GREEN ROUTING PROTOCOLS EMPLOYING DUAL-RADIO COOPERATION

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Master of Science Thesis

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The undersigned hereby certify that they have read and recommend to the Faculty of Electrical Engineering, Mathematics and Computer Science for acceptance a thesis entitled

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by

Yuning Liu

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Abstract

Nowadays energy issue has already become a serious global problem. In the beginning of the 21st century, the whole world started to investigate new technologies to reduce energy consumption. Smart grid is one of these innovative solutions. With the emergence of the smart grid, the smart house project started. The new system in the smart house project is different from the traditional home automation system. It is about smart houses interacting with smart grids to achieve energy efficiency and sustainability. In order to achieve the smart house project, we need to look for new technologies that can be used in this smart house system.

In this thesis, we introduce the wake-up radio into ZigBee technology and make the two radios transmit packets cooperatively. In this dual-radio cooperative transmission approach, the radio employed in ZigBee nodes can be kept off and be activated by the wake-up radio only when interested events occur. Therefore, it can conserve much energy wasted when there are no data packets to send. Meanwhile, we propose three routing protocols for this dual-radio cooperation. Through MATLAB simulation results, we find that each routing protocol has its superiority in different transmission environments. At last, we present the cooperative dual-radio protocol stack. With this protocol stack, we can choose suitable routing protocols based on the transmission environment dynamics.

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Acknowledgement

The idea of my thesis about green routing protocols employing dual radio cooperation came after a discussion with my supervisor dr. E. Onur and some researches on green wireless network communications.

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Delft Yuning Liu
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"Idea is the beacon. Without ideal, there is no secure direction; without direction, there is no life."

—*Leo Tolstoy*

Chapter 1

Introduction

In this chapter, we first present an introduction about the basic knowledge in the thesis project. Meanwhile, we define the technical problem we address in our thesis and propose a suggested solution. At last, we simply present the brief introduction of the thesis project and the framework about the report.

1-1 Emergence of Smart Grid

Nowadays the energy sources, such as fossil, coal and natural gas, become more and more precious and the usage cost of energy in general is more and more expensive since the sources are scarce. Nevertheless, the traditional power grid of 20th century generates and distributes power from a few central power generators to a large number of users. This power grid has many disadvantages. The worst problem is the waste of energy during the energy transmission and storage. Meanwhile, with the increasing pressure on environmental protection, energy conservation and persistence is a major challenge for the society [1]. In order to solve these problems, many countries investigate new technologies to improve the old system. They without exception look upon smart grid as future development direction of power grid [2, 3, 4, 5].

Smart grid is a gradual development process accompanied with the technology innovation, demands of energy saving and managements needs [6]. It is a powerful upgrade of 20th century power grids which can route power in more optimal ways to respond to a very wide range of conditions, and to charge a premium to those that use energy during peak hours. The emergence of the smart grid brings the evolution of the power grid.

1-2 Concept of Smart Grid in Daily Life

With the emergence of smart grid concept, a number of companies have entered to the home area network (“home grid”) space, such as Plug Smart, a brand of Juice Technologies, LLC, Tendril, Control4, and Energy Hub. Recently ZigBee technology is widely employed in home automation system since ZigBee home automation offers a global standard for interoperable products enabling smart homes that can control appliances, lighting, environment, energy management and security, as well as the expandability to connect with other ZigBee networks. Smart homes allow consumers to save money, be more environmentally aware, feel more secure and enjoy a variety of conveniences that make homes easier and less expensive to maintain. In this thesis, we introduce how ZigBee can enable the concept of smart grid efficiently in our daily life.

1-2-1 ZigBee Technology and Technical Problem

The low rate (LR) wireless personal access network (WPAN) (IEEE 802.15.4/LR-WPAN) is intended to serve a set of industrial, residential, and medical applications with very low power consumption, low cost requirement, and relaxed needs for data rate and QoS [7, 8]. The low data rate enables the LR-WPAN to consume little power.

ZigBee technology is a low data rate, low power consumption, low cost, wireless networking protocol targeted toward automation and remote control applications [9]. In ZigBee technology, it often employs a protocol known as carrier sense multiple access with collision avoidance (CSMA/CA) at the datalink layer.

CSMA/CA is a protocol for carrier transmission in 802.11 networks [10]. This protocol acts to prevent collisions before they happen. In CSMA/CA, the node should sense the channel and check to be sure the channel is free and then it can transmit the packets. The CSMA/CA protocol is very effective when the medium is not heavily loaded since it allows devices to transmit with minimum delay [11]. ZigBee also uses the backoff algorithm for channel access and employs acknowledgement mechanism to send ACK packet to confirm that the data packet arrived intact.

However, due to the attributes of the ZigBee technology, the operation radio of ZigBee nodes should do many tasks such as monitoring the channel, sensing the channel and transmitting the packets. Therefore when the arrival rate of the packets is low or there is no packet transmission for a long period, the radio may waste a lot of energy in monitoring the channel, so that the MAC layer is not energy efficient. However, if we can make some modifications to keep the operation radio off and turn on it only when there are packets that need to be transmitted, this problem will be solved.

1-2-2 Suggested Solution

In order to prevent the energy wasted by the operation radio in ZigBee, we will introduce the wake-up radio into ZigBee technology and use this wake-up radio to monitor the channel and sense the channel. When there are data packets need to be transmitted, the wake-up radio will activate the operation radio of ZigBee to transmit the data packets.

After introducing the wake-up radio into ZigBee technology, there will have two pairs of transmitters and receivers for a ZigBee node. Figure 1-1 and 1-2 show the node model of ZigBee and the new node model of modified ZigBee, respectively. Here, the name "radio" used by ZigBee technology refers to the main radio and the transmitter and receiver which use the main radio to transmit packets are the main transmitter and main receiver. We call the new pair which uses the wake-up radio to transmit packets the wake-up transmitter and wake-up receiver. In this new model, the wake-up radio is always on and the main radio is kept off. When there are packets that need to be transmitted, it first uses the wake-up radio to transmit wake-up packet to wake up the node in the routing path. Then the main radio is turned on and it is used to transmit the data packet. Figure 1-3 shows this transmission procedure.

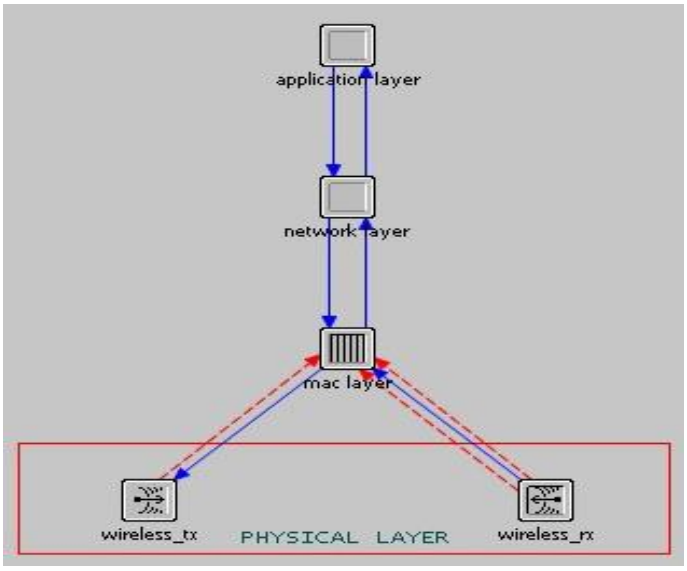

Figure 1-1: Node model of ZigBee.

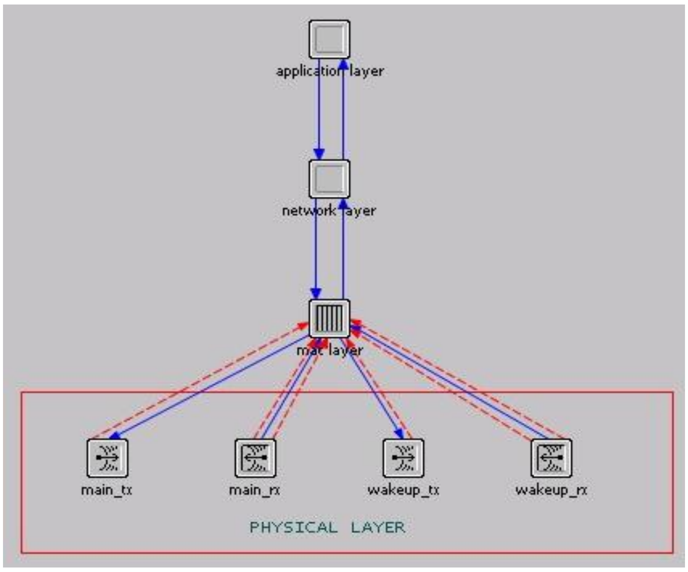

Figure 1-2: Node model of modified ZigBee.

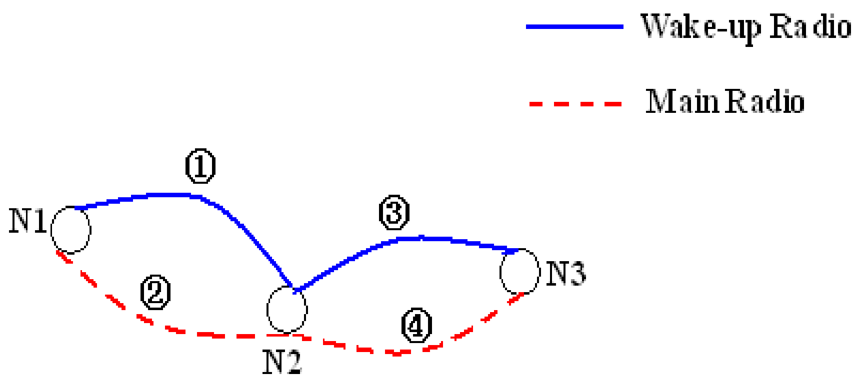

Figure 1-3: Transmission procedure.

To explain this mechanism, we introduce a possible scenario in Figure 1-3. Assume node N1 wants to transmit a data packet to node N3. First N1 uses the wake-up radio to transmit a wake-up packet to N2, then N1 switches to use the main radio to send the data packet to N2. After N2 receives the data packet successfully, N2 still uses the wake-up radio to transmit the previous wake-up packet to N3, then the main radio of N2 and N3 is turned on and N2 sends the data packet to N3.

1-2-3 Wake-Up Receiver

The basic principle of merging wake-up radio with main radio is to leave the main radio off and wake it up asynchronously only when needed. A dedicated wake-up receiver can continuously monitor the channel, listening for a wake-up signal from other nodes and activating the main receiver upon detection [12]. By maximizing the node sleep time without compromising network latency, the usage of wake-up receivers can improve energy consumption performance. In order to be practical, the power consumption of the wake-up receiver must be minimized while still preserving adequate sensitivity to detect the wake-up signal [12].

Wake-up receiver schemes can be classified according to four different factors. In [13], the authors give the classification of the wake-up receiver. Figure 1-4 shows the classification of the wake-up receiver schemes. In this figure the wake-up receiver scheme is classified as passive wake-up receivers and active wake-up receivers based on their power sources. In the former scheme, wake-up circuitry is triggered by the external energy sources but in the active wake-up receiver scheme, the internal battery is used. Based on the wake-up channels, if the wake-up signal is sent using the same channel as the main radio communication channel, it is called the shared wake-up channel scheme. However, if a separate channel is used for the wake-up signaling, it is referred as the separate wake-up channel scheme. Besides these two kinds of classification, during the transmission, if all the nodes which receive the signal wake up, the scheme is known as the range-based wake-up scheme. However, if every node has its own bit sequence address which is used to differentiate each node and the wake-up signal contains a bit sequence of the destination. After receiving the wake-up signal, all nodes check whether the bit sequence refers to them, if the two bit sequences match, the destination wakes up. This scheme is called identity-based wake-up. The former scheme can be used for multicasting and the latter allows unicasting. If use radio signals as wake-up signals, the scheme is referred as radio-based wake-up. However, if using acoustic signals to trigger the wake-up, it is called the acoustic wake-up.

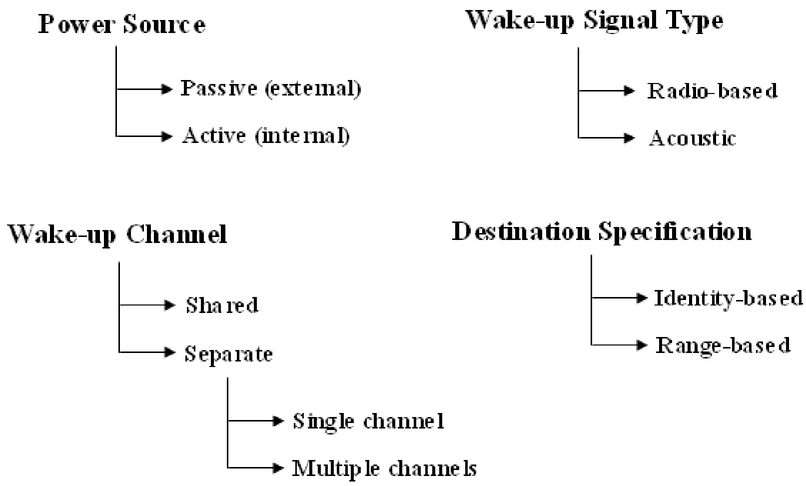

Figure 1-4: Classification of wake-up receiver schemes.

1-3 Overview of Thesis Project

1-3-1 Problem Definition

ZigBee is a potential candidate technology for future home automation appliances. The current scheme of MAC layer in ZigBee is not energy efficient as described in Section 1-2-1. However, wake-up radio consumes energy much less than the operation radio in ZigBee. Therefore, if introducing the wake-up radio into ZigBee and using it to do the tasks before transmitting the data packet, such as monitoring the channel, sensing the channel and activating the main radio, it will improve the performance of MAC and reduce the energy consumption.

1-3-2 Novelty of Thesis Project

In this thesis project, we introduce a new collaboration scheme in wireless sensor networks (WSNs) with an aim to reduce energy consumption. Also, we introduce a dynamic routing mechanism which allows the transmitter to choose the most efficient route dynamically upon changes in channel conditions. After simulation by MATLAB, we show that in different transmission environments of wireless sensor networks (WSNs), we should choose suitable routing protocols for packet transmission so as to conserve the transmission energy. At last, we present the cooperative dual-radio protocol stack. In this cross-layer protocol stack, the routing protocol is altered depending on the channel dynamics.

1-3-3 Framework of Report

This report is mainly composed of four chapters. Chapter 2 is the literature review of the whole thesis project. In Chapter 3, we present the energy consumption calculation model and show MATLAB simulation results which find out the influencing factors to the transmission energy consumption. In Chapter 4, we propose three different routing protocols for dual-radio cooperation and present simulation results in the wireless sensor networks (WSNs) based on the energy consumption model proposed in Chapter 3. In Chapter 5, we describe the new cooperative dual-radio protocol stack and show some implementation results of the dual-radio cooperative transmission in WSNs. At last, the report ends with a brief conclusion.

Chapter 2

Literature Review

In this chapter, we present an extensive literature survey about the thesis topic. We define the smart grid and describe how home intelligent control system can interact efficiently with the smart grid. Through comparison of some candidate technologies, we choose the most competent technology for this home intelligent control system. Meanwhile, we describe some important concepts which are applied in the thesis project, such as the dual-radio WSN, event-driven WSN, and cross-layer approach.

2-1 Smart Grid

2-1-1 Definition of Smart Grid

The definition of the smart grid is dependent on what the grid can do and differs from the stakeholder's viewpoint. However, no matter how to define it, the definition should include stated benefits or desired outcomes for certain parties or for technologies. One simple definition of smart grid is "the electric delivery infrastructure from electrical generation to end-use customer, integrated with information and communication technologies" [14]. The main functions of the smart grid are as follows:

- Be able to heal itself.
- Motivate consumers to actively participate in operations of the grid. In the smart grid, consumers are informed, involved and active and their demands penetrate broadly in the whole grid.
- Resist attacks.
- Provide higher quality power that will save money wasted from outages.
- Accommodate all generation and storage options.
- Enable electricity markets to flourish.

- Run more efficiently. The smart grid will use the green sources such as wind, solar, geothermal and tidal. However the generation of these sources is more intermittent and less predictable than the traditional sources like coal, natural gas and nuclear powered plants. The subsystems of the smart grid must be able to adjust to fluctuating energy supplies. On the consumer end, the grid must respond to varying demands caused by daily usage variations, changing weather, component outages and even disasters [15]. So increasing the subsystems' intelligence and visibility can make better management and distribution of available power and decrease reliance on spinning reserves. Thus increase the efficiency of the system.
- Enable higher penetration of intermittent power generation sources [16].

2-1-2 Smart Grid in Different Areas

In different areas of the world has its own definition and attributes of smart grid. In the following, we will give the different definition of the smart grid in different areas of the world.

United States:

According to [14], besides the functions mentioned above, the smart grid in the United States enables active participation by consumers in demand response. It also accommodates all generation and storage options and enables new products, services, and markets. Meanwhile, it can optimize asset utilization and operating efficiency. From the security viewpoint, it operates resiliently against both physical and cyber attacks. Most importantly, the smart grid in US can provide quality power that meets 21st-century needs.

Europe:

In [17], the European Technology Platform defines smart grids as electricity networks that can intelligently integrate the behaviors and actions of all users connected to it across a shared information and communications network so that the grid can efficiently deliver sustainable, economic and secure electricity supplies.

The smart grid in Europe is flexible since it fulfills customers' needs while facing the changes and challenges. It is also a grid that is accessible as it grants connections access to all network users, particularly renewable power sources and high-efficiency local generation with no or low carbon emissions. Considering that the smart grid in Europe assures and improves security and quality of supply, consistent with the demands of the digital age, with excellent resilience in the face of hazards and uncertainties, it is very reliable. Meanwhile it provides best value through innovation, efficient energy management, and “level playing field” competition and regulation, it is said to be very economical.

Smart grids employ innovative products and services together with intelligent monitoring, control, communication, and self-healing technologies in order to:

- Better facilitate the connection and operation of generators of all sizes and technologies (e.g. renewable).
- Optimize grid operation and usage (e.g. reducing losses) and grid infrastructure.
- Provide consumers with greater information and options for choice of supply, and allow them to play a part in optimizing the operation of the system.
- Significantly reduce the environmental impact of the whole electricity supply system.
- Maintain or even improve the existing high levels of system reliability, quality and security of supply.
- Maintain and improve the existing network services efficiently (e.g. adequate short-circuit power at point of grid connection, efficient and reliable alarm and fault management for self-healing procedures in distribution networks, adequate (bidirectional) protection concepts for distributed generation, etc).
- Foster market integration towards an integrated EU electricity market [18].

China:

Smart grid in China is defined as an electricity transmission and distribution system that incorporates traditional and cutting-edge power engineering, sophisticated sensing and monitoring technology, information technology and communications so as to provide better grid performance and to support a wide range of additional services to consumers. Firstly, the Smart Grid must accommodate different data transport technologies while also providing a migration path to a common, shared technology that will reduce cost and complexity while sharply increasing security and reliability. The migration path moves technologies from the core to the edge, and eventually out of the network entirely [15]. Meanwhile, the communications protocol standard used by the smart grid must be not only interoperable but must also be proven, secure, and reliable [15]. Therefore it can reduce system complexity, thereby providing a better grid performance.

2-1-3 Advantages of Smart Grid

Compared to the traditional grid, the resources in smart grid can generate everywhere and the power flows from everywhere, so the behavior of smart grid is chaotic. In short, the system's supply and consumption of the smart grid will become more decentralized and distributed so the system's condition will be more dynamic and less predictable. Therefore it will provide more opportunities for optimization.

Due to the significant advantages of smart grid technology, it can increase the connectivity, automation and coordination between the suppliers, consumers and networks of the electrical grid that perform either long distance transmission or local distribution tasks. Meanwhile, the smart grid uses two-way digital technology to control appliances at consumers' homes when delivering electricity from suppliers to consumers, so it can also satisfy the consumers' requirements to save energy, reduce cost and increase reliability and transparency.

2-1-4 Technology Layers of Smart Grid

According [14], the smart grid has four technology layers: power conversion/ transport/ storage/ consumption layer, sensor/actuator layer, communication layer and decision intelligence layer. Figure 2-1 shows the four layers. In the bottom layer, the energy is converted, transmitted, stored and consumed. The sensor/actuator layer perceives the environment and controls the bottom layer. The communication layer performs the task that transmitting the information between the devices that connected to the grid and the controllers. However, the smartness of the smart grid depends on the decision intelligence layer, which contains the computer programs, intelligent electronic devices, substation automation systems, control centers and enterprise back offices.

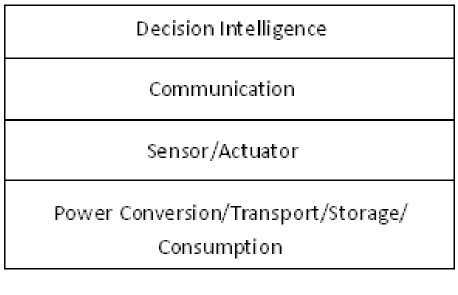

Figure 2-1: Smart grid technology layers.

2-2 Home Intelligent Control System

2-2-1 Description of Home Intelligent Control System

The architecture of the home intelligent control system is very simple and it just contains a system controller and several sensors. When different events occur, these sensors which have different functions will send command messages to the system controller, then the system controller will start corresponding procedures based on these command messages.

The home intelligent control system can adjust the incident angle of the sunlight to the room and humidity of the room, also it can keep the quality of the air in good condition. Meanwhile it can let the household appliances work not in the energy peak hour. The home intelligent control system may provide the following functions:

- When the sunlight shines straight into the room and make the temperature of the room exceed a threshold temperature, the temperature sensor will send a command message to the system controller, then the control system will adjust the angle of the louver window so that it can protect the furniture from ultraviolet radiation and keep the temperature of the room in a comfortable level.
- When the humidity of the room is high, then the humidity sensor will send command message to ask the system controller to turn on the air conditioner to dehumidify.
- When the content of the carbon monoxide or carbon dioxide in the air is high, the gas concentration sensor will tell the system controller to open the air vent so as to improve the quality of the air in the room.
- While not in the energy peak hour (after 10 p.m. or before 7 a.m.), the sensor will inform the system controller, then the control system will let the household appliances such as dish washer and washing machine work based on the consumers’ demands.

Figure 2-2 shows the architecture of the home intelligent control system.

Figure 2-2: Architecture of home intelligent control system.

In the home intelligent control system showed in Figure 2-2, when the sunlight shines straight into the room through the louver window and make the temperature of room exceed the threshold temperature (assume 30℃) set by the consumer, the temperature sensor will send a command message to the controller system asking for adjusting the angle of the louver window. When the humidity sensor senses the humidity of the room is high, it will send a message to ask the system controller to turn on the air conditioner to dehumidify. When the content of the carbon monoxide or carbon dioxide in the air is high, the gas concentration sensor will ask for opening the air vent. In this system, it gives the overall energy consumption conditions and consumers can choose when to use the household appliances in order to reduce the cost for energy usage. When the consumer wants to use the dish washer or the washing machine, the sensor will first senses whether it is in the energy peak hour. If it is in the non-energy peak hour, the sensor will inform the system controller to let them work. If it is in the energy peak hour, the system will inform the consumer that using the household appliances in this period will cost more money for the energy usage. If the consumer does not need to use them immediately, the sensor can delay this command and send the command message for the usage of the household appliances to the system controller until it is not in the energy peak hour. However, if the consumer needs to use the household appliances immediately, the sensor will send the command message to the system controller and let them work at once. In a word, this home intelligent control system is an event-driven control system which makes the consumers' demands penetrate broadly in the whole system.

2-2-2 Concept of Smart Grid in Home Intelligent Control System

In the home intelligent control system, the concept of the smart grid is mainly embodied in two aspects.

Firstly, in the smart grid, it refines the resolution of consumers' demands to the grid. In this home intelligent control system, each function of this system satisfies the consumers' request in specific respect. It cannot only make the temperature and the humidity of the room always in a comfortable level, but also can refresh the air of the room frequently. Meanwhile, this system can let the household appliances work avoiding the energy peak hour.

Secondly, according to the consumers' demands, the home intelligent control system can make the household appliances work in non-energy peak hour. Therefore it can let them work with more stable power supply, meanwhile it can reduce the power usage cost for consumers since the power rate per hour in the non-energy peak hour is lower than that of the energy peak hour.

2-3 Candidate Technologies

2-3-1 Candidate Technologies for Home Intelligent Control System

There are many technologies that can be used in small area networks, such as Bluetooth, Wi-Fi and Zigbee. In this section, we will give some basic knowledge of these candidate technologies and choose the most competent technology for the home intelligent control system after comparison.

Bluetooth:

Bluetooth is an open wireless technology which uses short wavelength radio transmission to exchange data over short distances from fixed and mobile devices, create personal area networks (PANs) with high levels of security. Bluetooth uses a radio technology called frequency-hopping spread spectrum, which chops up the data being sent and transmits chunks of it on up to 79 bands (1 MHz each) in the range 2402-2480 MHz(ISM) [19].

Bluetooth is a standard communications protocol primarily designed for low power consumption, with a short range (power-class-dependent: 100 m, 10 m and 1 m, but ranges vary in practice; see table below) based on low-cost transceiver microchips in each device [19].

Class	**Maximum Permitted Power**		**Range**
	mW	**dBm**	**(approximate)**
Class 1	100	20	~100meters
Class 2	2.5	4	~10meters
Class 3	1	0	~1meters

Table 2-1: Classes of Bluetooth.

Basic unit of networking in Bluetooth is piconet. One master may communicate with up to 7 slaves in a piconet. Figure 2-3 shows this master-slave structure. All devices share the master's clock which is defined by the master. Two or more piconets can form the scatternet. In Figure 2-4, the scatternet consists of two piconets, the linking device of the piconets can be slaves on both piconets or a master of one piconet and a slave of another.

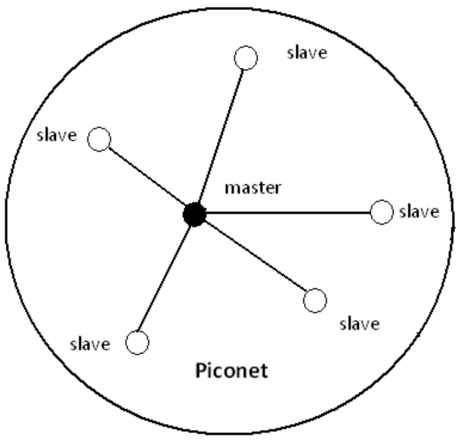

Figure 2-3: Bluetooth piconet.

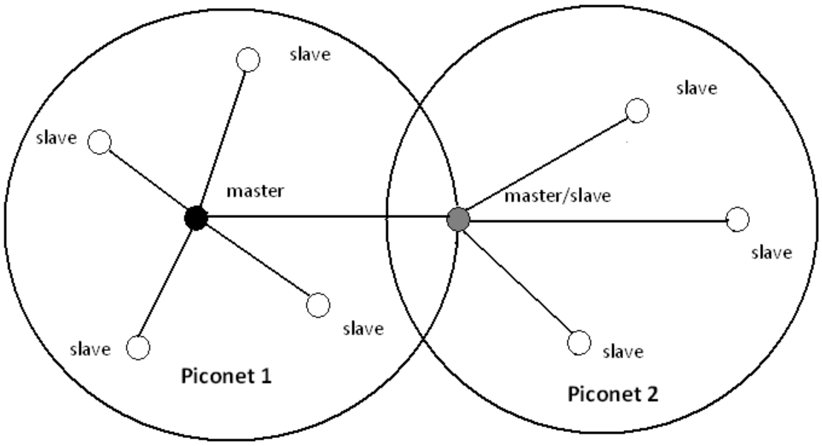

Figure 2-4: Bluetooth scatternet.

In security aspect of Bluetooth, service-level security and device-level security work together to protect Bluetooth devices from unauthorized data transmission [20]. The security methods include authorization and identification procedures so that Bluetooth can provide a secure way to connect and exchange information between devices such as faxes, mobile phones, telephones, laptops, personal computers, printers, Global Positioning System (GPS) receivers, digital cameras, and video game consoles.

In today's market, Bluetooth is widely used in many areas. The applications are listed below:

- Wireless control of and communication between a mobile phone and a handsfree handset. This was one of the earliest applications to become popular.
- Wireless networking between PCs in a confined space and where little bandwidth is required.
- Wireless communication with PC input and output devices, the most common being the mouse, keyboard and printer.
- Transfer of files, contact details, calendar appointments, and reminders between devices with OBEX.
- Replacement of traditional wired serial communications in test equipment, GPS receivers, medical equipment, bar code scanners, and traffic control devices.
- For controls where infrared was traditionally used.
- For low bandwidth applications where higher USB bandwidth is not required and cable-free connection desired.
- Sending small advertisements from Bluetooth-enabled advertising hoardings to other, discoverable, Bluetooth devices.

- Wireless bridge between two Industrial Ethernet (e.g., PROFINET) networks.
- Three seventh-generation game consoles, Nintendo's Wii and Sony's PlayStation 3 and PSP Go, use Bluetooth for their respective wireless controllers.
- Dial-up internet access on personal computers or PDAs using a data-capable mobile phone as a wireless modem like Novatel mifi. Short range transmission of health sensor data from medical devices to mobile phone, set-top box or dedicated telehealth devices.
- Allowing a DECT phone to ring and answer calls on behalf of a nearby cell phone.
- Real-time location systems (RTLS), are used to track and identify the location of objects in real-time using “Nodes” or “tags” attached to, or embedded in the objects tracked, and “Readers” that receive and process the wireless signals from these tags to determine their locations [19].

Wi-Fi:

Simply put, Wi-Fi is connectivity. Wi-Fi networks use 802.11 radio technologies to provide secure, reliable, fast wireless connectivity. A Wi-Fi network can be used to connect electronic devices to each other, to the Internet, and to wired networks which use Ethernet technology. Wi-Fi networks operate in the 2.4 and 5 GHz radio bands, with some products that contain both bands (dual band) [21]. Table 2-2 gives the basic information about Wi-Fi technology.

Wi-Fi Technology	**Frequency Band**	**Bandwidth or maximum data rate**
802.11a	5 GHz	54 Mbps
802.11b	2.4 GHz	11 Mbps
802.11g	2.4 GHz	54 Mbps
802.11n	2.4 GHz, 5 GHz, 2.4 or 5 GHz (selectable), or 2.4 and 5 GHz (concurrent)	450 Mbps

Table 2-2: Wi-Fi technology.

Everyone can use Wi-Fi, almost anywhere in the world. A home Wi-Fi network can connect a family's computers, media and display devices together to share hardware and media resources such as printers, audio files and Internet access. So that everyone in the family can share all the files without cables running throughout the home.

Wi-Fi networks also work well for small businesses, providing connectivity between mobile salespeople, floor staff and behind-the-scenes finance and accounting departments [21]. The built-in flexibility of a Wi-Fi network makes small businesses easy and affordable to change and grow since small businesses are dynamic. Meanwhile many corporations also provide wireless networks to their off-site and telecommuting workers to use at home or in remote offices. And some large companies and campuses often use Wi-Fi to connect buildings.

Besides the Wi-Fi networks mentioned above, Wi-Fi also allows communications directly from one computer to another without the involvement of an access point [22]. This is known as the ad-hoc mode of Wi-Fi transmission. Another common type of Wi-Fi network for personal use is called an infrastructure network. In this mode, each device connects to a central point which manages the communications, such as the use of a home broadband internet connection.

In security part, a Wi-Fi network using Wi-Fi Protected Access 2 (WPA2) is both secure and private. That means users can control who connects to their network and the transmissions across their network cannot be read by others. In the following part, we will introduce how WPA2 secures the network.

1. Securing a New Network:

- Change the network name (SSID) from the default name.
- Change the administrative credentials (username and password) that control the configuration settings of your Access Point/Router/Gateway.
- Enable WPA2-Personal (aka WPA2-PSK) with AES encryption.
- Create a network passphrase that meets recommended guidelines.
- Enable WPA2 security features on the client device and enter the passphrase for the network [23].

2. Securing an Existing Network:

When adding a new device to the Wi-Fi network, it’s a great time to make sure to take advantage of the highest level of security the devices are capable of. Take the opportunity to ensure the network is configured for WPA2. If the network was set up some time ago, or a service provider configured the home network, it may be worth checking that it’s configured for the highest level of security. If the network is configured for an older generation of security (WEP or WPA) the Wi-Fi Alliance recommends to move to more WPA2 [23].

Wi-Fi has a lot of advantages. Wireless networks are easy to set up and inexpensive [24]. They're also unobtrusive, when in a hotspot users may not even notice unless they want to look for a place to use their laptops. Meanwhile, Wi-Fi allows the deployment of local area networks (LANs) without wires for client devices, thus it can reduce the costs of network deployment and expansion.

Wi-Fi also has some limitations. First, the range of Wi-Fi networks is limited. In addition, Wi-Fi has fairly high power consumption compared to some other standards and this high power consumption of Wi-Fi makes battery life in mobile devices become a problem. Finally, in high density areas, an excessive number of access points in the area, especially on the same or neighboring channel, can prevent access and cause interfere with other devices' use of other access points, thus resulting in the decreased signal-to-noise ratio(SNR) between access points.

Compared with Bluetooth, these two technologies both have many applications: setting up networks, printing or transferring files. They use the same radio frequencies. However, they have many differences at the same time.

Wi-Fi is intended for resident equipment and its applications. The category of applications is outlined as wireless local area network (WLAN). Oppositely, Bluetooth is intended for non-resident equipment and its applications. The category of applications is outlined as the wireless personal area network (WPAN). Besides this, the Wi-Fi is intended as a replacement for cabling for general local area network access in work areas. While, Bluetooth is a replacement for cabling in a variety of personally carried applications in any ambience and can also support fixed location applications such as smart energy functionality in the home [19]. Additionally, Wi-Fi consumes higher power which leads to a faster connection and better range from the base station.

ZigBee:

ZigBee is a specification for a suite of high level communication protocols which use small, low-power digital radios based on the IEEE 802.15.4-2003 standard for wireless home area networks (WHANs).

ZigBee operates in the industrial, scientific and medical (ISM) radio bands: 868 MHz (Europe), 915 MHz (USA and Australia) and 2.4 GHz (jurisdictions worldwide).

ZigBee is a low-cost, low-power, wireless mesh networking standard. The low cost makes the ZigBee technology to be widely deployed in wireless control and monitoring applications. The low-power usage allows longer life with smaller batteries. Meanwhile, the mesh networking has many benefits:

- This topology is highly reliable and robust. Should any individual router become inaccessible, alternative routes can be discovered and used.
- The use of intermediary devices in relaying data means that the range of the

network can be significantly increased, making mesh networks highly scalable.

- Weak signals and dead zones can be eliminated by simply adding more routers to the network [25].

Figure 2-5 shows a simple ZigBee network.

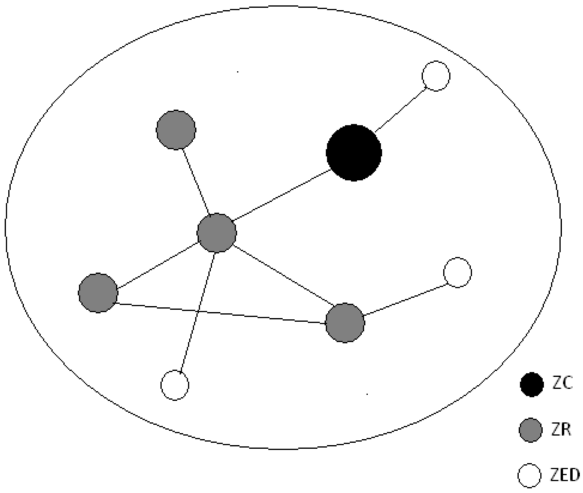

Figure 2-5: ZigBee network.

In Figure 2-5, there are three different types of ZigBee devices in the network:

- ZigBee coordinator (ZC): This device starts and controls the network. It stores information about the network, including acting as the Trust Center and being the repository for security keys. Since the coordinator starts the network originally, there is exactly one ZigBee coordinator in each network.
- ZigBee Router (ZR): These devices extend network area coverage, dynamically route around obstacles and provide backup routes in case of network congestion or device failure. They can connect to the coordinator and other routers and also support child devices [25].
- ZigBee End Device (ZED): These devices contain just enough functionality to talk to either the coordinator or a router, so they just can transmit or receive messages, but cannot perform any routing operations. They must be connected to either the coordinator or a router and do not support child devices [25]. A ZED requires the least amount of memory, and therefore can be less expensive to manufacture than a ZR or ZC [26].

Since ZigBee protocols are intended for use in embedded applications requiring low data rates and low power consumption, the typical application areas are as follows:

- Home Entertainment and Control-Smart lighting, advanced temperature control, safety and security, movies and music.
- Home Awareness-Water sensors, power sensors, energy monitoring, smoke and fire detectors, smart appliances and access sensors.
- Mobile Services-m-payment, m-monitoring and control, m-security and access control, m-healthcare and tele-assist.
- Commercial Building-Energy monitoring, HVAC, lighting, access control.
- Industrial Plant-Process control, asset management, environmental management, energy management, industrial device control, machine-to-machine (M2M) communication [26].

Figure 2-6 shows the ZigBee target markets.

Figure 2-6: ZigBee target market [27].

ZigBee technology has many advantages. It is based on 2.4GHz MAC/PHY IEEE 802.15.4 standard and can co-exist with other 2.4GHz technologies. ZigBee supports for interoperability, secure communications and simpler slave only implementations. In addition, ZigBee uses power save mechanisms in network layer and the network layer is thin, flexible and future-proof. Meanwhile, ZigBee uses simple and intuitive pairing mechanism. Finally, ZigBee supports for many different applications and allows for vendor specific applications and transactions.

ZigBee looks rather like Bluetooth but is simpler, has a lower data rate and spends a lot of time snoozing [28]. This characteristic makes the devices' battery life in the ZigBee network longer than the devices in the Bluetooth network with the same energy. Meanwhile, the operational range of ZigBee is longer than Bluetooth thus makes the operational area much larger than Bluetooth.

2-3-2 Comparison of Candidate Technologies

From the brief introductions and comparisons of above technologies, we can see that each technology has its advantages and can be used in different areas. However, ZigBee is more competent in the usage of the home intelligent control system since other technologies all have some limitations in the usage of this system.

Although the Bluetooth networks' low-power cost can satisfy the home intelligent control system's demand of saving power and help the consumers reduce the usage cost. However, in one piconet or scatternet of the Bluetooth network, at any given time, data can be transferred between the master and one other device. That means when two or more sensors in the home intelligent control system want to transmit command packet to system controller, the system controller can only receive the command packet from one sensor and ignore the packets from other sensors. Therefore it will not satisfy all the sensors' demands and meanwhile reduce the efficiency of the home intelligent control system.

Wi-Fi technology can solve the one-to-one communication at one moment problem of the home intelligent control system that Bluetooth has. However, Wi-Fi has fairly high power consumption compared to some other standards. Therefore it cannot achieve the goal of saving energy and satisfy the consumers' demand of saving usage cost.

Considering ZigBee technology, it can not only prevent the difficulties that Bluetooth and Wi-Fi technologies have, but its operational range is also suitable for the home intelligent control system. Besides these, ZigBee is a low-cost, low-power standard. These two attributes can satisfy the demand of saving energy and usage cost. Meanwhile, the mesh networking topology of ZigBee is highly reliable and robust and ZigBee is widely used in many kinds of areas, thus this technology is well developed and deployed. In a word, ZigBee is more competent for this home intelligent control system. Table 2-3 shows the comparison of these candidate technologies.

Technology	Advantage	Disadvantage
Bluetooth	Low-power cost.	Cannot deal with the commands from different sensors at the same time.
Wi-Fi	Can deal with the commands from different sensors at the same time.	Fairly high power consumption.
ZigBee	Low-power cost. Can deal with the commands from different sensors at the same time.	

Table 2-3: Comparison of candidate technologies.

2-4 Dual-Radio Wireless Sensor Network

In wireless sensor networks (WSNs), energy efficiency is critical, particularly for large-scale deployments. In order to increase the energy efficiency and prolong the lifetime of the WSN, a new scheme which employs two types of radios for different purposes in the sensor has turned up. We usually call these two radios the low-bandwidth radio and high-bandwidth radio.

The high-bandwidth radio operates with much greater energy efficiency than the low-bandwidth radio, in terms of energy per bit transmitted. However, the larger radio also has a much higher state transition cost and idle energy consumption, more than 10 times that of the low bandwidth radio [29, 30, 31]. Therefore, using the high-bandwidth radio if there is no data to send or if data needs to be transmitted occasionally, it is counter-productive to energy efficiency. In order to reduce energy consumption, the high-bandwidth radio should be kept off and to be turned on only when there are data packets that need to be transmitted. On the other hand, the low-bandwidth radio is less energy efficient but consumes much less energy when in idle mode. We can keep this low-bandwidth radio almost-always on and use it to activate the high-bandwidth radio. Therefore it is ideal for transmitting data packet as well as remaining monitoring the transmission channel for long time periods, especially when techniques such as Low-Power Listening [32] are used.

This dual-radio scheme has been widely used in many wireless sensor networks. The simulation results presented in [33, 34, 35] all show that the mechanism of dual-radio can provide significant energy savings compared to traditional wireless sensor networks which only use one radio for packet transmission.

2-5 Event-Driven Wireless Sensor Network

Wireless sensor network can be divided into three categories due to different ways of its activity patterns [36]. The first kind is time-driven WSN. In this kind of WSN, nodes forward collected data to the sink periodically and it is usually used for environment monitoring. The second is query-driven WSN, where nodes send gathered data only when they received a query from the sink [37]. This kind of WSN is sometime used in storage room. The third kind is event-driven WSN. In this kind of WSN, nodes forward an alert to the sink when a particular event occurs such as a forest fire.

In event-driven WSNs, sensor nodes only send little condition information to sink during usual time and send emergent information when event occurs [38]. That means the event-driven WSNs usually operate under an idle or light load and become active when interested events arrive. Therefore, the event-driven WSNs can prevent the waste of energy consumption for waiting for the events' arrival so that it can prolong the lifetime of the network.

In [39], the authors present the classification of the events. Figure 2-7 shows this classification of the events. Based on the timing of the event, the events can be classified into scheduled events and non-scheduled events. When an event is scheduled at a specific time, the event is called a scheduled event. When an event occurs non-deterministically, the event is called a non-scheduled event.

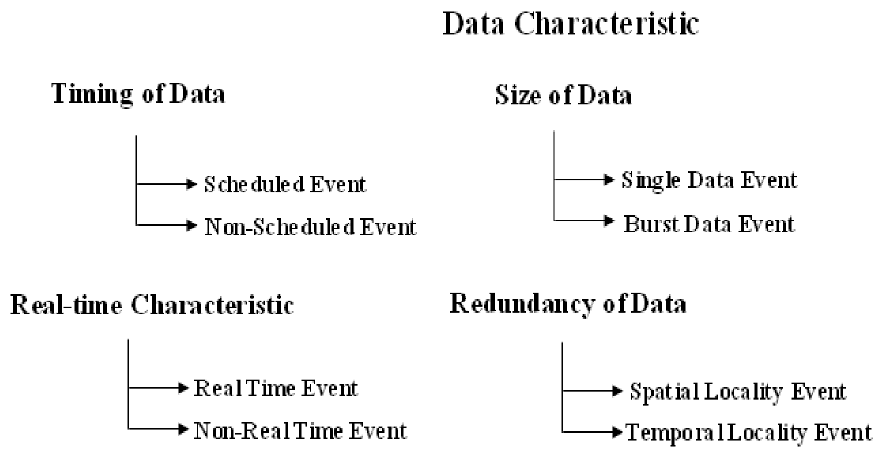

Figure 2-7: Classification of events.

According to the size of the data, events can be classified into single data events and burst data events. A single data event requires a report of a small data item to generate a few data packets. However, a burst data event requires a report of a large data to generate a packet stream. Based on the redundancy characteristics of the data that are closely related with the locality characteristics of the event, the events can be classified into spatial locality events and temporal locality events. When an event can be detected by multiple sensor nodes nearby, the event is classified as a spatial locality event. If a node detects multiple consecutive events but there exist a significant redundancy among the data reports, the events can be classified as a temporal locality event.

Based on the real-time characteristic of an event, the events are classified into real time events and non-real time events. The real-time characteristic is related with the latency tolerance characteristics of an application for the event. The events with hard or soft deadlines are classified as a real-time event. Events that can tolerate a considerable latency are classified as a non-real time event.

2-6 Cross-Layer Approach

Cross-layer optimization is an escape from the pure waterfall-like concept of the OSI communications model with virtually strict boundaries between layers [40]. The cross-layer approach can transport feedback dynamically via the layer boundaries to compensate for overload, latency or other mismatch of requirements and resources by any control input to another layer. We will use this cross-layer approach in the cooperative dual-radio protocol stack in Chapter 5.

The cross-layer approach is widely used in the communication networks for different purposes. In [41], the authors present a physical (PHY)/ medium access control (MAC)/ network (NET) cross-layer analytical approach for determining the optimal number of the clusters in dense wireless sensor networks. In [42], the authors design a cross-layer routing protocol for wireless sensor networks to increase the efficiency of the communication of the network. In [43], they present an efficient hybrid medium access control (HMAC) protocol with an embedded cross-layer optimization solution to provide routing-layer coarse-grained end-to-end quality-of-service (QoS) support for latency-sensitive traffic flows for wireless sensor networks.

Chapter 3

Energy Consumption Model

In this chapter, we present the energy consumption model for transmission which we will use during the work in this report. Meanwhile, we give some MATLAB simulation results to show the variation tendency of data packet transmission energy consumption with the changes of some conditions.

3-1 Transmission Energy Consumption

3-1-1 Energy Consumption Calculation Model

In order to compute the energy consumption of the wake-up packet and data packet transmission, first we have to obtain the energy consumption per bit for transmitting those packets. There has been a significant research in the area of energy modeling in wireless sensor networks (WSNs). Here, we assume a simple model where the transmitter dissipates power to run the radio electronics (P_{ct}) and power amplifier (P_{PA}), and the receiver dissipates power in radio electronics (P_{cr}) only [44]. This model is widely used by researchers as in [45, 46, 47]. The power consumption of the power amplifier can be obtained as

$$P_{PA} = (1+\alpha)P_{out}(d) \quad (Watt/bit), \tag{3-1}$$

where $\alpha = \xi/\eta$, with η represents the drain efficiency of the RF power amplifier and ξ denotes the peak-to-average ratio [46]. The transmit power $P_{out}(d)$ depends on the distance between transmitter and receiver.

$$P_{out}(d) = E_b R_b \frac{(4\pi)^2}{G_t G_r \lambda^2} M_l N_f \times d^{\gamma} \quad (Watt/bit). \tag{3-2}$$

In Eq. (3-2), E_b is the required energy per bit at the receiver for a given BER requirement (P_b), R_b is the bit rate, d is the distance between transmitter and receiver, γ is the path loss exponent, G_t and G_r are the antenna gains of the transmitting and receiving antennas respectively, λ is the wavelength of the carrier signal, M_l is the link margin, N_f is the receiver noise figure and equals to N_r/N_0 with N_0 the single-sided thermal noise power spectral density (PSD) and N_r the total effective noise at the receiver input. Table 3-1 shows the unit of all the parameters in Eq. (3-1) and Eq. (3-2).

Parameters	**Unit**
$\alpha, \xi, \eta, \gamma$	*1*
E_b	*J/bit*
R_b	*bps*
G_t, G_r	*dBi*
M_l, N_f	*dB*
λ, d	*m*

Table 3-1: Parameter unit.

The energy consumption per bit for transmitter and receiver can be written as

$$E_{bt} = \frac{(1+\alpha)P_{out}(d)}{R_b} + \frac{P_{ct}}{R_b} \quad (J/bit), \tag{3-3}$$

and

$$E_{br} = \frac{P_{cr}}{R_b} \quad (J/bit). \tag{3-4}$$

Then the energy consumption per bit for the total energy consumption is

$$E_{bit}(d) = E_{bt} + E_{br} = \frac{(1+\alpha)P_{out}(d)}{R_b} + \frac{P_{ct}}{R_b} + \frac{P_{cr}}{R_b} \quad (J/bit). \tag{3-5}$$

If the packet length is l bits, then the total energy consumption for transmitting a packet of length l equals to

$$E(d) = E_{bit}(d) \times l \quad (J). \tag{3-6}$$

3-1-2 Parameters for Wake-Up Radio and Main Radio

For many parameters used in the energy consumption model mentioned in above section, we have to set different values according to the attributes of wake-up radio and main radio.

Wake-Up Radio:

In [48, 49, 50], the wake-up radio employs on-off keying (OOK) modulation scheme. Here, we also assume the wake-up radio employs the OOK modulation scheme. From the modulation curve of the OOK (Figure 3-1), we can obtain that when BER $P_b = 10^{-3}$,

$$\frac{E_{bw}}{N_0} = 11dB,$$

and E_b in Eq. (3-2) is

$$E_{bw} = -193dB.$$

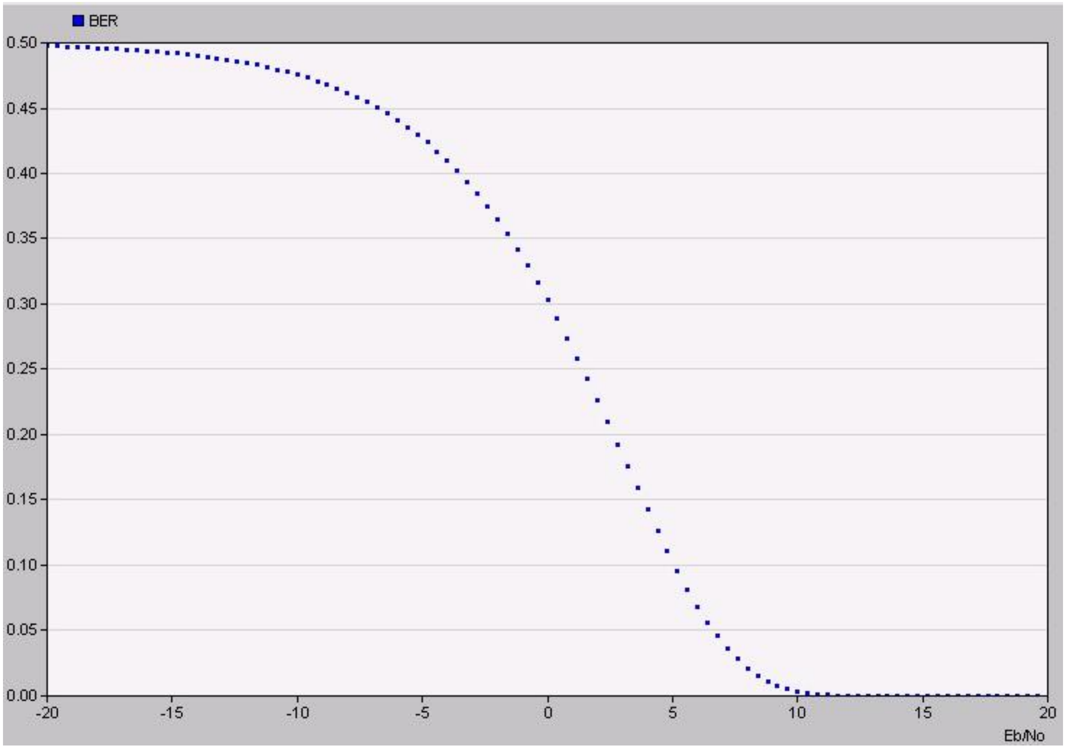

Figure 3-1: Modulation curve of OOK.

In [48], they present the packet format of the wake-up packet. Figure 3-2 shows the packet format of wake-up packet, from the figure we can obtain that the packet length $l_w = 24bits$. In Figure 3-2, flag bit is used to indicate if there is payload part included or not. The payload part contains link configuration information of the main radio, such as PHY interface selection, modulation scheme, channel and coding rate.

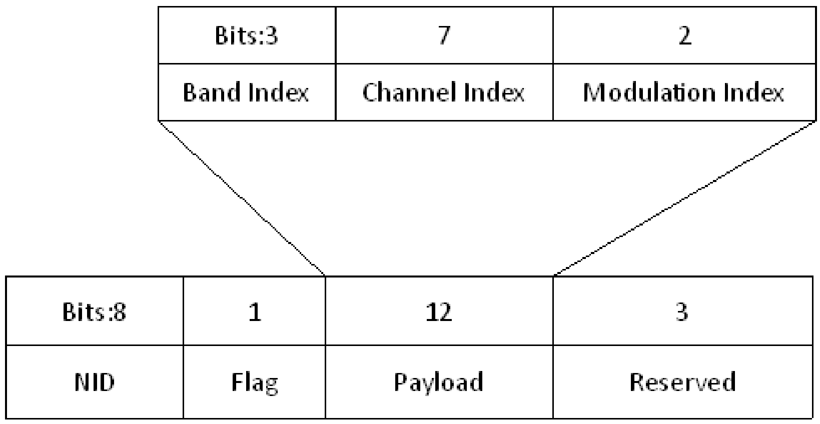

Figure 3-2: Wake-up packet format.

Main Radio:

According to IEEE standard for 802.15.4-2006 [51], Zigbee employs offset quadrature phase-shift keying (O-QPSK) modulation for 2450MHz operation band. Figure 3-3 shows the modulation curve of O-QPSK modulation scheme that the main radio uses, we can obtain that when BER $P_b = 10^{-3}$,

$$\frac{E_{bm}}{N_0} = 6.8dB,$$

and E_b in Eq. (3-2) is

$$E_{bm} = -197.2dB.$$

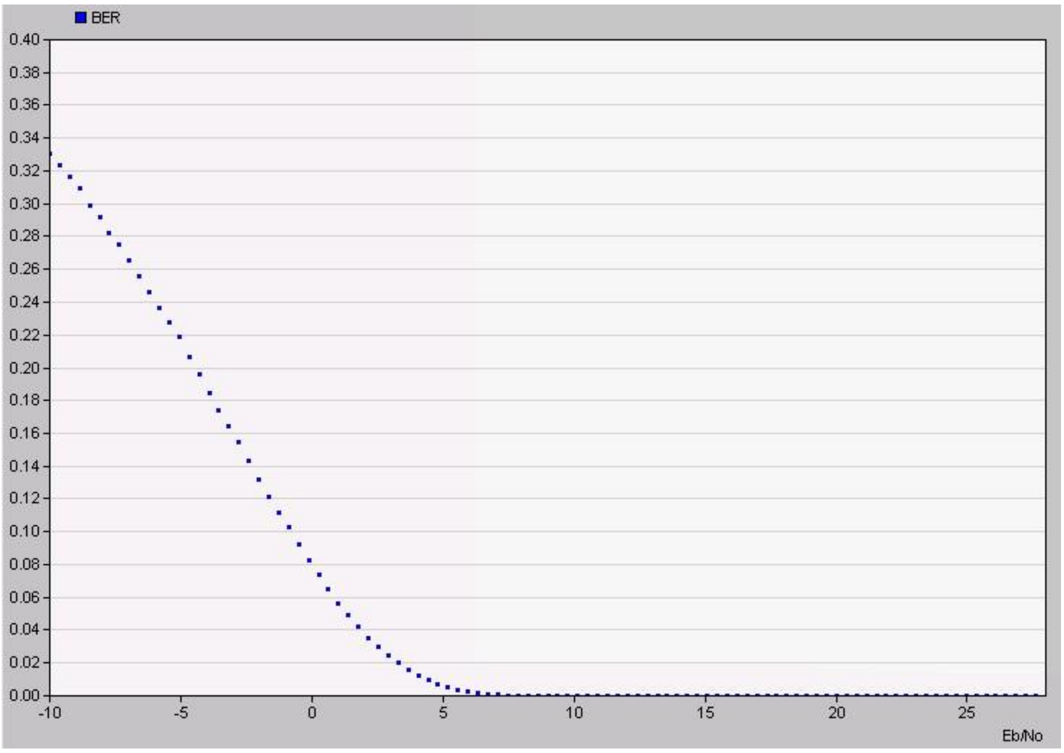

Figure 3-3: Modulation curve of O-QPSK.

Figure 3-4 shows the packet format of Zigbee data packet. The data packet contains a synchronization header (preamble plus start of packet delimiter), a PHY header to indicate the packet length, and PHY service data unit (PSDU). According to [9], the preamble is designed for the acquisition of symbol and chip timing, and in some cases may be used for coarse frequency adjustment. Within the PHY header, 7 bits are used to specify the length of the payload. Here, we assume the length of the PSDU is 10 bytes, so that the data packet length $l_m = 128 bits$.

Bits:32	**8**	**8**	**≤ 127Bytes**
Preamble	**Start-of-packet Delimiter**	**PHY Header**	**PHY Service Data Unit(PSDU)**

Figure 3-4: Data packet format.

Besides the parameters of required energy per bit and packet length, in [44, 48, 52, 53, 54], they provide the values for other parameters which can be used in our case. Table 3-2 shows the parameters for the wake-up radio and main radio.

Parameter	Wake-up Radio	Main Radio
α	1.47	1.47
P_b	10^{-3}	10^{-3}
$G_t G_r$	$0.5dBi$	$0.5dBi$
M_l	$40dB$	$40dB$
N_f	$10dB$	$10dB$
N_0	$-204dB/Hz$	$-204dB/Hz$
γ	2 (free space)	2 (free space)
P_{ct}	$53\mu W$	$82mW$
P_{cr}	$50\mu W$	$99.9mW$
c	3×10^{-8}	3×10^{-8}
f_c	$2399.5MHz$	$2402MHz$
R_b	$100kbps$	$250kbps$
E_b	$-193dB$	$-197.2dB$
l	$24bits$	$128bits$

Table 3-2: Parameters for wake-up radio and main radio.

3-2 Relation Between Transmission Distance and Transmission Energy Consumption

Assume in a simple small network, a sender wants to transmit a packet to a receiver and there is one relay node between them. Figure 3-5 shows this simple network.

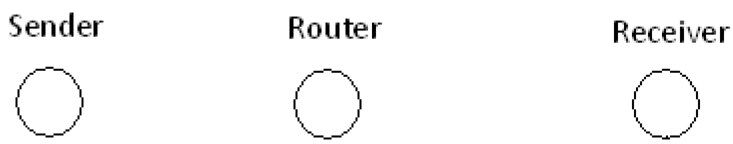

Figure 3-5: Small network architecture.

3-2-1 Routing Strategies for Dual-Radio Cooperation

The transmission range of wake-up radio is less than 10 meters while the transmission range of main radio is less than 70 meters so that the data packet transmission from the sender to the receiver in above small network has two possibilities. The first possibility is that the sender sends the data packet to the router, then the router sends the data packet to the receiver. The second choice is that the sender directly sends the data packet to the receiver. In the following, we will present the calculation of the total energy consumption for transmitting a wake-up packet and a data packet from the sender to the receiver using two different routing strategies.

Routing Strategy 1:

Under this condition, the sender first sends the wake-up packet to the router. After receiving the wake-up packet, the router knows there is a data packet that needs it to be relayed. Then the router sends an acknowledgement message to the sender and turns on its main radio. Until receiving the acknowledgement message, the sender turns on its main radio and sends the data packet to the router. After receiving the data packet, the router turns off the main radio and switches to use the wake-up radio to relay the previous wake-up packet to the receiver. Similarly, the receiver will send back an acknowledgement message to the router. After receiving the acknowledgement, the router turns on the main radio again and sends the data packet to the receiver. If the receiver receives the data packet successfully, it will send an acknowledgement packet to the router, then the router relays it to the sender. After that, all the nodes will turn off the main radio and wait for the next transmission. However, if the transmission fails, the receiver will send the message for retransmission. The route of the wake-up packet and the data packet transmission are the same, and is denoted as {S, R, D}, S is the source, D stands for the destination and R is the node which relays the packet. Figure 3-6 shows the routing procedure.

In this case, the total energy consumption for transmitting the packets is

$$E_{total\ \ 1} = \left(E_w(d_1) + E_w(d_2)\right) \times l_w + \left(E_m(d_1) + E_m(d_2)\right) \times l_m. \tag{3-7}$$

In Eq. (3-7), $E_w(d)$ and $E_m(d)$ stand for the energy consumption of transmitting the wake-up packet and data packet respectively. d_1 is the distance between the sender and the router, d_2 is the distance between the router and the receiver.

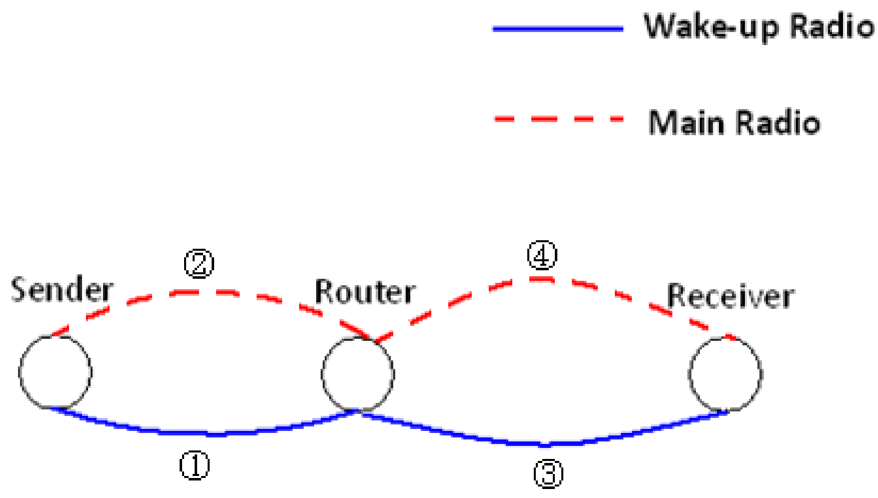

Figure 3-6: Routing strategy 1.

Routing Strategy 2:

In this case, the sender first sends the wake-up packet to the router, then the router relays the wake-up packet to the receiver. After receiving the wake-up packet, the receiver sends back an acknowledgement message to the router and turn on its main radio. Then the router relays the acknowledgement to the sender but does not turn on the main radio. When receiving the acknowledgement, the sender switches to use the main radio and directly sends the data packet to the receiver. If the transmission is successful, the receiver will sends back an acknowledgement to the sender and then the sender and the receiver will turn off the main radio and switch to use the wake-up radio for the next transmission. However, if the transmission fails, the receiver will ask for retransmission. The route of the wake-up packet transmission is the same as that of condition 1 which is denoted as {S, R, D}. However the route of the data packet transmission is marked as {S, D}, there is no relay node between the source and the destination since the sender directly sends the data packet to the receiver. Figure 3-7 shows this transmission procedure.

Under this condition, the total energy consumption for transmitting the packet is

$$E_{total\_2} = \left(E_w(d_1) + E_w(d_2)\right) \times l_w + E_m(d_1 + d_2) \times l_m. \qquad (3\text{-}8)$$

In Eq. (3-8), $E_w(d)$ and $E_m(d)$ stand for the energy consumption of transmitting the wake-up packet and data packet respectively. d_1 is the distance between the sender and the router, d_2 is the distance between the router and the receiver.

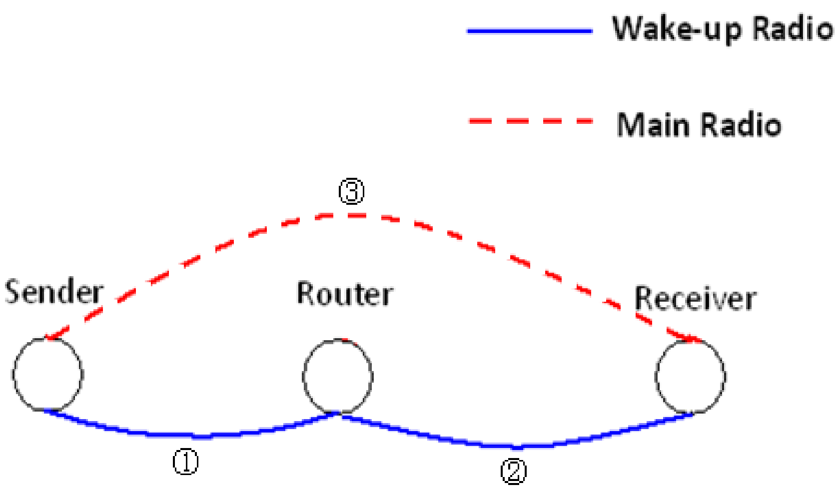

Figure 3-7: Routing strategy 2.

3-2-2 Comparison of Transmission Energy Consumption by Two Different Routing Strategies

In Figure 3-5, assume that the distance between the router and the receiver (d_2) is 5 meters, and the distance between the sender and the router (d_1) varies from 1 meter to 10 meters. Then we use MATLAB to obtain the trends of the energy consumption using two different routing strategies with the change of d_1. Figure 3-8 shows the energy consumption of packet transmission using routing strategy 1 and 2.

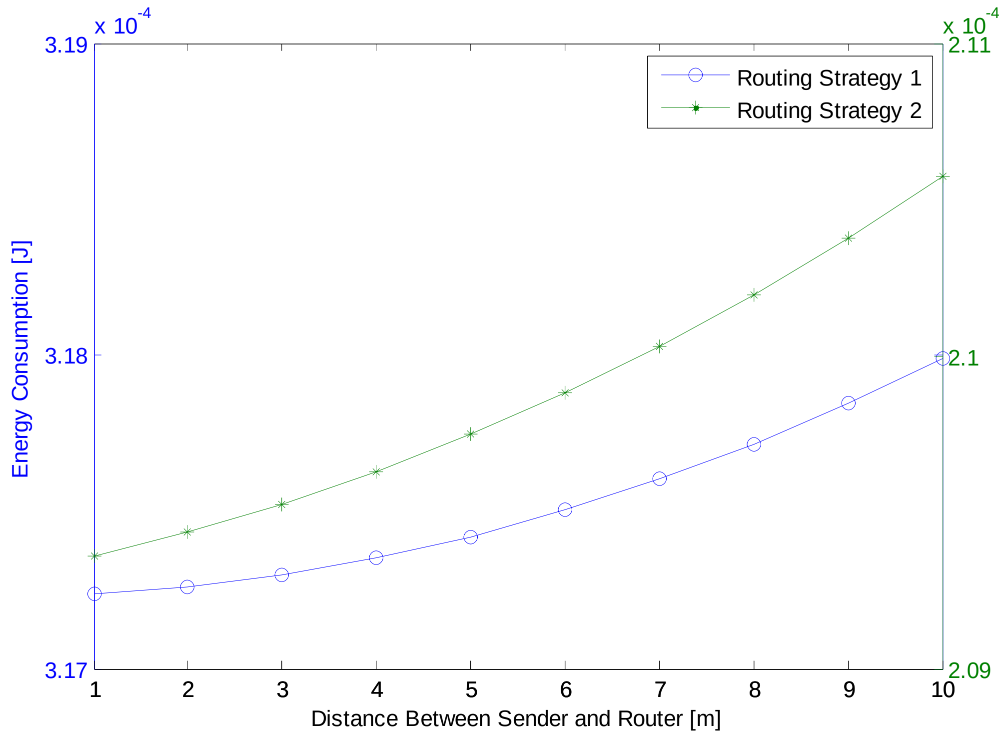

Figure 3-8: Energy consumption of packet transmission by RS1 and RS2.

In Figure 3-8, the line marked by "○" is the energy consumption of packet transmission by routing strategy 1 and the line marked by "*" is the energy consumption of routing strategy 2. The value in left y axis represents for the energy consumption of routing strategy 1 and the right one is for routing strategy 2. From this figure, we can obtain that with the increasing of the distance between the sender and the router, the total energy consumption of transmitting a wake-up packet and a data packet rises. Meanwhile, the total transmission energy consumption of routing strategy 1 is larger than that of routing strategy 2.

3-3 Transmission Energy Consumption in Linear Topology

3-3-1 Routing Strategies for Data Packet Transmission

Since wake-up radio and main radio have different transmission range, after waking up the nodes which need to transmit or receive the packet, it may have two or more different routing strategies for data packets' transmission. Therefore energy consumption of the main radio changes when using different routing strategies to transmit the data packet.

In order to find these variations, we will study the case of linear topology for simplicity in this chapter. Assume that the distance between the sender and the receiver (d) starts from 20 meters to 70 meters (the transmission range of ZigBee), and the distance grows by 10 meters in each step. Meanwhile, the distance between the two adjacent nodes is fixed as 10 meters and each node in the route only wakes up the adjacent node in the next hop. However, the data packet transmission has two or more routes. In many cases, there are two or more routings to transmit the data packet using the same hops. We choose energy consumption as a routing metric where optimal route is the one which consumes less energy.

Figure 3-9 shows the data packet transmission procedures when the distance between the sender and the receiver is 20 meters. The path marked by the route identifier "①" means the sender sends the data packet directly to the receiver which only uses one hop. The path marked by the route identifier "②" means that the sender first sends the data packet to N2, then N2 relays the packet to the receiver.

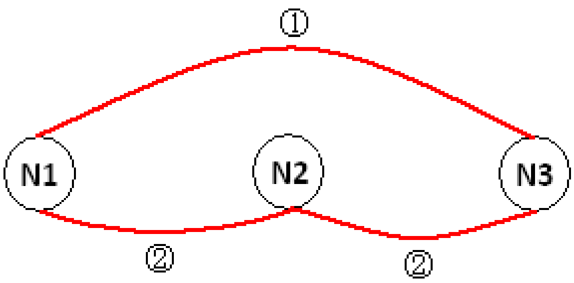

Figure 3-9: Routing strategies when $d = 20\ m$.

Figure 3-10 to figure 3-14 show the routings when d is 30 meters, 40 meters, 50 meters, 60 meters and 70 meters respectively.

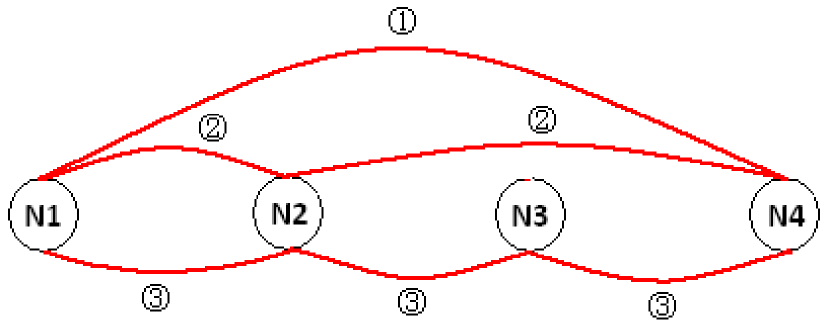

Figure 3-10: Routing strategies when $d = 30\ m$.

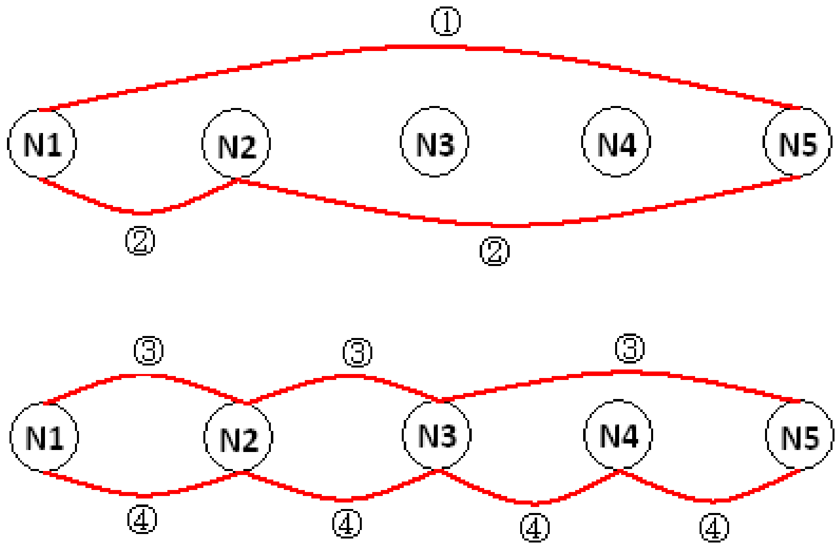

Figure 3-11: Routing strategies when $d = 40\ m$.

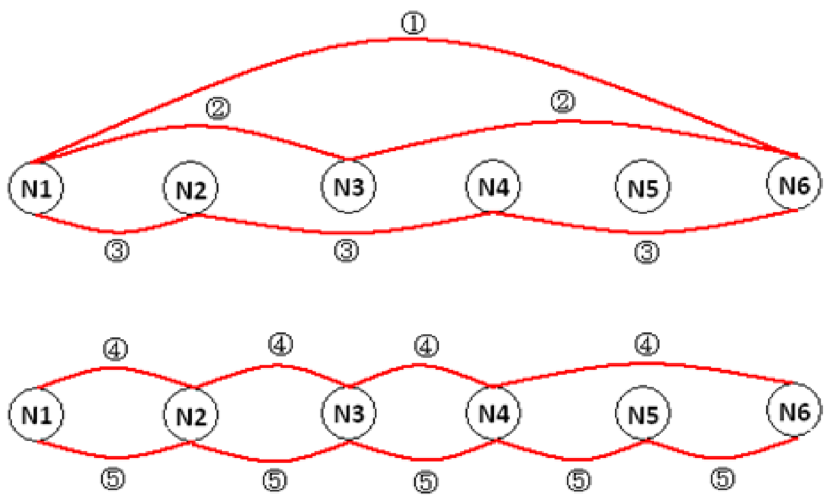

Figure 3-12: Routing strategies when $d = 50\ m$.

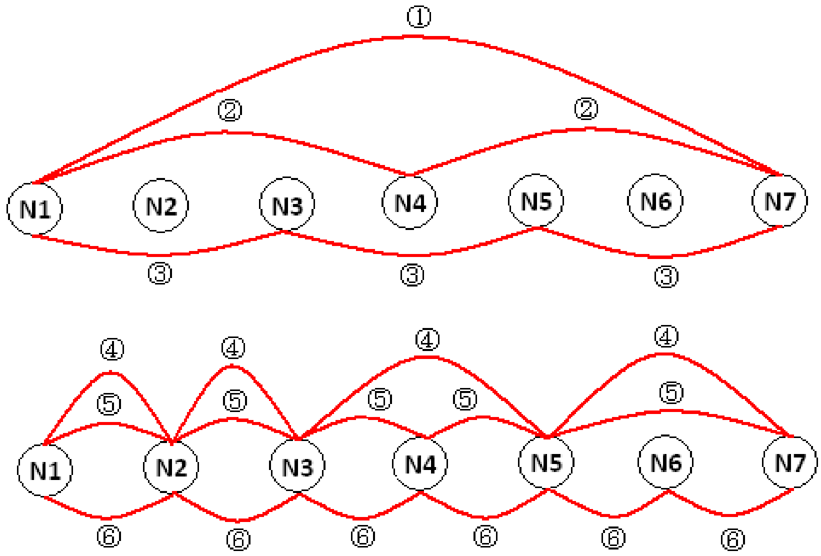

Figure 3-13: Routing strategies when $d = 60\ m$.

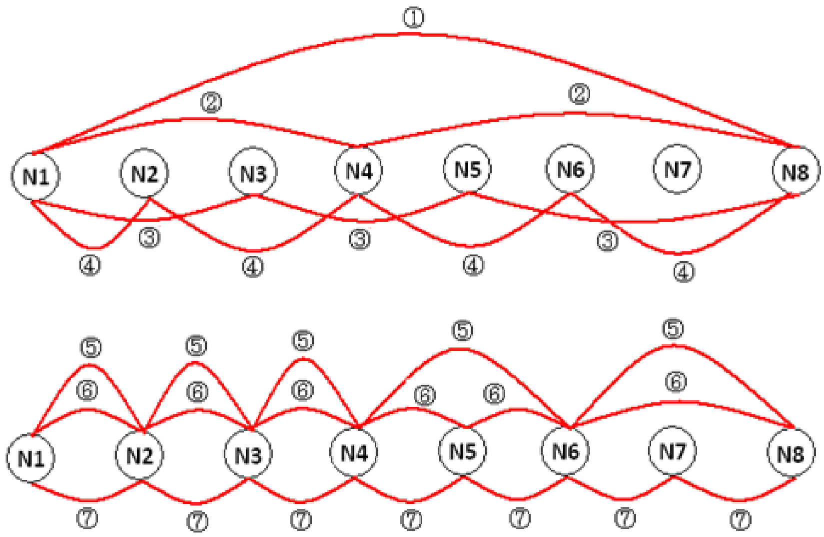

Figure 3-14: Routing strategies when $d = 70\ m$.

3-3-2 Energy Consumption of Data Packet Transmission in Free Space

Figure 3-15 to 3-20 show the variations of the energy consumption of data packet transmission for different transmission distance when the path loss exponent is 2 (free space). In these figures, the route identifiers are the route identifiers that can be seen in Figure 3-9 to 3-14.

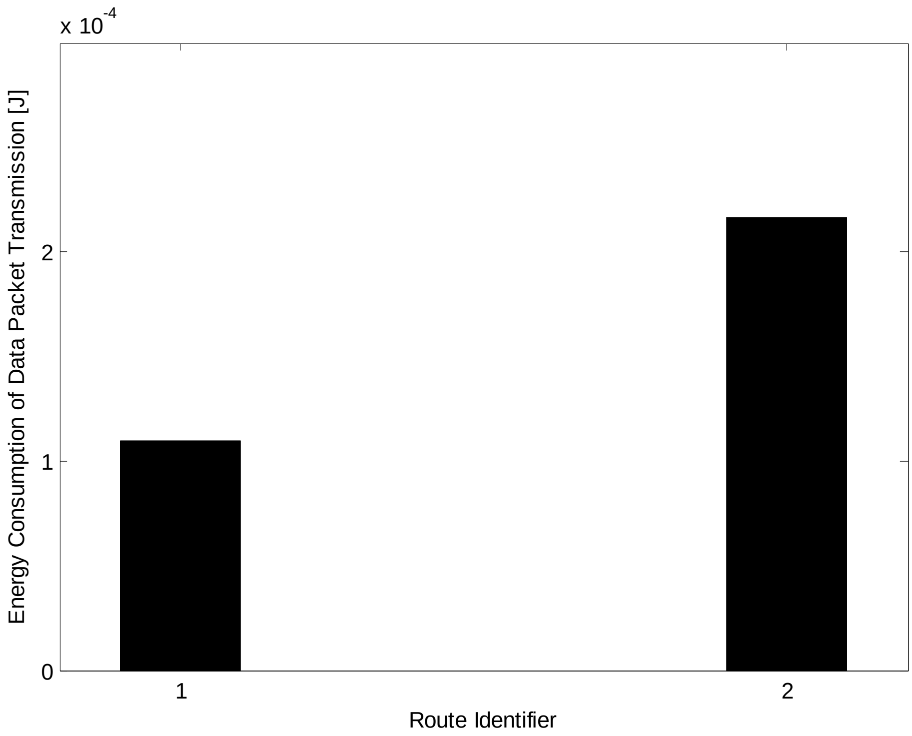

Figure 3-15: Energy consumption of data packet transmission when $d = 20\ m$.

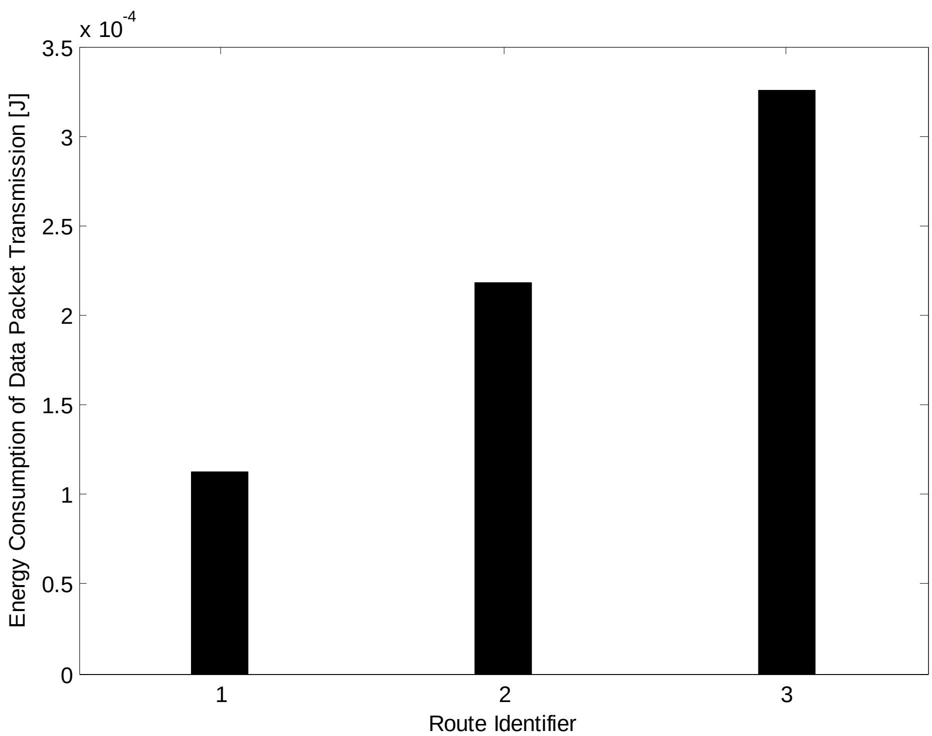

Figure 3-16: Energy consumption of data packet transmission when $d = 30\ m$.

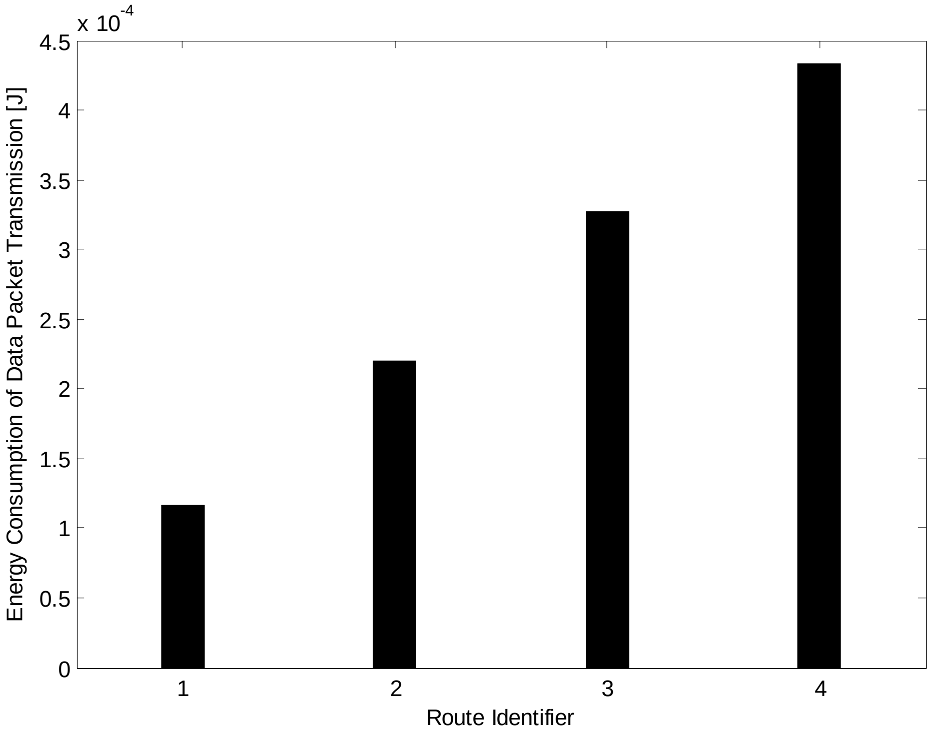

Figure 3-17: Energy consumption of data packet transmission when $d = 40\ m$.

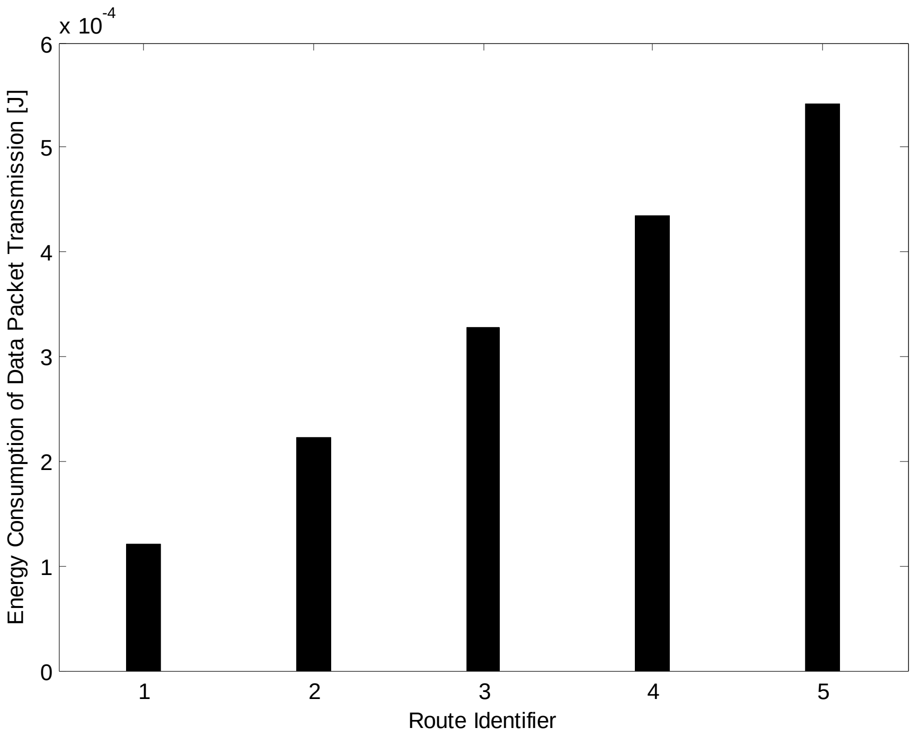

Figure 3-18: Energy consumption of data packet transmission when $d = 50\ m$.

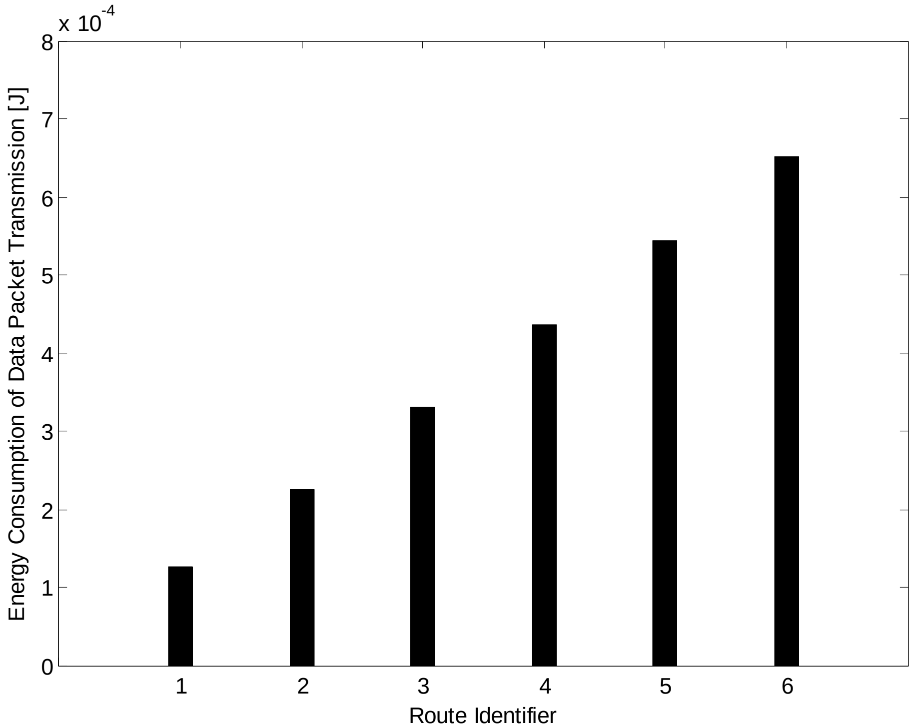

Figure 3-19: Energy consumption of data packet transmission when $d = 60\ m$.

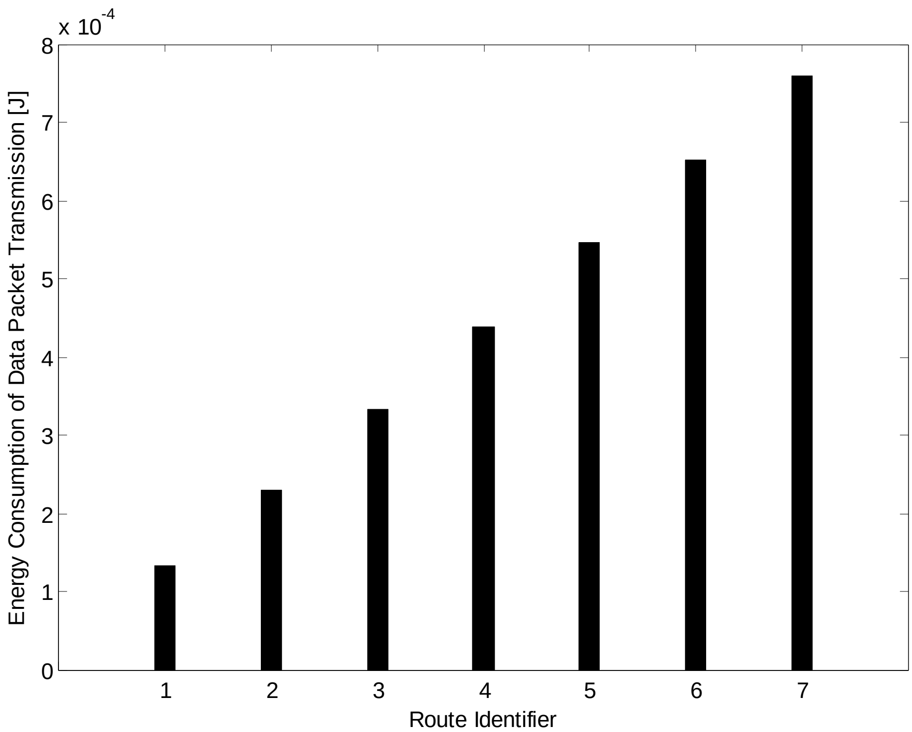

Figure 3-20: Energy consumption of data packet transmission when $d = 70\ m$.

We can see clearly from above figures that when increase the route identifier number, the energy consumption of data packet transmission shows an increasing tendency. Meanwhile, if the sender directly sends the data packet to the receiver costs less energy than that using the maximum hops to transmit the data packet when the distance between the sender and the receiver is different. That means directly transmitting the data packet in free space can reduce the transmission energy consumption. The reduced energy consumption percentage can be computed by the following equation,

$$p = \frac{E_{max} - E_{direct}}{E_{max}} \times 100\%. \quad (3\text{-}9)$$

In Eq. (3-9), E_{max} is the energy consumption of data packet transmission which uses the path that is denoted by the maximum route identifier (in Figure 3-9 to Figure 3-14) to transmit the data packet. This transmission route is the same as that of transmitting the wake-up packet. E_{direct} is the energy consumption of data packet transmission which directly sends the data packet from the sender to the receiver.

After calculation, we can obtain that when the distance between the sender and the receiver rises, this energy consumption reduction goes up. Figure 3-21 shows the relation between the reduced energy consumption percentage and the distance between the sender and the receiver.

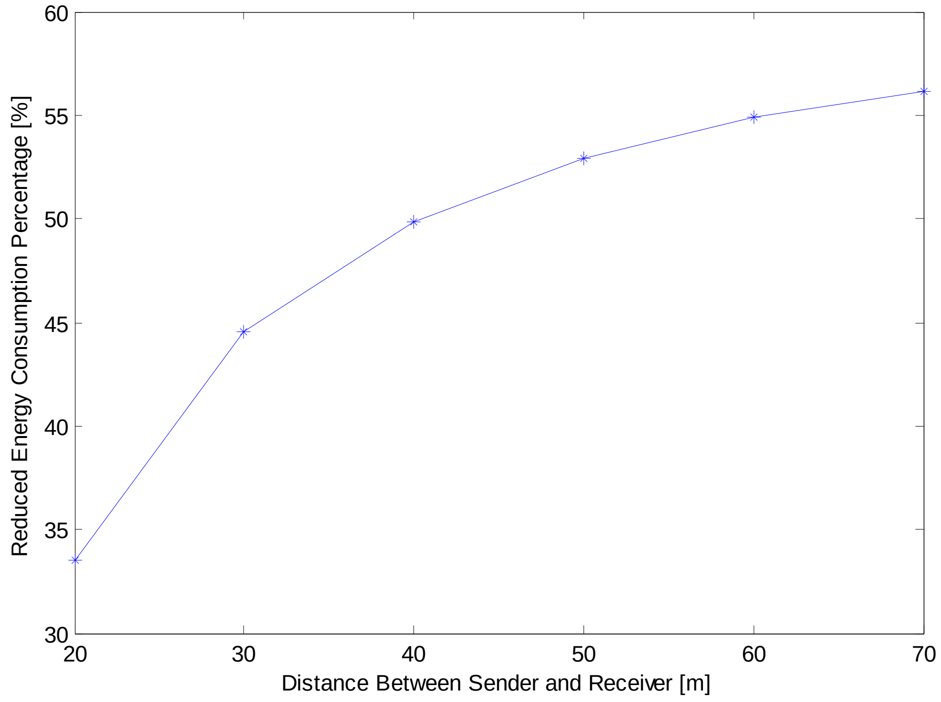

Figure 3-21: Reduced energy consumption percentage v.s distance between sender and receiver.

In Chapter 3, Eq. (3-5) gives the calculation of transmission energy consumption per bit. In this equation, it has three terms. The first term is mainly determined by the transmission distance. The second term and the third term are determined by the transmission hops when all the parameters are fixed. Since if the route identifier number is larger, the packet will go through more intermediate nodes during the transmission, so that it will cost more dissipation energy of the nodes in the route. Here, we divide these three terms into two parts. The first part contains the first term and the second part is composed of the second and the third terms. The Eq. (3-5) can be simply rewritten as

$$E_{bit} = k_1 d^{\gamma} + k_2. \tag{3-10}$$

In Eq. (3-10), d is the transmission distance, γ is the path loss exponent, k_1 is a constant, k_2 is proportional to the route identifier number.

Figure 3-22 shows the curve of exponential function. In this figure, we can see that when the exponent of x is larger, the curve goes up more rapidly. Therefore, we can obtain that when the path loss exponent becomes larger, the transmission distance starts to become dominated over the power consumption term in Eq. (3-10).

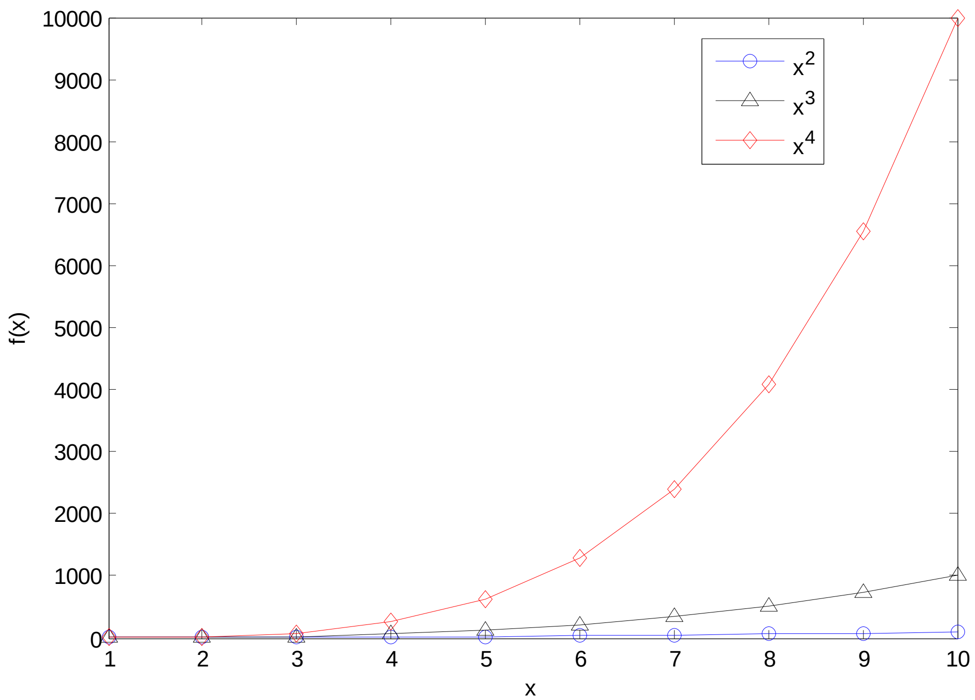

Figure 3-22: Exponential function.

When the path loss exponent is 2, the order of magnitude of the first part in Eq. (3-10) is smaller than that of the second part. Therefore the second part is dominant in energy consumption calculation which means that when there are more nodes in the transmission route, it will cost more transmission energy. When transmit packets in the free space, the tendency of data packet transmission energy consumption goes up with the increasing of the route identifier number. Therefore, it is better to directly send the data packet from the sender to the receiver when transmission in free space.

3-3-3 Energy Consumption of Data Packet Transmission in Path Loss Exponent 3 Environment

The following six figures show the changes of the energy consumption of data packet transmission for different transmission distance when the path loss exponent is 3.

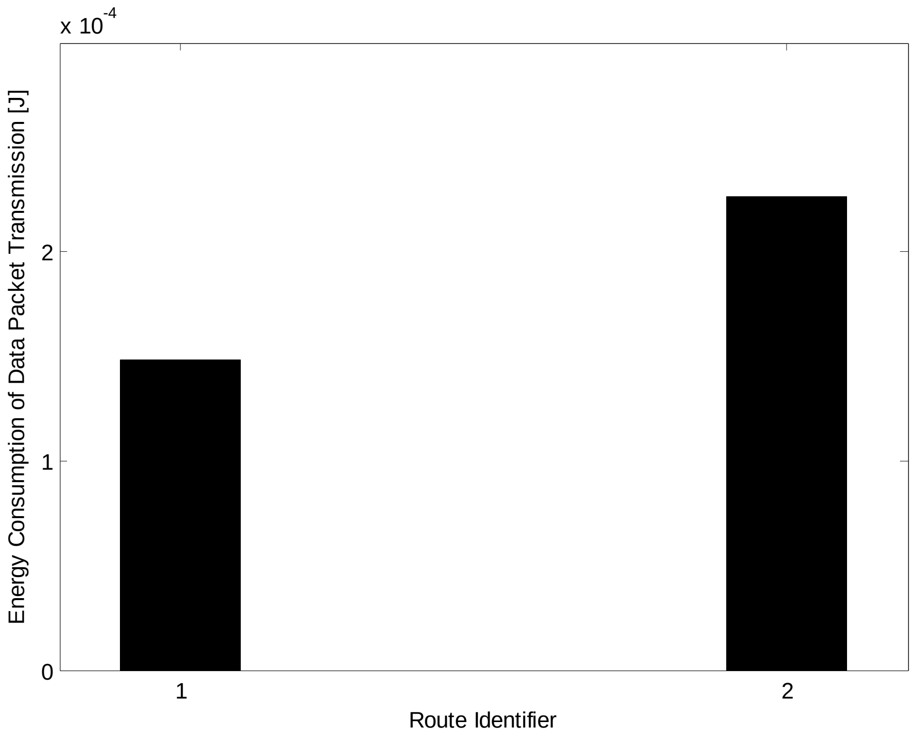

Figure 3-23: Energy consumption of data packet transmission when $d = 20\ m$.

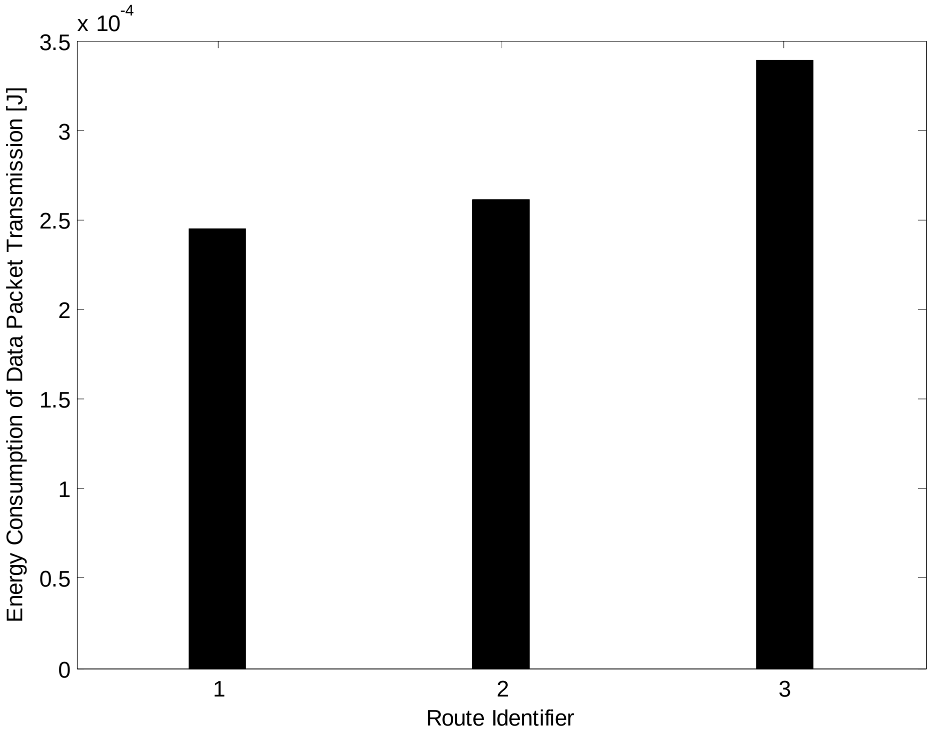

Figure 3-24: Energy consumption of data packet transmission when $d = 30\ m$.

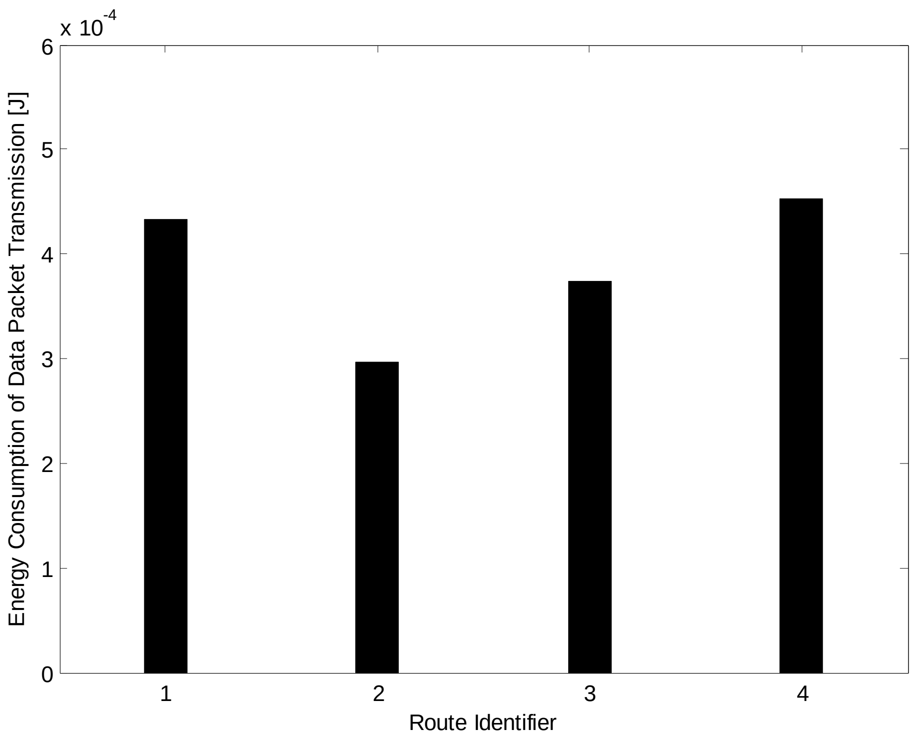

Figure 3-25: Energy consumption of data packet transmission when $d = 40\ m$.

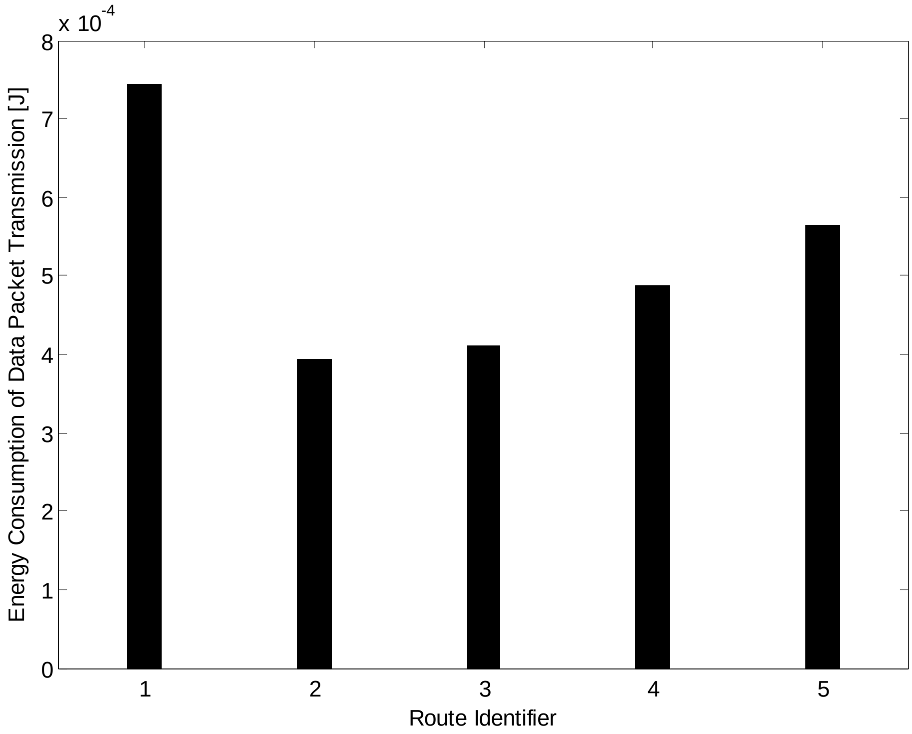

Figure 3-26: Energy consumption of data packet transmission when $d = 50\ m$.

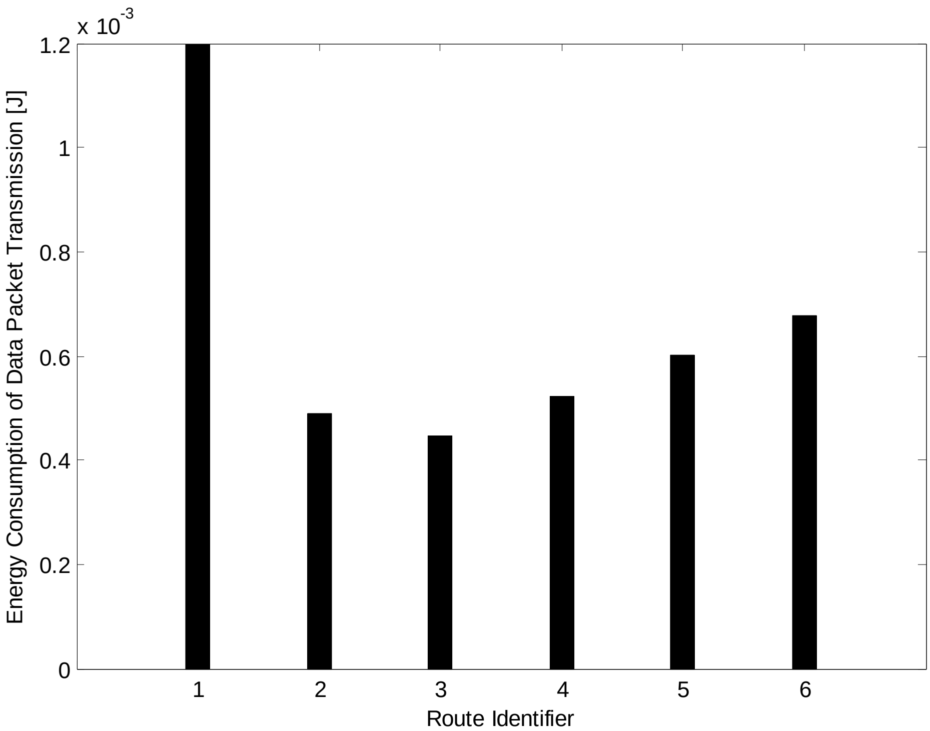

Figure 3-27: Energy consumption of data packet transmission when $d = 60\ m$.

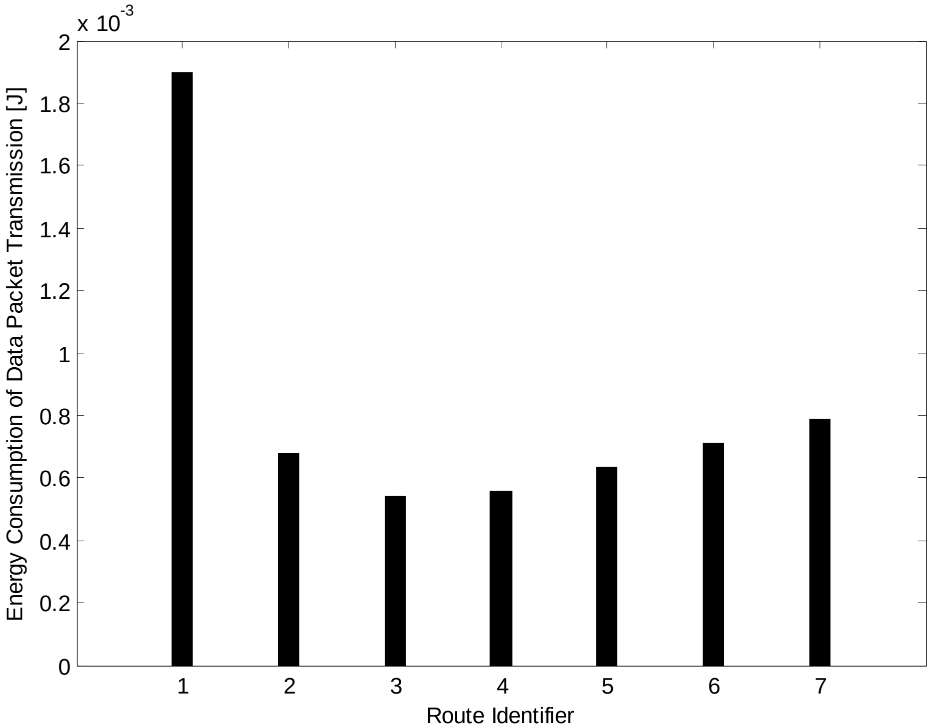

Figure 3-28: Energy consumption of data packet transmission when $d = 70\ m$.

From above figures, we can obtain that when the path loss exponent is 3, the variation tendency has three different conditions.

- When the distance between the sender and the receiver is 20 meters or 30 meters, with the increase of the route identifier number, the energy consumption of transmitting data packet rises.
- When the distance from the sender to the receiver is 40 meters or 50 meters, using the path which is denoted by route identifier 2 to transmit the data packet costs the minimum energy.
- When the distance between the sender and the receiver is 60 meters or 70 meters, the minimum transmission energy consumption occurs in using the path that is marked by route identifier 3 to transmit the data packet.

When the path loss exponent is 3, the orders of magnitude of the first part and the second part in Eq. (3-10) change sharply. At the beginning, the order of magnitude of the first part is larger than that of the second part which means the first part dominates the transmission energy consumption, so the trend of the energy consumption decreases. When the orders of magnitude of these two parts are close to each other, it will use the minimum energy to transmit the data packet. After that, the order of magnitude of the first part becomes smaller than that of the second part. Therefore the second part is dominant in energy consumption calculation. In this case, the tendency of the energy consumption grows with the increasing of the route identifier number.

When transmitting packets in path loss exponent 3 environment, we cannot determine the best route which allows for less energy consumption. Therefore, in the next chapter we will introduce a routing protocol which can be able to define the route with less energy consumption.

3-3-4 Energy Consumption of Data Packet Transmission in Harsh Environment

Figures in this section show the variation trend of the energy consumption of data packet transmission for different transmission distance when the path loss exponent is 4.

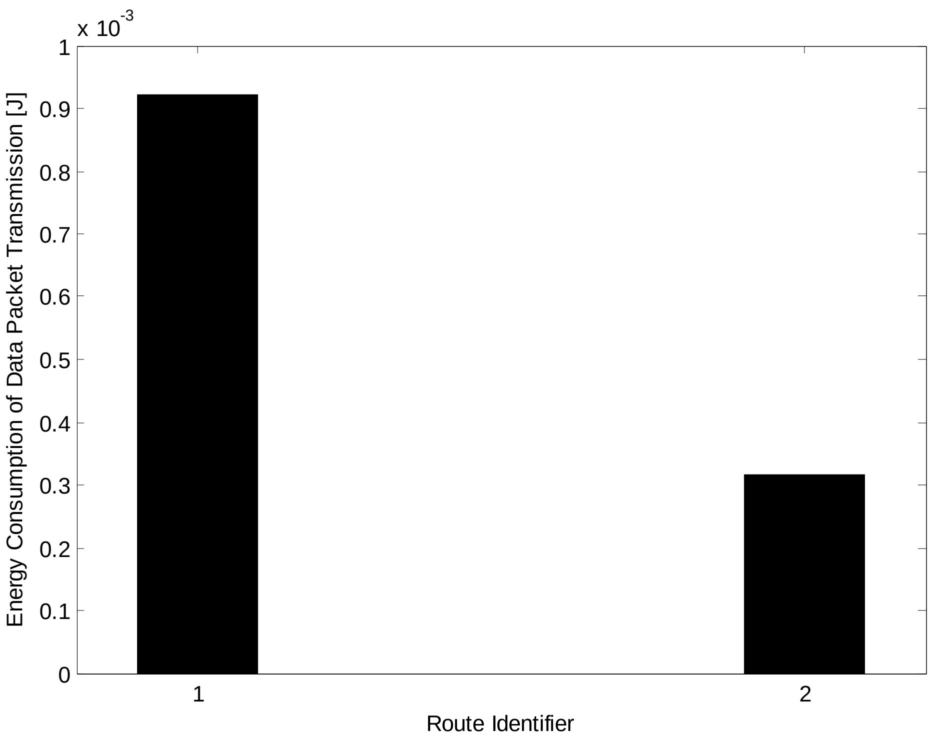

Figure 3-29: Energy consumption of data packet transmission when $d = 20\ m$.

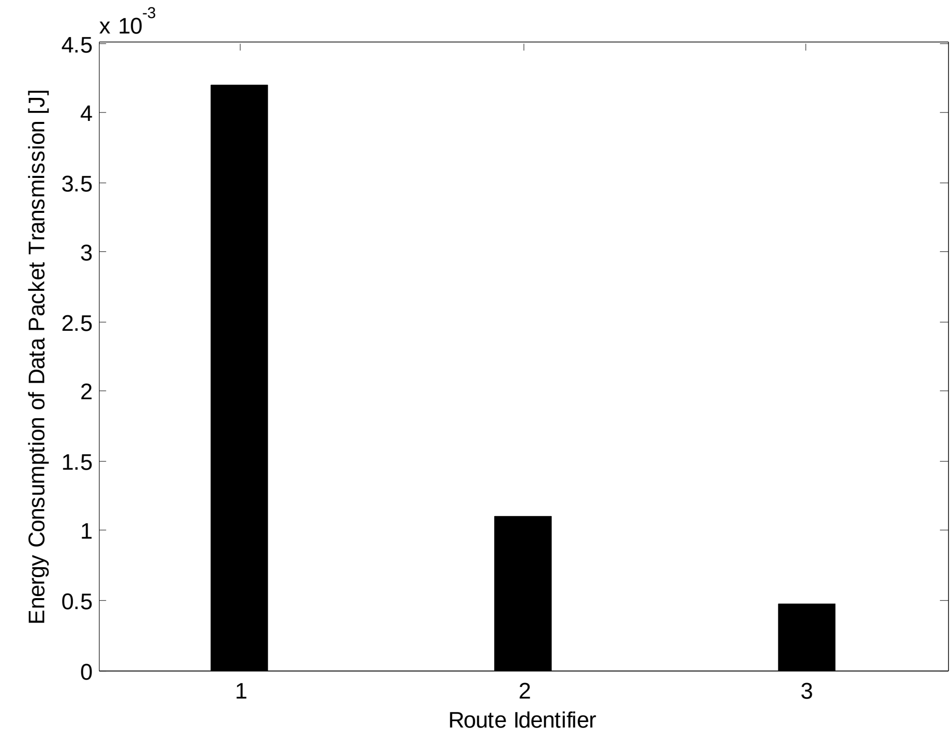

Figure 3-30: Energy consumption of data packet transmission when $d = 30\ m$.

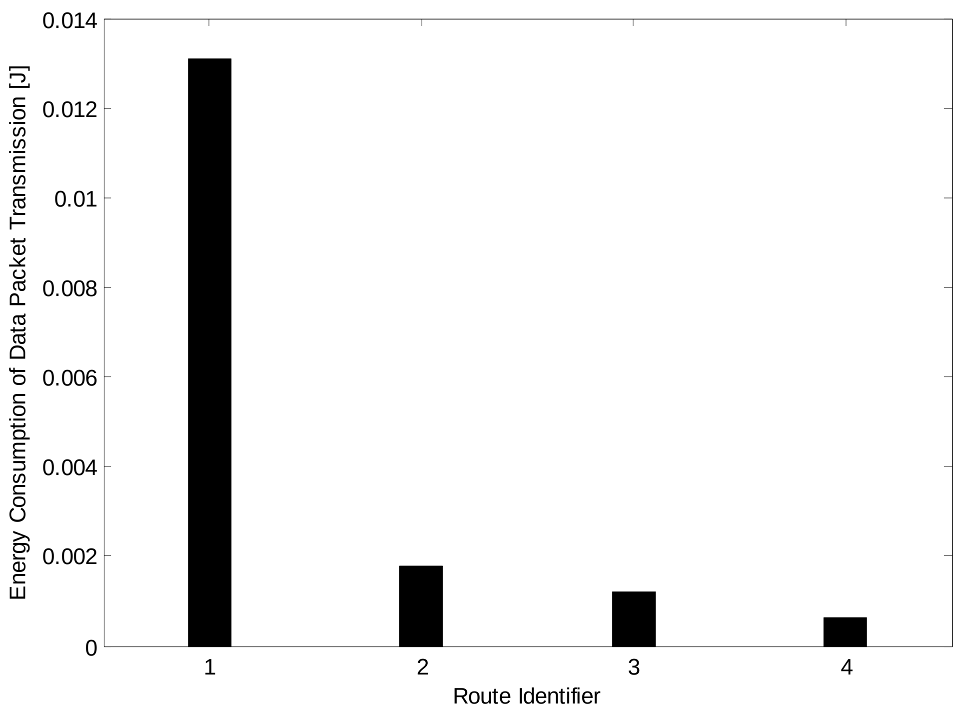

Figure 3-31: Energy consumption of data packet transmission when $d = 40\ m$.

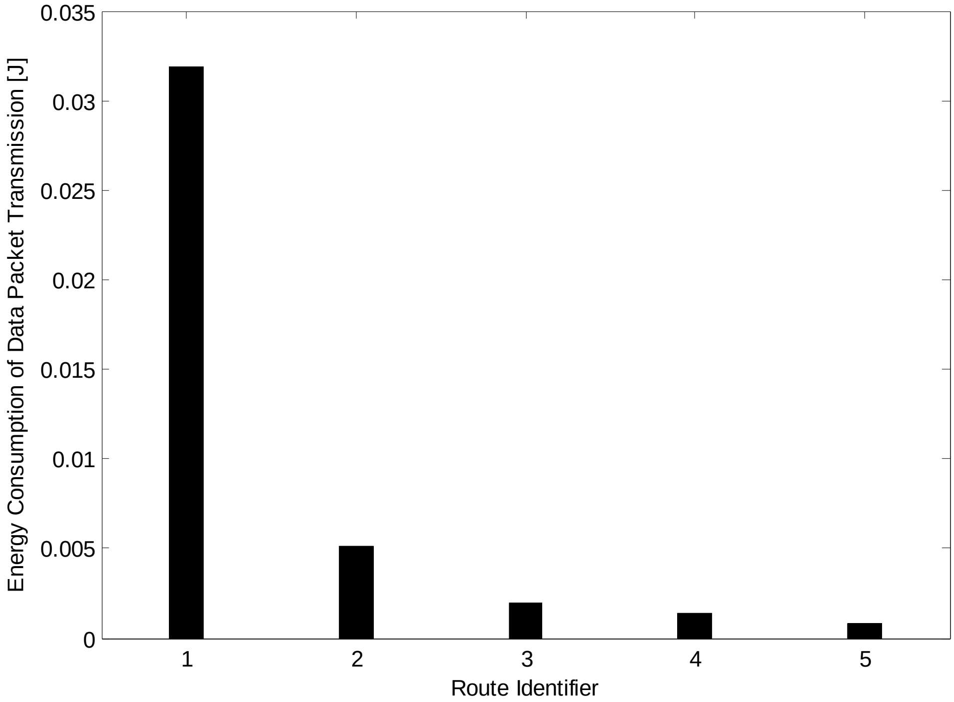

Figure 3-32: Energy consumption of data packet transmission when $d = 50\ m$.

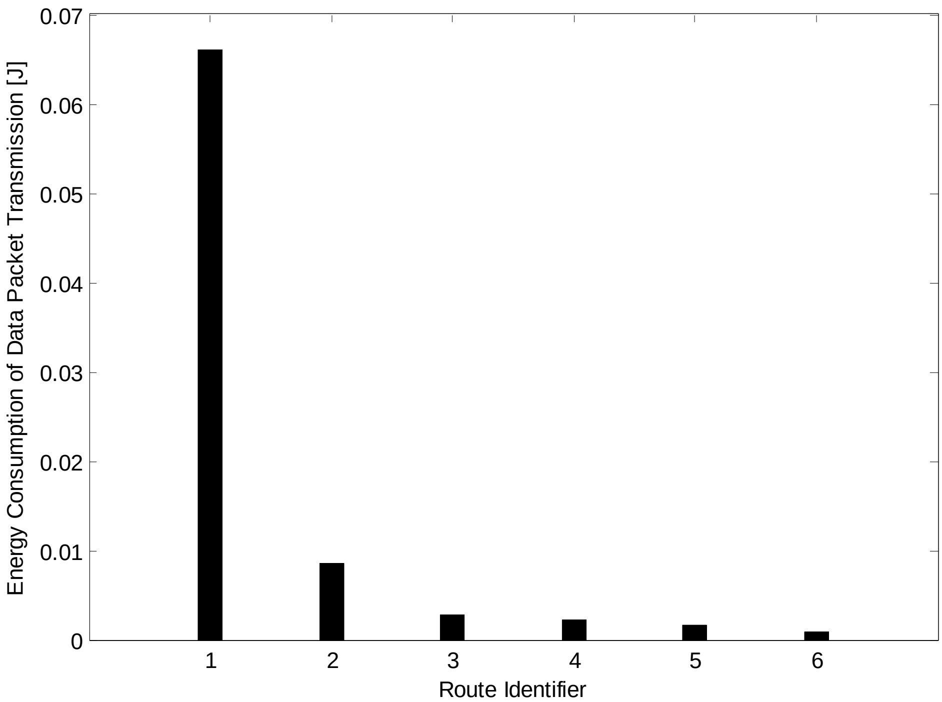

Figure 3-33: Energy consumption of data packet transmission when $d = 60\ m$.

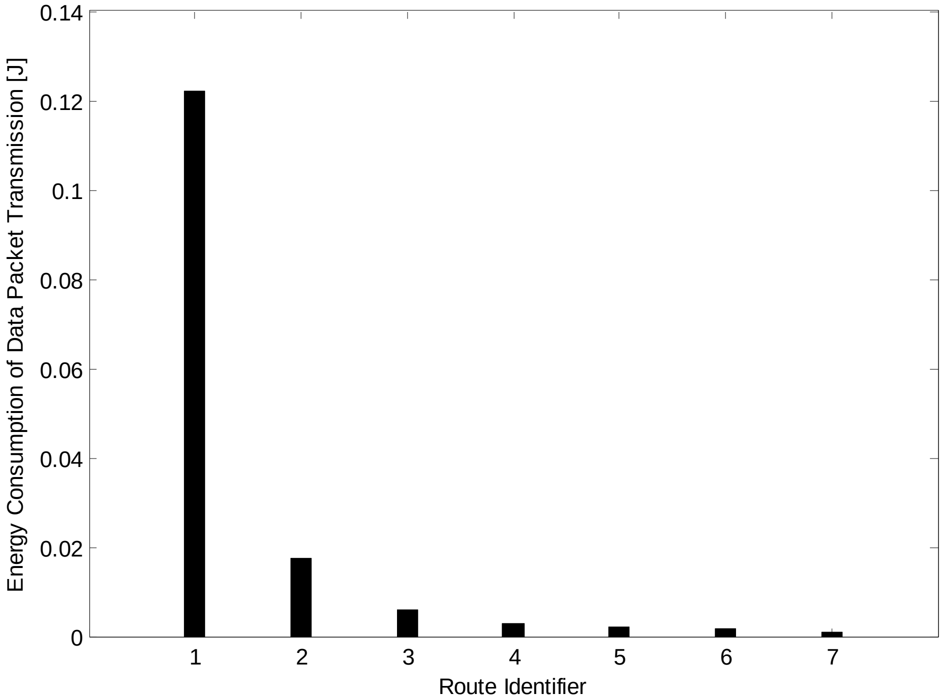

Figure 3-34: Energy consumption of data packet transmission when $d = 70\ m$.

When the path loss exponent is 4, the variation tendency of energy consumption of data packet transmission is opposite of that in free space. The energy consumption of data packet transmission shows the decreasing trend with the increase of route identifier number.

When the path loss exponent is 4, the order of magnitude of the first part is much larger than that of the second part in Eq. (3-10). In this case, the first part dominates the transmission energy consumption. That means when d^4 is larger, it will cost more transmission energy consumption. Therefore when transmission in harsh environment, the trend of transmission energy consumption declines when increase the route identifier number to transmit the data packet.

3-4 Conclusion

All the results showed in this chapter indicate that the transmission energy consumption is affected by the routing strategy which is in turn influenced by the distance between two peers and path loss exponent.

For transmission in linear topology, we have to use different routing strategies when transmitting packets in different conditions. When in the free space it is better to directly transmit the data packet from the sender to the receiver. While transmitting the packet in harsh environment, using the same route of the wake-up packet transmission to transmit the data packet is the best choice. However, when the path loss exponent is 3, we cannot determine the best route which costs less energy consumption.

Chapter 4

Energy Consumption in WSNs

In this chapter, we verify our results of last chapter using MATLAB simulation with three different routing protocols which we designed for dual-radio cooperation. Meanwhile, we use MATLAB to simulate the transmission procedures using these three routing protocols in wireless sensor networks (WSNs) and calculate the average transmission energy consumption. At last, we propose that we should choose different routing protocols based on the transmission environment in a WSN which employs dual-radio cooperative transmission.

4-1 Routing Protocols

There are two kinds of radios to transmit different packets-the wake-up radio and the main radio, so that they may use the same or two different routing strategies to transmit these two kinds of packets. Here, we assume the wake-up radio employs Dijkstra’s algorithm to find the shortest path from the sender and the receiver, then it uses this path to transmit the wake-up packet. Meanwhile, we present three different routing strategies for the main radio. After comparing these three routings, we want to find which routing strategy will cost the least energy when transmitting a wake-up packet and a data packet in WSNs.

Dijkstra's algorithm:

Dijkstra's algorithm is conceived by Dutch computer scientist Edsger Dijkstra in 1956 and published in 1959 [55]. It solves the single-source shortest path problem for a graph with nonnegative edge path costs and produces a shortest path tree. It is a greedy algorithm. A greedy algorithm makes at each step in the computation the best choice at that moment in the hope that the global optimum is reached at the end [56].

For a graph **G** = **(V, E)** where **V** is a set of vertices and **E** is a set of edges. Dijkstra's algorithm keeps two sets of vertices **S** and **V-S**, **S** is the set of vertices whose shortest paths from the source have already been determined and **V-S** is the remaining vertices. We assume **d** is array of best estimates of shortest path to each vertex and **p** is an array of predecessors for each vertex.

The basic operation of Dijkstra's algorithm is described as follows:

1. Initialize **d** and **p**.
2. Set **S** to empty.
3. While there are still vertices in **V-S**
   - Sort the vertices in **V-S** according to the current best estimate of their distance from source.
   - Add **u**, the closest vertex in **V-S**, to **S**.
   - Relax all the vertices still in **V-S** which connect to **u** [57].

Routing Protocols:

Routing Protocol 1: In this routing protocol, wake-up packet transmission and data packet transmission both use the same shortest path that computed by Dijkstra's algorithm. Here, we name this routing protocol as Shortest Path Transmission Protocol (SPTP). Figure 4-1 shows the transmission procedure by SPTP. In this figure, S is the sender and R is the receiver. The transmission path from S to R showed in this figure is the shortest path computed by Dijkstra's algorithm. The wake-up radio and the main radio both follow this path to transmit the packets. In this case, S first uses the wake-up radio to send the wake-up packet to the adjacent node in the shortest path, after this wake-up packet being received successfully, S will turn on the main radio to send the data packet to this node. If this data packet is received successfully, this node will send the previous wake-up packet to the next node in the route using the wake-up radio, and then switches to use the main radio to send the data packet to that node. Similarly, the wake-up packet and data packet will be relayed by two radios alternately until they reach the receiver R. In the transmission procedure, the wake-up radio is always on and the main radio is turned on only when the nodes need to transmit or receive the data packet and after finish the transmission, the main radio will be turned off.

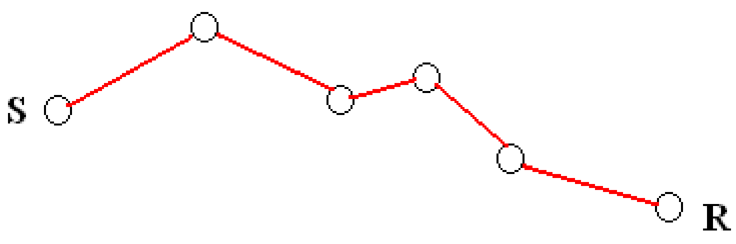

Figure 4-1: Routing protocol 1 (SPTP).

Routing Protocol 2: In this routing protocol, transmitting the wake-up packet uses the shortest path computed by Dijkstra's algorithm. There are two different conditions for data packet transmission. When the distance between the sender and the receiver (D_{SR}) is less than 70 meters, the data packet is transmitted directly from the sender to the receiver. However, when D_{SR} is larger than 70 meters, first we have to find the node (N) in the shortest path computed by Dijkstra's algorithm which makes the distance between the sender and the node N (D_{SN}) closest to 70 meters and less than 70 meters. After finding this node the sender first sends the data packet to node N, then node N relays the data packet to the receiver. This routing protocol is called as Direct Transmission within Maximum Range Protocol (DTMRP). Figure 4-2 shows the transmission procedure by DTMRP. This figure shows the transmission path of the wake-up packet and the main packet when $D_{SR} \leq 70m$. S is the sender and R is the receiver. The solid line shows the path of transmitting wake-up packet which is obtained through Dijkstra's algorithm while the dashed line shows transmission path of the data packet. Under this condition, S first uses the wake-up radio to transmit the wake-up packet through the shortest path until it reaches the receiver R. At this moment, all the nodes in the route are awake but only S and R turn on their main radios. After that, S sends the data packet directly to the receiver R. In the transmission procedure, the wake-up radio is always on and the main radio is turned on only when the nodes need to transmit or receive the data packet and after finish the transmission, the main radio will be turned off.

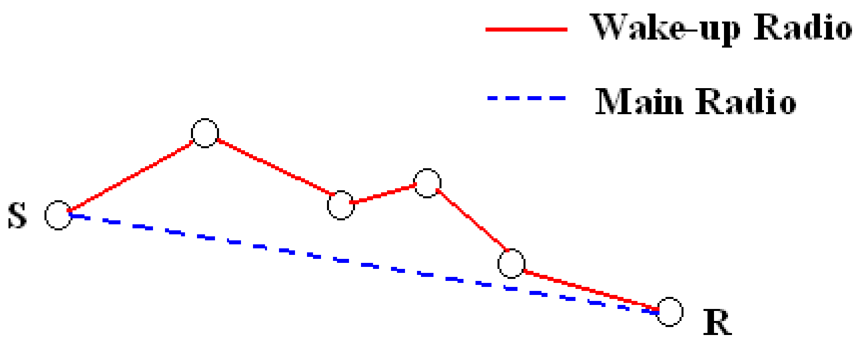

Figure 4-2: Routing protocol 2 (DTMRP).

Routing Protocol 3: In this routing protocol, wake-up packet transmission makes use of the shortest path computed by Dijkstra's algorithm. For data packet transmission, we will find a node N in this shortest path to relay the data packet. This node N will make the sum of the distance D_{SN} and D_{NR} is less than those using other nodes in the shortest path to relay the data packet. After finding node N, the data packet will be transmitted to the node N, and then N relays the data packet to the receiver. This routing protocol is named as Minimum Sum of Distance Transmission Protocol (MSDTP). Figure 4-3 shows this transmission protocol. In this figure, S is the sender and R is the receiver. The solid line is the shortest path for wake-up packet transmission and the dashed line is the data packet's transmission path. Using MSDTP to transmit packets, we have to wake up all the nodes between S and N first. After that, S and N will turn on their main radios and S will send the data packet to N. When the data packet reaches N, N switches to use the wake-up radio to transmit the wake-up packet to the next node in the route. After waking up all the nodes between N and R, N and R will turn on the main radio. Then N sends the data packet to the receiver R. In the transmission procedure, the wake-up radio is always on and the main radio is turned on only when the nodes need to transmit or receive the data packet and after finish the transmission, the main radio will be turned off.

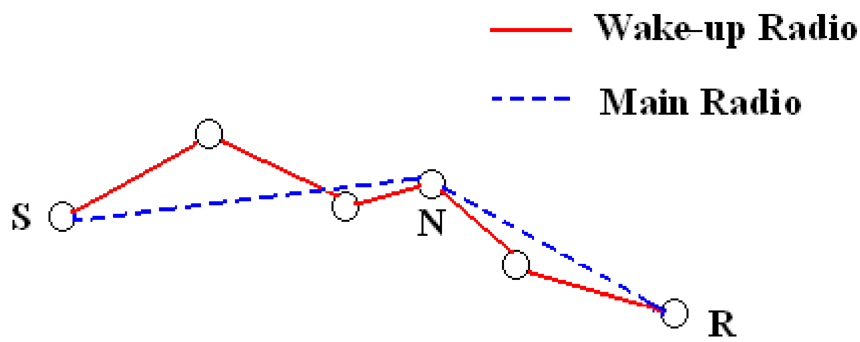

Figure 4-3: Routing protocol 3 (MSDTP).

4-2 Prerequisites and Experiment Method

Prerequisites:

1. Assume the network is a wireless sensor network (WSN).
2. The area of the network is $80 \times 80m^2$.
3. In order to make the algorithm simple, assume that the distance between the sender and the receiver is less than 140 meters.

Experiment Method: First we randomly put a certain number of sensors in the network area of $80 \times 80m^2$. In the network, it randomly chooses a sender and a receiver. We use three different routing protocols mentioned above to transmit a wake-up packet and a data packet to calculate the transmission energy. Simulations are repeated 100 times and the average energy consumption of the network is computed. The average energy consumption of the network is obtained under different path loss exponent conditions when the number of sensor is 100, 200, 300 and 400.

Figure 4-4 to Figure 4-7 show the random WSN architectures which have 100, 200, 300 and 400 sensors respectively.

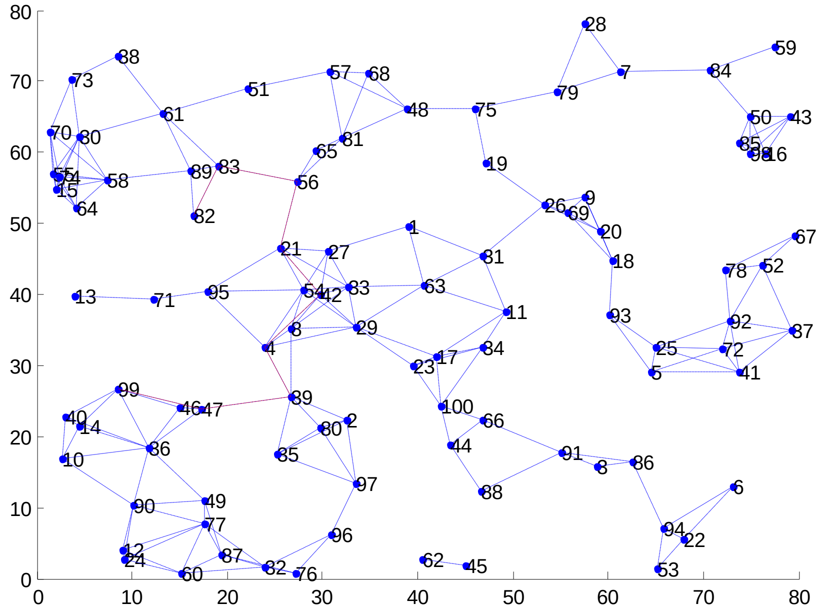

Figure 4-4: WSN of 100 sensors architecture.

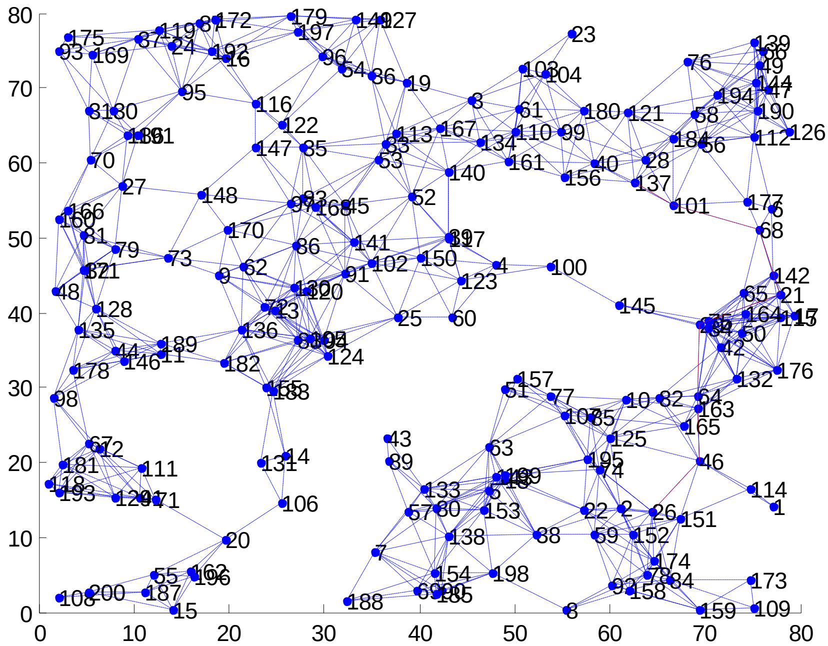

Figure 4-5: WSN of 200 sensors architecture.

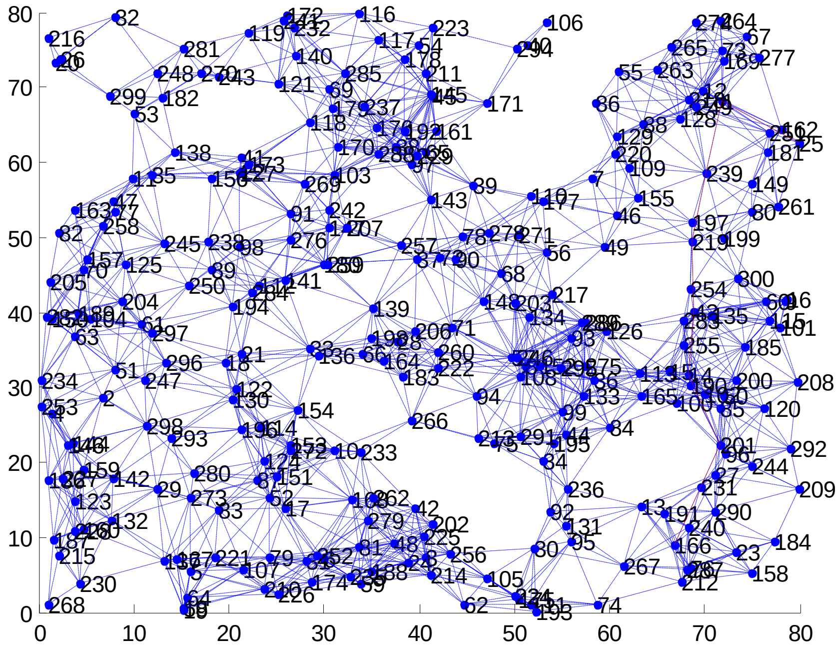

Figure 4-6: WSN of 300 sensors architecture.

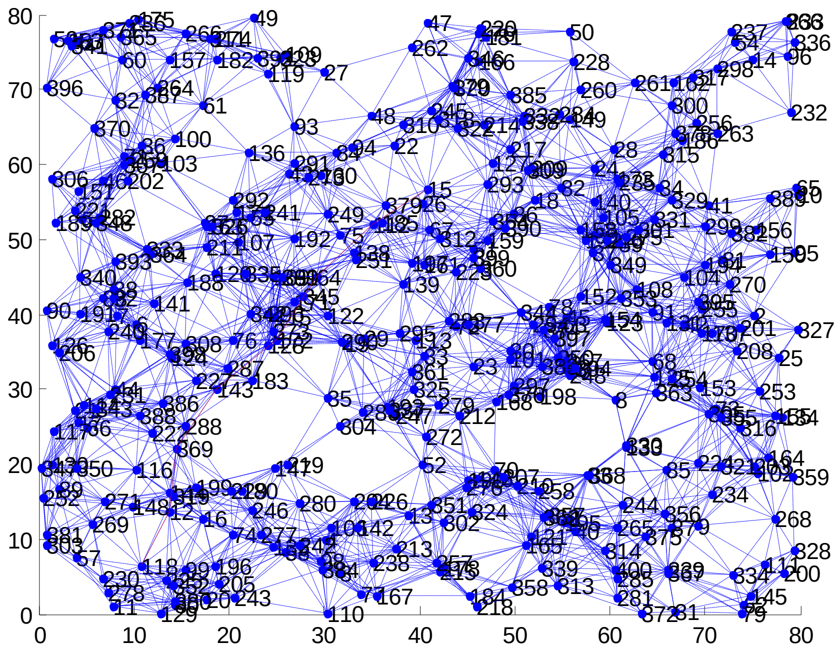

Figure 4-7: WSN of 400 sensors architecture.

4-3 Average Energy Consumption of Dual-Radio Cooperation in WSNs

4-3-1 Average Transmission Energy Consumption of WSNs in Free Space

Figure 4-8 to Figure 4-11 show the average energy consumption of the WSNs using three different routing protocols when the path loss exponent is 2.

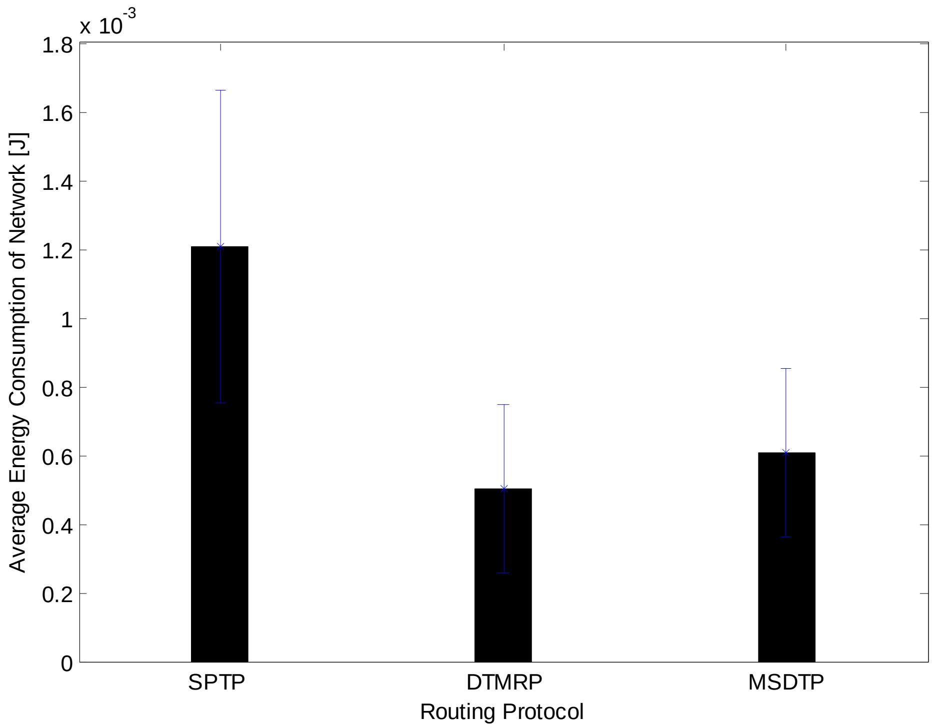

Figure 4-8: Energy consumption of three routing protocols in WSN of 100 sensors.

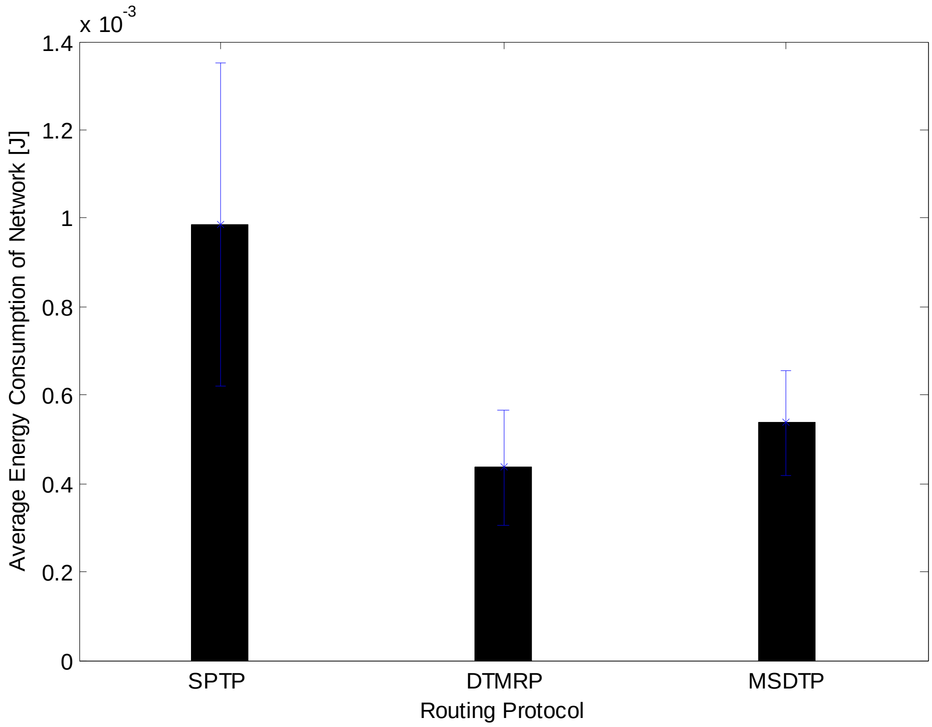

Figure 4-9: Energy consumption of three routing protocols in WSN of 200 sensors.

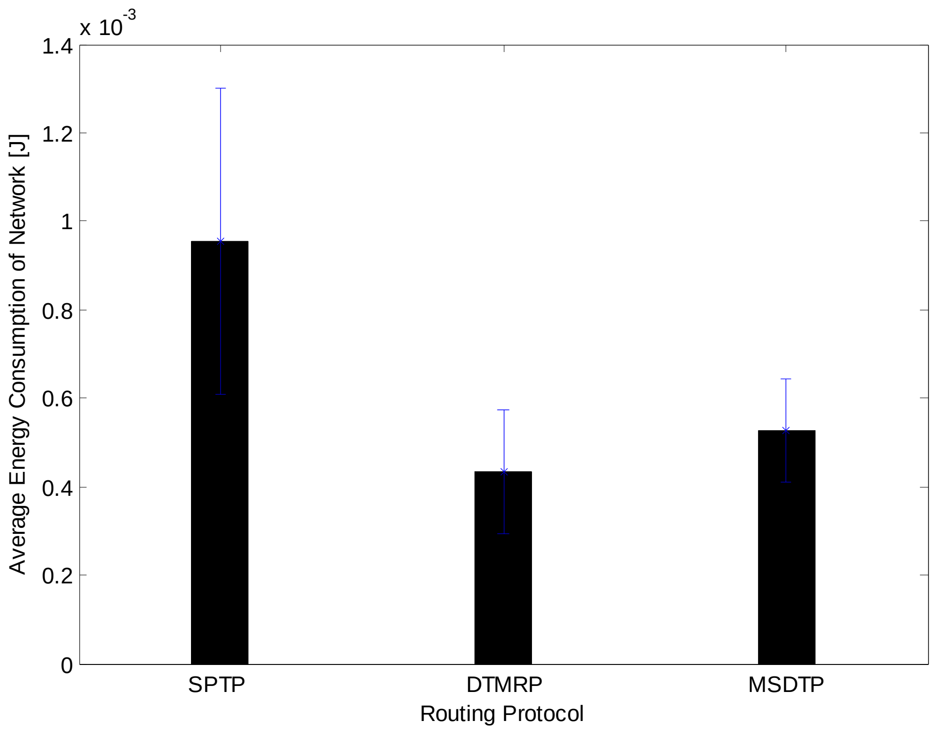

Figure 4-10: Energy consumption of three routing protocols in WSN of 300 sensors.

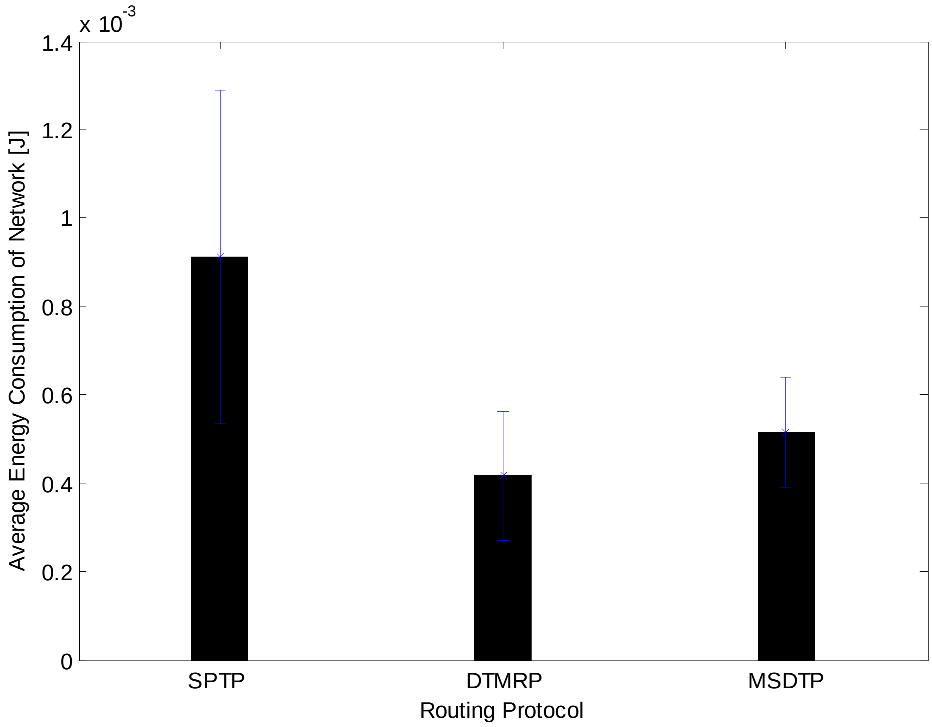

Figure 4-11: Energy consumption of three routing protocols in WSN of 400 sensors.

From above four figures, it is obvious that when transmitting packets in the free space, using DTMRP will cost the lowest average transmission energy consumption.

In Chapter 3, we simply rewrite Eq. (3-5) as Eq. (3-10). When the path loss exponent is 2, the order of magnitude of the first part in Eq. (3-10) is smaller than that of the second part. Therefore the second part is dominant in energy consumption calculation which means that when there are more nodes in the transmission route, it will cost more transmission energy. Therefore, directly transmit the data packet within the transmission range of the main radio allows for less energy consumption. This result confirms the results showed in Section 3-3-2. When transmit packets in the free space, DTMRP uses the fewest nodes to relay the data packet, so it costs the lowest transmission energy consumption.

4-3-2 Average Transmission Energy Consumption of WSNs in Path Loss Exponent 3 Environment

The following figures show the average energy consumption of the network in three different routing protocols when the path loss exponent is 3.

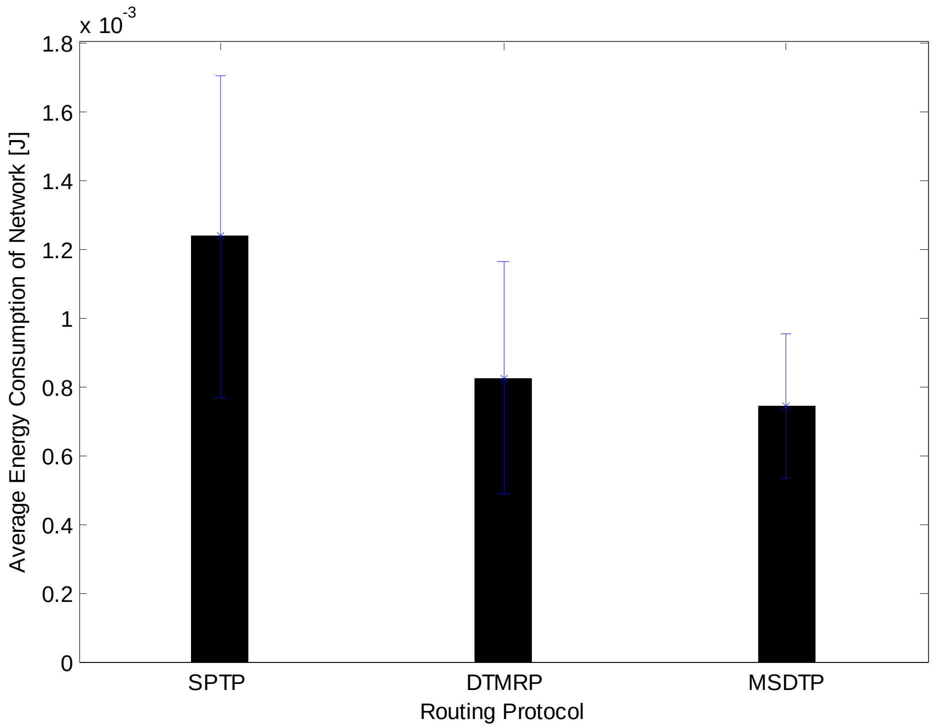

Figure 4-12: Energy consumption of three routing protocols in WSN of 100 sensors.

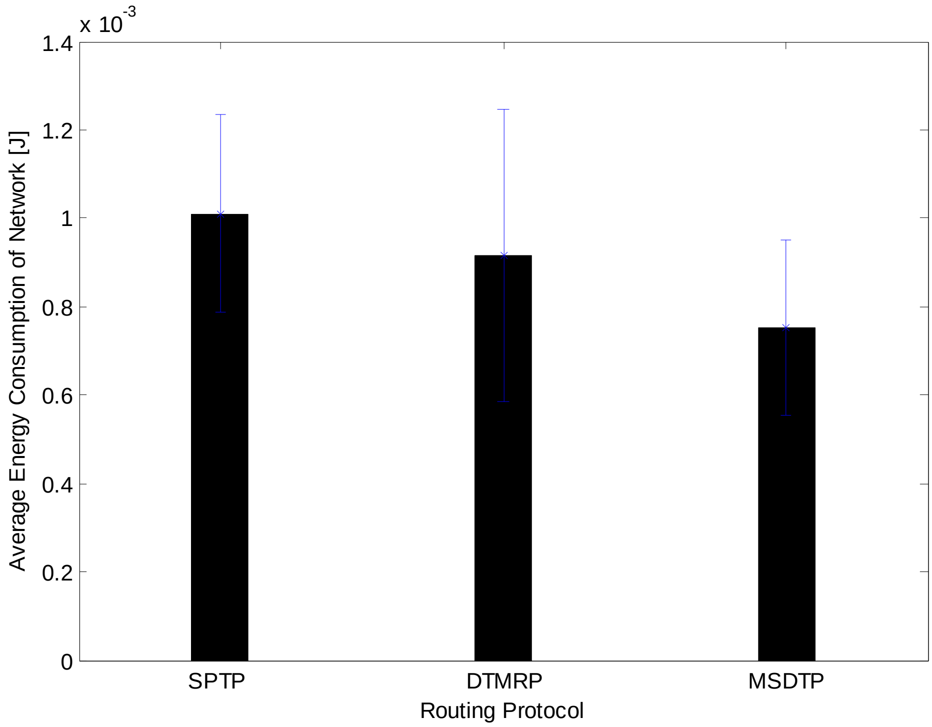

Figure 4-13: Energy consumption of three routing protocols in WSN of 200 sensors.

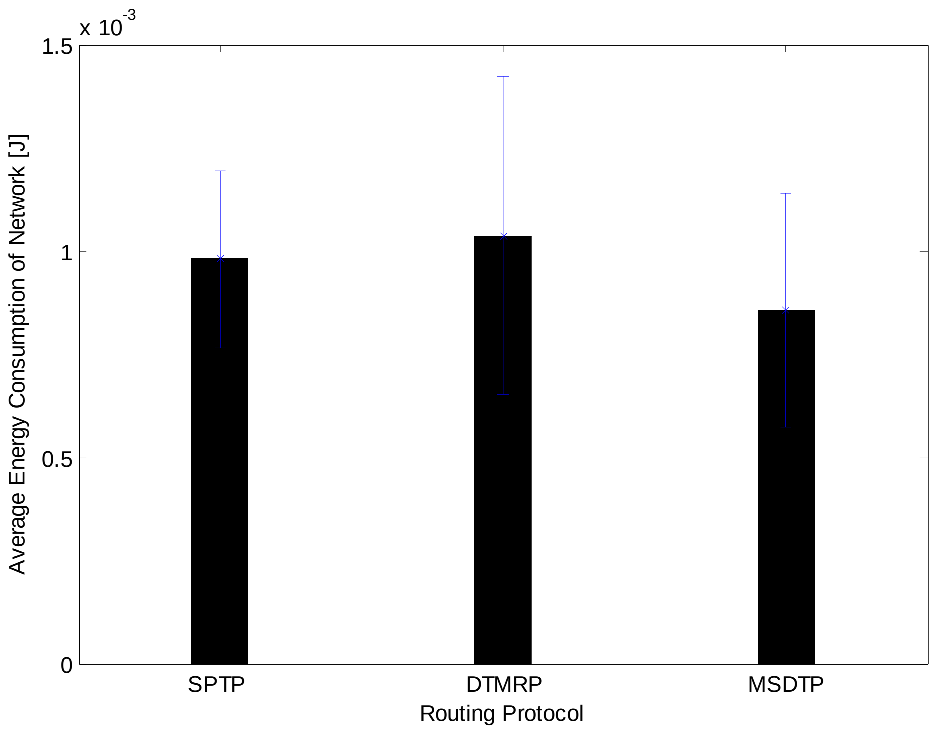

Figure 4-14: Energy consumption of three routing protocols in WSN of 300 sensors.

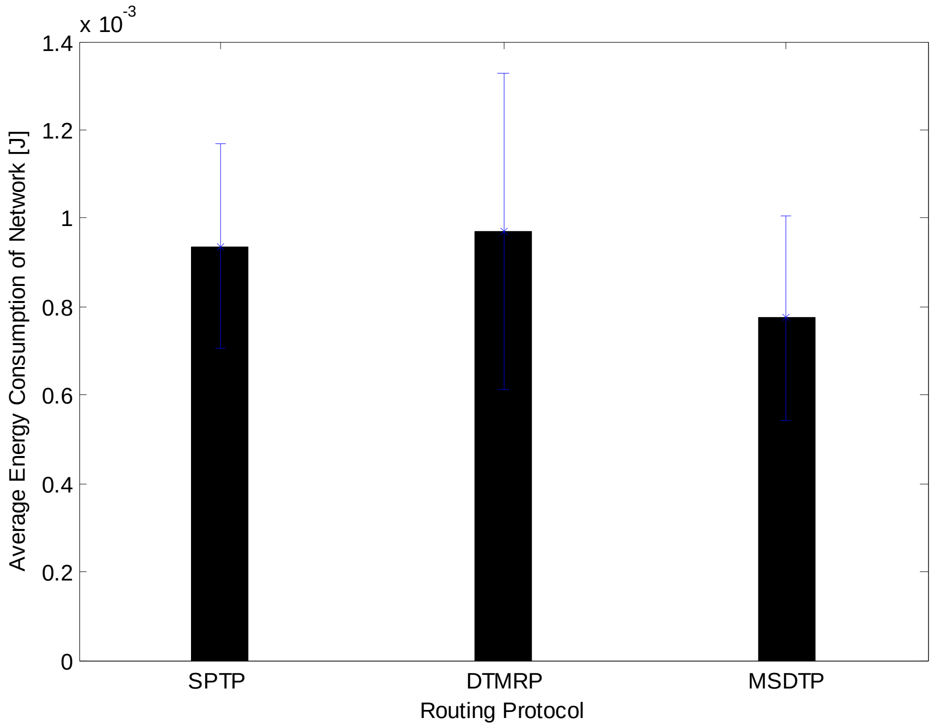

Figure 4-15: Energy consumption of three routing protocols in WSN of 400 sensors.

From above figures, we can find that when the path loss exponent is 3, using MSDTP to transmit the packets can save the transmission energy. This result solves the problem of finding the best transmission route with lowest energy consumption mentioned in Section 3-3-3.

When the path loss exponent is 3, the orders of magnitude of the first part and the second part in Eq. (3-10) change sharply. Only when the orders of magnitude of these two parts are close to each other, it will use the minimum energy to transmit the packets. Using MSDTP for dual-radio cooperative transmission makes the orders of magnitude of the two parts close to each other, so it costs the lowest transmission energy consumption.

4-3-3 Average Transmission Energy Consumption of WSNs in Harsh Environment

Figure 4-16 to Figure 4-19 show the average energy consumption of the network in three different routing protocols when the path loss exponent is 4.

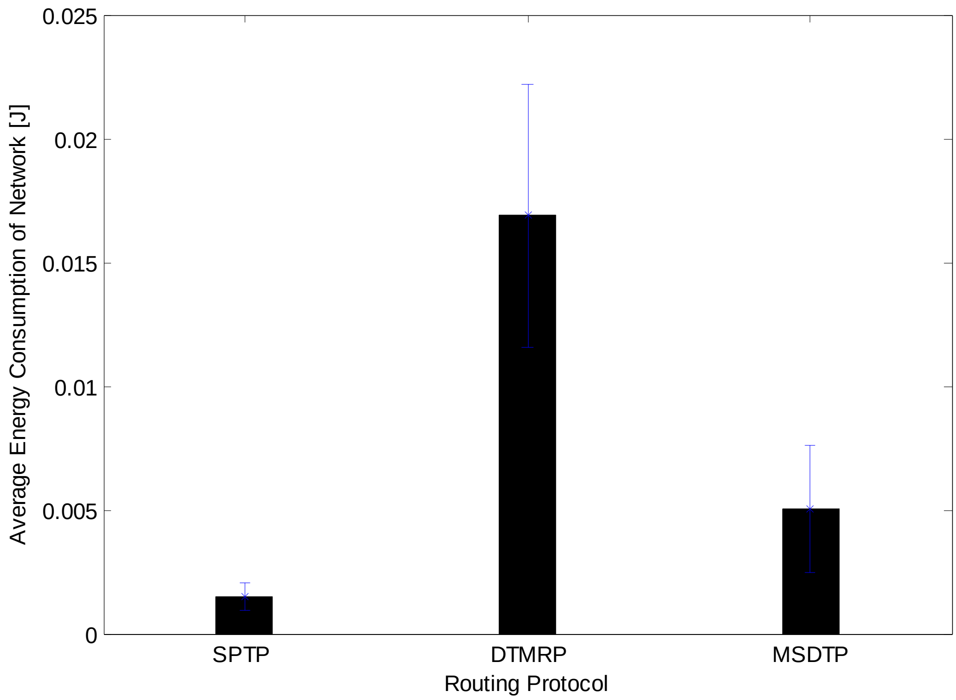

Figure 4-16: Energy consumption of three routing protocols in WSN of 100 sensors.

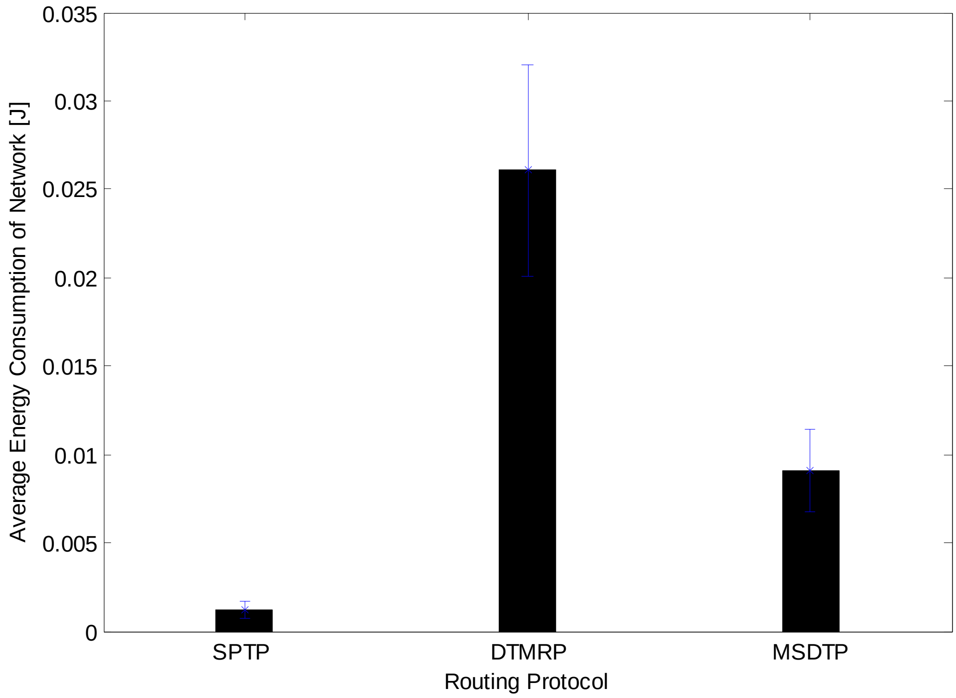

Figure 4-17: Energy consumption of three routing protocols in WSN of 200 sensors.

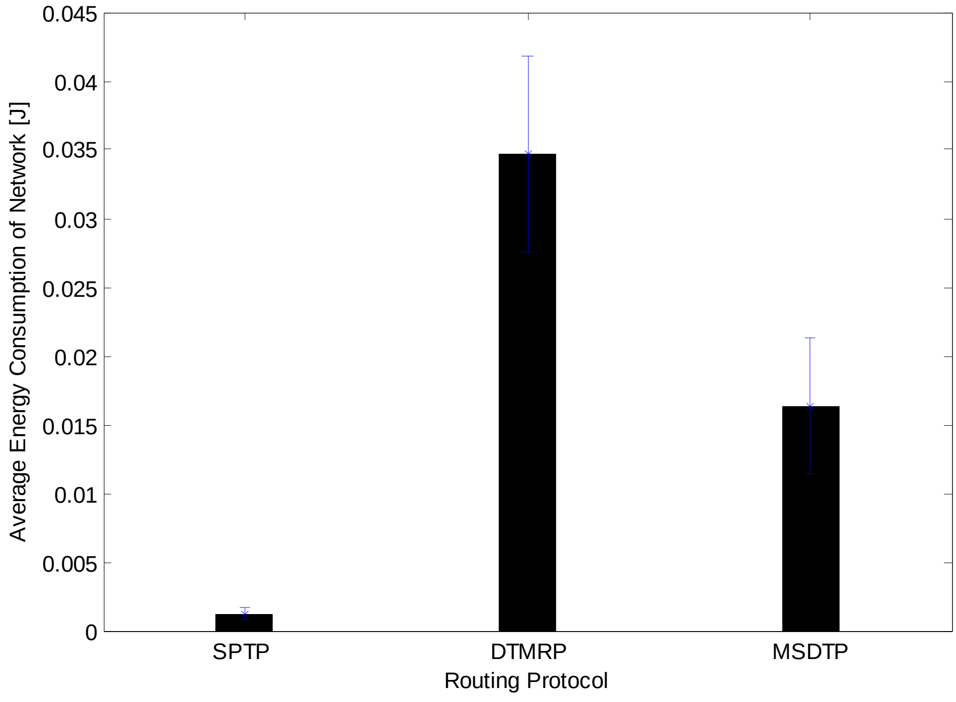

Figure 4-18: Energy consumption of three routing protocols in WSN of 300 sensors.

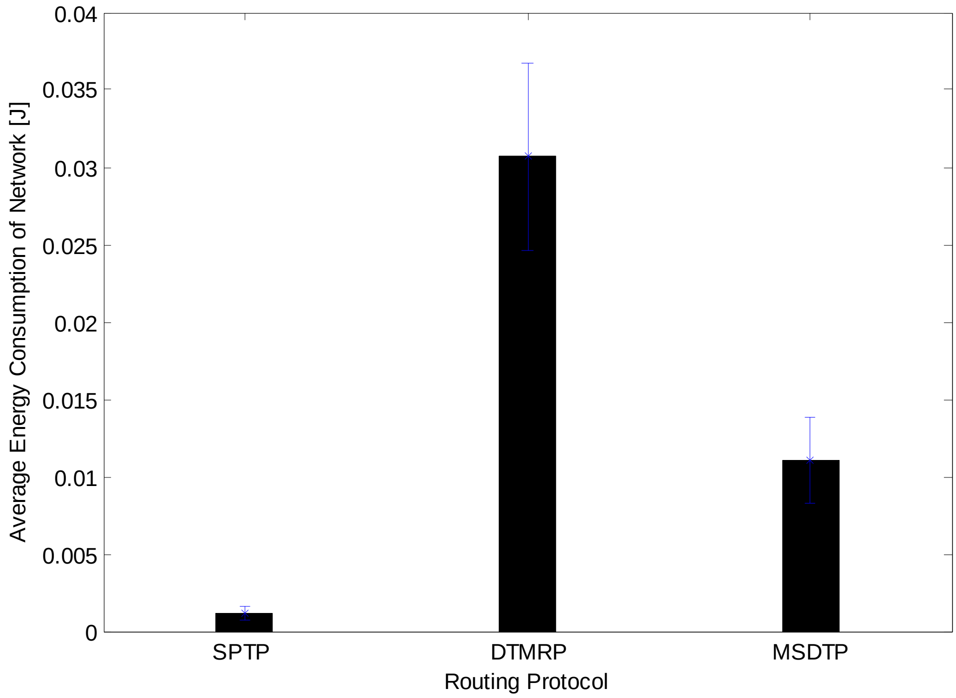

Figure 4-19: Energy consumption of three routing protocols in WSN of 400 sensors.

Above four figures show that using the same path to transmit the data packet as the wake-up packet is the best method when transmission through harsh environment. This result confirms the results showed in Section 3-3-4.

When the path loss exponent is 4, the order of magnitude of the first part is much larger than that of the second part in Eq. (3-10). In this case, the first part dominates the transmission energy consumption. That means when d^4 is larger, it will cost more transmission energy consumption. Therefore when transmission in harsh environment, the transmission distance is shorter, the transmission energy consumption is lower. The transmission distance of SPTP is the minimum, so the energy consumption is the lowest.

4-4 Conclusion

In this chapter, we present three different routing protocols for cooperative transmission of wake-up radio and main radio. All the results simulated by MATLAB show that each routing protocol has its superiority in different transmission environments.

In the wireless sensor networks (WSNs), when the transmission environment is close to the free space, it is better to use routing protocol 2 (DTMRP) which directly transmit the data packet from the sender to the receiver. When transmission through harsh environment, using routing protocol 1 (SPTP) to transmit packets can conserve transmission energy of the network. However, when the transmission environment is between the free space and harsh environment, routing protocol 3 (MSDTP) is the best choice. All these results confirm the results showed in Chapter 3.

Chapter 5

Issues

In this chapter, we present the protocol stack of ZigBee and its modified version-cooperative dual-radio protocol stack. We also describe how the modified protocol stack works. In the second section, we show the effect of the network density and the transmission range ratio of two cooperative radios to the network energy consumption.

5-1 Protocol Stack

5-1-1 ZigBee Protocol Stack

As with many IEEE networking standards, the 802.15.4 standard only defines the physical (PHY) and medium access control (MAC) layers. ZigBee builds upon the physical layer and medium access control defined in IEEE standard 802.15.4 (2003 version) for low-rate WPAN's [58]. ZigBee extends to the architecture which covers network, security, and application layers, as described in detail in [59]. The ZigBee protocol stack is shown in Figure 5-1.

According to [58, 60], IEEE 802.15.4 standard defines the PHY and MAC layer. The ZigBee specification goes on to complete the standard by adding four main components: network layer, application layer, ZigBee device objects and manufacturer-defined application objects. The main functions of the network layer are to enable the correct use of the MAC layer and provide a suitable interface for use by the upper layer-the application layer. The application layer is the highest-level layer defined by ZigBee specification. It is the effective interface of the ZigBee system to its end users. It comprises the ZigBee device object and its management procedures, and application objects defined by the manufacturer. The part of security service provider in the ZigBee protocol stack provides facilities for carrying out secure communications, protecting establishment and transport of cryptographic keys, cyphering frames and controlling devices. It builds on the basic security framework defined in IEEE 802.15.4.

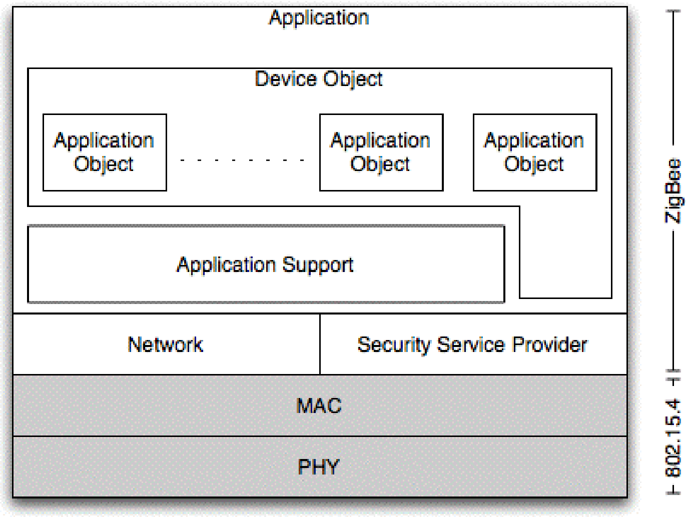

Figure 5-1: ZigBee protocol stack [59].

5-1-2 Cooperative Dual-Radio Protocol Stack

After introducing the wake-up radio into ZigBee technology, the protocol stack has changed. Figure 5-2 shows the architecture of the cooperative dual-radio protocol stack.

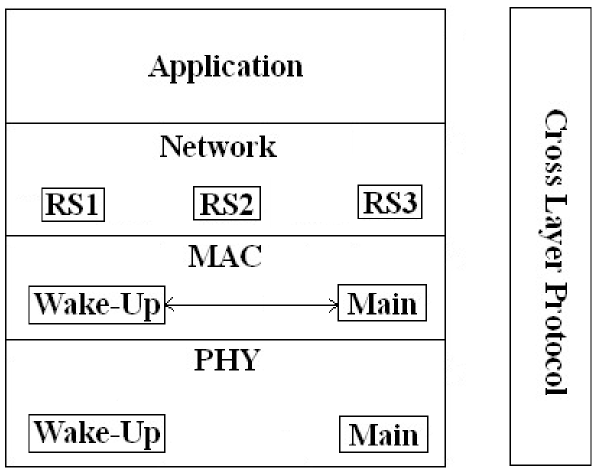

Figure 5-2: Cooperative dual-radio protocol stack.

In this protocol stack, PHY and MAC layers both have two parts-the wake-up radio part and the main radio part. The network layer has three parts for three different routing strategies for dual-radio cooperative transmission which are described in Section 4-1-1. Table 5-1 shows the PHY layer parameters for the wake-up radio and the main radio. All the parameters for wake-up radio are given in [48]. The MAC layer is responsible for the switch between the wake-up radio and main radio. For the switch scheme between the wake-up radio and the main radio, it has to be decided by the routing strategy which is used for transmitting packets. The different switch schemes in MAC layer are described in Section 3-2-1.

Radio	Bandwidth	Carrier Frequency	Data Rate	Modulation
Wake-up Radio	1MHz	2399.5MHz	100kbps	OOK
Main Radio	2MHz	2402MHz	250kbps	O-QPSK

Table 5-1: PHY parameters for wake-up and main radios.

The difficulty in this protocol stack is how to decide the routing strategy for the packet transmission in different transmission environments. In this thesis, we just consider the factor of path loss exponent in channel models and all the results showed in Chapter 4 prove that it is better to choose different routing strategies for different transmission environments. Here, the network layer can choose different routing strategies according to the path loss exponent provided by the PHY layer. First PHY layer should estimate the value of the path loss exponent through the information that channel provides, after that the PHY layer sends this estimated value to the network layer through MAC layer. After receiving this value, the network layer chooses the suitable routing strategy and tells the MAC layer to use corresponding switch scheme to achieve the final packet transmission.

5-1-3 Path Loss Exponent Estimation

The attenuation of signal during transmission procedure is caused by many factors and path loss is one of the most important factors. In the study of wireless communications, path loss can be represented by the path loss exponent, whose value is normally in the range of 2 to 4 [62]. However, in the cross-layer protocol mentioned in above section, the PHY layer has to estimate the value of path loss exponent firstly. Then the network layer can decide which routing strategy is used in the packet transmission.

There are many algorithms for path loss exponent estimation in different networks. In [63], they propose a path loss exponent estimation based on a known internode distance probability distribution. The authors use power measurements and the geometric constraints associated with planarity in a sensor network to estimate the path loss exponent. In [64], the authors consider a network where the path loss between a few low-cost sensors in measured and stored for future use. They propose an algorithm that employs interpolation techniques to estimate the path loss between a sensor and any arbitrary point in the network. In [65], a path loss estimator based on the method of least squares is discussed and used in the design of an efficient handover algorithm. In [66], the authors propose three estimation algorithms. In many situations, the network density is a design parameter and known. In other cases, it is possible to estimate the density ([67] gives the estimation method). If the network density is given, the path loss exponent can be estimated by the mean interference. However, if the network density is unknown, the estimation of path loss exponent can be obtained through virtual outage probabilities or cardinality of transmitting set. In this thesis, we will not discuss the details of these estimation algorithms further.

5-2 Implementation of Dual-Radio Cooperative Transmission

In wireless sensor networks (WSNs), the average energy consumption of transmitting packets using the cooperative transmission scheme is dependent on many factors, such as the routing protocol, network density, the ratio of main radio transmission range and wake-up radio transmission range (d_m/d_w) and so on. In Chapter 4, we show the effect of routing protocol to the average energy consumption of the WSNs. In this section, we will show some MATLAB simulation results and check if the factor of network density and transmission range ratio would affect average energy consumption of the WSNs.

5-2-1 Effect of Network Density

Figure 5-3 to Figure 5-8 show the variation of the average energy consumption of the WSN by using three different routing protocols when in different transmission environments. Here, we assume the area of the WSN is $80 \times 80m^2$ and the number of sensors increases from 100 to 400 by adding 100 sensors in each step.

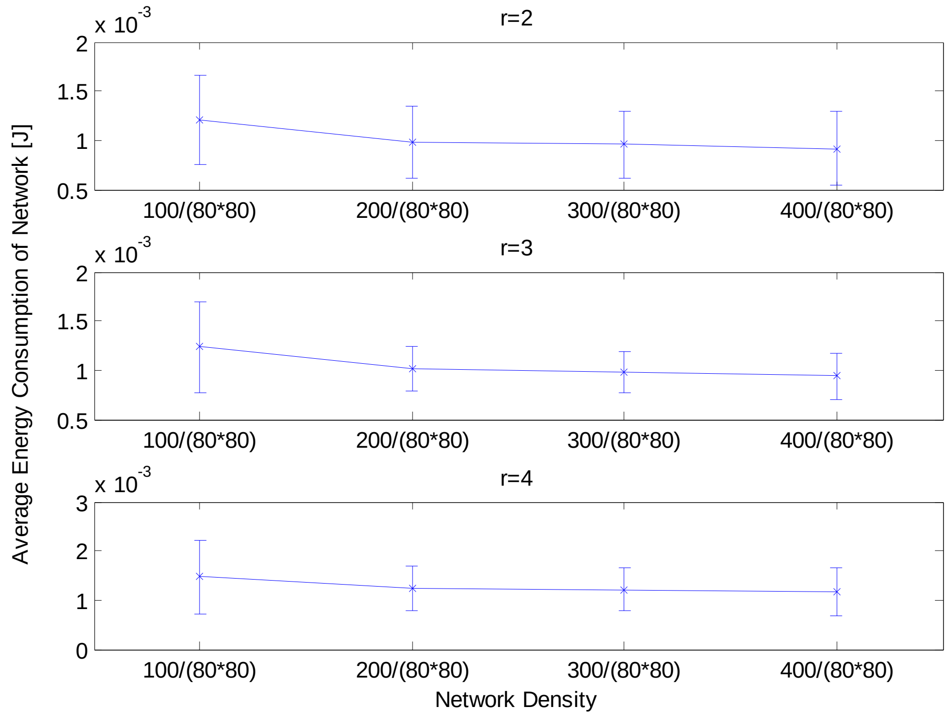

Figure 5-3: Effect of network density to energy consumption by SPTP.

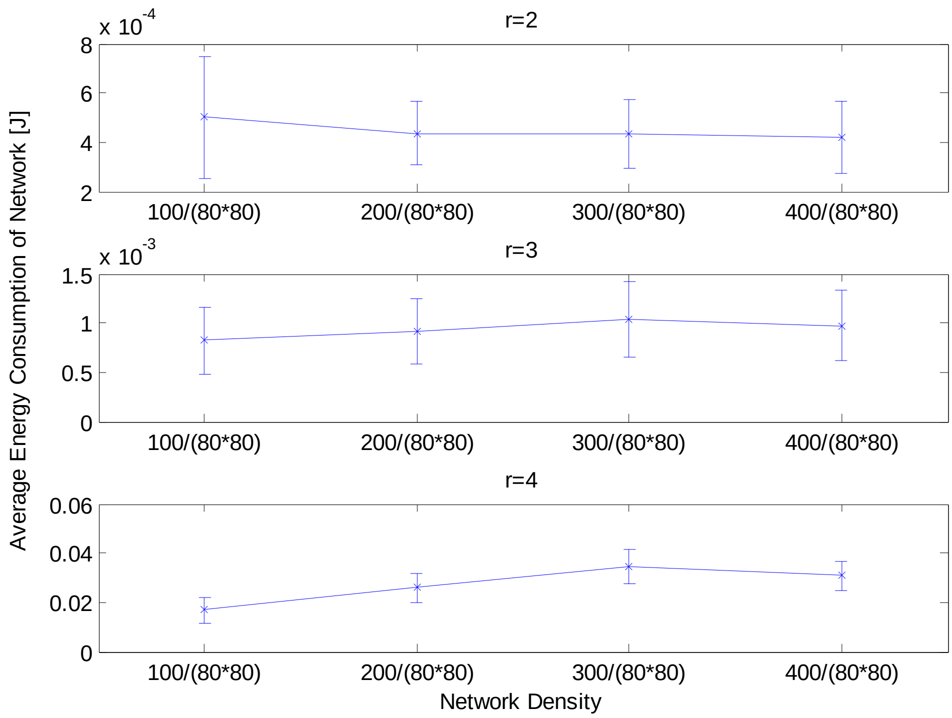

Figure 5-4: Effect of network density to energy consumption by DTMRP.

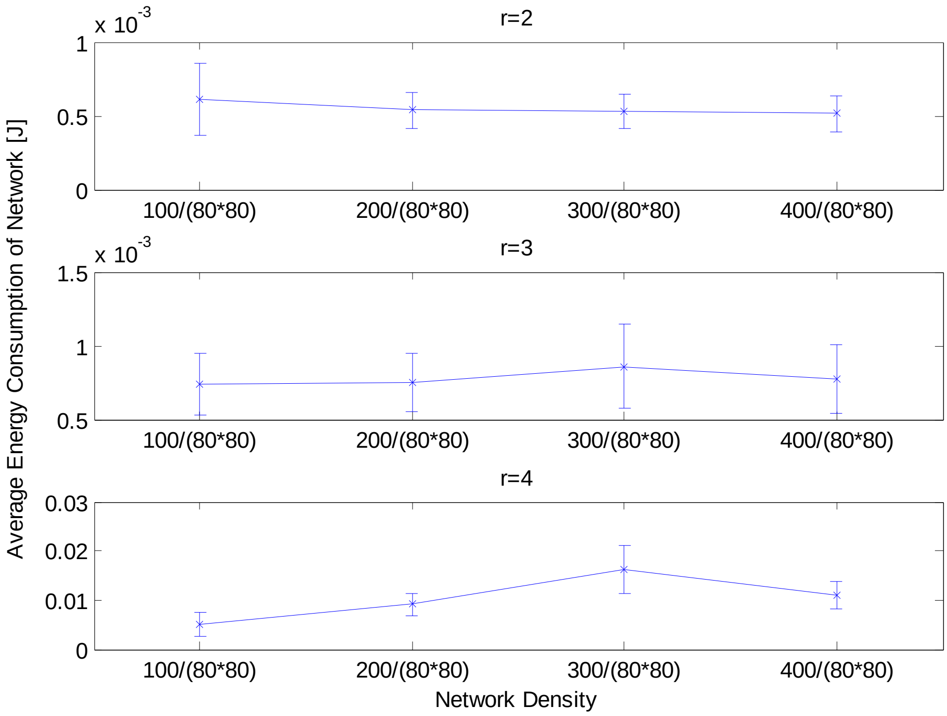

Figure 5-5: Effect of network density to energy consumption by MSDTP.

From above figures, we can obtain that with the growth of network density, the variation trends of the average energy consumption using routing protocol 1 (SPTP) decrease when the path loss exponent is 2, 3 and 4.

However, if we use routing protocol 2 (DTMRP) or routing protocol 3 (MSDTP), when the path loss exponent is 2, the average energy consumption of the WNS goes down slightly with the increase of the network density. When transmitting in path loss exponent 3 environment and harsh environment, the trend of the average energy consumption first goes up and then goes down a little. The maximum average energy consumption occurs when there are 300 sensors in the WNS of $80 \times 80m^2$.

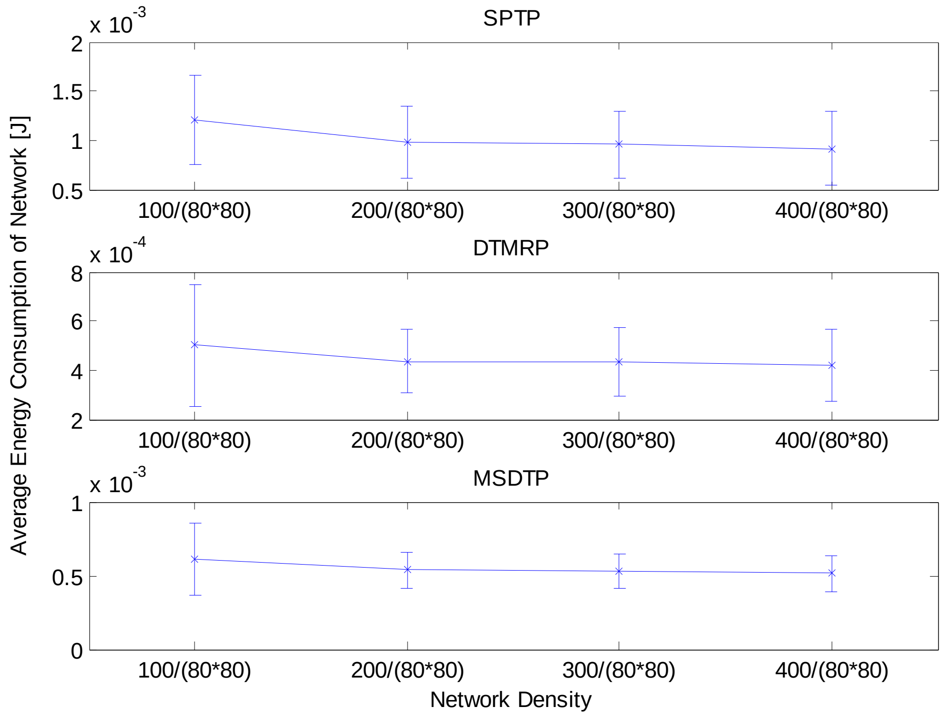

Figure 5-6: Effect of network density to energy consumption when $\gamma = 2$.

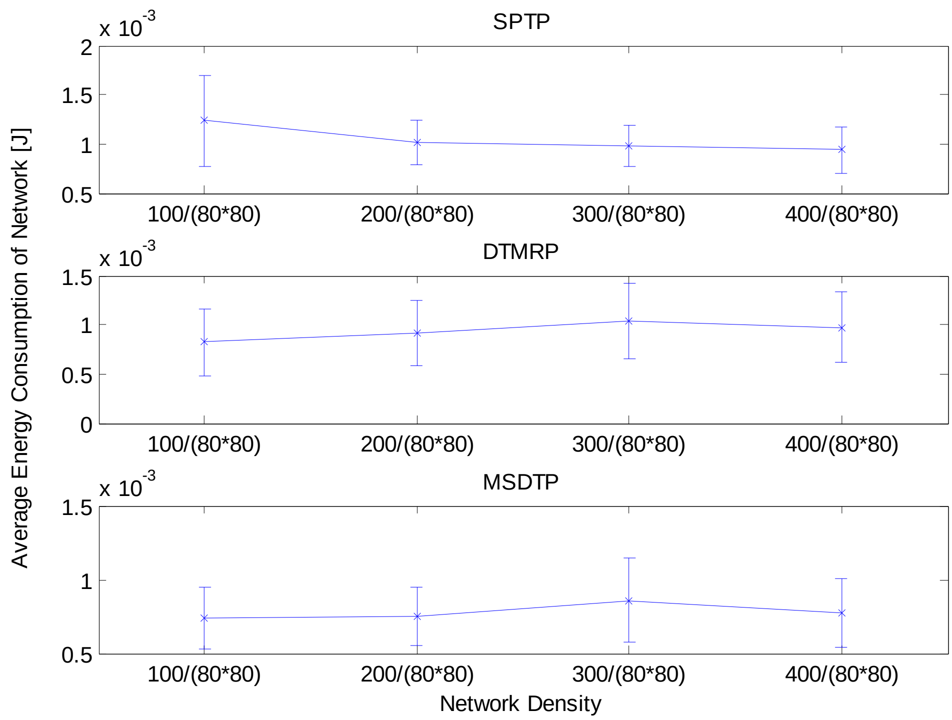

Figure 5-7: Effect of network density to energy consumption when $\gamma = 3$.

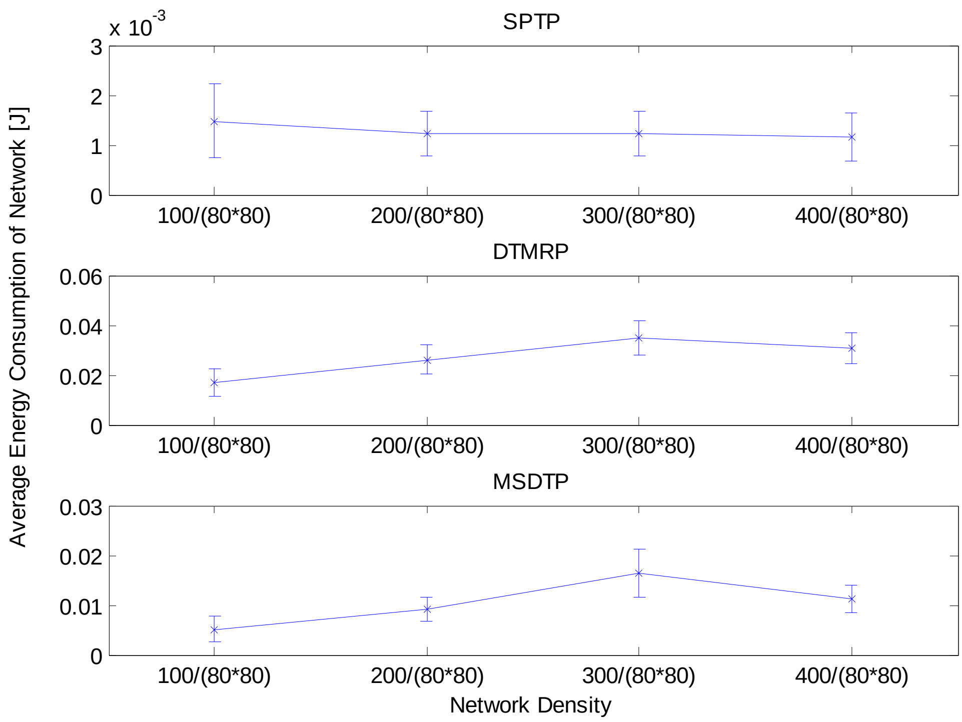

Figure 5-8: Effect of network density to energy consumption when $\gamma = 4$.

From Figure 5-6 to Figure 5-8, we can find that when the path loss exponent is 2, the average energy consumption of the network declines slightly with the increase of the network density.

When the path loss exponent is 3 or 4, the average energy consumption of the network decreases with the rise of the network density by using SPTP to transmit the packets. However, if using DTMRP or MSDTP for packets transmission, the trend of the average energy consumption first rises to the maximum when the network density is $300/(80 \times 80)$, then it decreases.

5-2-2 Effect of Transmission Range Ratio

In this thesis, we assumes that the transmission range of the wake-up radio (d_w) is 10 meters and the transmission range of the main radio (d_m) is 70 meters. However, if the transmission range of the wake-up radio is larger and other parameters are not changed, the energy consumption of the packet transmission may be different.

The following figures show the variation of the average energy consumption of the WSN using three routing protocols with the change of d_m/d_w when transmitting packets in distinct transmission environments. Here, we assume there are 100 sensors in the WSN whose area is $100 \times 100m^2$. The transmission range of the main radio is fixed as 70 meters and the transmission range of the wake-up radio increases from 10 meters to 40 meters by adding 10 meters in each step.

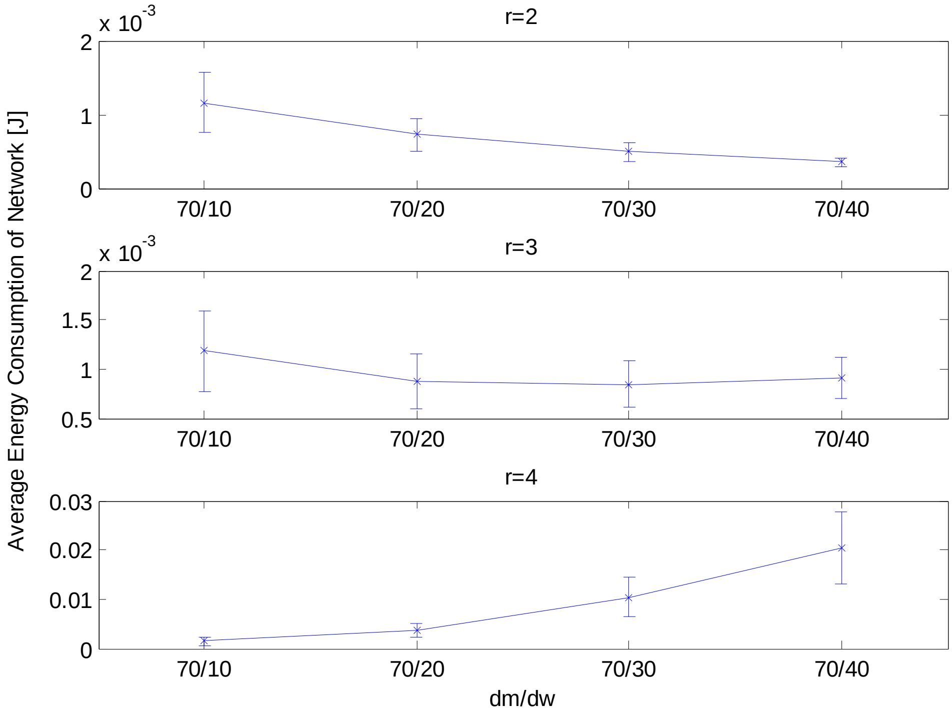

Figure 5-9: Effect of d_m/d_w to energy consumption by SPTP.

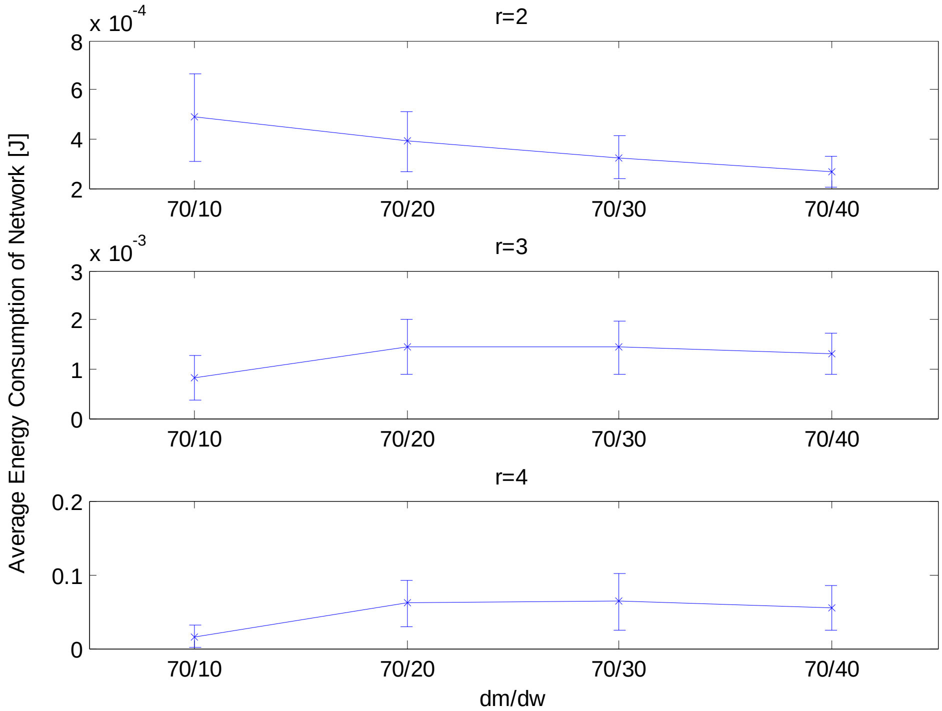

Figure 5-10: Effect of d_m / d_w to energy consumption by DTMRP.

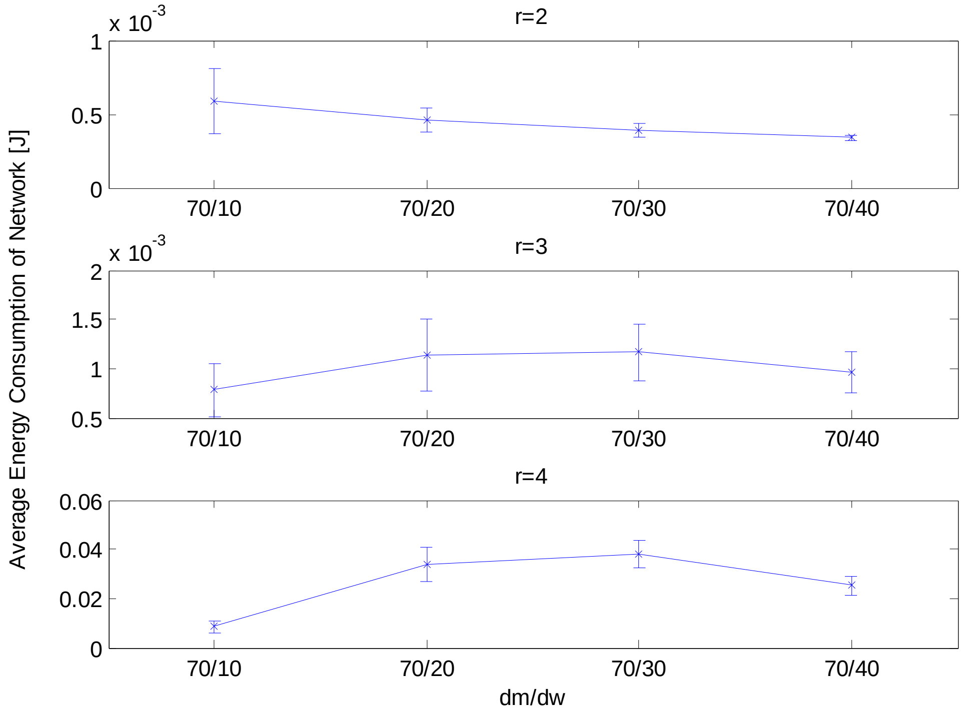

Figure 5-11: Effect of d_m / d_w to energy consumption by MSDTP.

From above figures, when using SPTP to transmit packets, the average energy consumption of the WSN declines with the decrease of d_m/d_w when the path loss exponent is 2 or 3. However, when the path loss exponent is 4, the variation of the average energy consumption shows the opposite trend.

When using DTMRP or MSDTP for packet transmission, the average energy consumption falls with the decrease of d_m/d_w when transmitting in the free space. However, if the path loss exponent is 3 or 4, the tendency of the average energy consumption first goes up and then goes down slightly.

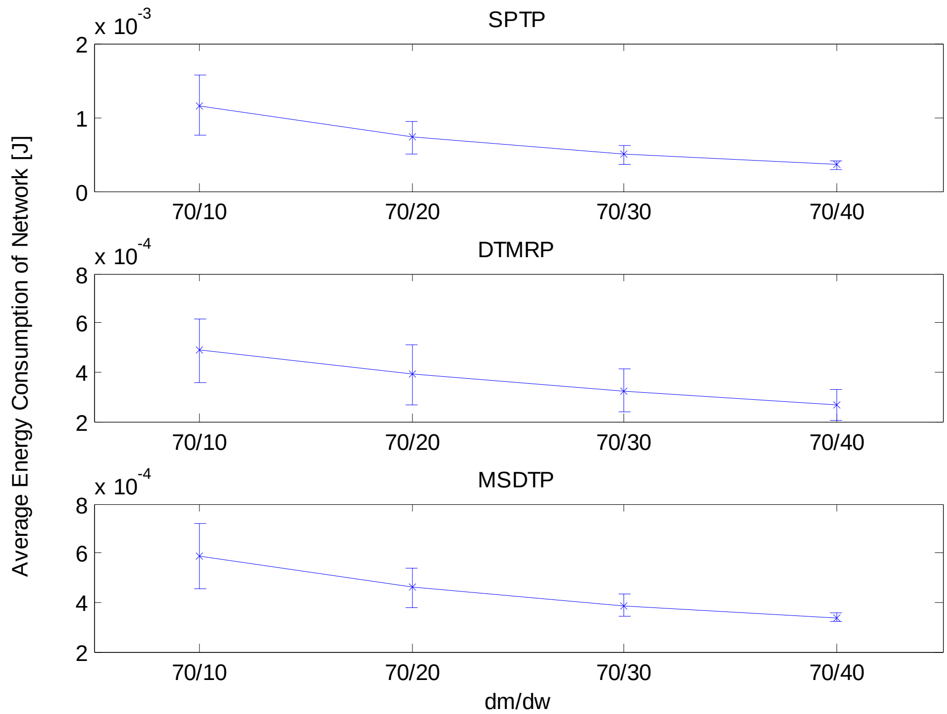

Figure 5-12: Effect of d_m/d_w to energy consumption when $\gamma = 2$.

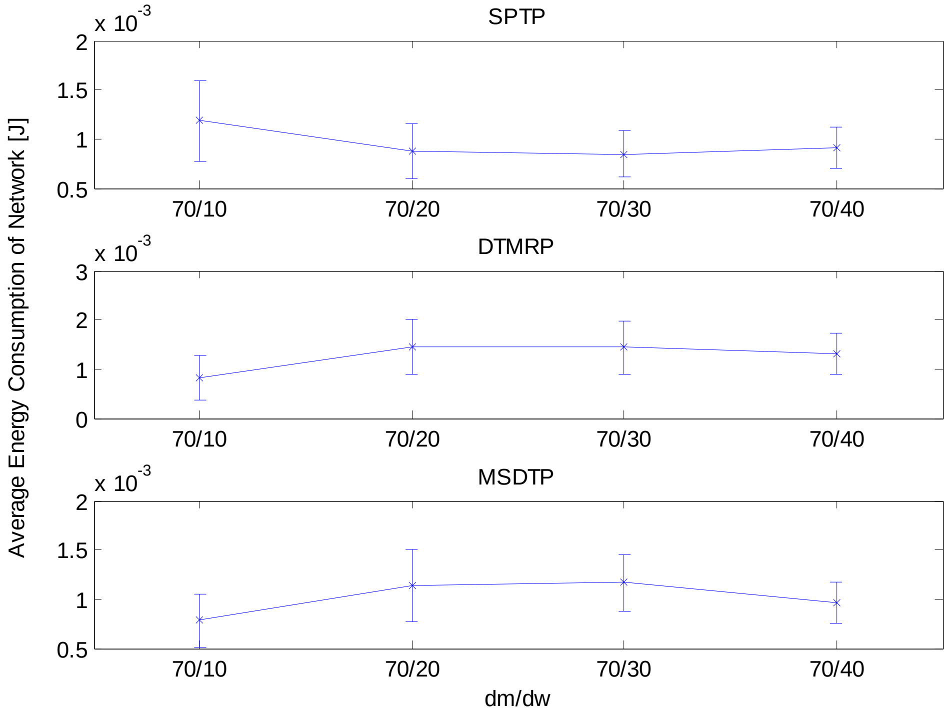

Figure 5-13: Effect of d_m/d_w to energy consumption when $\gamma = 3$.

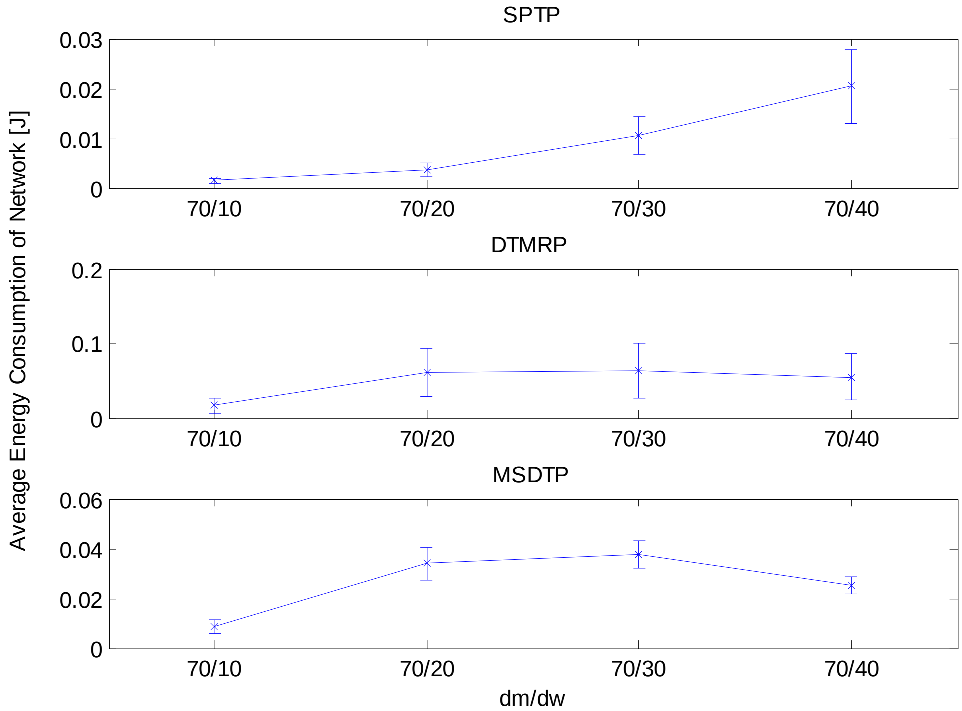

Figure 5-14: Effect of d_m/d_w to energy consumption when $\gamma = 4$.

We can see from above figures that when transmission in the free space, the average energy consumption of the network falls with the decrease of d_m/d_w by using three routing protocols.

When the path loss exponent is 3, with the decrease of d_m/d_w, the average energy consumption declines by using SPTP to transmit packets. However, if using DTMRP or MSDTP, the average energy consumption first goes up and then drops slightly.

When transmitting packets in harsh environment, with the decrease of d_m/d_w, the average energy consumption rises by using SPTP to transmit packets. However, if using DTMRP or MSDTP, the average energy consumption first increases slightly and then decreases.

5-3 Conclusion

The cross-layer protocol stack presented in this chapter provides the chance for packet transmission with dual-radio cooperation. Using dual-radio cooperative transmission in WSNs can save much transmission energy. The average energy consumption of the WSNs is also affected by the factors of network density and transmission range ratio of the two radios besides the routing protocol.

Chapter 6

Conclusion

6-1 Summary

In the period when energy is more and more scarce and precious, reducing energy consumption becomes more and more important. For engineers and energy consumers, trying to find and use technologies which can save energy turns into a good way to relieve energy issue.

In this thesis report, we present a suggested solution which introduces the wake-up radio into ZigBee technology. This solution provides a new cross-layer protocol and achieves the goal of dual-radio cooperation in packet transmission. Most importantly, from theoretical aspect this solution conserves the energy which wastes by the main radio the original ZigBee technology uses. Meanwhile the routing protocols designed for the dual-radio cooperation in this report provide suitable routing algorithm when transmitting packets in different transmission environments. From the MATLAB simulation results showed in this thesis report, we can obtain that when transmitting packets with the dual-radio cooperation scheme in linear topology or WSNs, the routing protocols should be altered based on the channel dynamics.

If this scheme can be used in our daily life, it certainly will bring a lot of benefits to the communication networks. However, this scheme does not consider all the factors which effect the transmission signal attenuation, so it still needs some improvements before implementation in the real life.

6-2 Future Work

In this thesis, we just consider the path loss exponent factor of transmission signal attenuation. However, in practical transmission model, it still needs to consider the fading, multipath component and some other factors (these factors are discussed in [68]).

In wireless communications, fading is deviation of the attenuation that a carrier-modulated telecommunication signal experiences over certain propagation media [69]. The fading may vary with time, geographical position or radio frequency, and is often modelled as a random process. Multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths [70]. Causes of multipath include atmospheric ducting, ionospheric reflection and refraction, and reflection from water bodies and terrestrial objects. Therefore result in the multipath inference during the transmission [71].

If consider all the factors in transmission channel model, the energy consumption model will be more complex. And there will be more factors which affect the energy consumption of the packet transmission. Therefore all the results showed in Chapter 3 and Chapter 4 may be different.

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Glossary

List of Acronyms

WPAN	Wireless Personal Access Networks
WSN	Wireless Sensor Network
PAN	Personal Area Network
GPS	Global Positioning System
WPA	Wi-Fi Protected Access
SNR	Signal-to-Noise Ratio
WLAN	Wireless Local Area Network
WHAN	Wireless Home Area Network
PSD	Power Spectral Density
OOK	On-Off Keying
O-QPSK	Offset Quadrature Phase-Shift Keying
PSDU	PHY Service Data Unit
SPTP	Shortest Path Transmission Protocol
DTMRP	Direct Transmission within Maximum Range Protocol
MSDTP	Minimum Sum of Distance Transmission Protocol

List of Symbols

P_{ct} Transmitter Dissipates Power in Radio Electronics

P_{cr} Receiver Dissipates Power in Radio Electronics

P_{PA} Power Amplifier

η Drain Efficiency of the RF Power Amplifier

ξ Peak-to-average Ratio

P_{out} Transmit Power

E_b Required Energy Per Bit

R_b Bit Rate

γ Path Loss Exponent

G_t Transmitter Antenna Gain

G_r Receiver Antenna Gain

λ Wavelength

M_l Link Margin

N_f Noise Figure

N_0 Single-sided Thermal Noise Power Spectral Density

N_r Effective Noise

l Packet Length