack, this thesis classified them as ZigBee routing protocols.

3.2 AODV

The AODV routing protocol is a pure on-demand routing algorithm. In (Perkins & Royer, 2003) AODV maintains and discovers routes between two nodes, when these two nodes need to communicate with each other. AODV is a reactive routing algorithm classified under the hop-by-hop routing protocols. Sequence numbers are used by AODV to ensure maintenance of the freshness of routes and utilisation of the most recent routing information. AODV has two main objectives,
broadcasting discovery packets, and distributing information about changes in location.

AODV differs from any other routing protocol by its use of the sequence number of the source and the destination. It broadcasts a route request packet (RREQ) across the network in order to find a route to the intended destination. When a source node needs to communicate with another node, which has no route in its routing table, a path discovery process is initiated by the broadcast of the RREQ packet from the source node to its neighbours. The RREQ packet includes the source node's address, the destination node's address, the current sequence number of the source node, the broadcast ID, the most obtained sequence number of the destination node and hop counter as shown in Figure 3-1. Where Type is the type of the packet, J, R, and G are flags for join, repair, and gratuitous flag to indicate that the RREQ is unicast to specific destination IP.

![Figure 3-1 The RREQ header (Perkins & Royer, 2003)](image)

The source address and the broadcast ID identify each RREQ packet. The broadcast ID is increased by one, each time the source node sends a new RREQ packet. If the node has received this RREQ previously, it drops the redundant new
one and would not rebroadcast it. Otherwise, if the receiver node knows the route to the destination, it would send back a Route Reply packet (RREP), which contains the destination's sequence number and other information on how to get to the destination node as shown in the RREP header Figure 3-2.

If the receiver node does not know the route to the destination, it will rebroadcast RREQ to its neighbours and increment the hop counter. This process of sending Route Request packet (RREQ) is shown in Figure 3-3.
In AODV, the validity of a route at the intermediate node is verified by comparing the existing destination sequence number with the destination sequence number in the RREQ packet. If the corresponding destination sequence number is greater than or equal to the destination sequence number, which is contained in the broadcasted RREQ packet, then the intermediates node will update that in the routing table and forward that sequence number in the RREQ packet. Any node, which sends a RREP, places the current sequence number of the destination and its distance in hops to the destination into the RREP. Subsequently, a RREP is sent back to the source along the path followed by the RREQ. Once the source node receives the RREP packet, it compares the number of hops with the number of hops in the routing table to select the shortest path, and the sequence number of the destination node with the sequences numbers of the destination node in the routing table in order to select the freshest route. After that, the source node will transmit the data packets to the destination. If the route discovery timer expires and the source node does not receive any RREP, the source node will rebroadcast the RREQ to its neighbours. This route discovery process is repeated for a predetermined maximum number of attempts. If no route is discovered after the maximum number of attempts, the session will be aborted.

If a link failure occurs, while the route is active and any neighbour of the upstream node is using that link, the node creates a Route Error packet (RERR) to the source node informing it about the unreachable destinations. The RERR packet contains all the IP addresses of the unreachable destination nodes due to the link break and their sequence numbers, which are incremented by one, as shown in Figure 3-4, where N is the no delete flag; set when a node has performed a local repair of a link, and upstream nodes should not delete the route. Upon receiving the RERR, if the source node still needs the route, it must reinitiate the route discovery process. Subsequently, the source node rebroadcasts the RREQ packet and invalidates those routes in its routing table.
The main advantage of the AODV protocol is that it uses the on demand approach for establishing routes. The AODV has also low control messages overheads comparing with other routing protocols, and uses less network bandwidth. The AODV is also scalable for big high density networks, is a loop-free and reliable routing protocol because of using the destination sequence number, fault-tolerant protocol that can cover any fault through routing data (Jing & Lee, 2004).

On the other hand, the serious drawback of this protocol is the multiple RREP packets generated in response to a single RREQ packet. This can lead to heavy control overhead added to the already heavy control overhead occurring due to the RREQ packets flooding across the network. This overhead is very costly and results in serious redundancy, contention, and collision. During the route discovery process, a RREQ packet is sent out to all neighbours. Each neighbour rebroadcasts the RREQ packet to its neighbours, without taking into account if the neighbour is about to be out of the coverage range or not. In time, this could fail to send the data along the discovered route due to the link break occurring by one neighbour moving outside the range of the previous node in the path.

In addition, the serious drawback of the AODV routing protocol, especially when applied in the WSN, is that it does not consider the energy level of the wireless sensor nodes and the WSN in the transferring data process, the route
discovery process, and the transmission and reception processes. Therefore, one of the objectives in this research is to reduce the energy consumption speed and increase the lifetime of the WSN by improving on the AODV routing protocol.

3.3 Cluster-Tree

The cluster tree protocol is a self-organised protocol that supports network redundancy to achieve fault tolerance in the network. The cluster tree protocol uses packets negotiation to form either a single cluster network or a multi-cluster network. The cluster formation process includes two stages: select the cluster-heads of the WSN, subsequently, the non-cluster-head nodes in the WSN join the cluster-heads in order to form the clusters (Ergen, 2004).

3.3.1 Single Cluster Network

In (IEEE P802.15, 2001), a single cluster network contains only one cluster-head. All the nodes are connected to the cluster-head with one hop, and the network topology becomes a star topology. Each node in the network is waiting to receive a HELLO packet from the node, which acts as a Cluster-Head (CH). The HELLO packet includes the cluster-head MAC address and the cluster-head ID number, which is equal to zero (0) in the single cluster network. If any node fails to receive a HELLO packet for a certain period of time, this node will be converted to act as a cluster-head. Then, it will distribute a new HELLO packet to all neighbour nodes, and waits to receive the CONNECTION REQUEST packet from the neighbours. If it does not receive any CONNECTION REQUEST packets, it will turn back into regular node and wait again for receiving a HELLO packet. The cluster-head can also be selected based on some features such as the transmission range, power level, computing ability, or location information.
As shown in Figure 3-5, once the cluster-head receives a CONNECTION REQUEST packet from a neighbour node, it will reply by a CONNECTION RESPONSE packet. The CONNECTION RESPONSE packet includes a node ID of the non cluster-head node. Finally, the non cluster-head, that receives the node ID, will send an Acknowledgment packet (ACK) to the cluster-head node.

If the cluster-head reaches the maximum limit of the node IDs, or reaches any other defined limitations, it would reject any new node connection. This rejection is signalled by assigning a special ID to that node. The list entry of all neighbours and the routes would be updated periodically by sending HELLO packets. A node could receive HELLO packet from other node that belongs to other cluster. Consequently, the node saved the Cluster ID (CID) of the transmitting node in its neighbours list. After that, it would transmit the CID with the neighbour node ID inside the LINK STATE REPORT to its cluster-head. Subsequently, the cluster-head would know with which clusters it has an intersection. LINK STATE REPORT packet also allows the cluster-head to identify of any existing trouble in the network. If the cluster-head wants to update the topology of the network, it will
achieve that by sending a TOPOLOGY UPDATE packet. If the cluster-head stopped, then the transmitting of the HELLO packet would stop. Therefore, all nodes would know that they have lost the cluster-head. Subsequently, the cluster-head will be reconfigured by repeating the same process (IEEE P802.15, 2001).

### 3.3.2 Multi-Cluster Network

Multi-cluster networks need a Designated Device (DD) to give a unique Cluster ID to each cluster-head, and to calculate the shortest path from the cluster to the designated device. After the designated device has joined the network, it would act as a cluster-head, and would send HELLO packet to the neighbours. If the cluster-head receives the HELLO packet, it would send the CONNECTION REQUEST and would join the designated device to form cluster zero (Cluster 0). If the cluster-head is connected directly to the designated device, the cluster-head will become a border node with two logical addresses. As shown in Figure 3-6, if a regular node received the HELLO packet from the designated device instead of its cluster-head, it would act as a border node to its parent. The cluster-head would send a NETWORK CONNECTION REQUEST packet to setup the connection with the designated device. Subsequently, the border node would send a CID REQUEST packet to the designated device. If the designated device sent CID RESPONSE packet, that contains the new cluster ID CID, to the border node, the border node would send a NETWORK CONNECTION RESPONSE packet to the cluster-head with the new CID. In addition, the cluster-head would inform its nodes about the new CID. A multi-cluster network consisting of many single clusters are shown in Figure 3-7 (IEEE P802.15, 2001).

The cluster tree protocol does not also consider the energy levels of the wireless sensor nodes in choosing the cluster head or determining the number of the clusters required in each network. Another drawback of the cluster tree protocol is that it uses static nodes to act as cluster-heads during the whole lifetime of the network, which makes these nodes die quickly. Therefore, considering the energy
levels of the wireless sensor nodes in defining the cluster-heads and the number of clusters is another aim to achieve in this research.

Figure 3-6 Link CH with DD by border node (IEEE P802.15, 2001)

Figure 3-7 Multi-cluster network consists of many single clusters (IEEE P802.15, 2001)
3.4 Conclusion

This chapter has provided an overview of two ZigBee routing protocols, the AODV and the cluster-tree. These routing protocols are used in ZigBee standard in order to establish the WSN and to transfer data among the wireless sensor nodes. These routing protocols can be classified under more than one of the classifications used in Chapter 2 categories. This thesis classified them as ZigBee routing protocols, because the implementation of the network layer of ZigBee standard is based on these two routing protocols.

The AODV routing protocol is selected in the ZigBee standard, because it is a very efficient routing protocol. AODV has low control message overheads compared with other routing protocols, and uses less network bandwidth. AODV is also scalable in high density networks, a loop-free and a reliable routing protocol because of the use of the destination sequence number, and fault-tolerant protocol that can cover any fault through routing data. On the other hand, the AODV does not consider the energy level of the wireless sensor nodes in the transferring data, the route discovery, and the transmission and reception processes. Therefore, the AODV routing protocol cannot be considered as an energy aware routing protocol.

The cluster-tree protocol is also used in the ZigBee standard in order to establish the network and form the clusters of the wireless sensor nodes. However, this protocol does not consider the energy level of the sensor nodes in defining the number of the clusters or selecting the cluster-head nodes. The following chapters study different approaches to improve the AODV and cluster-tree in order to consider the energy of the sensor node and make them energy-aware routing protocols.
Chapter 4
Increasing Flat WSN Lifetime

4.1 Background and Motivation

In this chapter, a novel approach for increasing the lifetime of a WSN is presented. There are many routing protocols that deal with transferring data between wireless sensor nodes. Some of these routing protocols are concerned with the quality of service of transferring data across the WSN. However, there are other routing protocols, which are concerned with energy consumption which is important because of the limited battery resources of the wireless sensor nodes. The work in this chapter is based on the AODV routing protocol. AODV is one of the most efficient routing protocols in terms of shortest path and low power consumption and used in the latest standards of WSN "ZigBee".

As mentioned in the previous chapter, there are many constraints for AODV in terms of the overheads of control messages and mobility despite of being more efficient than other routing protocols. In addition, AODV is not an energy-aware routing protocol. AODV uses the same route to send all of the data from the source to the destination until this route dies. Therefore, the intermediate nodes over this route between the source and the destination nodes quickly use up their energy and
die. As a consequence, the lifetime of the whole network will be effected, especially if the dead nodes are vital nodes in the network such as the coordinator or the router nodes. This death of important nodes affects the network connectivity. This chapter proposes a technique to distribute the consumption energy of the nodes involved in the routing process between the source and the destination nodes among most of the nodes in the network. This technique aims to reduce the power consumption per node and increase the lifetime of the whole network.

### 4.2 Proposed Power Distribution Technique

In order to maximize the lifetime of the WSN, the proposed technique is concerned with balancing the power consumption and distributing the responsibilities of routing among the wireless sensor nodes. Therefore, this technique ensures that most of the wireless sensor nodes in the network participate in the communication and data transfer processes. Firstly, we are going to describe the energy model of the wireless sensor nodes, which will be used in the proposed approach. This energy model consists of several formulas. The first formula is related to the energy consumption rate. Consumption rate in this context means the rate of energy loss of each node. This rate ($\text{ConsRate}$) is the rate of the energy consumption for the node and can be calculated based on the following equation.

$$\text{ConsRate} = \frac{\text{InitEng} - \text{RemEng}}{\text{TimePeriod}} \quad (4-1)$$

Where, $\text{InitEng}$ is the initial energy level of the node, which this node had when it joined the network, $\text{RemEng}$ is the current energy level of the node, and $\text{TimePeriod}$ is the period of time that the node takes to consume this energy. The next formula is related to calculating the lifetime of each node, $\text{LifeTime}$. This lifetime is the period of time for which the node can be kept running before dying or stopping transmitting and receiving signals. The lifetime of a certain node can be measured by the following equation.
\[ \text{LifeTime} = \frac{\text{InitEng}}{\text{ConsRate}} \]  \hspace{1cm} (4-2)

The third formula is related to calculating the remaining lifetime of the wireless sensor node, \( \text{RemTime} \). This remaining lifetime means the period left for a node to keep running and serving the route.

\[ \text{RemTime} = \frac{\text{RemEng}}{\text{ConsRate}} \]  \hspace{1cm} (4-3)

The remaining energy of the node indicates the level of energy left in the node after losing some energy in transferring and receiving data. This remaining energy (\( \text{RemEng} \)) can be measured by the following formula.

\[ \text{RemEng} = \text{InitEng} - ((\text{PktT} \times TEng) + \text{PktR} \times REng) \]  \hspace{1cm} (4-4)

Where, \( \text{PktT} \) is the number of packets transmitted by this node, \( TEng \) is the transmission energy required to transmit each packet, \( \text{PktR} \) is the number of the received packets, and \( REng \) is the energy consumed by receiving one packet.

Distributing both the role of routing and power consumption among the wireless sensor nodes is the main concept of this approach. The maximisation of lifetime can be achieved by taking into account the changes of the energy level of the wireless sensor nodes simultaneously with the path discovery process and the forward process of AODV. The lifetime can be increased by balancing the energy consumption among the whole set of nodes. The AODV routing protocol chooses a certain path, which connects the source and the destination nodes based on both the number of hops between them, and the destination sequence number regardless of the power level of the intermediate nodes during the routing process. This path goes through the certain intermediate nodes, and will consume the power of these intermediate nodes, which will cause these intermediate nodes to quickly run out their power and die. When the intermediate nodes die, AODV will try to find a new
route to transmit the data between other intermediate nodes. These new nodes will also die after a certain time. In the proposed technique, most of the nodes in the WSN will act, at some time, as intermediate nodes between the source and the destination nodes. Although, there is an additional energy cost in establishing a new route between the source and the destination route, this is small and can be disregarded as shown in Equation (4-5). This establishing of route energy cost, \( EstRouteCost \) can be defined by the following formula.

\[
EstRouteCost = HopsNo \times txPower \times Time
\]  

(4-5)

Where, \( HopsNo \) is the number of hops between the source and destination, \( txPower \) is the transmission power for one packet, and \( Time \) is the time needed to transmit these discovery packets. Because of the very short time needed to establish a new route, the whole energy cost will be very small.

In addition, the proposed technique will try to keep most of the nodes running for their maximum lifetime. Each node, which has high-rate energy consumption and low remaining lifetime, will be turned off for a period of time. A high-rate energy consumption node is determined by comparing its energy consumption rate to that of the other nodes. This action will make the AODV routing protocol choose an alternative node or change the whole route to the destination node. Repeating this process can distribute the routing role among most of the nodes in the network, which is the focus of the proposed technique.
4.3 Implementation

As shown in Figure 4-1, some extra steps are required in order to implement the new approach within the existing AODV routing protocol. These steps are as follows:

Step 1: Any wireless sensor node that needs to send a message; has to check its routing table to look for a path to the destination node. Therefore, if the route is
available in the routing table, it will forward the message to the next node. Otherwise, the message will be saved in a queue, and the source node will send the RREQ packet to its neighbours to establish the discovery process, which has been explained in the AODV section 3.2 in Chapter 3.

**Step 2:** Before forwarding the message to the next hop, the procedure checks the energy consumption rate of the next hop.

**Step 3:** If this energy consumption rate is high, then the procedure will turn off the next hop for a certain period of time. Then it will remove the route from the routing table, which will lead the source node to initiate the discovery process again and find a new path to the destination node.

### 4.4 Simulation Model

This section describes the simulation environment, and shows the results of the simulation of the proposed approach of power consumption distribution based on the AODV routing protocol in a flat WSN. This simulation has been accomplished using the Network Simulator NS-2 version 2.29.2 (USC, 1989). The NS-2 simulation uses the AODV as a routing protocol to discover and maintain routes between the source and the destination nodes. Moreover, this simulation uses IEEE 802.15.4 as a Medium Access Control (MAC) protocol. IEEE 802.15.4 is a standard definition for the Physical layer (PHY) and the MAC layer of the low rate wireless personal area networks (LR-WPANs) which support simple devices such as wireless sensor nodes (IEEE Std802.15.4-2003, 2003).
The simulation model consists of 21 wireless sensor nodes in an area of size 80x80 meters with TwoRayGround radio model. These sensor nodes are distributed as shown in Figure 4-2. A traffic flow is generated between the source and the destination nodes in order to load the network. The traffic flow type is a constant bit rate (CBR) traffic connection with packet size 80 bytes. This CBR starts at 0.5 second after the simulation starts, and is renewed every 15 millisecond. Each simulation runs for 50 seconds. This simulation uses the NS-2 energy model, which represents the energy level of the wireless sensor nodes. This energy model include three initial values which are the initial energy (InitEng), transmission power of each packet (txPower), and the reception power of each packet (rxPower). The output of this model is the total remaining energy, packet transmission energy, and packets reception energy of each node. This NS-2 energy model decrements the node energy when the node transmits and receives packets by applying the following equations (Fall & Varadhan, 2007).

\[
\text{Node} \quad \text{Eng} \leftarrow \text{Node} \quad \text{Eng} - (\text{txPower} \times \text{txTime}) \tag{4-6}
\]

\[
\text{Node} \quad \text{Eng} \leftarrow \text{Node} \quad \text{Eng} - (\text{rxPower} \times \text{rxTime}) \tag{4-7}
\]
Where, $Node_{Eng}$ is the node energy, and initially it is equal to the initial energy of the node, $txTime$ is the time required to transmit each packet, and $rxTime$ is the time required to receive each packet. Therefore, Equation (4-6) decreases the node energy after transmitting each packet, and Equation (4-7) decreases the node energy after receiving each packet.

All the simulations in this thesis use a fixed network topology. However in the real world the topology of the WSN may be dynamic which means that the position of the nodes may change or the distribution of the node in the sensor field may be randomly. Moreover nodes may be added and removed at any time. Although, it may seem this render the simulation results less effective, this is not the case. The structure of the AODV routing protocol is originally based on the ad hoc networks which will be notified with any change in locations or number of nodes joining the network and updating the routing tables. In addition, the same protocol will prevent the same node in the WSN from serving more than one route in the same time which prevent the presence or the interference among the data transferring traffic from multiple sources in the network.

The simulation began with these initial values, which are related to the energy model. In the simulation, the initial full energy is set at 4.0 joules, the transmission power at 1.0 watts, and the reception power at 1.0 watts. These values are not really related to the realistic energy and power levels, however, these values are chosen to configure the simulation input parameters and will not affect the simulation efficiency, so it is based on the lifetime and power percentages rather than constant values. Most of the simulation parameters are shown in the following Table 4-1.
Table 4-1 Simulation Parameters Values

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter value</th>
</tr>
</thead>
<tbody>
<tr>
<td>InitEng</td>
<td>4.0 Joules</td>
</tr>
<tr>
<td>rxPower</td>
<td>1.0 Watts</td>
</tr>
<tr>
<td>txPower</td>
<td>1.0 Watts</td>
</tr>
<tr>
<td>Packet size</td>
<td>80 Bytes</td>
</tr>
<tr>
<td>Packet interval</td>
<td>15 Milliseconds</td>
</tr>
<tr>
<td>Simulation time</td>
<td>50 Seconds</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>21</td>
</tr>
<tr>
<td>Antenna type</td>
<td>OmniAntenna</td>
</tr>
<tr>
<td>Radio model</td>
<td>TwoRayGround</td>
</tr>
<tr>
<td>Grid size</td>
<td>80x80 meter</td>
</tr>
<tr>
<td>Routing protocol</td>
<td>AODV</td>
</tr>
<tr>
<td>MAC protocol</td>
<td>MAC/802_15_4</td>
</tr>
</tbody>
</table>

In this simulation, we compared the original AODV routing protocol to the new one with the extension of the distributed power consumption. The AODV routing protocol initially discovers the route from the source node to the destination node. Route A as shown in Figure 4-2 is the discovered route, which is initially selected to transfer the CBR packets to the destination node. In the original AODV, this route is used to transfer the whole number of packets, which means that the AODV routing protocol will not choose any other route as long as this route is still running. This leads the intermediate nodes to consume their power at a high rate, causing them to die and leave the network quickly. However, the proposed technique discovered that the circled node in Route A lost power quickly based on the equations (4-1) to (4-4). This high loss rate means that the rate of energy consumption for this node is high. Therefore, the new technique turns off the circled node for a certain period of time based on the remaining lifetime of the node in Route A. This action leads the source node to find a new route to deliver the remaining packets to the destination node. Consequently, AODV protocol establishes a new Route B as shown in Figure 4-2 to transfer the remaining packets.
from the source to the destination nodes. Regularly turning off the high consumption rate nodes for a period of time will balance the energy consumption and distribute the role of routing among the nodes. This also increases the number of live nodes in the network, and keeps them alive for the maximum time of the network lifetime.

In the simulation, this process of turning off the high consumption rate node will not start immediately after starting the forward process in the AODV. This will enable the initial route to serve the network for longer period before switching off the route. This time will be used to increase the energy consumption average of the node. In the simulation, a fixed time period has been defined before this process starts. However advance research is required in order to define the optimal time period require for switching between the routes.

4.5 Simulation Results

In the simulation, three performance values are estimated in the comparison between the AODV routing protocol and the proposed technique. These values are the energy consumption rate of the wireless sensor nodes, the lifetime of the nodes, and the lifetime of the whole network. The evaluation performance of these protocols has been carried out under the same traffic source, network loads, parameters, simulation environments, and the same conditions.

Results related to the energy consumption rate of the nodes in the network are shown in Figure 4-3, which shows the difference of the energy consumption rate of each wireless sensor node between the original AODV, and the new proposed technique. As shown in Figure 4-3, the energy consumption rates have been reduced for most of the sensor nodes. The average of energy consumption rate of the new technique is 0.143 joules per second, which is less than the average of the energy
consumption rate of the original AODV routing protocol, which is 0.151 joules per second.

![Consumption Rate of Sensor Nodes](image1)

**Figure 4-3 Consumption Rates of Wireless Sensor Nodes**

![Lifetime of Sensor Nodes](image2)

**Figure 4-4 Lifetime of Wireless Sensor Nodes**

Secondly, the lifetime of each wireless sensor node has been measured based on Equation (4-2) in the previous section. In Figure 4-4, the lifetime of the wireless sensor nodes in the original AODV routing protocol is compared with the lifetime
of the wireless sensor nodes in the proposed technique. Most wireless sensor nodes improved their lifetimes, and they ran for longer periods than in the original AODV routing protocol. While, the average lifetime of the wireless sensor nodes in the original AODV routing protocol was 27.5 seconds, the average lifetime of the wireless sensor nodes in the new proposed technique has been improved to 29.2 seconds. Therefore, the new approach has better lifetime average than the original AODV routing protocol.

![Wireless Sensor Network Lifetime](image)

**Figure 4-5 Lifetime of the Whole WSN**

Finally, after distributing the role of routing nodes among the sensor nodes, the energy consumption amount has been balanced among the wireless sensor nodes. The new proposed energy consumption distribution technique has increased the lifetime of the whole network compared to the original AODV routing protocol. Figure 4-5 shows the result of the simulation of the lifetime of the whole network based on the original AODV routing protocol and the estimated power consumption of the proposed technique. The lifetime of the whole network in the original AODV routing protocol was around 38 seconds, while the lifetime of the whole network based on AODV routing protocol with the new proposed technique was around 46
seconds. This means that the lifetime of the network has been increased around 8 seconds compared to its previous state.

4.6 Conclusion

The objective of this chapter is to investigate a proposed technique for increasing the flat WSN lifetime. The nodes in the flat WSN have the same level of functionality and routing responsibilities. This technique balances the power consumption among the nodes, and achieves better performance than the original AODV routing protocol in terms of reducing the energy consumption rate, increasing the lifetime of sensor nodes, and increasing the entire lifetime of the WSN. Furthermore, the proposed technique has increased the whole network lifetime by approximately 10% of its previous value. In comparison to the original AODV, the new technique has increased the lifetime per node, because this technique has increased the number of nodes, which can stay alive during the whole network lifetime.

The proposed technique process runs through executing the following steps. Firstly, the proposed technique calculated the energy consumption rate of each wireless sensor node. After that, the total lifetime and the remaining lifetime of each node were calculated. All these values were calculated based on the energy model formulas, described in this chapter. Therefore, the nodes, with a high-energy consumption rate and short remaining lifetime were turned off for a while. In this case, this action makes the AODV to choose another node or another route between the source node and the destination node. Repeating this process of turning off the high-energy consumption rate and short remaining lifetime nodes, the power consumption would be distributed among the nodes in the network. Therefore, the proposed technique protects some nodes from very quickly loosing their power and dying. Consequently, distributing the role of routing among the wireless sensor nodes and making them participate in the communication process can increase the
lifetime of these nodes and balance the power consumption among the whole nodes of the network, which will increase the lifetime of the whole network.

In addition, the proposed technique makes the AODV routing protocol an energy-aware routing protocol by changing the route to distribute the role of routing among the sensors and increase the lifetime of the flat WSN based on the energy consumption rate of the sensor nodes.
Chapter 5
Increasing Hierarchical WSN Lifetime

5.1 Background and Motivation

The previous approach of distributing the role of routing fairly among most of the network nodes was studied on flat WSNs that have one level of sensor nodes. Therefore, all of the wireless sensor nodes were acting and performing the same level of functionality and routing responsibilities. However, this chapter will study the use of the same approach over the hierarchical ZigBee architecture in order to increase the lifetime and distribute the responsibilities of routing among the wireless sensor nodes in multi level WSN. The structure of the WSN in this chapter consists of three levels of nodes, which can execute three types of functionality. This specification of a hierarchical network is based on three types of devices, which are defined in the ZigBee standard. These are the ZigBee coordinator, the ZigBee router, and the ZigBee end device. In this architecture, only one ZigBee coordinator is permitted for each ZigBee network. This coordinator forms the network, act as IEEE 802.15.4 FFD, and may also perform as a router after establishing the whole network. While the routers are optional devices, these routers can link to the
coordinator or other routers. These routers act as IEEE 802.15.4 FFD, participate in the routing of messages, and broadcast and route data to their own end device. The end devices are optional, but they can perform very low power operations. They can link to other FFDs such as the coordinator or routers (Ergen, 2004).

The AODV routing protocol is used in hierarchical WSNs to discover the routes between any two nodes. However, the same constraints of the AODV related to the energy level of the wireless sensor nodes still exist in a hierarchical WSN. In addition, AODV still uses the same route to send all the data produced by one source to the destination node until this route dies. Therefore, the intermediate nodes between the source and the destination very quickly lose their energy and die in comparison to nodes that do not form conduits or form them with much lower activity. Moreover, the lifetime of the whole network will be affected, especially if the dead nodes are key nodes (such as the coordinator or the router nodes) which affect the network connectivity. Consequently, we propose a technique to distribute the consumption of energy among the wireless sensor nodes by distributing the role of routing over these nodes. This process aims to increase the lifetime of the network coordinator, the routers, and the whole network in a hierarchical WSN.

5.2 Main Idea

Distributing the role of routing and distributing the power consumption among the wireless sensor nodes, especially the router nodes, in the hierarchical wireless sensor node is the main idea of this approach. AODV chooses a certain route to send the data from a source node to a destination node. Based on the energy model, which was explained in the previous chapter, any intermediate router node, which has a high level of energy consumption, will be turned off for a period of time. This will make the source node using the AODV routing protocol, choose another route to cover the breakdown between the source and the destination nodes. By repeating this process, the distribution of power consumption and the role of
routing can be guaranteed among most of the nodes in the WSN, which will lead to a reduction in the overall energy consumption rate and an increase the lifetime of the WSN.

### 5.3 Simulation Model

In this section, the simulation for the proposed technique of power consumption distribution over the hierarchical ZigBee WSN will be described. This simulation is accomplished using the Network Simulator NS-2 version 2.29.2 (USC, 1989). AODV has been used as a routing protocol for the simulation to discover and maintain the routes. Moreover, the IEEE 802.15.4 standard protocol has been used for the PHY and the MAC layers specification. Three levels of network have been designed in a ZigBee compliant architecture. The first level includes the Personal Area Network (PAN) coordinator. Each ZigBee network should have only one PAN coordinator. The second level includes the router nodes, and the third level includes the end device nodes.

![Figure 5-1 The Simulation Model with Three Levels Structure](image)

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-69-
As shown in Figure 5-1, the simulation model consists of 21 wireless sensor nodes in a square area of size 50X50 meters with TwoRayGround as the radio model and OmniAntenna as antenna model. The distance between any two neighbour nodes is 10 meters. The range of the wireless signal transmission is 16 meters. The grid size is different here than the size of the grid in the previous chapter 4, because we have defined the distance and the transmission range in this simulation in order to guarantee the hierarchy architecture.

These 21 wireless sensor nodes are distributed among the three levels as shown in the Figure 5-1. Where node 0 is acting as the PAN coordinator, the set of nodes {1, 2, 19, 16, 13, 11, 9, and 7} are acting as the routers, and the end devices are the nodes {3, 20, 18, 17, 14, 15, 12, 10, 8, 6, 5, and 4}.

First, the PAN coordinator has started to initiate the whole network. Subsequently, the groups of routers will start joining the network one by one and connecting to the PAN coordinator. Finally, the end devices will join the network by connecting to the PAN coordinator through the routers. The end devices can only communicate with a router, while the router can link directly to the coordinator or can link to another router. Therefore, there are many transmission paths in this network; one such paths scenario is shown in Figure 5-2.
Chapter 5 Increasing Hierarchical WSN Lifetime

After all of the nodes have been started and joined the network, the WSN will be loaded by generating CBR traffic from node 14 to the PAN coordinator with a packet size 80 byte and is renewed every 15 millisecond. The energy model of the simulation is based on the NS-2 energy model, which represents the energy level of the wireless sensor nodes. This energy model includes three initial values. These values are the initial energy ($\text{InitEng}$), the required power to transmit each packet ($tx\text{Power}$), and reception power of each packet ($rx\text{Power}$). The output of this model is the remaining energy, packets transmission energy, and packets reception energy of each node (Fall & Varadhan, 2007). At the beginning of the simulation, these three energy and power values have been initiated; the initial energy has been initiated at 4.0 joules, the transmission power 1.0 watts, and the reception power 1.0 watts. Table 5-1 shows most of the simulation parameters.

Table 5-1 Simulation Parameters Values

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter value</th>
</tr>
</thead>
<tbody>
<tr>
<td>InitEng</td>
<td>4.0 Joules</td>
</tr>
<tr>
<td>rxPower</td>
<td>1.0 Watts</td>
</tr>
<tr>
<td>txPower</td>
<td>1.0 Watts</td>
</tr>
<tr>
<td>Parameter Name</td>
<td>Parameter value</td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Packet Size</td>
<td>80 Bytes</td>
</tr>
<tr>
<td>Packet Interval</td>
<td>15 Milliseconds</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>100 Seconds</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>21</td>
</tr>
<tr>
<td>Number of Routers</td>
<td>8</td>
</tr>
<tr>
<td>Number of EndDevices</td>
<td>12</td>
</tr>
<tr>
<td>Antenna Type</td>
<td>OmniAntenna</td>
</tr>
<tr>
<td>Radio Model</td>
<td>TwoRayGround</td>
</tr>
<tr>
<td>Grid Size</td>
<td>50X50 meter</td>
</tr>
<tr>
<td>Transmission range</td>
<td>16 meter</td>
</tr>
<tr>
<td>Distance between neighbours</td>
<td>10 meter</td>
</tr>
<tr>
<td>Routing Protocol</td>
<td>AODV</td>
</tr>
<tr>
<td>MAC Protocol</td>
<td>MAC/802_15_4</td>
</tr>
</tbody>
</table>

A comparison between the original AODV and this new approach of distributing the power consumption has been made in the simulation. As shown in Figure 5-3, the first route through node 16 is the initial route to transfer the CBR packets between the source node 14 and the coordinator node 0. This route will be used to transfer the data packets until any failure happens or one of the intermediate nodes dies.
However, the new proposed approach discovered that node 16 in the original route 1 was losing its power quickly based on the energy model equations (4-1) to (4-4) in Chapter 4. Subsequently, our technique turned off the high consumption rate node 16. After that, the AODV routing protocol forced the source node to find another route to deliver the remaining packet to the destination node such as the solid route through node 11 in Figure 5-3. Consequently, repeating this process has led to a distribution of the role of routing amongst the network nodes, and to an increase in the average lifetime of the PAN coordinator, routers, and the whole network. However, there is a cost involved in establishing the new route. In this simulation, establishing new route needs $3 \times 10^{-5}$ seconds, which means that the establishment route cost energy based on equation (4-5) in Chapter 4, is equal to $6 \times 10^{-5}$ joules, which is $15 \times 10^{-5}$% of the node energy. Therefore, this small value was discarded during the simulation.

5.4 Simulation Results

In this simulation, six results have been compared in examining the difference between the original AODV routing protocol and the new one with our extended approach for distributing the role of routing and the power consumption among the wireless sensor nodes. The evaluation performance of these protocols has been carried out under the same traffic source, the same network loads, the same parameters, and the same simulation environment as in normal conditions.

<table>
<thead>
<tr>
<th>PAN Coordinator</th>
<th>AODV</th>
<th>New AODV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Consumption Rate (Joule/Sec)</td>
<td>0.124</td>
<td>0.113</td>
</tr>
<tr>
<td>Lifetime (Second)</td>
<td>32.2</td>
<td>35.5</td>
</tr>
</tbody>
</table>
As shown in Table 5-2, the power consumption rate of the PAN Coordinator in both protocols has been reduced by 0.011 joules per second in the new proposed technique (NewAODV).

Subsequently, the lifetime of the PAN coordinator has been compared in both protocols. The AODV routing protocol with our extension has increased the lifetime of the PAN coordinator by more than 3 seconds as shown in Table 5-2.

Figure 5-4 shows the comparison of the power consumption rate of the router nodes in the AODV routing protocol with the new AODV with our extension (NewAODV). These results show that power consumption rates have been reduced for most of the routers in the network. In the original AODV routing protocol, the average rate of the power consumption for routers was 0.074 joules per second. While the averages rate of the power consumption for routers in the AODV routing protocol with our extension was reduced to be 0.068 joules per second. Therefore, the new AODV routing protocol has achieved a better performance than the original one in terms of reducing and distributing power consumption.

![Consumption Rate of Routers](image)

**Figure 5-4 Consumption Power Rate of the Router Nodes**
Chapter 5 Increasing Hierarchical WSN Lifetime

In Figure 5-5, the lifetimes of the router nodes have been compared in both techniques. The average lifetime of the routers in the original AODV routing protocol was around 59 seconds. However, the AODV routing protocol with our extension has increased the average lifetime of the routers to reach 62 seconds. Therefore, the new approach has improved the average lifetime of the router nodes by around 3 seconds.

![Figure 5-5 Lifetime of the Router Nodes](image)

![Figure 5-6 Consumption Power Rate of all Nodes](image)
Subsequently, a comparison between the power consumption rate of all the nodes in the WSN in the original AODV routing protocol and in the new approach has been shown in Figure 5-6. The average power consumption rate of the wireless sensor nodes in the original AODV routing protocol was 0.053 joules per second. The average power consumption rate in the new approach has been reduced to 0.048 joules per second. Therefore, the average lifetime of the wireless sensor nodes in the new approach has been increased to 114 seconds. The average lifetime of the wireless sensor nodes in the original AODV routing protocol was 109 seconds. The distribution of the lifetime of individual nodes is shown in Figure 5-7 for both the AODV and the new AODV routing protocols.

5.5 Conclusion

AODV routing protocol is a useful routing protocol for flat WSNs and hierarchical WSNs, based on both the IEEE 802.15.4 and ZigBee standards. However, this protocol does not take into consideration the changes of the energy level of the wireless sensor nodes through the communication or the routing processes. This may lead to critical problems in routing data, and it may limit the
network lifetime. Therefore, in WSNs, energy consumption is a significant concern, because all of the wireless sensor nodes are using batteries as a power supply.

In this chapter, we have studied the proposed technique to balance the energy consumption among the wireless sensor nodes by distributing the role of routing among the wireless sensor nodes over the hierarchical WSN. By making most of them participate in the communication process, this proposed technique has increased both the lifetime of the whole network, and the number of nodes which will remain alive for a period of time.

The performance evaluation in terms of the network lifetime was conducted using the NS-2 simulator. We compared the original AODV routing protocol with the one with our extension under the same simulation conditions and parameters values. Results showed that the new proposed technique has improved the performance in terms of increasing the total network lifetime, and decreasing the energy consumption rate of each wireless sensor node in the hierarchical WSNs.

Based on the simulation results, the new approach has better performance than the original AODV routing protocol in term of increasing the lifetime of the PAN Coordinator by around 8%, increasing the lifetime of the routers by around 6%, and increasing the lifetime average of the whole network by around 5% in the hierarchical network compared to the original lifetimes.

Although, the increment in the lifetime is not very large, it is still important in many real time applications, where every second the application lifetime is significant and it is vital to keep the application running as long as possible, for example in a fire alarm applications. The new routes used might not be the shortest paths in the network. However, they are energy efficient.
Chapter 6
Reducing the Transmission and the Reception Powers

6.1 Background and Motivation

The transmission and the reception powers consumed in sending and receiving data packets are the main source of energy consumption in any wireless sensor node. Therefore, reducing the amount of consumed power through the transmission and reception operations in the routing protocol will lead to an increase in the lifetime of the WSN and distribution of the consumed power among all the wireless sensor nodes. This chapter proposes a mechanism to reduce the transmission and the reception powers for the frequently used nodes. This proposed techniques and a hybrid technique with the distributing power consumption approach described in Chapter 4 have been compared with the original AODV routing protocol. Simulation results based on NS-2 showed that the hybrid technique and the proposed mechanism have better performance than the original AODV routing protocol. The new mechanism and the hybrid technique have increased the lifetime of the WSN by around 40%, and 70% respectively.
In the data transmission process from a source node to a destination node, all the sensor nodes use the same communication standard and routing protocol. Therefore, the amount of energy consumed for transmitting and receiving one packet to the destination node is the same fixed value for each sensor node (Shorey et. al., 2006). Consequently, reducing the amounts of the reception and transmission powers from one node to another, will save energy, and increase the lifetime of these nodes.

The objective of this chapter is to establish a model for reducing the transmission and the reception powers during the routing process and to investigate its efficiency on the WSNs, and on distributing the consumption power among the wireless sensor nodes. This technique distributes the power consumption among the nodes, and can achieve better performance than the original AODV routing protocol in terms of reducing the rate at which the energy is consumed, while increasing the lifetime of the sensor nodes and the WSN.

6.2 Proposed Mechanism

In this chapter, we introduce a new mechanism to balance the consumption energy in the network by preventing critical nodes from consuming all their energy before other nodes in the network do. These critical nodes spend most of their energy in the transmission and the reception processes rather than on standby status or any other status.

The main idea of the proposed technique is that the nodes, which have high energy and low power consumption, will cover a greater area. While the nodes, which have high power consumption, will cover a smaller area. This is achieved by decreasing the amount of the transmission and the reception powers for those nodes, which reduce their energy most quickly, as a result of forwarding a large number of packets in the route between the source and the destination. Therefore, these nodes
will cover less area than other nodes in the network. However, the minimum amount of the transmission and reception powers preserved should be sufficient to transmit and receive packets for the distance between the node and its immediate neighbours. In the real life, if the distance between neighbours is not known, we can find out the minimum powers required is to reach neighbouring nodes when creating the network.

Our idea is based on (Cheng et al., 2005) dynamic power management system to balance the consumption of power among the nodes in the network based on reducing the transmission power using the following formula:

$$Pt = P_{Init} \frac{Pres}{Pf}$$  \hspace{1cm} (6-1)

Where $Pt$ is the transmission power, $P_{Init}$ is the power spent on the initial transmission, $Pres$ is the residual power, and $Pf$ is the full power.

However, this proposed model does not consider the reception power. Therefore, reducing the transmission power is not sufficient alone to balance the consumption power in the WSN. In addition, Cheng et al. (2005) did not consider the distance between the nodes, and the reception power in reducing the amount of the transmission power. In addition, their dynamic power management could reduce the transmission power to a value less than the minimum required power for delivering of a packet to a neighbour node, which would lead to stopping the node from taking part in the communication process in the WSN, while it still actually has some power to continue working and serving the network. In our model, the nodes will keep serving the network until they lose all their power.

In our model, each node can individually adjust its transmitting power and reception power based on its remaining and initial energy. We reduced the
transmission power and the reception power based on the following mathematical formulas:

\[ P_t = P_{tInit} \frac{RemEng}{InitEng} \quad (6-2) \]

\[ P_r = P_{rInit} \frac{RemEng}{InitEng} \quad (6-3) \]

Where, \( P_r \) is the reception power, \( P_{rInit} \) is the initial reception power, \( RemEng \) is the remaining energy of the sensor node, and \( InitEng \) is the initial full energy of the node.

We calculate the remaining energy of the node based on our energy model in Chapter 4. However, this proposed technique attempts to reduce the transmission power and the reception power until reaching the minimum power, which is required to transmit the packet between two nodes over a certain distance. The relationship between the transmission power, \( P_t \), the received power, \( P_r \), and the transmission distance \( d \), can be found from the following formula (Fall & Varadhan, 2007):

\[ P_r = \frac{P_t \cdot G_t \cdot G_r \cdot h_t^2 \cdot h_r^2}{d^4 \cdot L} \quad (6-4) \]

Where \( G_t \) is the antenna gain for the transmitter, \( G_r \) is the antenna gain for the receiver, \( h_t \) is the height of the transmitter antenna, \( h_r \) is the height of the receiver antenna, and \( L \) is the system loss. These parameters have been set to constant values in the simulation model, because the simulation configured to run in error free environment. Therefore, changing the value of these parameters may affect the transmission process and the reliability of transferring the data packets. However, it does not affect the process of reducing the transmission and reception powers.
6.3 Implementation

In this chapter, we describe the implementation of two algorithms. The first one is for the previously proposed technique for reducing the transmission and the reception powers of the low energy nodes over the basic AODV routing protocol. The second implementation is the hybrid technique using this technique together with the approach discussed in Chapter 4 for distributing the consumption power and reducing the average consumption power for the wireless sensor nodes.

These two implementations are explained in the following flow charts:

![Flow Chart](image)

Figure 6-1 Flow Chart to implement the new technique over the basic AODV.
Chapter 6 Reducing the Transmission and the Reception Powers

Start Sending Message

No

1. Insert message in queue.
2. Send a RREQ packet to the neighbours.

Yes

1. Check energy consumption speed of the next hop node.

No

Is the consumption speed high?

Yes

1. Turn off the node.
2. Remove the route.
3. Initiate the process again.

1. Forward message to the next hop.
2. reduce the transmission and the reception power of the node.

End

Figure 6-2 Flow Chart to implement the hybrid technique.

As shown in Figures 6-1 and 6-2, in order to implement this technique, some steps have been added to the basic AODV routing protocol. These steps are as follows:

Step 1: Any wireless sensor node that needs to send a message; has to check its routing table and look for a path to the destination node. Therefore, if the route is available in the routing table, it will forward the message to the next node. Otherwise, the message will be saved in a queue, and the source node will send the RREQ packet to its neighbours initiating the discovery process of the AODV routing protocol.
Chapter 6 Reducing the Transmission and the Reception Powers

Step 2: We have reduced the transmission and reception powers of the node involved in the forward process based on Equations (6-2) and (6-3). However, the minimum value of these powers should be enough to forward the data packet over the minimum distance to reach the next neighbour in the route.

Step 3: In order to merge this technique with the distributed power consumption technique described in Chapter 4 to produce a hybrid technique, we have implemented this approach during the forward process, while sending the message to the next hop. This approach checks the energy consumption rate of the next hop. If the energy consumption rate is high for this intermediate node, then the procedure will turn off the next hop for a certain period of time. After that, the current route will be removed from the routing table, which will lead the source node to initiate the discovery process again and find a new path to the destination node.

6.4 Simulation Model

This section describes the simulation environment, and shows the results of the simulation of the previous proposed technique of reducing the transmission and reception powers of the wireless sensor node. In addition, this section shows the simulation results of the hybrid technique between this new mechanism and the distributed power consumption technique. Both of them are based on the basic AODV routing protocol. This simulation is accomplished using the Network Simulator NS-2 version 2.29.2 (USC, 1989). The NS-2 simulation uses AODV as a routing protocol to discover and maintain the routes between the source and the destination nodes. Moreover, this simulation uses IEEE 802.15.4 as a Medium Access Control (MAC) protocol. IEEE 802.15.4 is a standard definition for the Physical layer (PHY) and the MAC layer of the low rate wireless personal area networks (LR-WPANs) which support simple devices such as wireless sensors (IEEE Std 802.15.4-2003, 2003).
The simulation model consists of 21 wireless sensor nodes as shown in Figure 6-3 in an area of size 80x80 meters using the TwoRayGround radio model. These sensor nodes are distributed systematically. The distance between each two neighbour nodes is 16 metres. The range of the wireless signal transmission initially is 30 metres. A traffic flow is generated between a source and a destination node. The traffic flow type is Constant Bit Rate (CBR) traffic connection with packet size 80 bytes. This CBR starts after 0.5 second of the simulation start time and redundant each 15 milliseconds. Each simulation runs for 500 seconds.

This simulation uses the NS-2 energy model, which represents the energy level of the wireless sensor nodes. The energy model include three initial values: the initial energy (InitEng), transmission power of each packet (txPower), and the reception power of each packet (rxPower). The output of this model is the total remaining energy, packets transmission energy, and the reception energy of each node. This NS2 energy model decrements the node energy, when the node transmits
and receives packets by applying the following equations as mentioned in Chapter 4 (Fall & Varadhan, 2007).

\[
Node_{Eng} \leftarrow Node_{Eng} - (txPower \times txTime) \quad (4-6)
\]

\[
Node_{Eng} \leftarrow Node_{Eng} - (rxPower \times rxTime) \quad (4-7)
\]

Where, \( Node_{Eng} \) initially is equal to the initial energy of the node, \( txTime \) is the time required to transmit each packet, and \( rxTime \) is the time required to receive each packet. The simulation begins with these initial values, which are related to the energy model. In this simulation, the initial full energy is equal to 4.0 joules, the transmission power is equal to 1.0 watt, and the reception power is equal to 1.0 watt. These simulation values and other simulation parameters are shown in the following Table 6-1.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>InitEng</td>
<td>4.0 Joules</td>
</tr>
<tr>
<td>rxPower</td>
<td>1.0 Watt</td>
</tr>
<tr>
<td>txPower</td>
<td>1.0 Watt</td>
</tr>
<tr>
<td>Packet Size</td>
<td>80 Bytes</td>
</tr>
<tr>
<td>Packet Interval</td>
<td>15 Milliseconds</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>500 Seconds</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>21</td>
</tr>
<tr>
<td>Antenna Type</td>
<td>OmniAntenna</td>
</tr>
<tr>
<td>Radio Model</td>
<td>TwoRayGround</td>
</tr>
<tr>
<td>Grid Size</td>
<td>80X80 meter</td>
</tr>
<tr>
<td>Distance between</td>
<td>16 meter</td>
</tr>
<tr>
<td>neighbours</td>
<td></td>
</tr>
<tr>
<td>Routing Protocol</td>
<td>AODV</td>
</tr>
<tr>
<td>MAC Protocol</td>
<td>MAC/802.15.4</td>
</tr>
<tr>
<td>CPThresh</td>
<td>10.0</td>
</tr>
<tr>
<td>CSThresh</td>
<td>2.13643*e'</td>
</tr>
<tr>
<td>RXThresh</td>
<td>2.13643*e'</td>
</tr>
<tr>
<td>L</td>
<td>1.0</td>
</tr>
<tr>
<td>Gt</td>
<td>1.0</td>
</tr>
<tr>
<td>Gr</td>
<td>1.0</td>
</tr>
<tr>
<td>Ht</td>
<td>1.5 meter</td>
</tr>
<tr>
<td>Hr</td>
<td>1.5 meter</td>
</tr>
</tbody>
</table>
In our simulation based on the two-ray ground reflection model, the transmitter antenna gain, and the receiver antenna gain are \( (G_t = G_r = 1) \). The transmit antenna height is the same as that of the receiver antenna height and equal to 1.5 \( (h_t = h_r = 1.5 \text{ m}) \). The system loss of the antenna is also equal to one \( (L = 1) \). Therefore, we can simplify equation (6-4) to the following simplest form:

\[
Pr = \frac{5.0625 \cdot Pt}{d^4}
\]  

(6-5)

As shown in Figure 6-3, the crossed wireless sensor nodes in the dashed route has less transmission and reception powers than the other nodes in the same route. In addition, the dotted route is used, because the approach for distributing the power consumption detects that one node in the dashed route has lost its power quickly, so it turns that node off for a small period of time, which caused the source node \( (S) \) to find another route in order to reach the destination node \( (D) \). By repeating the process of reducing the transmission and the reception powers, and distributing the role of routing data among the wireless sensor nodes as it is implemented over the AODV routing protocol, we have achieved a better performance.

### 6.5 Simulation Results

In this simulation, performance indexes are compared for three protocols: the basic AODV routing protocol, the new technique of reducing the powers, and the hybrid technique. These indexes are the rate of the energy consumption of the wireless sensor nodes, the lifetime of the nodes, and the lifetime of the WSN. The performance evaluation of these protocols has been carried out under the same traffic source, the same network loads, the same parameters, and the same simulation environments.
Figure 6-4 Energy consumption rate of the wireless sensor nodes over the three techniques

Figure 6-4 shows the simulation result of the energy consumption rate of each node over the three techniques. The new technique has reduced the energy consumption rate of most of the node over the basic AODV routing protocol. However, the hybrid technique has decreased the energy consumption rate for most of the nodes to a value less than that of both the basic AODV and the new technique. While, the average of the energy consumption rate of the wireless sensor nodes in the basic AODV was around 0.074 joule per second, the new technique has reduced the average to reach around 0.043 joule per second. The hybrid technique has further decreased the average of the energy consumption rate to 0.029 joules per second.

Consequently, the lifetime of the wireless sensor nodes has been increased by both the new technique and the hybrid technique compared with the original lifetime of the nodes using AODV. Consequently, the new technique has raised the average lifetime of the wireless sensor node to reach 147 seconds, while the hybrid technique has increased the average lifetime to reach 183 seconds. Where, the
original average lifetime of the wireless sensor nodes was around 76.5 seconds as shown in Figure 6-5.

![Figure 6-5 Lifetime of the wireless sensor nodes over the three protocols](image)

Assuming that the lifetime of the WSN is equal to the maximum lifetime of the wireless sensor nodes or the lifetime of the last dead node, because all the nodes can achieve the same role and functionality if they stay alive, then the lifetime of the
wireless sensor node can be calculated by applying the following equation explained in Chapter 4:

\[
\text{LifeTime} = \frac{\text{InitEng}}{\text{ConsRate}}
\]  

(4-2)

Where, \( \text{ConsRate} \) is the consumption rate of the wireless sensor node. The following equation calculates the consumption rate explained in chapter 4.

\[
\text{ConsRate} = \frac{\text{InitEng} - \text{RemEng}}{\text{TimePeriod}}
\]  

(4-1)

Where, \( \text{TimePeriod} \) is the running time of the wireless sensor node.

The lifetime of the WSN in this simulation was around 240 seconds based on the basic AODV routing protocol. Figure 6 clearly shows that the new technique has increased the lifetime of the WSN to 338.5 seconds. The hybrid technique has almost doubled the lifetime of the WSN to be around 416 seconds.

It is obvious from all the previous simulation results that the new technique has achieved better performance than the basic AODV routing protocol. However, the hybrid technique has achieved the best performance in terms of reducing the average energy consumption rate of the wireless sensor nodes, increasing the average lifetime of the wireless sensor nodes, and increasing the lifetime of the whole WSN.

6.6 Conclusion

The AODV routing protocol is a widely used in WSNs, which is based on both the IEEE802.15.4 and ZigBee standards. However, this protocol does not take into consideration the changes in the battery energy level of the wireless sensor nodes through the communication or the routing processes. This may lead to critical problems in routing data, and may limit the network lifetime. Energy consumption is a significant concern to many researches concerned with WSN.
In this chapter, we have proposed a new technique to decrease the transmission and the reception powers of the wireless sensor nodes to a minimum power level based on the remaining energy level, which is still sufficient to transmit a single packet across a fixed distance between the node and its immediate neighbours. Subsequently, we have merged this new technique with the technique proposed in Chapter 4 to reduce the consumption among the wireless sensor nodes by distributing the role of routing among the wireless sensor nodes, and requiring most of them to participate in the communication process. This proposed new technique together with the hybrid technique aim to increase the lifetime of the whole network, and to increase the number of nodes, which will remain active for a maximum period of time.

The performance evaluation in terms of the network lifetime, power consumption of the nodes, and the nodes lifetime, was conducted using the NS-2 simulator. We have compared the original AODV routing protocol with the new technique and the hybrid technique under the same simulation conditions and parameters values. Results have shown that the proposed technique has improved the performance in terms of increasing the total network lifetime, and decreasing the energy consumption rate of each wireless sensor node in the WSNs by around 40%.

Based on the simulation results, the hybrid approach has achieved better performance than the original AODV routing protocol, as it has increased the lifetime of the whole WSN by around 70% in the WSN.
Chapter 7
Dynamic Cluster-heads Lifetime-efficiency in WSN

7.1 Background and Motivation

The ZigBee routing layer utilises the cluster-tree and the AODV routing protocols in order to establish the network. However, both protocols do not consider the energy level of the nodes in the network establishment process or in the data routing process. In this chapter, we propose a mechanism to make the cluster-tree an energy aware routing protocol by distributing the responsibility of cluster-heads amongst the wireless sensor nodes in the same cluster based on the ZigBee standard. The cluster-tree routing protocol supports single or multi-cluster networks. However, each single cluster in the multi-cluster network has only one fixed node acting as a cluster-head. These cluster-heads are fixed in each cluster for the network lifetime. Consequently, using these cluster-heads for the complete network lifetime will cause them to die quickly, and all the entire nodes linked to these cluster-heads will be disconnected from the main network. Therefore, the proposed technique, to distribute the role of the cluster-head among the wireless sensor nodes in the same cluster, is vital to increase the lifetime of the sensor nodes in the clusters.
and in the whole network. Our proposed technique is better in terms of performance than the original structure of these protocols, which are cluster-tree and AODV. It has increased the lifetime of the wireless sensor nodes, and increased the lifetime of the WSN by around 50% of the original network lifetime.

The objective of this chapter is to design a model by which to distribute the role of cluster-heads among the wireless sensor nodes and to examine its efficiency in WSNs, and on distributing the power consumption among the wireless sensor nodes. This technique increases the lifetime beyond that which would have been sustained by the original AODV and Cluster-tree routing protocols.

7.2 Related Works

Figure 7-1 Multi-cluster network consists of many single clusters (IEEE P802.15, 2001)

Dividing the network into clusters can reduce the number of devices sharing the same channel and reduce the control overhead, which leads to more energy saving. As shown in Figure 7-1, the cluster-tree network consists of many single clusters. The cluster-tree network has a special node called Designated Device (DD), which is linked to these single clusters and acts as the network coordinator. In
each single cluster, there is a cluster-head, which is responsible for establishing the cluster and asking the wireless sensor nodes to join the cluster. Therefore, this cluster-head performs more operations than any other regular node in the cluster, which will lead to this cluster-head consuming more energy than the other ordinary nodes in the cluster. Consequently, distributing the role of the cluster-head from one node to another will distribute the cluster-head operations and save more energy, which will lead to an increase in the lifetime of these nodes and the network lifetime. Therefore, the main problem of the cluster-tree routing protocol is that the power consumption of the cluster-heads will lead to them dying quickly. This will isolate the other ordinary nodes in the clusters and loose the entire cluster from the WSN.

LEACH is one of the most famous clustering protocols. In LEACH, some nodes nominate themselves to act as a cluster-heads. These sensor nodes will choose a random number between zero and one. If this number is less than the threshold value of the node, then this node will act as a cluster-head. LEACH distributes the role of cluster-heads among the wireless sensor nodes by repeating the process of choosing the cluster-heads based on the threshold value \( T(n) \) of the node \( n \), which is calculated based on the following formula as mentioned in Chapter 2 (Jolly & Latifi, 2006).

\[
T(n) = \frac{p}{1 - p(r \mod (1/p))} \tag{2-1}
\]

Where, \( p \) is the set of the nodes, which nominated themselves to be cluster-heads, and \( r \) is the random number between zero and one. Obviously, the threshold value is not depended on the energy level of the nodes in choosing the cluster-heads. However, there are two drawbacks of using this protocol. Firstly, LEACH assumes that the energy levels of the wireless sensor nodes in the network are the same for each node, therefore any node can nominate itself to act as cluster-head.
Second, LEACH also presumes that each node always has data to send to the base station based on the transmission schedule.

Another clustering protocol is Power Efficient Gathering in Sensor Information Systems (PEGASIS). PEGASIS is suggested as an enhancement to LEACH. The patterns, which are formed by the wireless sensor nodes, are considered as clusters. In PEGASIS, each node can talk only to its neighbours, but can directly talk to the base station (Jolly & Latifi, 2006). On the other hand, this protocol assumes that each node has the capability to link directly to the base station, which is not possible in most cases. PEGASIS also requires that each node to have a database to store information about the locations of its neighbours, which will lead to greater demands for memory and power.

One of the best clustering protocols is the cluster-tree topology, which is included into the ZigBee standard. The cluster-tree protocol is a self-organised protocol and supports network redundancy to provide fault tolerance in the network. The cluster-tree protocol uses packet negotiation to form either a single cluster network or a multi-cluster network. The cluster formation process is comprised of two stages; selection of the cluster-head and expanding links to the other nodes in the network (Ergen, 2004).

However, in each single cluster there is only one fixed node acting as a cluster-head during the entire network lifetime. This cluster-head has to expend more energy to manage and maintain links between the nodes inside the cluster, and among the clusters. Therefore, the cluster-heads form the bottlenecks of the cluster-tree network.

In the cluster-tree, the ZigBee end-device can act as a leaf node in the cluster. The ZigBee router can be connected to the cluster-tree network as a cluster-head or leaf node. As shown in Figure 7-1, the ZigBee coordinator will always act
as a DD. This DD is responsible for establishing the network, forming the links between the cluster-heads and the DD, choosing the shortest path to each cluster, and assigning a unique cluster identity number (ID) to each cluster. Moreover, there are border nodes to connect the single clusters with each other on the way to the DD. These border nodes could be any leaf node in the network, or they could themselves be the cluster-heads.

7.3 Proposed Mechanism

In this section, we introduce a new mechanism to distribute the role of the fixed cluster-head among some of the sensor nodes in each cluster of the cluster-tree network based on the AODV and cluster-tree routing protocols. In our protocol, we will modify the cluster-tree topology based on the LEACH idea to distribute the role of the cluster-head among some nodes in the same cluster, but this distributed process is based on the remaining energy of the wireless sensor nodes inside the cluster. By regularly choosing the most capable device to act as a cluster-head, we can distribute power consumption and increase the network lifetime. If the consumption power of the cluster-head is very high, then the AODV routing protocol will choose another node to act as a cluster-head in order to distribute the responsibility of the cluster-head among other wireless sensor node in the same cluster. The new node, which acts as the cluster-head, should have more energy remaining than the existing one. In addition, it has to be a Full Function Device (FFD). Hence, only a ZigBee router can act as a cluster-head.

The AODV routing protocol chooses the new cluster-head based on a weighted value. This value has been generated to identify the next cluster-head in the cluster when the consumption rate of the current cluster-head is high. This weight $W$ is represented in the following weight formula

\[ W = \text{RemEngRatio} + NN + H \]  

(7-1)
Where, $NN$ is the number of the neighbour nodes, $H$ is the number of hops from the source node to this node, and $RemEngRatio$ is the ratio of the remaining energy of the node. This ratio can be calculated based on the following formula:

$RemEngRatio = \frac{RemEng}{InitEng}$  \hspace{1cm} (7-2)

Where, $InitEng$ is the initial level of the node energy, which is provided to the node, when this node joined the network, and $RemEng$ is the remaining energy of the wireless sensor nodes. This remaining energy can be calculated by applying the Chapter 4 equation.

$RemEng = InitEng - ((PktT \times TEng) + (PktR \times REng))$  \hspace{1cm} (4-4)

Where, $PktT$ is the number of packets transmitted by this node. $TEng$ is the transmission energy required to transmit each packet. $PktR$ is the number of the received packets. $REng$ is the energy consumed by receiving one packet. However, if the $W$ value was the same for more than one node, AODV will choose any one of them.

As explained in Chapter 4, the rate of the energy consumption of the cluster-heads can be calculated based on this formula.

$ConsRate = \frac{InitEng - RemEng}{TimePeriod}$  \hspace{1cm} (4-1)

Where, the $TimePeriod$ is the period of time that the node takes to consume this amount of the energy.

There are two phases in establishing the network and routing the data. The cluster-tree protocol is responsible for the first phase of establishing the network. This phase includes dividing the WSN into several clusters, then choosing the
cluster-heads of each single cluster, and asking the wireless sensor nodes to join the cluster-heads.

The AODV routing protocol is responsible for the second phase of routing the data and sending the data from the source to the destination nodes. Consequently, during the AODV phase the new cluster-head will be chosen during the forward process based on the weight value calculated using Equation (7-1). The next section will show the implementation of choosing the cluster-heads.

### 7.4 Implementation

![Flow chart to implement the new technique](image)

Figure 7-2 Flow chart to implement the new technique
As shown in Figure 7-2, the implementation of this technique goes through two phases. The first phase, which is "establishing the network" phase, includes the following steps:

Step 1: After starting the network, the wireless sensor nodes will be divided into several clusters in the WSN.

Step 2: One node will be chosen as a cluster-head in each cluster. This cluster-head will use the negotiation system of the cluster-tree protocol discussed in Chapter 3 to send joining messages to the nodes near the cluster-head.

Step 3: After that, the cluster-heads will send invitations to the wireless sensor nodes in each cluster asking them to join the cluster-heads to form the clusters.

The second phase includes the "transferring data process" and the "distributing the role of cluster-head process". The AODV routing protocol is responsible for sending the data from the source to the destination nodes. The role of distribution is determined by regularly selecting a set of new cluster-heads based on the weight value in Equation (7-1).

Step 1: When any wireless sensor node needs to send a message, it has to check its routing table and look for a path to the destination node. Therefore, if the route is available in the routing table, it will forward the message to the next node. Otherwise, the message will be saved in a queue, and the source node will send the RREQ packet to its neighbours to commence the discovery process.

Step 2: During the forwarding of the message to the destination, the rate at which power is consumed by the cluster-head will be calculated based on the energy model in Chapter 4. If the energy consumption rate is high, then the procedure will choose another node to act as cluster-head based on the W value in Equation (7-1).
Step 3: Then the procedure will remove the route from the routing table of the source, which will lead the source node to initiate the discovery process in phase 2 again and find a new path to the destination node through the new cluster-head.

7.5 Simulation Model

![Simulation Module for Cluster-tree WSN](image)

Figure 7-3 Simulation Module for Cluster-tree WSN

This section describes the simulation environment, and shows the results of the simulation of the proposed technique for distributing the responsibility of the cluster-head over more than one node in each cluster. These results are based on the AODV and cluster-tree routing protocols. This simulation is performed using the Network Simulator NS-2 (USC, 1989). The simulation uses AODV as a routing protocol to discover and maintain the routes between the source and the destination.
nodes. Moreover, this simulation uses IEEE 802.15.4 as a Medium Access Control (MAC) and Physical layer (PHY) protocols (IEEE Std 802.15.4-2003, 2003).

The simulation model consists of 81 wireless sensor nodes distributed in a grid area of size 80x80 meters with the TwoRayGround radio model. These sensor nodes are distributed randomly into five clusters; each cluster has a cluster-head, and there is a Designated Device acting as the coordinator of the WSN as shown in Figure 7-3. The distance between any two neighbour nodes is 16 meters. The range of the wireless signal transmission is 30 meters. A CBR traffic flow is generated between the source node and the coordinator in order to load the network with packet size 80 bytes and is renewed each 15 milliseconds. This CBR flow starts after establishing the network and after all the nodes have joined the cluster-heads in order to form the clusters. Each simulation runs for 500 seconds.

This simulation uses the NS-2 default energy model, which represents the energy level of the wireless sensor nodes. The energy model includes three initial values: the initial energy of the nodes (InitEng), the transmission power (txPower), which is used up transmitting each packet, and the reception power (rxPower), which is consumed on receiving each packet. The output of this model is the total remaining energy, packets transmission energy, and the reception energy of each node. This NS-2 energy model decreases the current energy of the node, when the node transmits and receives packets by applying the following equations as mentioned in Chapter 4 (Fall & Varadhan, 2007).

\[ \text{Node}_\text{Eng} = \text{Node}_\text{Eng} - (\text{txPower} \times \text{txTime}) \]  
\[ (4-6) \]

\[ \text{Node}_\text{Eng} = \text{Node}_\text{Eng} - (\text{rxPower} \times \text{rxTime}) \]  
\[ (4-7) \]

Where, \( \text{Node}_\text{Eng} \) is the node energy, and initially is equal to the initial energy of the node, \( \text{txTime} \) is the time required to transmit each packet, and \( \text{rxTime} \) is the time required to receive each packet. In this simulation, the initial full energy
is equal to 4.0 joules. The transmission power and the reception power are equal to 1.0 watt. Most of the simulation parameters are shown in Table 7-1.

### Table 7-1 Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>InitEng</td>
<td>4.0 Joules</td>
</tr>
<tr>
<td>rxPower</td>
<td>1.0 Watt</td>
</tr>
<tr>
<td>txPower</td>
<td>1.0 Watt</td>
</tr>
<tr>
<td>Packet Size</td>
<td>80 Bytes</td>
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<tr>
<td>Packet Interval</td>
<td>15 Milliseconds</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>500 Seconds</td>
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<td>Number of Nodes</td>
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<td>Antenna Type</td>
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<tr>
<td>Radio Model</td>
<td>TwoRayGround</td>
</tr>
<tr>
<td>Grid Size</td>
<td>80X80 meter</td>
</tr>
<tr>
<td>Distance between neighbours</td>
<td>16meter</td>
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<tr>
<td>Routing Protocol</td>
<td>AODV</td>
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<td>MAC Protocol</td>
<td>MAC/802_15_4</td>
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<tr>
<td>System Loss (<em>L</em>)</td>
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</tr>
<tr>
<td>Gain Transmitter antenna (Gt)</td>
<td>1.0</td>
</tr>
<tr>
<td>Gain Receiver antenna (Gr)</td>
<td>1.0</td>
</tr>
<tr>
<td>Transmitter Hieght (Ht)</td>
<td>1.5meter</td>
</tr>
<tr>
<td>Receiver Hieght (Hr)</td>
<td>1.5meter</td>
</tr>
</tbody>
</table>

As shown in Figure 7-3, the cluster-head node (4) has high power consumption. Therefore, our proposed technique calculates the weight values for some of the router nodes. These routers are the candidates to assume the role of the cluster-head. Only one cluster-head can serve the cluster at a time in our proposed technique.

### 7.6 Simulation Results

In this simulation, performance indexes are compared against the basic AODV and cluster-tree routing protocols, and the new technique of distributing the role of cluster-head among more than one wireless sensor node in the same cluster. The indexes include the energy consumption rates of wireless sensor nodes, the
lifetime of the nodes, and the lifetime of the WSN. The performance evaluation of these protocols has been carried out under the same traffic source, the same network loads, the same parameters, and the same simulation environments.

![Power Consumption Rate](image)

**Figure 7-4 Power consumption rate of the wireless sensor nodes**

Figure 7-4 shows the simulation result of the energy consumption rate of each node using both the new technique and the original AODV and cluster-tree routing protocols. The new technique has reduced the energy consumption rate of most of the nodes to less than the basic AODV and cluster-tree routing protocols. While the average energy consumption rate of the wireless sensor nodes in the basic AODV was around 0.0128 joules per second, the new technique has reduced the average to around 0.0083 joules per second.

Consequently, the lifetime of the wireless sensor nodes has been increased by using the new distributing technique instead of the original fixed cluster-head protocol. The new technique has raised the average lifetime of the wireless sensor node to 1899.8 seconds, where, the original average lifetime of the wireless sensor nodes was around 1795.2 seconds as shown in Figure 7-5.
Assuming that the lifetime of the WSN is the lifetime of the critical nodes, the coordinator and the cluster-heads, then the lifetime of the WSN in this simulation was around 600 seconds based on the basic AODV and cluster-tree routing protocols. Figure 7-6 clearly shows that the new technique has increased the lifetime of the WSN to around 900 seconds.
It is obvious from the simulation results that the new technique has better performance than the original AODV and Cluster-tree routing protocols in terms of reducing the average energy consumption rate of the wireless sensor node, increasing the average lifetime of the wireless sensor nodes, and increasing the lifetime of the whole WSN.

7.7 Conclusion

Energy consumption is a significant concern in the WSNs, especially as the energy consumption of the cluster-heads in the cluster-tree network has to be high because of the numerous operations, which they manage in the network. The cluster-tree has fixed nodes act as cluster-heads during the complete WSN lifetime leading to exhausting their power quickly and loosing the entire cluster's nodes from the network.

In this chapter, we have proposed a new technique to distribute the role of cluster-head among some of the wireless sensor nodes based on a weight value including the remaining energy of the sensor nodes. This proposed new technique aims to increase the lifetime of the whole network, and increase the number of nodes, which will remain alive for the maximum period of time.

The performance evaluation in terms of network lifetime was conducted using the NS-2 simulator. We compared the original AODV and cluster-tree routing protocols with the new technique under the same simulation conditions and parameters values. Results show that the proposed technique has improved the performance in terms of increasing the total network lifetime, and decreasing the energy consumption rate of each wireless sensor node in the WSNs by around 50% of the original network lifetime.
Chapter 8
Selecting the Number of Clusters and the Cluster-heads in WSN

8.1 Background and Motivation

Clustering wireless sensor nodes and choosing leader nodes to aggregate data sent is considered as a primary method for conserving energy and increasing network lifetime. Many researchers have worked on designing clustering protocols for WSN. However, few of the clustering algorithms have considered how to determine the number of clusters and the selection of the best cluster-head required in each cluster. In particular, none of these clustering algorithms has considered the energy level of the wireless sensor nodes in order to determine how many clusters are required in the network and the selection of the optimal node to act as the cluster-head in each cluster. In this chapter, we have applied a new technique to determine the number of clusters and define the best cluster-head for each cluster in the WSN based on the energy level of the wireless sensor nodes. We have compared this technique with the cluster-tree protocol of the ZigBee standard. Based on the simulation results, the new clustering technique has increased the lifetime of the
WSN by around 35% compared to the original lifetime using the cluster-tree routing protocol.

A large density of sensor nodes in WSNs may improve the network performance in terms of fault tolerance and enhance the nodes communications in the network (Akyildiz et al., 2004). However, this density will increase the data redundancy and increase the number of transmissions, and the number of the control messages between the sensor nodes and the sink node. Obviously, the transmission of redundant data will consume more energy and decrease the network lifetime without many benefits. Therefore, dividing this large number of nodes into groups (clusters), and defining one node as leader node (cluster-head) for each group as shown in Figure 8-1, will reduce the number of transmissions between the sensor nodes and the sink node (coordinator) by aggregating the redundant data at the cluster-head of each cluster. After that, the cluster-heads will only forward one version of the redundant data to the coordinator or the base station.

Figure 8-1 Wireless Sensor Nodes within three clusters (Oyman & Ersoy, 2004)
The objective of this chapter is to propose a model for dividing the wireless
sensor nodes into clusters and defining the cluster-heads based on the energy level
of the nodes and provide evaluation of its efficiency in WSNs. This technique
increases the lifetime beyond that which would have been sustained by the original
cluster-tree protocol over the ZigBee standard. The number of clusters in the WSN
is determined based on the full initial energy of the wireless sensor nodes in the
WSN. In addition, the cluster-heads are determined in each cluster based on the
remaining energy of the wireless sensor node. Therefore, the node that has the
highest remaining energy will serve as the cluster-head of the cluster.

8.2 Related Works

The cluster-head controls the communication process both among the nodes
in the cluster, and also between the nodes in the cluster and the PAN coordinator.
The cluster-head is also responsible for aggregating the gathered data before
sending the data to the sink node directly or through multi-hop communications.
The cluster schema can conserve energy in the WSN in two ways. Firstly, the
existence of the cluster-head reduces the overall number of transmissions to the sink
node. Secondly, the cluster schema has increased the number of nodes in the sleep
mode, because the cluster-head can manage many of the cluster nodes activity based
on some form of TDMA-based Scheduling (Valjic & Xia, 2006). There are many
algorithms and techniques for grouping the wireless sensor nodes into categories
such as tree-clustering, k-mean clustering, and expectation maximization clustering.
However, in this section, we will concentrate on the algorithms concerned with
calculating the optimal number of clusters and the cluster-head selection process.

Linked Cluster Algorithm in (Baker & Ephremides, 1981) is a clustering
technique, which chooses the cluster-heads based-on Identification number (ID).
The sensor node that has the highest ID among its one-hop neighbours will become
the cluster-head. While, in Adaptive Clustering technique, the sensor node will
become a cluster-head, if it has the lowest ID among the sensors within one hop neighbours (Lin & Gerla, 1997).

There are other weight value dependent clustering algorithms such as the Distributed Clustering algorithm and the Weighted Clustering algorithm. The node with the largest weight value will be chosen as a cluster-head and the weight value represents a mobility related parameter in the Distributed Clustering algorithm (Bassagni, 1999). In contrast, the Weighted Clustering algorithm chooses the cluster-head based on the smallest weight value. In addition, this weight value represents many parameters such as node degree, sum of distance to all neighbours, rate of the node, the total time the node served as cluster-head (Chatterjee et al., 2002).

Other clustering algorithms generate a predefined number of clusters such as the Max-Min D-cluster and the connectivity based K-hop clustering algorithms. The maximum distance between each node and the cluster-head in the Max-Min D cluster should at most be equal to the distance (d) hops and at least equal to one hop. Therefore, the maximum number of hops is equal to d, and the minimum number of hops is equal to one. This means each cluster has a complexity of O(d) (Amis et al., 2000). The K-hop clustering algorithm divides the wireless sensor nodes into K-clusters based on a combination of the node degree and the node ID (Nocetti et al., 2002).

Some clustering protocols divide the WSN into clusters based on the type of collected data from the sensor nodes such as Local Negotiated Clustering Algorithm (LNCA). LNCA chooses the number of clusters based on correlated data readings (Valjic & Xia, 2006).
One of the latest clustering protocols is the cluster-tree protocol, which is supported by one of the latest WSN standards “ZigBee standard”. The cluster-tree protocol is a self-organised protocol that supports network redundancy to cover the fault tolerant in the WSN. Cluster-tree protocol uses packet negotiation to form either a single cluster network or a multi-cluster network. The cluster formation process is comprised of two stages, selection of the cluster-head and the formation of links to the other nodes (ZigBee Alliance, 2005). However, neither of these operations, choosing the number of clusters or choosing the cluster-head in each cluster, considers the energy level of the wireless sensor node. As shown in Figure 8-2 the multi-cluster network consist of many single clusters, and each single cluster has a cluster-head, the Designated Device (DD) is acting as the main cluster-head or the coordinator of the WSN.

In this chapter, we will apply a clustering technique based on the remaining energy of the wireless sensor node to choose the number of clusters in the WSN,
and to define the best cluster-head of each cluster. This technique will be applied based on the ZigBee standard.

8.3 Proposed Mechanism

In this section, we introduce a new mechanism to calculate the number of clusters in the WSN before establishing the network and to define which node will act as the cluster-head for each cluster in the WSN.

Assuming that the number of clusters in the cluster-tree network is equal to $CN$ clusters and the consumption of these "CN" clusters can equally share the full energy, $\text{FullEng}$, of the WSN. Therefore, each cluster can consume energy up to the maximum energy consumption, $\text{MaxCons}$. This $\text{MaxCons}$ can be calculated based on the following formula:

$$\text{MaxCons} = \frac{\text{FullEng}}{CN} \quad (8-1)$$

Consequently, any cluster in the new number of clusters, $\text{NewCN}$, should consume less than the $\text{MaxCons}$ in order to reduce the consumption energy of each cluster. Based on (Miyagoshi et al., 2005) the energy consumption of the cluster is equal to the total of energy consumed by transmitting data and receiving data from each node in the cluster. Therefore, the best case for consuming energy in a cluster is transmitting a data packet to the coordinator from the furthest node in the network through one cluster's nodes. This will keep the other nodes in the other clusters staying in the sleep mode. The consumption energy of the best case will be the minimum consumption energy, $\text{MinCons}$, which each cluster can consume in our mechanism. This $\text{MinCons}$ can be calculated by sending one data packet from any of the furthest nodes to the coordinator based on the following formula:

$$\text{MinCons} = \text{NoHops} \times \text{PktNo} \times (\text{TEng} + \text{REng}) \quad (8-2)$$
Where, \( \text{NoHops} \) is the number of hops between the furthest node in the
network and the coordinator, \( \text{PktNo} \) is the number of packets transferred from the
furthest node to the coordinator. In the best case, the \( \text{PktNo} \) is equal to one packet in
order to calculate the minimum consumption energy, \( \text{TEng} \) is the transmission
energy required to transmit one packet from any node to reach the other node in the
rout, and \( \text{REng} \) is the energy consumed by receiving one packet. The \( \text{TEng} \) and
\( \text{REng} \) can be calculated based on the following equations respectively:

\[
\text{TEng} = \text{txPower} \cdot \text{txTime} \quad (8-3)
\]

\[
\text{REng} = \text{rxPower} \cdot \text{rxTime} \quad (8-4)
\]

Where, \( \text{txPower} \) is the transmission power required to transmit one packet,
\( \text{txTime} \) is the required time to transmit each packet, \( \text{rxPower} \) is the reception power
consumed by receiving each packet, \( \text{rxTime} \) is the required time to receive each
packet.

Therefore the new cluster number \( \text{NewCN} \), can be calculated based on the
following formula.

\[
\text{NewCN} = \frac{\text{FullEng}}{\text{MinCons}} \quad (8-5)
\]

After calculating the new number of clusters \( \text{NewCN} \), the cluster-head in
each cluster will be determined based on the remaining energy, \( \text{RemEng} \). In
addition, there are a few constraints for any node acting as cluster-head.

Assuming that, \( \text{CH} \) is a set including all the nodes that can be acting as
cluster-heads in each cluster.

\[
\text{CH} = \{ \text{node } i \} , i \in \{1,...,n\} \quad (8-6)
\]
Where, \( n \) is the number of the nodes inside the cluster, and \( R \) is a set including all the remaining energy of the \( n \) nodes.

\[
R = \{\text{RemEng}_i\}, i \in \{1, ..., n\} \tag{8-7}
\]

Therefore, the cluster-head \( CH \) of the cluster will be the node that has the maximum remaining energy.

\[
\max_{i=1, ..., n} (\text{RemEng}_i) \rightarrow CH \tag{8-8}
\]

Where,

\[
CH \notin LN \tag{8-9}
\]

Where, \( LN \) is a set including all the leaf nodes in the cluster. Therefore, the first constraint for finding the optimal node to act as cluster-head is that the cluster-head node should not be a leaf node in the cluster, which means that the cluster-head should be a router node in order to be able to communicate with several nodes and this router should have as many neighbour nodes as possible which is not always available for the leaf nodes. The second constraint is that the remaining energy of the node, \( \text{RemEng} \), should not be equal to zero.

\[
CH = \text{null, if RemEng} = 0 \tag{8-10}
\]

This remaining energy can be calculated based on the energy model in Chapter 4 by applying the following equation.

\[
\text{RemEng} = \text{InitEng} - ((\text{PktT} \times T\text{Eng}) + (\text{PktR} \times R\text{Eng})) \tag{4-4}
\]

Where, \( \text{InitEng} \) is the initial energy of the node, \( \text{PktT} \) is the number of packets transmitted by this node. \( T\text{Eng} \) is the transmission energy required to transmit each packet as calculated in Equation (8-3). \( \text{PktR} \) is the number of the received packets. \( R\text{Eng} \) is the energy consumed by receiving one packet as...
calculated in Equation (8-4). The third constraint for choosing the cluster-head is that the cluster node should be the node with the maximum number of neighbour nodes in the cluster, because if any fault happens in any neighbour path, the cluster-head can use any other neighbour paths. However, if the remaining energy value and the other constraints were all the same for more than one node, our proposed technique will choose any one of them to act as cluster-head randomly.

8.4 Implementation

![Flow chart to implement the new technique](image)

Figure 8-3 Flow chart to implement the new technique
This section will show the implementation of dividing the WSN into number of clusters and choosing the cluster-head for each cluster. As shown in Figure, 8-3 the implementation of this technique goes through the following steps:

**Step 1:** While starting the WSN, the network should calculate the Full energy of the WSN.

**Step 2:** Then, the minimum consumption energy of each cluster, \( MinCons \), should be calculated based on equation (8-2).

**Step 3:** The WSN should be divided into number of clusters equal to \( NewCN \), after calculating \( NewCN \) based on equation (8-5).

**Step 4:** After dividing the WSN into clusters, a set including all the nodes in each cluster, which have the ability to be the cluster-head of those clusters, will be defined.

**Step 5:** The cluster-head for each cluster will be selected based on the maximum remaining energy and other constraints as defined in equation (8-8).

**Step 6:** The cluster-heads will start sending invitations to the neighbour sensor nodes in the WSN asking them to join the cluster-heads in order to form the clusters.

### 8.5 Simulation Model

This section describes the simulation environment, and shows the results of the simulation to verify the proposed technique for defining the number of clusters in the WSN, and choosing the cluster-heads in each cluster. The simulation is accomplished using the Network Simulator NS-2. The simulation uses AODV as a routing protocol to discover and maintain the routes between the source and the destination nodes. Moreover, this simulation uses IEEE 802.15.4 as a Medium
Access Control (MAC) and Physical layer (PHY) protocols (IEEE std 802.15.4, 2003).

The simulation model consists of 101 wireless sensor nodes distributed in a grid area of size 80x80 meters with the TwoRayGround radio model. These sensor nodes are distributed systematically and there is a central node, which acts as the network coordinator as shown in Figure 8-4. The distance between any two neighbour nodes is around 7 meters. The range of the wireless signal transmission is 9 meters. A CBR traffic flow is generated between four source nodes and the coordinator with a packet size of 80 bytes in order to load the network. Each CBR flow is renewed every 15 milliseconds. All the CBR flows are initiated after establishing the network and forming the clusters. Each simulation runs for 500 seconds.

This simulation uses the NS-2 default energy model, which represents the energy level of the wireless sensor nodes. The energy model includes three initial values: the initial energy of the nodes (\(InitEng\)), the transmission power (\(txPower\)) that is used on transmitting each packet, and the reception power (\(rxPower\)), which is consumed on receiving each packet. The output of this model is the total remaining energy, packets transmission energy, and the reception energy of each node. This NS-2 energy model decreases the current energy of the node, when the node transmits and receives packets by applying the following equations as mentioned in Chapter 4 (Fall & Varadhan, 2007).

\[
Node\_Eng = Node\_Eng - (txPower \times txTime) \quad (4-6)
\]

\[
Node\_Eng = Node\_Eng - (rxPower \times rxTime) \quad (4-7)
\]

Where, \(Node\_Eng\) is the node energy, and initially it is equal to the initial energy of the node, then it will be the current energy of the node.
In this simulation, the initial full energy is equal to 4.0 joules. The transmission power and the reception power are equal to 1.0 watt. These simulation parameters are shown in Table 8-1.

**Table 8-1 Simulation Parameters**

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>InitEng</td>
<td>4.0 Joules</td>
</tr>
<tr>
<td>rxPower</td>
<td>1.0 Watt</td>
</tr>
<tr>
<td>txPower</td>
<td>1.0 Watt</td>
</tr>
<tr>
<td>Packet Size</td>
<td>80 Bytes</td>
</tr>
<tr>
<td>Packet Interval</td>
<td>15 Milliseconds</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>500 Seconds</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>101</td>
</tr>
<tr>
<td>Antenna Type</td>
<td>OmniAntenna</td>
</tr>
<tr>
<td>Radio Model</td>
<td>TwoRayGround</td>
</tr>
<tr>
<td>Grid Size</td>
<td>80x80 meter</td>
</tr>
<tr>
<td>Distance between neighbours</td>
<td>7 meter</td>
</tr>
</tbody>
</table>
Chapter 8 Selecting the Number of Clusters and the Cluster-heads in WSN

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission Range</td>
<td>9 meter</td>
</tr>
<tr>
<td>Routing Protocol</td>
<td>AODV</td>
</tr>
<tr>
<td>MAC Protocol</td>
<td>MAC/802_15_4</td>
</tr>
<tr>
<td>System Loss (L)</td>
<td>1.0</td>
</tr>
<tr>
<td>Gain Transmitter antenna (Gt)</td>
<td>1.0</td>
</tr>
<tr>
<td>Gain Receiver antenna (Gr)</td>
<td>1.0</td>
</tr>
<tr>
<td>Transmitter Height (Ht)</td>
<td>1.5 meter</td>
</tr>
<tr>
<td>Receiver Height (Hr)</td>
<td>1.5 meter</td>
</tr>
</tbody>
</table>

Figure 8-5 ZigBee's randomisation clusters and cluster-heads

After starting the network based on the ZigBee cluster-tree protocol, the network was divided into four clusters and the cluster-heads have been chosen randomly. Figure 8-5 shows the four clusters of the wireless sensor nodes, and the four cluster-heads of these clusters.

In the simulation, the full energy of the WSN is equal to 400 joules. In order to calculate the minimum consumption energy based on Equation (8-2), we need to
know that the number of hops from the furthest node to the coordinator is equal to five. The packet number is equal to three, because in order to send one data packet in AODV, three packet should be sent through these hops which are the route request RREQ, the route reply RREP, and the data packet DATA. In addition, the transmission and the reception powers are equal to 1.0 watt, and the time required to transmit and receive these packets through the hops is approximately 1.5 seconds. By substituting these values in equation (8-2), where

\[ MinCons = 6 \times 3 \times ((1 \times 1.5) + (1 \times 1.5)) = 54 \text{ joules} \]

Therefore, the new number of clusters based on our clustering technique is seven in terms of Equations (8-5) in the proposed model. In addition, the cluster-heads were selected based on the remaining energy as in Equation (8-8), and the other constraints as shown in Figure 8-6.
8.6 Simulation Results

In the simulation, we have compared these two techniques, the ZigBee cluster-tree technique, and our proposed clustering technique together in terms of energy consumption rate of the wireless sensor nodes, the lifetime of the wireless sensor nodes, and the lifetime of the WSN. The performance evaluation of these clustering techniques has carried out under the same traffic source, network load, parameters, and the same simulation environment conditions.

![Energy Consumption Rate](image)

**Figure 8-7 Energy consumption rate of the sensor nodes**

The first simulation results have been compared, were the energy consumption rates of the wireless sensor nodes in the WSN. Figure 8-7 shows the simulation results of the energy consumption rates of the sensor nodes in the WSN using both techniques separately. The new proposed clustering technique has reduced the energy consumption rate of the most nodes to a value less than the ZigBee cluster-tree protocol. Consequently, the average of the energy consumption rates for the wireless sensor nodes in the cluster-tree protocol was around 0.019...
joules per second, while the new clustering technique has reduced this average to become around 0.009 joules per second.

![Nodes Lifetime Graph](image)

**Figure 8-8 Wireless sensor nodes lifetime**

Consequently, the new clustering technique has increased the lifetime of most of the wireless sensor nodes more than the cluster-tree protocol. Figure 8-8 shows the simulation results of the lifetime for the wireless sensor nodes in both techniques. The lifetime average of the wireless sensor nodes has increased from 428 seconds in the cluster-tree protocol to reach 602 seconds in the new clustering technique.

Assuming that the lifetime of the WSN is the lifetime of the last cluster-head in the network. Therefore, the new clustering technique has increased the lifetime of the WSN more than the ZigBee cluster-tree protocol by approximately 35% as shown in Figure 8-9.
Figure 8-9 Cluster-heads lifetime in the WSN

Obviously, all the simulations results prove that our proposed clustering technique has better performance than the ZigBee cluster-tree protocol in terms of reducing the energy consumption rate average for the wireless sensor nodes, increasing the lifetimes average for the wireless sensor nodes, and increasing the lifetime of the entire WSN.
8.7 Conclusion

The ZigBee standard uses the cluster-tree protocol in order to establish the WSN and link the nodes to each other. The cluster-tree protocol divides the network into clusters and chooses the cluster-head of each cluster without any consideration of the energy power of the wireless sensor nodes.

In this chapter, we have proposed a new clustering technique to divide the WSN into several clusters and to choose the cluster-head of each cluster based on the energy level of the wireless sensor nodes. The proposed technique aims to increase the network lifetime by assigning the cluster-head role to the most capable node in each cluster in the WSN, and by determining the number of the clusters in the WSN based on the energy level of the sensor nodes.

The performance evaluation in terms of network lifetime, nodes lifetime, and nodes energy consumption rate was conducted using the NS-2 simulator. A comparison between the new clustering technique and ZigBee cluster-tree protocol has been conducted under the same simulation conditions. Results show that the new clustering technique has improved the performance of the WSN in terms of increasing the network lifetime, and decreasing the energy consumption rate of the wireless sensor nodes by approximately 35% compared with the original ZigBee cluster-tree protocol.
9.1 Background and Motivation

The AODV routing protocol is a famous routing protocol used in WSNs because it is very efficient in use of bandwidth, delivery ratio, and control messages overheads compared with other routing protocols. AODV uses the number of hops and a sequence number to discover the shortest and the freshest route in the WSN. Routing protocols based on the shortest path are not usually energy aware routing protocols. Therefore, the AODV is not an energy aware routing protocol in term of discovering routes or transferring data between the source and the destination nodes.

In this chapter, a new technique is introduced in order to make the AODV discover the routes based on the energy levels of the intermediate nodes between the source and the destination nodes. This technique selects the route with the highest energy levels in order to transfer the data. Because of the regular change in the energy levels of the sensor nodes over the route, we have merged our distributing technique in Chapter 4 with this new technique in order to distribute the role of routing among the wireless sensor nodes, initiate the route discovery process, and utilise the highest
energy route frequently. The new technique and the hybrid technique increased the lifetime of the WSN by around 5.5% and 8% respectively.

AODV is supported by one of the latest WSN standards "ZigBee standard", because it is a very efficient routing protocol compared with other routing protocols. AODV has low control messages overheads, and also uses less network bandwidth. Additionally AODV is also scalable for large density networks, and it offers loop-free and reliable routing because it uses the destination sequence number in order to know the valid freshest route. AODV has the ability to offer fault tolerance feature to cover any fault and node failure in the network through routing the data (Jing & Lee, 2004). The AODV routing protocol chooses the shortest route between the source and the destination nodes in order to transfer the data, however this selection method is not an energy aware selection technique, especially in this type of energy aware WSNs where saving energy, and increasing the network lifetime are significant demand. In addition, reducing the number of hops in the WSN may not be as important as in the internet, when selecting the shortest path through millions of hops is required. Obviously, the AODV does not consider the energy level of the wireless sensor nodes in the route discovery process.

9.2 Related Works

In (Jing & Lee, 2004) is proposed a technique to find the energy efficient route between two nodes based on the power cost of sending and receiving packets. However, the main drawback of this technique is that it does not consider the actual energy level of the nodes over the routes between the source and the destination nodes in order to determine the optimum route. In addition, they only consider the transmission and reception powers consumption cost. However, the low cost of the transmission and reception power consumption does not always mean that this route has the highest energy available to transmit the data. In addition, the transmission and reception power may be different from one node to another in the WSN,
especially, when applying our proposed technique in Chapter 6 to reduce the transmission and reception powers of each node.

The technique proposed in (Kim & Jang, 2006) is to improve AODV by applying an Energy Mean Value (EMV) algorithm. However, the EMV technique delays sending the RREP packet back to source node waiting for other RREQ packets through other routes, which may make the route discovery timer expire at the source node before receiving any RREP packet, leading the source node to initiate the route discovery process again. This will cause extra overhead of the control messages in the network. In addition, the EMV calculates the energy of the route by dividing the whole energy into the number of nodes in the WSN and then calculating the energy of the nodes participating in the route, which is not the actual energy of the nodes over that route.

Therefore, we have proposed a new algorithm to make the AODV routing protocol selecting the highest energy route in the WSN during the route discovery process. This route should have the highest energy at the time the route discovery process initiated. In order to keep using the routes that have the highest energy, we have merged this new technique with our previous approach in Chapter 4 to initiate the route discovery process several times rather than one time. This hybrid technique will guarantee selecting the highest energy route frequently.

9.3 Proposed Mechanism

Our proposed technique is to consider the amount of remaining energy of the intermediate wireless sensor nodes in each route in order to determine the best route in term of energy. In the AODV, the route selection is based on the number of hops, the shortest path, and the destination sequence number to make sure that the route is the freshest route between the source and destination nodes. However, the shortest path is not always the best path to transfer the data. Even while driving, shortest
route can be the slowest, or the worst serviced route to reach a certain destination in any trip. Our proposed technique discovers the highest energy route in the AODV route discovery process based on the energy level of the intermediate nodes in order to transfer the data between the source and the destination nodes. The route energy “RoutEng” represents the remaining energy of all the intermediate nodes on the route between the source and the destination, as shown in the following formula.

\[
RoutEng = \sum_{i=1}^{n} RemEng(i)
\]  (9-1)

Where, \( n \) is the number of nodes on the route to the destination node, and \( RemEng \) is the remaining energy of the sensor node and this remaining energy can be calculated based on the following formula as mentioned in Chapter 4:

\[
RemEng = InitEng - ((PktT \times TEng) + (PktR \times REng))
\]  (4-4)

Where, \( InitEng \) is the initial energy of the wireless sensor node, \( PktT \) is the number of packets transmitted by this node, \( PktR \) is the number of the received packets, \( TEng \) is the transmission energy required to transmit one packet from any node to reach the other node in the rout, and \( REng \) is the energy consumed by receiving one packet. The \( TEng \) and \( REng \) can be calculated based on the following equations respectively same as in Chapter 8:

\[
TEng = txPower \times txTime
\]  (8-3)

\[
REng = rxPower \times rxTime
\]  (8-4)

Where, \( txPower \) is the transmission power required to transmit one packet, \( txTime \) is the required time to transmit each packet, \( rxPower \) is the reception power consumed by receiving each packet, and \( rxTime \) is the required time to receive each packet.
Therefore, after calculating the route energy for all the available routes between the source and the destination nodes, our proposed technique will select the maximum route energy value ($\text{Max} (\text{RoutEng})$) of the highest energy route in order to use it in transferring the data packets.

In the original AODV, once the route is discovered, the source node will not be able to discover new routes, until the intermediate nodes on the route die because it has already selected the shortest path. Consequently, in our protocol because the energy level is always changeable and in order to refresh the route discovery process and selecting the highest energy route frequently, we have merged our proposed technique in chapter 4 with this new technique. This hybrid technique will calculate the energy consumption rate of the intermediate nodes and turn off the high consumption rate node. This will always cause the source node to look frequently for the highest energy route in the network, and distribute the routing process among most of the sensor nodes in the network.

9.4 Implementation

In order to implement our proposed technique, we have added an extra (32 bit) field to three structures in the AODV routing protocol, the RREQ, RREP headers, and the AODV routing table. These three fields will be used to save the value of the routes energy in order to compare them and find the highest energy route among them. The format of both of the RREQ, and the RREP packets become as shown in the Figures 9-2 and 9-3 with the added Route Energy fields.
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Start sending message

Dose the route exist in the routing table?

1. Insert message in queue.
2. RREQ Route Energy = 0.
3. Fill up some more fields in the RREQ header.
4. Broadcast the RREQ to the neighbours.

Is this the destination node?

1. RREQ Route Energy += Node energy.
2. Broadcast the RREQ to the neighbours.

Is this the destination node?

1. RREQ Route Energy += Node energy.
2. Update the route details in the route table including the route energy.
3. the RREP Route Energy = Destination node energy.
4. Send the RREP to the source node.

Is the consumption speed high?

1. Forward message to the next hop.

End

Check energy consumption speed of the next hop node.

Is this the source node?

1. Send the data message using the same detail of the route table

End

Figure 9-1 Flow chart to implement the new energy-efficient route discovery process

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In addition, the format of the routing table in our implementation includes the following fields with the route energy for each route:

- Route destination node address.
- Route destination sequence number.
- Route source node address.
- Route hops count.
Chapter 9 Energy-efficient Route Discovery Process in AODV

- RREQ ID.
- Next hop address.
- Routing flag.
- Route expire time.
- Route energy.

As shown in Figure 9-1, the implementation of the new proposed technique and the hybrid technique go through the following steps:

Step 1: when a source node does not find any route in the routing table to the destination node, it will initiate the route discovery process by broadcasting a RREQ packet which includes initial rout energy value equal to zero.

Step 2: any node that will receive the RREQ has to save the reverse route in the routing table before doing any further steps. If this node is not the destination node then it will add its remaining energy to the route energy field in the RREQ and broadcast that RREQ to its neighbours.

Step 3: when a destination node receives the RREQ, it will add its remaining energy to the route energy field and update the route details in the routing table. In addition, the destination node will send back a RREP packet with initial route energy value equal to the destination node energy.

Step 4: any intermediate node, will receive the RREP, will add its remaining energy to the RREP route energy value, and forward the RREP to the next hop in the reverse route.

Step 5: after receiving the RREP packet by the source node, it will compare the route energy in the RREP with the route energy in the routing table in order to select the maximum route energy. If the RREP route has the highest energy, then the source node will update the route details in the routing table and forward the
data packets based on that route. Otherwise, it will forward the data to the destination node through the highest route energy in the routing table.

**Step 6:** during the forward process in the AODV, the hybrid technique will check the consumption rate of the intermediate nodes based on the proposed approach in chapter 4 and allow the source node to initiate the discovery process again when any of these nodes has a high energy consumption rate. This will frequently keep the source node looking for the highest energy route in the WSN.

### 9.5 Simulation Model

This section describes the simulation environment, and shows the results of the simulation to verify the proposed technique of discovering the highest energy route in the WSN. This simulation is implemented using the Network Simulator NS-2 (USC, 1989). The simulation uses the original AODV, the new proposed AODV (AODVeng), and the hybrid AODV of the new technique with the technique of distributing the role of routing among the nodes (AODVeng+dist), as routing protocols to discover and maintain the routes between the source and the destination nodes. Moreover, this simulation uses IEEE 802.15.4 as a Medium Access Control (MAC) and Physical layer (PHY) protocols (IEEE std 802.15.4, 2003).
Chapter 9 Energy-efficient Route Discovery Process in AODV

The simulation model consists of 101 wireless sensor nodes distributed in a grid area of size 80x80 meters with the TwoRayGround radio model. These sensor nodes are distributed systematically and there is a central node acting as the network coordinator as shown in Figure 9-4. The distance between any two neighbour nodes is around 7 meters. The range of the wireless signal transmission is 9 meters. A traffic flow is generated between few source nodes and the coordinator as a destination node in order to load the network. The traffic flow type is Constant Bit Rate “CBR” traffic connection with packet size 80 bytes. This CBR is renewed each 15 milliseconds. All the CBR flows are initiated after establishing the network, and all the nodes joining the network. Each simulation runs for 800 seconds.

This simulation uses the NS-2 default energy model, which represents the energy level of the wireless sensor nodes. The energy model includes three initial values: the initial energy of the nodes (InitEng), the transmission power (txPower), which is used on transmitting each packet, and the reception power (rxPower),
which is consumed on receiving each packet. The output of this model is the total remaining energy, packets transmission energy, and the reception energy of each node. As mentioned in Chapter 4, this NS-2 energy model decreases the current energy of the node, when the node transmits and receives packets by applying the following equations (Fall & Varadhan, 2007).

\[
\text{Node} \_ \text{Eng} \leftarrow \text{Node} \_ \text{Eng} - (txPower \times txTime) \tag{4-6}
\]

\[
\text{Node} \_ \text{Eng} \leftarrow \text{Node} \_ \text{Eng} - (rxPower \times rxTime) \tag{4-7}
\]

Where, \text{Node} \_ \text{Eng} is the node energy, and initially it is equal to the initial energy of the node, then it will be the current energy of the node.

In this simulation, the initial full energy is equal to 4.0 joules. The transmission power and the reception power are equal to 1.0 watt. These simulation parameters and others are shown in Table 9-1.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>InitEng</td>
<td>4.0 Joules</td>
</tr>
<tr>
<td>rxPower</td>
<td>1.0 Watt</td>
</tr>
<tr>
<td>txPower</td>
<td>1.0 Watt</td>
</tr>
<tr>
<td>Packet Size</td>
<td>80 Bytes</td>
</tr>
<tr>
<td>Packet Interval</td>
<td>15 Milliseconds</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>800 Seconds</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>101</td>
</tr>
<tr>
<td>Antenna Type</td>
<td>OmniAntenna</td>
</tr>
<tr>
<td>Radio Model</td>
<td>TwoRayGround</td>
</tr>
<tr>
<td>Grid Size</td>
<td>80X80</td>
</tr>
<tr>
<td>Distance between neighbours</td>
<td>7 meter</td>
</tr>
<tr>
<td>Transmission Range</td>
<td>9 meter</td>
</tr>
<tr>
<td>Routing Protocol</td>
<td>AODV</td>
</tr>
<tr>
<td>MAC Protocol</td>
<td>MAC/802_15_4</td>
</tr>
<tr>
<td>System Loss ,(L,)</td>
<td>1.0</td>
</tr>
<tr>
<td>Gain Transmitter antenna ,(Gr)</td>
<td>1.0</td>
</tr>
<tr>
<td>Gain Reciever antenna ,(Gr)</td>
<td>1.0</td>
</tr>
<tr>
<td>Transmitter Height ,(Ht)</td>
<td>1.5 meter</td>
</tr>
<tr>
<td>Receiver Height ,(Hr)</td>
<td>1.5 meter</td>
</tr>
</tbody>
</table>
9.6 Simulation Results

In this simulation we have compared the using of the three routing protocols: the original AODV, the new proposed AODV discovering the routes based on the route energy (AODV_eng), and the hybrid of the AODV_eng with our distributing approach in chapter 4 to distribute the role of routing and reduce the energy consumption rate (AODV_eng+dist), in the WSN. The comparison was conducted by contrasting these techniques in terms of energy consumption rate of the wireless sensor nodes, the lifetime of the wireless sensor nodes, and the lifetime of the WSN. The performance evaluation of these routing techniques has been conducted under the same traffic source, network load, parameters, and the same simulation environment conditions.

![Energy Consumption Rate](image)

**Figure 9-5 Energy consumption rate of the sensor nodes**

The first simulation results compare the energy consumption rates of the wireless sensor nodes in the WSN. Figure 9-5 shows the simulation result of the energy consumption rate of each node in the WSN using the three techniques separately. The new proposed technique and the hybrid technique have reduced the rate at which energy is consumed for most nodes to less than the original AODV.
routing protocol. Consequently, the average energy consumption rates for the wireless sensor nodes in the original AODV was approximately 0.033 joules per seconds, the new technique AODVeng has reduced the average to 0.029 joules per seconds. However the hybrid technique, AODVeng+dist, has achieved the best result, where it reduce the energy consumption rate average to 0.023 joules per seconds.

Figure 9-6 Wireless sensor nodes lifetime

Consequently, the hybrid and the new techniques have both increased the lifetime of the wireless sensor nodes more than the original AODV routing protocol. Figure 9-6 shows the simulation results of the lifetime of the wireless sensor nodes for the three techniques. The lifetime average of the wireless sensor nodes has increased from approximately 313 seconds in the original AODV protocol to reach approximately 345 and 430 seconds in the new AODVeng technique and the hybrid technique AODVeng+dist respectively.

Assuming that, the lifetime of the WSN is the maximum lifetime of the sensor nodes or the lifetime of the last node to die in the network. Therefore, the hybrid technique has increased the lifetime of the WSN 8% more than the original
AODV protocol. It allowed more than 10% of the nodes to stay active for more than 550 seconds (e.g., in this 101 nodes WSN more than 10 nodes stayed alive more than 550 seconds, where the original AODV allowed for 3 nodes only to stay active after 550 seconds). In addition, the new technique has also increased the lifetime of the WSN by 5.5% as shown in Figure 9-7.

![WSN Lifetime](image)

Figure 9-7 Wireless sensor network lifetime

Obviously, all the simulations results prove that both, the new proposed technique $AODV_{eng}$ and the hybrid technique $AODV_{eng+dist}$ technique, have achieved better performance than the original AODV routing protocol in term of reducing the energy consumption rates average for the wireless sensor nodes, increasing the lifetime average for the wireless sensor nodes, and the lifetime for the entire WSN.

### 9.7 Conclusion

The AODV routing protocol is based on hops count and the destination sequence number in order to find the shortest and the freshest route. Therefore, the AODV routing protocol is not an energy aware routing protocol either in
transferring data or in discovering routes between the source and the destination nodes.

In this chapter, we have proposed a new technique to choose the highest energy route in the WSN based on the energy level of the intermediate wireless sensor nodes on the route to the destination node. The proposed technique aims to increase the network lifetime by transferring the data through the highest route energy in the network. We have merged this new technique with our previous approach in Chapter 4 in order to have a hybrid technique. This hybrid technique distributes the role of routing among the sensor nodes and makes the source node to initiate the route discovery process many times in order to select the highest route energy, because the route energy level is always changeable in the network depending on the data transmission and reception processes.

The performance evaluation in terms of the network lifetime, nodes lifetime, and nodes energy consumption rate was conducted using the NS-2 simulator. Comparisons between the hybrid, the new technique, and the original AODV routing protocols were accomplished under the same simulation conditions. Results show that the hybrid and the new technique have improved the performance of the WSN in terms of increasing the network lifetime, and decreasing the energy consumption rate of the wireless sensor nodes by around 8% and 5.5% respectively compared to the original AODV routing protocol.
Chapter 10
Conclusion and Future Work

10.1 Summary

In the previous chapters, a set of energy-aware WSN routing techniques for increasing the WSN lifetime were introduced. These algorithms have been presented, implemented, and studied. Their performances have been verified via the simulations results in NS-2.

Finding a feasible path for a data packet from a source node to a destination node is an essential task in WSNs. Many types of routing protocols for WSNs have been implemented for different applications such as military applications, health applications, home automation applications, and commercial applications. Despite this variation, it seems that one routing protocol cannot provide all the required functionality of routing. Moreover, one protocol cannot fit all the different scenarios and traffic patterns of WSN applications. This is due to the specific characteristics of WSNs. These characteristics include limited memory size, restricted energy, bandwidth constraints, mobility, and dynamic topologies.

The literature reviewed in this thesis contained two stages consisting of a general review and literature review. The general review was conducted in order to
Chapter 10 Conclusion and Future Work

identify the up-to-date developments for WSNs, the wireless communication standards mechanisms of WSNs, the structure of the wireless sensor node, the types of wireless sensors, and the field of applications that can use wireless sensors. Since the work in this research is focused on routing approaches, the literature review was focused on routing protocols and the categories of these routing protocols based on different classifications. Three main categories identified are the routing protocol based on the network structure, Flat, Hierarchical, and Location based routing protocols.

For instance, the Flat routing protocols are proposed for small scale WSNs. However, they might not be considered as an effective routing solution for WSN. This is because the sensor nodes in such networks do not execute general functions with low battery power and with a limited bandwidth. The Hierarchical routing protocols are proposed for large scale WSNs in order to divide the roles of the sensor nodes into several levels. However, each node requires extra overhead in terms of having large routing tables and updating information about network topology changes. This overhead results in increasing the consumption of network bandwidth and battery lifetime of nodes and the creation of unnecessary network control traffic overhead. Location-based routing protocols are performing well in a large field of WSNs. However, they depend on one condition, which is the location of each node. This location information should be available for each node, which increases the overhead as well. In addition, calculating this location especially for indoor applications can be difficult, where satellite positioning techniques cannot be applied.

Note that, this literature review was conducted continuously and in parallel with the other research steps through the period of research study. This was necessary to ensure that recent developments in related areas would be continuously fed back to the other activities in this research.
There are other routing protocols supported by one of the latest WSN technology "ZigBee". This thesis has categorised them under ZigBee routing protocols. These protocols are the AODV and the cluster-tree routing protocols. Both of them are useful and efficient routing protocols for WSNs compared with others. However, these protocols do not take into consideration the changes in battery energy levels of the wireless sensor nodes through establishing, communication, and data routing processes. This may lead to critical problems in routing data and limit the network lifetime.

In this research, the focus was on balancing the effects of some factors on routing protocols such as reducing a single route lifetime, increasing the network lifetime, and the reduction of other effects on the route cost and power. This idea has been researched previously, but not extensively.

In summary, routing is one important topic in the WSN domain. Every routing protocol has its strengths and weaknesses and aims at a specific application. In addition, the strengths of one protocol in an application could be a drawback in another application. Current routing protocols provide routing solutions up to a certain level of specific scenarios. However, they lack the ability to handle other scenarios with similar features.
10.2 Contribution and Future Work

This thesis has made contributions in making routing protocols in WSNs energy-aware and increasing the network lifetime of WSNs. The purpose of this thesis is to investigate the possibility of saving energy in WSNs by making routing protocols energy-aware. We have investigated six approaches in order to study that as summarised below.

1. **Balancing power consumption of sensor nodes in flat WSNs and distributing the role of routing over the existing AODV routing protocol.** This thesis presents a mechanism to distribute the routing process among most of the sensor nodes in the network, and make them share the power consumption in order to forward a message from the source node to the destination node. This mechanism is based on the AODV routing protocol. The simulation results have verified the advantage of our mechanism offered to increase the lifetimes of the wireless sensor nodes, and the lifetime of the WSN.

2. **Balancing power consumption of the sensor nodes in hierarchical WSNs and distributing the role of routing over the existing AODV routing protocol.** We have implemented the role of routing distributing technique over hierarchical WSNs based on the AODV routing protocol. Simulation results have shown an obvious improvement of the network performance in term of increasing the lifetime of the PAN coordinator, the lifetime of the routers, and the lifetime of the WSN.

3. **Reducing the transmission and reception powers through the routing process of the AODV routing protocol.** Considering the amount of the transmission and reception powers in the routing
protocol in order to save energy and increase the network lifetime, we produced a technique to reduce the transmission and the reception powers based on the consumption rate of the sensor nodes. This technique has been implemented over the AODV routing protocol. The simulation results have shown remarkable improvement of the WSN lifetime.

4. **Distributing the role of the cluster-heads dynamically based on the energy level of some nodes in each cluster.** Increasing the WSN lifetime based on distributing the role of the cluster-head between some of the nodes in each cluster is a new technique presented in this thesis in order to increase the network lifetime. A significant improvement to the network lifetime has been achieved by applying this technique. This contribution won the best paper prize in an international conference in the UK.

5. **Selecting the number of clusters and the cluster-heads based on the wireless sensor nodes' energy.** We aim to choose the number of clusters and the best cluster-head node in each cluster based on the energy level of the sensor nodes. The network lifetime has been increased by applying this clustering approach, where we select the node with the greatest energy to act as cluster head.

6. **Choosing the highest energy route based on the energy level of the intermediate nodes on the routes between a source and a destination nodes.** Selecting the route based on the shortest path strategy is not an energy-aware method. In order to make the route discovery process energy-aware process, the highest energy route is selected to act as the route between the source and the destination
nodes. We have increased the lifetime of the WSN by implementing this approach.

Our analysis implies that it is possible to increase the lifetime of the WSNs, and save energy by up to 70% by using energy-aware routing protocols. These approaches might affect other network factors such as time delay, which depend on individual application requirements. However, these approaches have achieved better performance in term of saving energy.

Finally, this thesis has achieved all of the proposed objectives mentioned in Chapter 1. Future work will be considered out in order to enhance other network factors over these approaches such as the quality of service (QoS), error ratio, and time delay. Additionally, merging these approaches together in one hybrid technique, and studying its evaluation are main objectives to be achieved in future work. Finally, we hope the work presented in this thesis can help stimulate related research on energy-aware WSN routing protocols.
References


References


