Thesis for the Degree of Doctor of Philosophy

Hop-based Energy Aware Routing Scheme for Wireless Sensor Networks

Jin Wang

Department of Computer Engineering

Graduate School

Kyung Hee University

Seoul, Korea

February, 2010

Hop-based Energy Aware Routing Scheme for Wireless Sensor Networks

by

Jin Wang

Supervised by

Prof. Sungyoung Lee, Ph.D.

Department of Computer Engineering

Graduate School

Kyung Hee University

Seoul, Korea

February, 2010

Hop-based Energy Aware Routing Scheme for Wireless Sensor Networks

by
Jin Wang

Supervised by
Prof. Sungyoung Lee, Ph.D.

Submitted to the Department of Computer Engineering
and the Faculty of Graduate school of
Kyung Hee University in partial fulfillment
of the requirement for Degree of
Doctor of Philosophy

Dissertation Committee:

____
Choong Seon Hong, Professor (Chair)

____
Young-Koo Lee, Professor

____
Kyesan Lee, Professor

____
Sungwon Lee, Professor

____
Sungyoung Lee, Professor

This thesis is dedicated to the memory of

My **Father** Wang Shenghua

My **Mother** Jin Lanying

Acknowledgement

First of all, I would like to express my sincere gratitude to my supervisor, Prof. Sungyoung Lee who provided me an excellent opportunity to do the Ph.D. research in the Ubiquitous Computing Lab (UCLab) at Kyung Hee University.

I am also grateful to Prof. Young-Koo Lee who is my co-supervisor as well as Prof. Jinsung Cho who gives me continuous support throughout my PhD study. I am especially thankful to Prof. Brian J. d'Auriol for his excellent guidance on our USN (Ubiquitous Sensor Network) group as well as for his valuable comments and suggestions on my research papers. I am indebt to Prof. Kwang-Cheng Chen and Prof. Kenji Kawahara who gave me invaluable help during my journal paper preparation process.

Special thanks to my dissertation committee Professors whose comments and suggestions greatly improved the quality of my dissertation.

I am also grateful to all the members in our UCLab as well as many of my Chinese friends. I will never forget the happy time we enjoyed together during the last 5 years. Special thanks to my brother Jin youqiang.

Last but not least, I wish to express my deepest gratitude to my parents. This thesis will never be completed without your continuous encouragement and support. I hope it can be a good present for both of your 60^{th} Birthdays.

Jin Wang

February 2010,

Seoul, Korea

Abstract

The advances in MEMS (Micro Electro-Mechanical Systems) as well as in wireless communication technologies have motivated the development of billions of tiny and low cost sensor devices as well as various applications of wireless sensor networks (WSNs).

Energy conservation is one of the biggest challenges to the successful application of WSNs since the tiny sensor nodes have very limited resource such as energy, memory as well as communication and computation capacities. Once the sensors are deployed, they are left unattended and battery recharge is practically impossible. Up to now, many studies have be done in energy efficient routing algorithms or protocols for WSNs. However, only a few works has been done from hop number point of view, as can be seen from related work in chapter 2.

Our motivations behinds the study of hop number lies in the following three aspects. First, we see that direct transmission is used under small scale network while multi-hop transmission is used under large scale network. We want to find the factors which influence the transmission manner. Second, it is commonly agree that multi-hop transmission is usually more energy efficient than single hop transmission when the average source to destination distance is large. However, how to determine the optimal hop number so that the total energy consumption is minimal is not well addressed. Third, the hot spot phenomenon affects the network lifetime directly. Namely, the nodes close to sink node will become hot spot nodes and die quickly if multi-hop transmission is used. On the other hand, nodes far away from sink node will die quickly if direct transmission is used. How to further balance the energy consumption among the sensor nodes so as to prolong network is another challenge job.

In this thesis, we focus on prolonging the network lifetime of WSNs by reducing and balancing energy consumption during routing process from hop number point of view. Different from the other algorithms which select the next

hop node based on criteria like shortest-path, max-residual energy or probability based, we select the next hop node from hop number point of view. More specifically, we try to minimize the total energy consumption along multi-hop route during routing process by carefully select proper intermediate nodes. We first deduce the optimal hop number with minimal energy consumption under one dimensional sensor network. We then extend this result and provide an empirical selection criterion of the sub-optimal hop number as well as proper individual nodes under practical network environment. The resulting multi-hop route is both energy efficient and energy balancing.

We then propose a Hop-based Energy Aware Routing (HEAR) algorithm, which combines the general routing mechanism with hop-based nature during routing process in WSNs. The routing phase consists route setup phase and route maintenance phase. Each node has two tables which are routing table and neighboring table and each node can make local decision of its next hop without knowing the whole network knowledge. From the detailed explanations and numerical illustrations we can see that HEAR algorithm is a simple, distributed and localized routing algorithm which can be easily implemented for the practical engineering applications.

We also provide extensive simulation results and comparisons between our HEAR and other five routing algorithms which are direct transmission, greedy, MRE, LEACH and HEED algorithms. The simulations are done under different network factors like node number, transmission radius, BS location, network scale, traffic pattern as well as network structure (flat and hierarchical). We find that our HEAR has a better performance than the other algorithms in terms of energy consumption, hop number, network lifetime etc.

Table of Contents

Acknowledgement……………………………………………………………………...v

Abstract………………………………………………………………………………..vi

Table of Contents…………………………………………………………………….viii

List of Figures…………………………………………………………………………xi

List of Tables………………………………………………………………………….xiii

Chapter 1 Introduction 1

1.1 Wireless sensor networks 1

1.1.1 Applications of WSNs 3

1.1.2 Sensor node architecture 4

1.1.3 Communication architecture 6

1.1.4 Challenges and research issues in WSNs...7

1.2 Motivation 9

1.3 Focus of the dissertation 13

1.4 Problem statement...14

1.5 Contributions 14

1.6 Outline of the dissertation 15

Chapter 2 Background..16

2.1 Unique nature of routing in WSNs 16

2.2 Routing challenges and design issues in WSNs..18

2.3 Routing protocols for WSNs...21

2.3.1 Flat-based routing 21

2.3.2 Hierarchical-based routing...22

2.3.3 Location-based routing 25

Chapter 3 Overview of HEAR Algorithm 27

3.1 Uniqueness of HEAR algorithm *27*

3.2 HEAR algorithm *28*

3.2.1 Brief workflow of HEAR algorithm 29

3.2.2 A scenario of HEAR algorithm 31

3.2.3 Characteristics of HEAR algorithm 33

Chapter 4 Hop-based Energy Aware Routing (HEAR) Algorithm for WSNs........35

4.1 Relevant models *35*

4.1.1 Network model 35

4.1.2 Propagation model 36

4.1.3 Energy model 38

4.1.4 Traffic model 41

4.2 Analysis of relevant models *43*

4.2.1 Problem formulation 43

4.2.2 Determination of transmission manner 45

4.2.3 Determination of the optimal hop number 46

4.2.4 Determination of the sub-optimal hop number 52

4.3 HEAR Algorithm *54*

4.3.1 Basic assumptions 55

4.3.2 Route setup phase 56

4.3.3 Route Maintenance Phase 61

4.3.4 Routing workflow 62

4.3.5 Algorithmic process 64

Chapter 5 Performance Evaluation 67

5.1 Simulation environment *67*

5.2 Algorithms to compare *68*

5.3 Simulation results *70*

5.3.1 Energy consumption 70

5.3.2 Hop number 79

5.3.3 Network lifetime 82

5.3.4 Packet reachability 85

5.3.5 Comparison with LEACH and HEED 87
5.3.6 Hop spot phenomenon 90

5.4 Discussion *91*

Chapter 6 Conclusions and future work 95

List of Figures

Fig. 1. A typical sensor network example…………………………..................1

Fig. 2. Wireless sensor network layers……………………………………….…...2

Fig. 3. LOFAR_Agro project for agriculture monitoring………………………...3

Fig. 4. Sensor node architecture……………………………………………….5

Fig. 5. The sensor network protocol stack……………………………………..6

Fig. 6. Routing protocols in sensor networks: A taxonomy………………….13

Fig. 7. Sensors being dropped from airplane…………………………………19

Fig. 8. Three phases of Directed Diffusion protocol…………………………22

Fig. 9. LEACH routing protocol………………………………………….…...23

Fig. 10. State transitions in GAF………………………………………………25

Fig. 11. Brief workflow of HEAR algorithm………………………………….29

Fig. 12. Random sensor deployment in WSN…………………………………31

Fig. 13. Radio energy dissipation model………………………………………41

Fig. 14. One dimensional linear sensor network model………………………43

Fig. 15. Energy consumption under two models………………………………48

Fig. 16. Energy consumption under constraint conditions…………………….49

Fig. 17. Illustration of the next hop node selection criteria……………………57

Fig. 18. HEAR algorithm workflow………………………………………….....62

Fig. 19. Initialization process of HEAR algorithm…………………………….64

Fig. 20. Main process of HEAR algorithm…………………………………….65

Fig. 21. Final process of HEAR algorithm…………………………………….66

Fig. 22. Sensor network simulation environment……………………………...68

Fig. 23. Energy consumption under different R ………………………………71

Fig. 24. Energy consumption under different d ………………………………73

Fig. 25. Energy consumption under different N ……………………………...74

Fig. 26. Energy consumption under different BS location…………………….75

Fig. 27. Total energy consumption under small scale network………………..76

Fig. 28. Total energy consumption under large scale network………………...77

Fig. 29. Average energy consumption under different traffic pattern…………78

Fig. 30. Average energy consumption under different packet length…………79

Fig. 31. Hop number under different network topology…………………........81

Fig. 32. Hop number under different transmission radius……………………..82

Fig. 33. Hop number under different BS location……………………………..83

Fig. 34. Network lifetime under different network topology………………….84

Fig. 35. Network lifetime with BS placed inside……………………………...85

Fig. 36. Network lifetime with BS placed outside…………………………….85

Fig. 37. Packet reachability…………………………………………………....88

Fig. 38. Hop spot phenomenon………………………………………………..91

Fig. 39. Hop spot nodes under HEAR algorithm……………………………...92

List of Tables

Table 1 Routes of node 27 under different algorithms……………………..32

Table 2 Definition of network parameters………………………………….36

Table 3 Definition of hardware parameters…………………..…………….40

Table 4 Values of distance power gradients……………….…………….41

Table 5 Determination of transmission manner…......................................46

Table 6 Energy consumption under different hop number (a)……………...50

Table 7 Energy consumption under different hop number (b)……………...51

Table 8 Selection criterion of the sub-optimal hop number………………...52

Table 9 Node 1's neighboring table……………………………………...58

Table 10 Message structure……………………………….……………...59

Table 11 Simulation environment……………………………………..69

Table 12 Network metrics under various topologies………………………..87

Table 13 Average energy consumption (J) under 4 scenarios..……………..90

Table 14 Average network lifetime under 4 scenarios……….……………..90

Table 15 Performance comparison between different algorithms…………..94

Chapter 1 Introduction

1.1 Wireless sensor networks

The advances in MEMS (Micro Electro-Mechanical Systems) as well as in wireless communication have motivated the development of billions of tiny and low cost wireless devices as well as various kinds of wireless networks which connect these devices with or without any existing infrastructure.

Wireless sensor network (WSN) [1-11] is an important supplement of the modern wireless communication networks. It can be viewed as a network consisting of hundreds or thousands of wireless sensor nodes which collect the information from their surrounding environment and send their sensed data to remote control center which is called Base Station (BS) or sink node in a self-organized manner. WSNs can be viewed as a huge database which stores information about the environment to be monitored. Each sensor node will perform sensing, processing and communication functions inside the network.

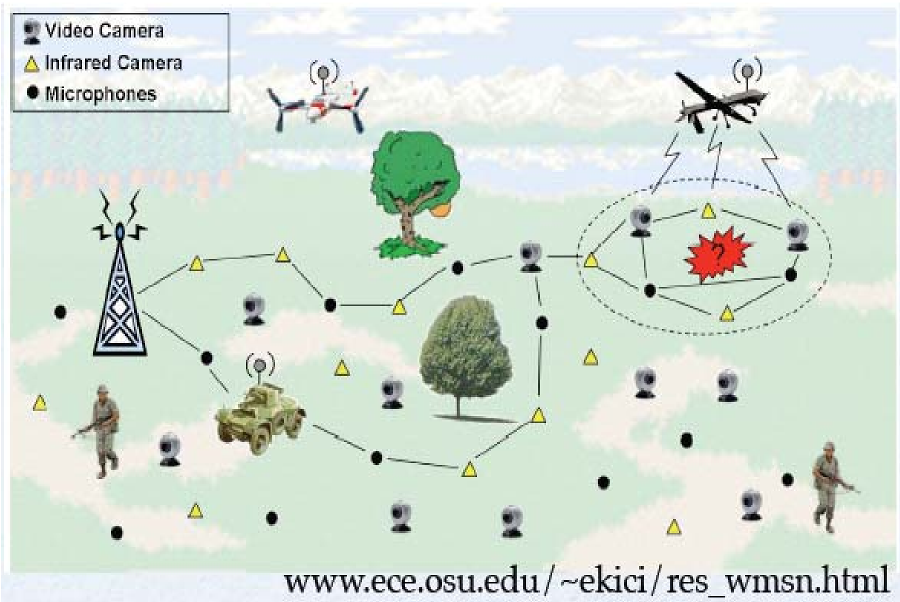


Fig. 1. A typical sensor network example

Fig. 1 shows a typical sensor network example. Sensor nodes are randomly deployed (e.g. dropped from airplane) in an environment and they will take a "snapshot" of their surrounding environment like temperature, humidity, sound or motion information. This information can be further aggregated and then sent to a remote BS through direct transmission or multi-hop transmission. Finally, the BS will analyze the collected information from sensors and make reasonable deduction or prediction about the event which has happened or to happen in the sensor network.

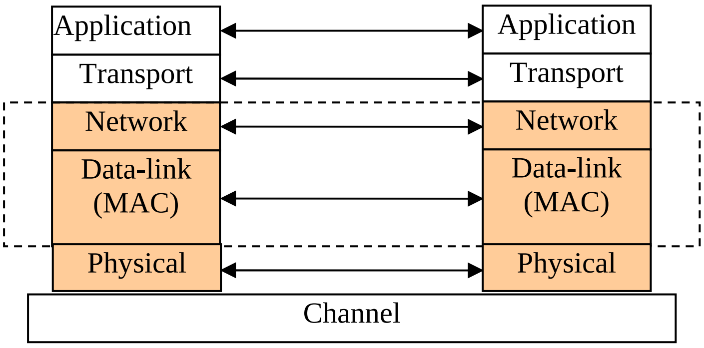


Fig. 2. Wireless sensor network layers

Based on the OSI (Open Systems Interconnection) Reference Model [2, 106], WSNs consist of five layers as is depicted in Fig. 2. The PHY (physical) layer is the basis of the five-layer architecture. It provides reliable communication channel between different devices, media and networks with certain bandwidth. MAC (Medium Access Control) layer mainly deals with the setup, maintenance and removal of the communication channel. The main tasks of network layer include route selection, multiplexing, flow control, error check, interconnection etc. It is relatively simple for wired network while it is very complex for WSNs since the network topology is dynamic. The most famous TCP/IP protocols lie in transport layer and they guarantee the reliable and transparent transport between two parties. Also, it is in charge of error correction and flow control. In the application layer, the end user can define different services or modules such as mail service. Usually, API (application programming interface) module is needed between adjacent layers to guarantee smooth communication.

In this thesis, we mainly study energy efficient routing algorithms in WSNs from network layer. Also, we consider hardware parameters of energy model from PHY layer. We assume that underlying MAC layer protocols are available and they can provide necessary support to the upper layers.

1.1.1 Applications of WSNs

Although wireless sensor networks were first proposed and supported by the U.S. military department, they have various applications [12-19] as below:

- **Military surveillance**: In a battle field, there is no fixed infrastructure and sensor nodes can be deployed in a self-organized manner to collect dynamic information like sniper's position, solder and tank's movement etc.

- **Agriculture and industry monitoring**: Fig. 3 shows an application of the LOFAR_Agro project for agriculture monitoring [19]. This project mainly focuses on reducing required amount of pesticide needed on a field by providing more detailed information about climate of that field. The farmers can improve the quality and quantity of their crop if more information about the weather, soil and pest is provided by WSNs [12]. Monitoring industrial process via WSNs can reduce unnecessary loss of cost since a warning message can be sent to the administrator beforehand [13, 15, 17].

Fig. 3. LOFAR_Agro project for agriculture monitoring

- **Healthcare**: WSNs provide another kind of treatment and care for the disabled or old people. Small sensor devices can be attached to a person to measure his/her physical condition like EEG (electroencephalogram), heart and pulse rate etc. Some high level information like a person's gesture, motion and feeling can also be deduced through WSNs.
- **Wildlife monitoring**: One of the famous examples here is the Great Duck Island experiment [15] which collected information about a special seabird named petrel living on the island. The petrel had once been a very difficult subject for zoologists to study due to the bad climatic condition on the island and abnormal lifestyle. With the help of WSNs, detailed study of such wildlife species can be provided.
- **Other applications**: There are many other WSNs related applications. For example, the pressure sensors can be used to monitor the stress levels in a building so as to prevent the building from collapsing [13]. WSNs can also be applied to monitor the traffic on the high way and provide traffic control so as to improve transportation quality. Some fast delivery companies like DHL or FedEx can manage the workflow of their cargos via WSNs.

In short, WSNs are still in the early development stage. Many applications can be envisioned once billions of tiny and low cost wireless sensor devices are produced and networked.

1.1.2 Sensor node architecture

Fig. 4 shows the sensor node architecture on a sensor board [16, 28]. Here, we can see that each sensor consists of four main components, namely sensing unit, processing unit, transmission unit and power unit. Also, it has two alternative components which are position finding system and mobilizer. It is worth noting that each sensor has limited resource in terms of energy, bandwidth, processing and memory which bring research challenges like routing, localization etc.

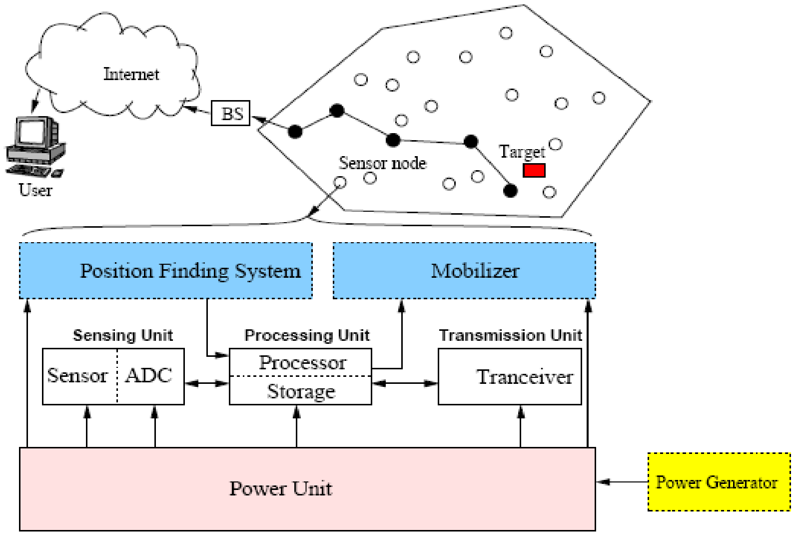


Fig. 4. Sensor node architecture (from [28])

- **Sensing unit**: The sensing unit usually consists of two sub-units which are sensor and ADC (Analog-to-Digital Converter) units. Since observed information is analogous signal, it needs to be transformed into digital signal for further processing with ADC devices.

- **Processing unit**: The processing unit also consists of two sub-units which are processor and storage units. The selection of processing unit is based on factors like power consumption, available memory etc. The memory is of special importance since it is tightly related with the size of data to be stored, processed and buffered for transmission.

- **Transceiver**: The transceiver is the most power hungry component on a sensor board. It is well known that "to transmit one bit message over 100 meters consumes about 1000 times energy than to process the message". Thus, other technologies such as coding and data fusion need to be adopted to reduce the length of message. Another important technique to reduce energy consumption is the introduction of wake-up mechanism in MAC layer [66, 67, 68].

- **Power unit**: Power unit provides necessary energy to all the components on board. Energy conservation is the primary concern for each sensor node since the battery can not be easily re-charged once they are deployed. Nowadays, two AA batteries are usually equipped, so how to use the limited energy efficiently is a hot and challenging research issue.
- **Two alternative components**: There are two alternative components which are position finding system and mobilizer. With the aid of position finding system (like GPS device), each node can know the location of other nodes and they can adjust their power level based on the relative distance. Thus, a huge amount of energy can be reduced. The static sensor node can become mobile if it is equipped with mobilizer. If the sink node was equipped with mobilizer, the whole network lifetime can also get prolonged since the load inside network can get evenly balanced.

1.1.3 Communication architecture

As is depicted in Fig. 5, each sensor node has the following five layers. Besides, it combines power management plane, mobility management plane and task management plane which are in parallel with these five layers. In this thesis, we mainly deal with energy efficient routing on the network layer while the study of energy model is related with the physical layer.

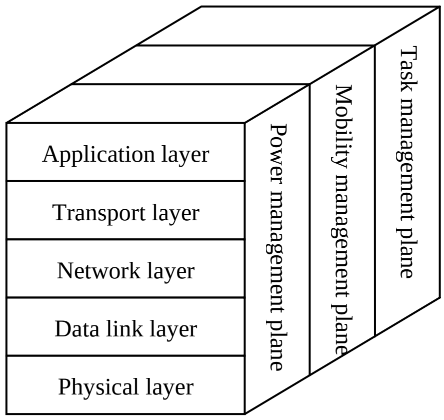


Fig. 5. The sensor network protocol stack

For a specific communication task, the physical layer determines a series of characteristics like operating frequency, modulation type, data coding, interface between hardware and software etc. The data link layer is responsible for managing most of the communication tasks on the link like MAC (medium access control) layer protocols, error control strategies and power control etc. The network layer is in charge of routing packet from source to destination node with certain QoS (quality of service) like energy, latency or packet delivery ratio etc. The transport layer can help to connect WSNs with outside network and maintain data flow. The application layer is responsible for connecting end user's applications or demands with underlying layers within the protocol stack. The interested readers can refer to [2, 106] for more information.

1.1.4 Challenges and research issues in WSNs

WSNs have the following unique characteristics which are different from traditional wired or wireless networks. First, there is no fixed infrastructure and sensors will self-organize via collaboration. Second, sensors are constrained to limited resources such as energy, bandwidth, processing and memory. Third, sensors may malfunction due to reasons like energy drainage, interference, movement or obstacles. Therefore, the network topology may change quickly and dynamically. Due to the unique characteristics above, WSNs have the following challenges and research issues to tackle.

- **Energy conservation**

Depending on the specific application, WSNs may have a lifetime of at least several months to years. Due to the fact that most sensors are powered by limited batteries, how to prolong the network lifetime is the primary challenge.

There are several key factors which can affect the energy consumption in WSNs. Since the sensor nodes are composed of sensing, communication and processing units, the energy consumption can also be divided into 3 parts correspondingly. First, some low power hardware components can be installed on the sensor board to reduce energy consumed during sensing phase. Second, the selection of different protocols on various layers can influence the energy consumption greatly. For example, the node sleeping and wakeup mechanism [86, 87, 88] can be introduced in the MAC layer to reduce energy consumption. Advanced signal processing techniques [89] can be adopted to help improve the processing efficiency of different kinds of data message. We can also combine the clustering and data mining mechanism during routing process to achieve energy efficiency. By adopting power control and power management, not only energy efficient but also network capacity and interference performance can get improved. Finally, we can use intelligent signal processing or data mining methods to reduce the amount of data or the number of transmission, which will cause reduced energy consumption.

- **Topology design**

The topology design and network coverage [90, 91, 92] of WSNs is of critical importance to network reliability, connectivity as well as energy consumption. The sensor nodes can be deployed either beforehand with specific pattern (like disk or grid) or promptly in a random distribution (e.g. dropped from airplane). How to balance the energy workload with the aid of topology design is a practical challenge to the successful application of WSNs.

- **Architecture design**

The WSNs must deal with modules like energy, processing and memory which are dynamically changing. The system should operate autonomously, changing its configurations as required by each application. So, the node’s inside architecture needs to be carefully designed based on hardware platform [108]. Also, the interconnection between WSNs and other networks needs to be considered [107]. Other function modules also need to be considered like localization, synchronization, signal processing and the storage and retrieval of data information under the whole architecture.

- **Collaborative signal processing**

The nodes in WSNs need to collaborate with each other to generate and forward useful information to remote sink node. Collaborative signal processing [89] in WSNs is a new research area. Important research issues include the degree of information sharing between nodes and how nodes fuse information from other nodes. Processing data from more sensors generally results in better performance but also requires more communication resources. Thus, the tradeoff between performance and resource utilization in collaborative signal processing should be considered.

Data fusion [69-76] is one representative approach of collaborative signal processing, which can largely reduce energy consumption. Beam forming [108] is another famous technique which combines the signal from several sensors and makes further processing to reduce energy consumption.

- **Security**

Security is a nontrivial problem for WSNs. It includes research issues like security infrastructure, key management, authentication, robustness to DoS (Denial of Service) attacks, secure routing, privacy etc [93, 94, 95]. To achieve a secure system, security must be integrated into every component module rather than each separate module since components designed without security can become a point of attack in WSNs.

Sensor networks have also thrust privacy concerns. The most obvious risk is that ubiquitous sensor technology might allow ill-intentioned individuals to deploy secret surveillance networks for spying on others. Employers might spy on their employees; shop owners might spy on customers; neighbors might spy on each other etc. There is a trend that as the sensor devices are becoming advanced, this trend might become worse if there is no law enforcement.

1.2 Motivation

Since energy conservation is the primary challenge for WSNs, how to utilize the energy efficiently during routing process so as to prolong network lifetime is an important research issue. The objective of energy conservation is not only to reduce energy consumption during routing process but also to balance energy consumption among the sensor nodes. If some sensor nodes die early, the whole network will quickly get partitioned and out of function [103].

Even though there are many energy efficient routing protocols and algorithms for WSNs, only a few papers study the energy consumption from hop number point of view. In fact, the factor of hop number is a very important network metric since it can affect many network performances. Taking two routes from the same source to destination node as an example, one route has just few hop number while the other route has many short hop number. Intuitively, the end to end delay, energy consumption, network lifetime as well as the packet delivery ratio will be different. Meanwhile, the routing overhead, interference, network capacity and link reliability will also change under various hop number. Thus, how to choose a proper multi-hop route will affect the network performance in terms of energy consumption, network lifetime, packet delivery ratio etc, which should be carefully considered.

There are many research issues need to be solved regarding hop number based network performances. For example, is single hop transmission more energy efficient or multi-hop transmission more energy efficient? Is more interference caused by single hop transmission with high power level or multi-hop transmission with multiple low powers? How about the selection of optimal hop number? By carefully studying the impact of hop number on other network factors, we can achieve improved network performance from hop-based aspect. Our thesis is mainly motivated and inspired by the following observations:

- **Single hop transmission VS multi-hop transmission**

For small scale network when sensor nodes are close to sink node, it is energy efficient to use single hop transmission (also called direct transmission). While for large scale network or when sensor nodes are far away from sink node, it is desirable to use multi-hop transmission. Since power attenuation is proportional to the forth order of distance if the transmission distance is long, it is more energy efficient to divide long distance into small sub-distances where the power attenuation is proportional to the square of distance.

From energy model point of view, if we choose direct transmission or few hops routing between source node and sink node, it will consume a huge amount of energy when the distance d is large, since the energy consumption is proportional to the fourth order of distance ($E \propto d^4$). On the other hand, if we choose too many short hops to transmit, the energy consumption will also be very large since the hardware circuit also consumes a non-neglectable amount of energy during each short hop process. Therefore, how to determine the transmission manner is a nontrivial problem because it depends not only on the distance but also on the hardware parameters of energy model.

- **Hot spot phenomenon**

Usually, there exist some hot spot nodes which will die earlier than other nodes in WSNs, causing short network lifetime. For example, when all sensor nodes use direct transmission, the nodes far away from sink node will die earlier since the energy consumption is proportional to the forth order of distance. Meanwhile nodes near sink node will have much residual energy, which causes a waste of energy resource. On the other hand, when all sensor nodes use multi-hop transmission, the nodes near sink node will have more traffic to forward and die quickly. Meanwhile the nodes far away from sink node will have much remaining energy by using short distance multi-hop transmission.

To alleviate the hot spot phenomenon, we need to balance the energy consumption among all sensor nodes by considering various factors like the transmission manner, traffic pattern, network topology etc.

- **Selection criteria of next hop node**

During multi-hop routing process, how to choose the next hop node is a critical issue. Depending on the purpose of various applications, a node might choose its next hop node based on criteria like maximal residual energy, largest degree, shortest path or other routing strategies.

The resulting multi-hop route will have different performance in terms of energy consumption, hop number and packet delivery ratio etc. For example, the latency is strictly required in some real time applications [54, 55]. Thus, shortest path routing is preferred. While in other applications where the network needs to survive as long as possible, the residual energy is an important factor during the selection of next hop node.

- **Optimal hop number**

Based on different selection criteria of next hop node under different routing algorithms for WSNs, the final hop number will be different. In fact, the factor of hop number can affect many network metrics such as energy consumption, interference, end to end latency, packet delivery ratio and throughput etc [30]. However, the role of hop number is not carefully studied up to now and it only plays a second role during selection of the next hop node.

If we only consider the energy consumption of communication phase, we can reduce the energy consumption from $k \cdot d^{\alpha}$ (for single hop transmission) to $n \cdot k \cdot (d/n)^{\alpha}$ (n-hop transmission), here k is a constant and $\alpha \in [2,4]$ [109]. However, the hardware radio circuit and control overhead also consume a non-neglectable amount of energy [105]. So, the situation becomes totally different: to route over too many short hops might consume more energy than to route over a few hops with longer distances.

Even though it is commonly agreed that multi-hop transmission is more energy efficient than direct transmission under large scale network, how to determine the optimal hop number and intermediate nodes so as to be energy efficient is a challenging job. In one dimensional linear sensor network, it is relatively easy to determine the theoretical optimal hop number given the source to sink node distance and hardware parameters in propagation and energy models. Under practical sensor network with random network topology, it is even harder to find suitable intermediate nodes with proper hop number and individual distances.

1.3 Focus of the dissertation

Our focus in this dissertation is to prolong the network lifetime of WSNs by reducing and balancing energy consumption during routing process from hop number point of view. In other words, we treat the optimal hop number as the first priority during the selection of next hop node. The optimal hop number is deduced with an objective to minimize the total energy consumption as well as to balance energy consumption among all sensor nodes during routing process.

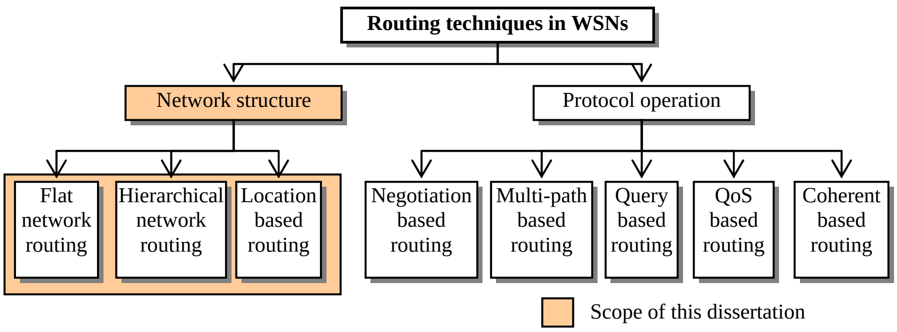


Fig. 6. Routing protocols in sensor networks: A taxonomy [28]

Fig. 6 shows the taxonomy of routing techniques in WSNs [28]. Based on network structure, routing protocols or algorithms in WSNs can be classified into three classes, namely flat-based, hierarchical-based, and location-based routing protocols. Based on the operating manner, routing techniques can be categorized into another five classes in the right part of Fig. 6 [27-65].

The left part of Fig. 6 is the focus of this dissertation. In this thesis, we study the flat, hierarchical and location-based routing protocols. We compare our HEAR algorithm with different routing algorithms like direct transmission, greedy, maximal remaining energy algorithms under flat structure WSNs. Also, we compared the performance of HEAR with LEACH [32, 33] and HEED [48] algorithms under hierarchical structure WSNs.

1.4 Problem statement

Hop-based energy efficient routing for WSNs is an important research area and hop number plays an important role on many network metrics, as we mentioned before. In this thesis, we take the first step to study hop-based routing for WSNs by study its influence on energy consumption, network lifetime as well as packet reachability etc. Later on, we will study its influence on other metrics like network capacity, throughput etc.

We propose a Hop-based Energy Aware Routing (HEAR) algorithm for WSNs which can determine the transmission manner, the optimal hop number as well as proper intermediate nodes during multi-hop routing process under practical sensor networks. During the selection of next hop node, the factor of optimal hop number is treated as the primary concern rather than other factors like maximal residual energy or shortest path. We find the optimal intermediate nodes by solving an optimization problem of minimizing the total energy consumption during multi-hop routing process under constraint conditions.

Finally, the hop spot phenomenon can also get alleviated under our HEAR algorithm for two reasons. First, the nodes far away from sink node will use short distance multi-hop transmission. Second, the nodes near sink node will not be chosen frequently to forward packets. Only the nodes along source to sink node line with similar distance are chosen. Consequently, the average network lifetime is prolonged.

1.5 Contributions

The contributions in this thesis lie in the following aspects.

(i) We determine the transmission manner under the constraint conditions like source to sink node distance and hardware circuit parameters.

(ii) We treat hop number as the first concern during selection of next hop node during energy efficient multi-hop routing process for WSNs. We thoroughly study the relationship between hop number and energy consumption from both theoretical and experimental aspects.

(iii) We deduce the optimal and sub-optimal hop number as well as intermediate nodes under both one dimensional and practical sensor network environment.

(iv) We propose a Hop-based Energy Aware Routing (HEAR) algorithm for WSNs. HEAR is a distributed and localized routing algorithm since the sensor nodes do not need to know the whole network knowledge and they make decision based on the local interaction with its neighbors.

(v) By using our HEAR algorithm, the hot node phenomena can get alleviated. On the one hand, the nodes far away from sink node can greatly reduce their energy via multi-hop routing. On the other hand, the nodes near sink node can also reduce their forwarding number since only the intermediate nodes with similar distance along the source to sink route will be chosen.

(vi) We make extensive theoretical and experimental simulations to validate the performance of our hop-based energy aware routing algorithm. Simulation results show that HEAR has a better performance than other five routing algorithms in terms of energy consumption, hop number, network lifetime and packet reachability etc.

1.6 Outline of the dissertation

The rest of the dissertation is organized as follows.

Some background and related work is presented in Chapter. We give an overview of our HEAR algorithm in Chapter 3. In Chapter 4, we propose HEAR algorithm with detailed explanation and analysis. Chapter 5 provides performance evaluation between HEAR and other five popular routing algorithms and Chapter 6 concludes this dissertation.

Chapter 2 Background

2.1 Unique nature of routing in WSNs

Routing in WSNs is a very challenging task due to the unique nature which distinguish itself from other wireless networks [20-26] like cellular network and MANETs (mobile ad hoc network) etc.

First, it is not possible to build addressing scheme for the deployment of hundreds or thousands of sensor nodes since the communication as well as computation overhead of address/ID maintenance is high. Thus, traditional IP based protocols may not be suitable for WSNs. In WSNs, it is usually more important to know the data attribute within certain area than to know the IDs of nodes from which data is sent.

Second, the data flow is different from traditional communication networks. Usually, there are four types of data flow, namely one to one (or peer to peer), one to many (like multicast), many to one and many to many (like flooding) [2]. In WSNs, the remote BS may broadcast its command like "send me the area with temperature above 80F" in a multicast manner and the relevant sensor nodes will report their collected data to the sink node in a many to one manner. In cellular network, the main communication paradigm is between each cellular user without realizing the existence of BS. In MANETs, each sensor self-organizes into a network and exchanges the information between each other via multi-hop transmission.

Third, the tiny and low cost sensors are constrained in resources like energy, bandwidth, processing and memory. Thus, it is impractical to recharge those unattended sensor nodes. However, the MANETs nodes (like laptops and PDAs) and cellular phone can get recharged easily. So, how to utilize the resource efficiently under the unique nature of WSNs is a challenge issue.

Fourth, the sensor nodes are usually assumed to be stationary in WSNs. But in some applications like robot sensor or sensor with mobilizer, the sensors may move and change their location, which causes unpredictable and frequent topology change. Consequently, the network performance like packet delivery ratio, energy consumption and end-to-end latency will get influenced.

Fifth, WSNs are application oriented which means the design requirements of a sensor network change with specific applications. For example, in application of precision battle field surveillance, the time delay is of the highest importance. While in the application of periodic seismic activity monitoring, the time delay is not very important since it is based on long term observations. Instead, the data accuracy or fidelity is the most important requirement.

Sixth, location awareness of sensor nodes is important since data monitoring is normally based on the area or location information. The location information can be obtained through alternatives like GPS (Global Positioning system) devices, directional antenna techniques or positioning algorithms [96-102, 112, 114]. Usually, it is not feasible to use GPS devices for three reasons: 1) GPS devices are relatively expensive compared to sensor nodes; 2) sometimes relative distance information is enough; 3) GPS may be out of function indoors, underwater, underground or with interference of obstacles. Therefore, we will prefer to use positioning or localization methods like triangulation algorithms to estimate their position based on received signal strength.

Last, there is more or less redundancy (or similarity) among data which are collected by many nearby sensors based on the same observations. Such redundancy needs to be reduced so as to improve the energy and bandwidth efficiency. Usually, a simple function like min, max or mean can be introduce to get an aggregated data value from many monitored values. Advanced signal processing techniques can also be introduced to predict the next coming data from those historical data records.

2.2 Routing challenges and design issues in WSNs

Due to the unique nature of routing above, the tradition routing protocols in MANETs (Mobile Ad hoc Networks) such as DSDV (Destination-Sequenced Distance Vector), DRS (Dynamic Source Routing) and AODV (Ad hoc On-demand Distance Vector) can not be used under WSNs environment. The main goal of routing in WSNs is to guarantee successful packet delivery from source to sink node under constraint requirements like energy consumption, end to end delay, packet delivery ratio and QoS (Quality of Service) etc. It is a nontrivial task with the existence of network dynamics, limited resources inside each node and security problem etc. In the following, we list some of the main routing challenges and design issues in WSNs.

- **Energy conservation**: Sensor node's lifetime heavily depends on the powered battery and they will use up their limited energy resource during sensing, processing and communication process. Especially, the process of communication consumes a significant amount of energy. So, energy efficient routing protocols and algorithms [31-64, 117, 118] need to be carefully designed. It is worth noting that to prolong network lifetime, we not only need to reduce the total energy consumption during each routing process but also need to balance the energy consumption among each sensor node.
- **Traffic model**: There are four types of traffic models in WSNs which are time-driven, event-driven and query-driven and hybrid [2, 27, 28] traffic models. In this thesis, we mainly use time-driven and event-driven model. Sec. 4.1.4 gives more explanation about different traffic models.
- **Node deployment**: Node deployment [90-92] in WSNs can be either deterministic or randomized. In deterministic deployment, the sensors are manually placed and data is routed through predetermined paths. In some other applications like battle field and wildlife monitoring, sensor nodes are randomly deployed like being dropped from an airplane (Fig. 7).

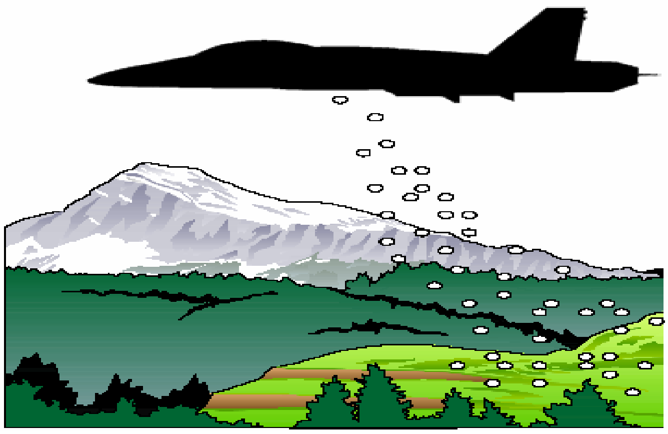


Fig. 7. Sensors being dropped from airplane

- **Network dynamics**: Most WSNs assume that sensor nodes are stationary. Even in that case, network dynamics can be easily observed. Sometimes, mobility of both BS and sensor nodes is necessary. Sometimes, the sensed phenomenon can be either dynamic or static depending on the application. For example, it is dynamic in target detection and tracking application while it is static in forest monitoring for early fire prevention application.

- **Data aggregation**: Data aggregation (a.k.a data fusion) [69-76] is a useful technique of collaborative signal processing. Through this technique, both the data size and number of transmission can be reduced, causing a large reduction of energy consumption. Data aggregation can be done with aggregation functions like duplicate suppression, minima, maxima and average etc.

- **Scalability and clustering**: The number of sensor nodes may be in the order of hundreds or thousands and sensor network routing protocols should be scalable enough to respond to events in the environment. Once an event occurs, most of the sensors can remain in the sleeping state while some others can provide the data of interest to sink node. Clustering [77-85, 117] is a useful technique to tackle scalability of WSNs.

- **Fault tolerance**: Some sensor nodes may fail due to reasons like lack of power, physical damage, interference or attack etc. [29, 31, 107]. The failure of sensor nodes should not affect the overall task of the sensor network. If many nodes fail, MAC layer [66, 67, 68] and routing [27-65] protocols must accommodate formation of new links or routes to send the data to remote sink node.

- **Node and link heterogeneity**: In many studies, all sensor nodes were assumed to be homogeneous, i.e., having equal capacity in terms of computation, communication and power. However, sensor nodes can have different capability depending on specific applications. The existence of heterogeneous sensors raises many technical issues. For example, some applications might require a diverse mixture of sensors to monitor temperature, pressure and humidity of the surrounding environment, to detect motion via acoustic signatures and to capture the image or video tracking of moving objects. Link heterogeneity means the communication can be uni-directional rather than bidirectional.

- **Quality of Service**: In some applications, data should be delivered within certain period of time; otherwise the data will be useless. Thus, bounded latency for data delivery is critical for time-constrained applications. For example, TEEN (Threshold-sensitive Energy Efficient sensor Network) protocol [54] and APTEEN (Adaptive Periodic Threshold-sensitive Energy Efficient sensor Network) protocol [55] are proposed for time-critical applications. In other applications, conservation of energy is more important than the quality of data sent. As the energy gets depleted, the network may be required to reduce the quality of the data to reduce the energy dissipation and prolong the total network lifetime [27, 28, 49].

- **Others**: There are some other issues in network layer such as coverage, connectivity [90-92] etc. In WSNs, sensor’s distribution, transmission power and deployment strategy can affect the performance of coverage. Also, high or medium density can prevent sensors from being isolated. However, under very low density network or when some nodes die out of power, there may exist isolated node or area.

2.3 Routing protocols for WSNs

As is depicted in Fig. 6, the routing protocols in WSNs can be divided into three classes based on network structure, which are flat-based routing, hierarchical-based routing and location-based routing protocols [27-65].

In the following, we will briefly introduce some of the representative routing protocols or algorithms for WSNs. More details can be found in [2, 27, 28].

2.3.1 Flat-based routing

In flat-based routing protocols, each node typically plays the same role and sensor nodes collaborate with each other to perform sensing task. Due to the large number of sensor nodes, it is not feasible to assign a global ID to each node. This reason has led to data centric routing where the BS sends queries to certain area and waits for data from the sensors located in the selected regions. Since data is being requested through queries, attribute-based naming is necessary to specify the properties of each interested data. Early works on data centric routing like DD (Directed Diffusion) [36, 37], SPIN (Sensor Protocols for Information via Negotiation) [31, 38] and GRAB (GRAdient Broadcast) [42] algorithms were shown to save energy through data negotiation and elimination of redundant data. These protocols have motivated the design of many other protocols with similar mechanism. The interested readers can refer to [37, 38, 42] for more details. Here, we will introduce DD as an example.

DD (Directed Diffusion) [36, 37] is a representative data aggregation protocol for WSNs. It is a data-centric and application aware paradigm in the sense that all data generated by sensor nodes is named by attribute-value pairs. In DD, the base station requests data by broadcasting interests which describes a required task to be monitored or reported by the relevant sensors. The interest is defined using a list of attribute-value pairs such as name of objects, interval, duration and geographical area etc. Each node receiving the interest can cache it for later use. As the interest is broadcasted through the network hop-by-hop, gradients are setup towards the requesting node. A gradient is a reply link to the neighbor from which the interest was received. It contains the information from where it is received, such as the data rate, duration and expiration time. Each sensor that receives the interest sets up a gradient toward the sensor nodes from which it received the interest. This process continues until gradients are setup from the sources all the way back to the base station. In this way, several paths can be established so that one of them is selected by reinforcement. The sink resends the original interest message through the selected path with a smaller interval, hence reinforcing the source node on that path to send data more frequently. Fig. 8 shows an example of DD routing protocol. DD suggests that each mobile sink needs to continuously propagate its location information throughout the sensor field so that all sensor nodes get updated with the direction of sending future data reports. However, frequent location update from multiple sinks leads to both increased collisions and rapid energy consumption.

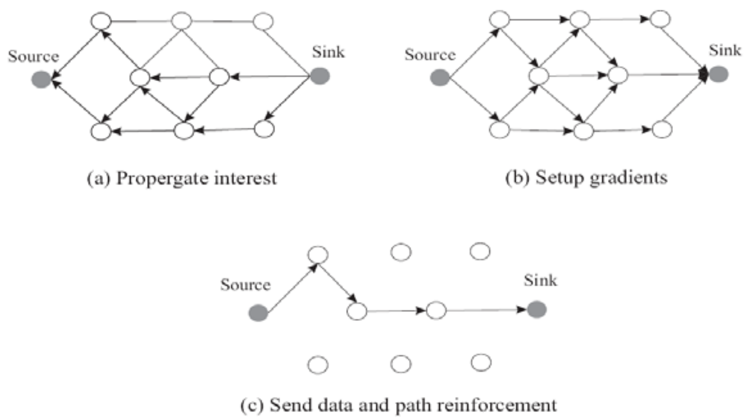


Fig. 8. Three phases of Directed Diffusion protocol

2.3.2 Hierarchical-based routing

Hierarchical-based (also called cluster-based) routing was first used in wire line networks. It is a famous routing paradigm with advantages of scalability and efficient communication. The concept of hierarchical routing can also be utilized to achieve energy efficiency during routing process in WSNs. In a hierarchical structure network, higher energy nodes can be used as cluster heads to perform management and coordination within each cluster while low energy nodes can be kept as sleeping nodes unless they have data to send. In this way, it can largely contribute to the whole network scalability, lifetime as well as energy efficiency. Hierarchical routing can also reduce energy consumption within a cluster by performing data aggregation. Hierarchical routing mainly utilizes two-layer routing where one layer is used for communication between cluster heads and the other layer is used for short range communication between cluster head and ordinary nodes within the same cluster.

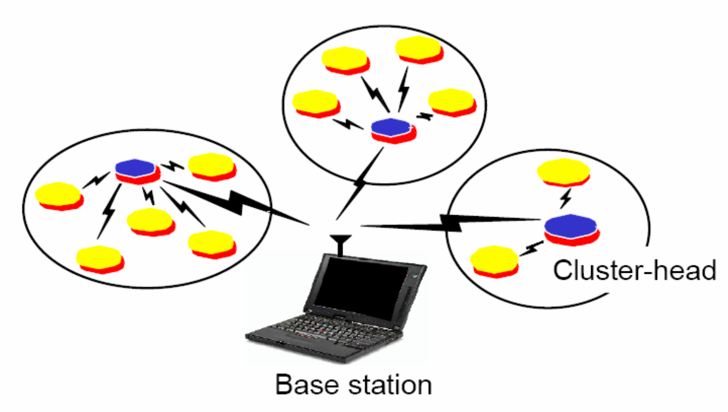


Fig. 9. LEACH routing protocol

LEACH (Low Energy Adaptive Clustering Hierarchy) [32, 33] is one of the most famous hierarchical routing algorithms for WSNs. In LEACH, sensors are organized into clusters. Each cluster has one CH (cluster head) which collects and aggregates information from its members and transmits the information to the base station directly, as is shown in Fig. 9. Each node takes turn to become cluster head so as to balance energy consumption. Each sensor node will choose a random number between 0 and 1 and a node becomes a cluster head for the current round if the random number is less than the following threshold:

$$T(n) = \begin{cases} \dfrac{p}{1 - p * (r \bmod 1/p)} & if \quad n \in G \\ 0 & otherwise \end{cases} \qquad (2.1)$$

where p is the percentage of cluster heads (e.g. 5%), r is the current round and G is the set of nodes which have not been cluster head by current round.

LEACH can achieve a factor of 8 reduction in energy consumption compared to direct communication and a factor of 4 to 8 compared to the MTE (minimum transmission energy) routing protocol. However, LEACH has a number of shortcomings. First, LEACH assumes that every node can directly transmit its data to the remote base station under their small scale network environment. However, one-hop direct transmission to remote sink node is not feasible in large scale WSNs due to the limited energy resource of sensors. Second, 5% of the cluster heads are randomly chosen. Thus, the distribution of cluster head number is quite uneven, which cause more energy consumption. Finally, LEACH is vulnerable to several attacks including HELLO flood, selective forwarding and Sybil attacks.

Power-efficient GAthering in Sensor Information Systems (PEGASIS) [41] is viewed as an improved version of LEACH. It is a chain based routing protocol which can save more energy compared to LEACH. The message can get aggregated along the chain and finally be sent to remote sink node via direct transmission by one random node on the chain. The main shortcoming is that PEGASIS requires global knowledge of the whole network. HEED clustering protocol [48] can not only minimize control overhead during communication process but also prolong network lifetime than other clustering algorithms like LEACH since the cluster heads are well distributed. It periodically selects cluster head based on a hybrid of node residual energy and a secondary parameter such as node proximity to its neighbors or node degree. Node with more residual energy will have a higher probability to be chosen as cluster head. Besides, it does not need global knowledge of the whole network and all intelligent decisions are made locally by sensor nodes.

2.3.3 Location-based routing

In location-based routing protocols, it is assumed that the sensor location information is known. The sensor nodes are addressed by their location and the location information can be obtained either through GPS device or through certain positioning or localization algorithms like triangulation method [96-102, 112, 114].

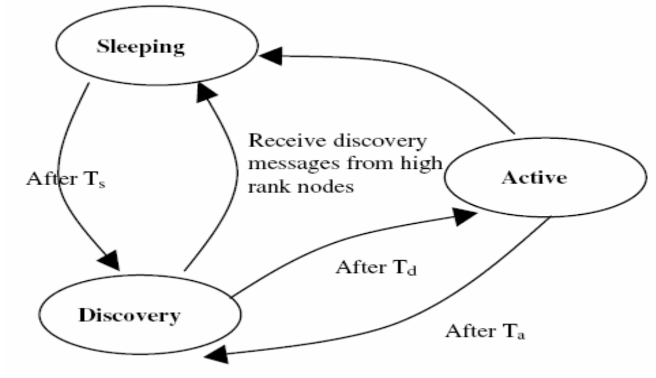


Fig. 10. State transitions in GAF

Fig. 10 shows an example of Geographic Adaptive Fidelity (GAF) [21, 22] which is an energy aware location-based routing algorithm for mobile ad hoc networks as well as WSNs. The network area is first divided into fixed zones which form a virtual grid. Inside each zone, nodes will elect one sensor node to stay awake for a certain period of time and then they go to sleep. This node is responsible for monitoring and reporting data to the BS on behalf of the nodes in the zone. Hence, GAF conserves energy by turning off unnecessary nodes in the network without affecting the level of routing performance. Each node uses its GPS-indicated location to associate itself with a point in the virtual grid. There are three states defined in GAF, namely discovery, active and sleep. Discovery is used for determining the neighbors in the grid; active is used for reflecting participation in routing and sleep is used when the radio is turned off. The sleeping neighbors adjust their sleeping time accordingly. Before the time of active node expires, sleeping nodes wake up and one of them becomes active.

There are other location-based routing protocols. For example, TTDD (Two-Tier Data Dissemination) [39] uses a two-tier data dissemination model to deal with sink mobility problem and reduce energy consumption by assuming that each node knows its location. MECN (Minimum-Energy Communication Network) [50] provides a minimum energy network for WSNs under the support of low power GPS and the authors in [51] make an extension of [50] by considering possible obstacles between any pair of communication nodes.

In this chapter, we first introduce the unique nature of routing in WSNs which is different from traditional wireless networks. Then, we present some routing challenges and design issues in WSNs like energy conservation, traffic model, node deployment, network dynamics etc. Finally, we briefly explain some representative routing algorithms or protocols under three classes of routing protocols for WSNs.

It can be seen in section 2.3 that the factor of hop number is not carefully addressed by most of the energy efficient routing protocols for WSNs. In fact, hop number has very important impact on many network metrics like energy consumption, routing overhead, interference etc [30]. Therefore, we will study the relationship between hop number and energy consumption as the first step. In the rest of the thesis, we will propose energy efficient routing algorithm from hop number point of view and will validate its performance through extensive theoretical analysis and simulations.

Chapter 3 Overview of HEAR Algorithm

3.1 Uniqueness of HEAR algorithm

Up to now, many energy efficient routing protocols have been proposed for WSNs. However, just a few of them study the network performance from hop number point of view, as can be seen from section 2.3. In fact, hop number has very important influence on many network metrics like energy consumption, routing overhead, interference etc., as we have mentioned in Sec. 1.2.

The authors in [43, 44, 45] present some pioneering work of studying different energy models under general wireless network. They mainly focus on theoretical study and proof of the optimal hop number. However, they treat every node equally which is not true for WSNs since source and intermediate node consume different amount of energy, as can be seen from energy model in Chapter 4. Also, more simulation work is needed since the real sensor network may not have such sensor nodes corresponding to the optimal intermediate nodes. Also the hop number should be an integer rather than a theoretical decimal value under practical sensor networks. The authors in [32, 33] treat energy consumption differently for source and intermediate node. However, they only consider direct transmission for each cluster head under their small scale network environment and do not consider multi-hop transmission nor provide a further deduction of the optimal hop number for both linear and real sensor network. The authors in [52] study selection of transmission manner from probability point of view. They present a probability of P_i to transmit data through multi-hop transmission and a probability of $(1-P_i)$ to transmit through single hop transmission to sink node. The authors in [53] study the energy consumption under both single hop and multi-hop transmission manners. They claim that the preference of multi-hop routing to single hop routing depends on source to sink distance and reception cost, which is consistent with our analysis in this thesis. However, the authors in [52, 53] only treat 2-hop routing as multi-hop transmission in their environment and do not provide further analysis with more than 2 hops transmission for practical WSNs. The author in [111] proposed a data forwarding scheme by splitting the data into direct transmission and h-hop multi-hop transmission. The selection of splitting ratio and h is a critical issue therein. The authors mainly focus on theoretical analysis and there is no deduction of optimal hop number. Also, the simulation work is not enough.

The uniqueness of HEAR algorithm lies in the following three aspects. First, we make further deduction of the optimal as well as sub-optimal hop number during routing process based on the theoretical analysis of [32, 33] and modify the formula in [43, 44, 45] to fit in practical WSNs environment. Second, we study multi-hop routing with more than 2 hops under both linear and practical sensor network environment. Third, we propose our HEAR algorithm with detailed workflow and explanation based on theoretical and experimental analysis. Finally, we make extensive simulations and comparison which shows that HEAR has better advantage over many other popular routing algorithms for WSNs such as LEACH and HEED etc.

3.2 HEAR algorithm

HEAR algorithm is a distributed and localized algorithm for practical sensor network, which combines the general routing mechanism with hop-based nature during routing process in WSNs.

Our work is mainly inspired by [30, 32, 33, 43, 44, 45]. The authors in [45] give theoretical guidance about how to choose the optimal hop number as well as intermediate nodes during multi-hop routing in general wireless networks under different energy consumption models. However, they mainly deal with one dimensional linear sensor network and they treat source and intermediate nodes equally, which is not true. Also, the deduced optimal hop number is a decimal value while it should be an integer value under practical sensor network. Our HEAR algorithm deals with both one dimensional and two dimensional sensor network where source and intermediate nodes consume different amount of energy. We also provide an empirical selection criterion of the sub-optimal hop number under practical sensor network when the optimal hop number might not be obtained due to random network topology.

3.2.1 Brief workflow of HEAR algorithm

The brief workflow of our HEAR algorithm is shown in Fig. 11. Once source node has data to send to BS, it will first determine the transmission manner based on our theoretical analysis in chapter 4. If direct transmission is more energy efficient, it will transmit its data directly to BS. Or else, it will use multi-hop transmission by determining its next hop node based on HEAR algorithm. If the next hop node is BS, the routing workflow will terminate. Otherwise, the next hop will repeat in an iterative way.

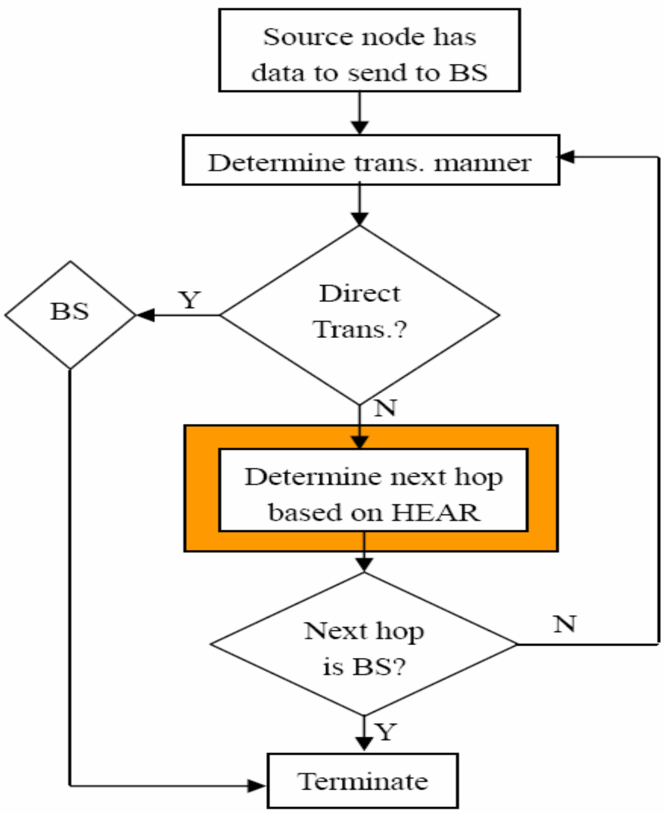


Fig. 11. Brief workflow of HEAR algorithm

We can see that how to determine the next hop based on HEAR algorithm (orange part in Fig. 11) is the key issue during routing process in WSNs. Inspired by the works in [43, 44, 45], we can get the optimal multi-hop number and the intermediate nodes once the source to sink node distance and hardware parameters are given. It is worth emphasizing that the selection criterion of next hop node is purely from hop number point of view in HEAR. The optimal hop number and intermediate nodes are derived by solving optimization function with an objective of minimizing the total energy consumption during multi-hop routing process in WSNs. Therefore, the resulting multi-hop route is energy efficient and it is obtained based on local decision by each node.

It is worth noting that the workflow of HEAR can be either real time or not real time, depending on the traffic pattern as well as the traffic load. Under low traffic load or under time-based traffic model when each node takes turn to send its data to the sink node, the data can be sent immediately after it is received. This is called real time transmission. Under heavy traffic or under event-based traffic model when several nodes have data to send simultaneously, a node may have several traffic sessions to forward. Thus, it will store certain traffic flows in its buffer and forward them later on when the current traffic is finished. This transmission is not real time.

If the transmission is not real time, the buffer size and buffer delay are two important factors for engineering design. If the buffer size is too large, it will cause long addressing time to search from buffer. If it is too small, it will cause high packet drop-off rate during traffic congestion period. As a rule-of-thumb, the buffer size is determined as $B = C \cdot RTT$, here B is buffer size, C is link rate and RTT is round trip time. For example, if the link rate is 1Gbps and the round trip time is 25ms, the final empirical buffer size is 25Mb. The buffer delay is determined by factors like switching methods, buffer size and packet length. Three popularly used switching methods are cut through (or direct) switching, store-and-forward switching and fragment free switching [109].

3.2.2 A scenario of HEAR algorithm

Fig. 12 shows an example of random sensor deployment in a $200 \times 200\, m^2$ area WSN, where BS is placed at (100, 100). There are 50 sensor nodes and they take turn to send their sensed data to the BS.

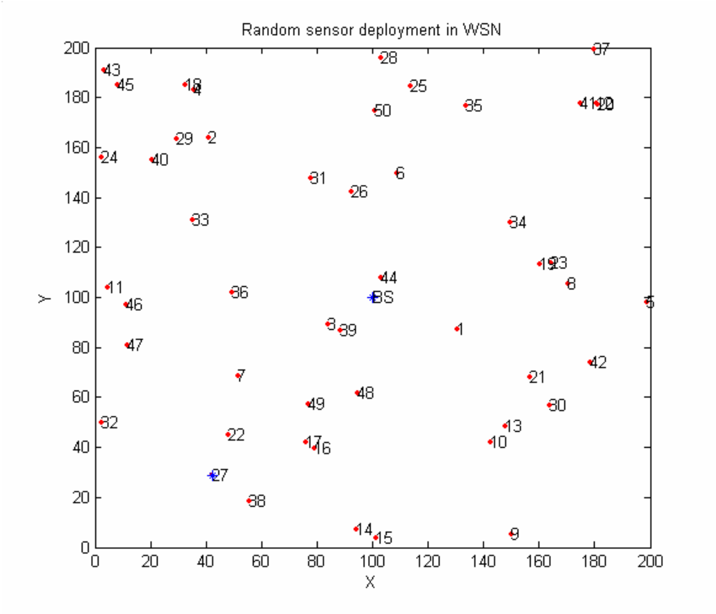


Fig. 12. Random sensor deployment in WSN

Our main proposal is to reduce and balance energy consumption during each routing process. For example, when source node 27 has data to send to BS, it will first determine its transmission manner, as is stated in Fig. 11. Since the distance to the BS is too long, it will choose multi-hop transmission. Based on various selection criteria of next hop node, the final route will be different. Table 1 shows the final routes of node 27 to the BS based on different routing algorithms. From Table 1 we find that the final route with different hop number will have different network performance in terms of energy consumption, network lifetime, link delay and reliability etc.

Here, we want to study the impact of hop number on network performance above and try to propose a hop-based energy aware routing solution which can reduce and balancing energy consumption without sacrificing other network performance.

Table 1 Routes of node 27 under different algorithms

	Direct Transmission	Greedy Algorithm	Maximal Residual energy	HEAR Algorithm
Final route	{27, BS}	{27, 49, BS}	{27, 38, 22, 7, 3, BS}	{27, 17, 48, BS}
Hop number	1	2	5	3
Energy cons.	Large	Medium	Large	Medium
Net. Lifetime	Short	Long	Medium	Long
Link delay	Short	Medium	Long	Medium
Link reliability	Best	Better	Bad	Better

As can be seen in Table 1 and Fig. 12, how to choose the next hop node is the critical issue during routing process. In some applications when link delay is critical, direct transmission or greedy routing is preferred. In other applications when network lifetime is critical, maximal residual energy routing is preferred.

In this thesis, our primary focus is to reduce and balance energy consumption during routing process. Given the source node to BS distance, we try to minimize the total energy consumption by all the involved nodes along the multi-hop route from source to BS. It is nontrivial task due to the following several reasons. First, we need theoretical analysis and deduction of the energy consumption, the optimal hop number and intermediate distances. Second, the theoretical results might not be applicable to the practical sensor network due to reasons like random sensor deployment, some restricted conditions etc. Finally, extensive simulation and comparison is needed to validate the hop-based routing performance.

Taking node 27 as an example, the selection criterion of next hop node based on HEAR algorithm is as follows. First, node 27 will treat all its neighboring nodes {7, 17, 17, 22, 38, 49} as its next hop candidates. Based on the theoretical analysis in the next chapter, it can deduce an optimal or sub-optimal hop number according to the hardware radio parameters and the relative distance to the BS d. For example, the optimal hop number is 3 when the total energy consumption is minimal. Then, it will try to find a neighboring node with distance $d_i \in (d/3, d/3+\Delta]$. If there are several neighbors which can meet this condition, node 27 will finally choose one of them which is closest to BS as the final next hop. Finally, the intermediate node will choose its next hop along the multi-hop route in an iterative way until the BS. It is worth noting that since the intermediate nodes are chosen with similar individual distance, the energy consumption can also get balanced among all the involved nodes.

3.2.3 Characteristics of HEAR algorithm

HEAR algorithm has the flowing characteristics:

(1) The relationship between hop number and energy consumption is studied from both theoretical and experimental point of view. The transmission manner, the optimal hop number and the corresponding intermediate nodes are derived.

(2) Both one dimensional linear sensor network and two dimensional real sensor network are studied. Usually, one dimensional linear network can be used in linear applications such as highway traffic monitoring, congestion control etc. and two dimensional sensor network has much wider applications.

(3) We study the performance of HEAR algorithm under different traffic patterns. At first, we let each node take turn to send their observed data to remote sink node, which is similar to time-based traffic model. Next, we randomly choose certain node to transmit its data to sink node, which is similar to event-based traffic model.

(4) We provide extensive simulation results. We not only study the factor of energy consumption but also some other network metrics like hop

number, network lifetime, packet reachability as well as hop spot phenomenon. We make extensive simulations under various network topologies by changing factors like node number, transmission radius, network scale, BS position etc. Simulation results show that HEAR algorithm is superior to other popular routing algorithms for WSNs like direct transmission, greedy, maximum remaining energy (MRE), LEACH and HEED algorithms.

(5) HEAR provides a common paradigm and workflow of the hop-based routing paradigm which can be adopted by other energy efficient routing protocols. It is a simple, distributed and localized routing algorithm where no global knowledge about the whole network is needed. Each node simply interacts with its neighbors and local intelligent decisions can be made to achieve good performance.

During routing process in WSNs, how to select the next hop node based on different selection criteria will greatly influence the network performance. The following next hop selection criteria are popularly used: a) Lowest-ID; b) Max-degree; c) Shortest-path; d) Max-residual energy; e) Greedy; f) Probability-based; g) others.

In this thesis, our selection criterion of the next hop node is to minimize the total energy consumption during each multi-hop routing process. We can find that energy consumption is reduced, network lifetime is prolonged and the hot spot phenomenon is alleviated in the following chapters.

Chapter 4 Hop-based Energy Aware Routing (HEAR) Algorithm for WSNs

4.1 Relevant models

4.1.1 Network model

The traditional WSN can be regarded as a directed graph $G = < V, E >$ where V represents the set of vertices and E represents the set of bidirectional or unidirectional links [2, 27, 28, 104]. We assume that there are N nodes randomly scattered in a two dimensional square field A . Two nodes are assumed to be neighbors if the Euclidean distance between them is less than their transmission radius. The objective of routing is to find a series of links from E so as to so as to connect source to destination node under certain constraints like energy efficiency, short latency or high data fidelity etc. The routing problem becomes very complex in WSNs due to factors like network dynamics, different traffic pattern as well as various applications.

We make the following assumptions about sensor network in this thesis:

- The sensor nodes are stationary. This is typical for WSNs even though sometimes there are some mobile sensor nodes or sink nodes.
- The sensor nodes are homogenous which means they have similar sensing, processing and communication capability.
- All sensor nodes are left unattended after deployment. Therefore, energy can not be recharged.
- There is only one sink node (or BS) placed inside or outside area A .
- The communication links are symmetric. Thus, if node v can receive a packet from node u , node u can also receive that packet from node v .

- The nodes can know the relatively distance to its neighbors as well as to sink node. Here, GPS device is not necessary for each of the sensor node. Some positioning or localization algorithms [96-102, 112, 114] can be used to get the relative distance information based on received signal strength.
- There is no big obstacles between source and sink node.

Table 2 lists the definition of the network parameters used in this thesis.

Table 2 Definition of network parameters

Parameter	**Definition**
A	Area of sensor network
N	Number of sensor nodes
R	Maximum transmission radius
l	Data length
BS	Position of Base Station
d	Distance between source and sink node

4.1.2 Propagation model

A radio channel between a transmitter u and a receiver v is established if and only if the power of the radio signal received by node v is above a certain threshold which is called the sensitivity threshold. Formally, there exists a direct wireless link between u and v if $P_r \geq \beta$, where P_r is the power of received signal by v and β denotes the sensitivity threshold [33, 109]. In wireless channel, radio propagation can be modeled as a power attenuation function of the distance between each communication pair.

In this thesis, we study the following free space and multi-path models. If the communication distance is less than a crossover distance ($d_{crossover}$), the Friss free space model is used (d^2 attenuation). If the distance is larger than $d_{crossover}$, multi-path model is used (d^4 attenuation). The crossover distance is defined as:

$$d_{crossover} = \frac{4\pi\sqrt{L}h_r h_t}{\lambda} \tag{4.1}$$

where:

$L \geq 1$ is the system loss factor not related to propagation,

h_r is the height of receiving antenna above ground,

h_t is the height of transmitting antenna above ground,

λ is the wavelength of the carrier signal.

If the distance is less than $d_{crossover}$, the transmit power is attenuated according to the Friss free space equation as follows:

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

where:

$P_r(d)$ is the receive power given a transmitter-receiver distance d,

P_t is the transmit power,

G_t is the gain of the transmitting antenna,

G_r is the gain of the receiving antenna,

λ is the wavelength of the carrier signal,

d is the distance between transmitter and receiver,

$L \geq 1$ is the system loss factor not related to propagation.

If the distance is larger than $d_{crossover}$, the transmit power is attenuated according to the two-ray ground propagation equation as follows:

$$P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4} \qquad (4.3)$$

where:

$P_r(d)$ is the receive power given a transmitter-receiver distance d,

P_t is the transmit power,

G_t is the gain of the transmitting antenna,

G_r is the gain of the receiving antenna,

h_r is the height of receiving antenna above ground,

h_t is the height of transmitting antenna above ground,

d is the distance between transmitter and receiver.

If we set the parameters as: $G_t = G_r = 1$, $h_t = h_r = 1.5m$, $L = 1$ (no loss) and 914 MHz with $\lambda = \frac{3\times10^8}{914\times10^6} = 0.328m$. We can get $d_{crossover} = 86.2m$ and Eq.(4.2) and (4.3) can be simplified as:

$$P_r = \begin{cases} 6.82\times10^4 \frac{P_t}{d^2}, & d < 86.2m \\ 2.25\frac{P_t}{d^4} & d \geq 86.2m \end{cases} \qquad (4.4)$$

4.1.3 Energy model

As can be seen from Fig. 4, one of the most important components therein is the power unit which provides necessary energy for all the other components on sensor board to work properly. Since all the components in Fig. 4 must fit into a matchbox size module, each sensor node has very limited resource of energy. For example, the total energy stored inside the smart dust mote is 1 Joul [17].

Energy efficiency is one of the primary challenging issues to the successful application of WSNs because the tiny sensors with limited energy can not be re-charged easily once they have been deployed. Since the radio device is the main source of energy consumption, how to design an energy efficient routing algorithm during communication process is one of the key issues for WSNs.

There are some other sources of energy consumption by the sensor nodes. For example, the technique of modulation/demodulation and coding/decoding from PHY layer consumes certain amount of energy. In the MAC layer, huge energy will be wasted if states like “active/idle/sleeping” are not well scheduled. Other factors such as packet collision and overhearing will waste the limited energy resource [66, 67, 68]. In general, the source of the energy consumption consists of three parts, namely sensing, processing and communication. In this thesis, we only consider the energy consumption during communication process due to the fact that “to transmit one bit of message over 100 meters consumes around 1000 times more energy than to process the message”.

The energy consumption in a sensor node can also be classified from useful energy consumption and wasteful energy consumption point of view. The useful energy consumption consists: 1) transmitting/receiving data; 2) processing query requests; 3) forwarding queries/data. The wasteful energy consumption consists: 1) idle listening to the media; 2) retransmitting due to packet collision; 3) overhearing; 4) generating/handling control packets [48].

Up to know, there are many different energy consumption models used in WSNs. The authors in [43, 44, 45] give the theoretical analysis of several energy models. Rodoplu and Meng [50] proposed a general model where the power consumption between two nodes at distance d is $u(d) = d^{\alpha} + c$ for some constants α and c. They use the model with $u(d) = d^2 + 2 \times 10^8$ which is viewed as RM-model in their experiments.

The energy consumption model we use in this thesis is called the first order radio model [32, 33]. Each sensor node will consume the following E_{Tx} amount of energy to transmit a l -bits message over distance d :

$$E_{Tx}(l,d)=\begin{cases} l\cdot E_{elec}+l\cdot\varepsilon_{fs}\cdot d^2, & if\, d<d_0 \\ l\cdot E_{elec}+l\cdot\varepsilon_{mp}\cdot d^4, & if\, d\geq d_0, \end{cases} \tag{4.5}$$

E_{Rx} amount of energy to receive this message:

$$E_{Rx}(l)=l\cdot E_{elec}, \tag{4.6}$$

and E_{Fx} amount of energy to forward this message:

$$E_{Fx}(l,d)=E_{Tx}(l,d)+E_{Rx}(l)=\begin{cases} 2l\cdot E_{elec}+l\cdot\varepsilon_{fs}\cdot d^2, & if\, d<d_0 \\ 2l\cdot E_{elec}+l\cdot\varepsilon_{mp}\cdot d^4, & if\, d\geq d_0. \end{cases} \tag{4.7}$$

The definition of radio parameters is listed in Table 3.

Table 3 Definition of hardware parameters

Parameter	Definition	Unit
E_{elec}	Energy dissipation	50 nJ/bit
ε_{fs}	Free space model of	10 pJ/bit/m^2
ε_{mp}	Multi-path model of	0.0013 pJ/bit/m^4
l	Data length	2000 bits
d_0	Distance threshold	$\sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$ m

Fig. 13 shows an energy dissipation model from where we can see each of the energy consumption part inside radio transceiver. It is consistent with Eq. (4.5) to (4.7) which explains vividly the two parts of energy consumption by electronic circuits (E_{elec}) as well as by radio amplifier (ε_{amp}).

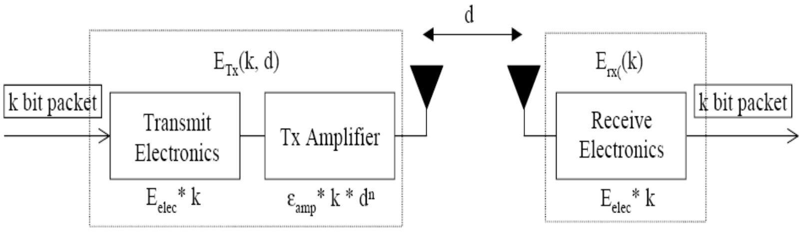


Fig. 13. Radio energy dissipation model

In order to normalize the constants, divide both expression by $l \cdot \varepsilon_{fs}$ in Eq. (4.5) and (4.7) so that radio consumes $T = E + d^2$ energy for transmission and $P = E$ energy for reception, where $E = E_{elec} / \varepsilon_{fs}$. So, the power needed for forwarding (reception and retransmission) is $u(d) = 2E + d^2$ and this is referred to as HCB-model [45].

In this thesis, we use the first order radio model since it is widely used by many other routing protocols. Here, it is also worth mentioning that the value of distance power gradient α can be other values rather than 2 or 4. Table 4 lists some other values used in practical wireless communication environment.

Table 4 Values of distance power gradients

Parameter	α
Free space	2
Urban area	2.7—3.5
Indoor line-of-sight (LOS)	1.6—1.8
Indoor no line-of sight	4—6

4.1.4 Traffic model

There are four types of traffic patterns for WSNs [2, 27, 38], namely time-based, event-driven, query-based and hybrid traffic pattern.

Time-based traffic pattern is commonly used in applications like temperature and seismic monitoring, video surveillance systems etc. where response latency is not very important but a trend (like a mean value) needs to be deduced or predicted based on long term observation data.

Event-driven traffic pattern is used for applications like target tracking or intrusion detection etc. When a target is entering into the nearby region of a sensor node, the target will be detected and tracked with an increased (or burst) traffic sent by involved sensor nodes to remote sink node.

DD (Directed diffusion) [36, 37] is a representative query-based routing protocol for WSNs. Once the remote sink node or the administrative center requests certain types of information from some area, it will send a query like "send me the four-let animal (or the highest temperature) information in the area of [x1, x2, y1, y2]". The query is attribute-based and it can be sent through multicast or broadcast. Once the corresponding sensor nodes receive this query, they will send back their data information as a response to this query within short time.

Hybrid traffic pattern is also commonly used. For example, during the time-based traffic monitoring period, the remote sink node may send a query to demand for certain information simultaneously. It is worth mentioning that node sleeping mechanism can also be introduced to improve energy efficiency based on certain scheduling. Taking time-based traffic pattern as an example, all the sensor nodes near the phenomenon do not need to turn on their sensing units all the time. Instead, just a few of them will switch on their sensing units in turn to finish the monitoring task.

In this thesis, we mainly adopt event-based and time-based traffic models. In event-based traffic model, source node will send its sensed data about sudden event to sink node. Thus, intermediate nodes do not generate additional data during forwarding process. In time-based traffic model, each node not only forwards its previous traffic but also generate its own observed traffic at certain time to transmit to its next hop.

HEAR algorithm mainly uses time-based and event-based traffic models in two forms. In the first form, each node takes turn to transmit its data through direct or multi-hop transmission. In the second form, each node is randomly chosen to report its sensed event information to sink node.

4.2 Analysis of relevant models

4.2.1 Problem formulation

Fig. 14 shows a one dimensional linear sensor network model where each sensor node is placed along a line with individual distance r_i. The distance between source and sink node is d and the energy model is called the first order radio model.

We model the one dimensional linear sensor network as follows. The number of sensor nodes along the line is N and the set of sensors is given as:

$$S = \{s_i, i \in \{1, \cdots, N\}\} \tag{4.8}$$

and the corresponding individual distance, i.e., the hop distance from each node to its next hop neighbor is given as:

$$R = \{r_i, i \in \{1, \cdots, N\}\} \tag{4.9}$$

The final node s_N will send the data directly to the sink node with distance r_N and sensor node s_i will forward the data from source node s_1 to its neighbor s_{i+1} with distance r_i in a hop-by-hop manner.

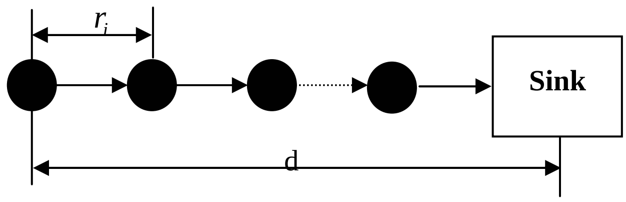


Fig. 14. One dimensional linear sensor network model

At first, we simplify the optimization problem by considering the simplest traffic model, which is that only the source node creates a l-bit message and all the intermediate nodes will forward this message to the remote sink node. Therefore, the traffic model can be viewed as event-based model. The energy consumption for each of the sensors is given as:

$$E = \{E_i, i \in \{1, \cdots, N\}\} \tag{4.10}$$

Our final goal is to find an n-hop route so that the total energy consumed by all of the sensors along the route is minimal. In other words, we try to find n optimal intermediate nodes with corresponding individual distances r_i, so that $\sum_{i=1}^{n} E_i$ is minimal.

It is worth mentioning that if we do not consider the part of energy consumption by hardware circuit and only consider the energy consumed during communication process, the energy consumption for direct transmission of l-bit message over distance d will be:

$$E_{dt} = l \cdot \varepsilon_{amp} \cdot d^{\alpha} \tag{4.11}$$

here, $\varepsilon_{amp} = \varepsilon_{fs}$ when $\alpha = 2$ and $\varepsilon_{amp} = \varepsilon_{mp}$ when $\alpha = 4$. Thus, if we equally divide the distance d into n pieces, the total energy consumption for n-hop transmission with individual distance $r_i = d / n$ will be:

$$E_{mh} = l \cdot n \cdot \varepsilon_{amp} \cdot (d / n)^{\alpha} = l \cdot \varepsilon_{amp} \cdot \frac{d^{\alpha}}{n^{\alpha - 1}} \tag{4.12}$$

It can be observed that the larger n is, more energy can be reduced by changing the transmission manner from direct transmission to multi-hop transmission. However, the part of energy consumption by hardware circuit (radio transceiver) can not be neglected. With short distance d, the part of energy consumption by hardware circuit $l \cdot E_{elec}$ is comparable to that consumed by communication process $l \cdot \varepsilon_{amp} \cdot d^{\alpha}$. Thus, the energy consumption with too many short hops could be even larger than that with direct transmission, which can also be seen from the following Eq. (4.13).

To transmit a one bit message over n-hop route will consume a total $E(n)$ amount of energy as follows:

$$E(n) = (E_{elec} + \varepsilon_{amp} \cdot r_1^{\alpha}) + \sum_{i=2}^{n-1} \varepsilon_{amp} \cdot r_i^{\alpha} + 2 \cdot (n-1) \cdot E_{elec} = (2n-1) \cdot E_{elec} + \sum_{i=1}^{n} \varepsilon_{amp} \cdot r_i^{\alpha}. \quad (4.13)$$

here, $\sum_{i=1}^{n} r_i = d$. Our objective is to find the minimal value of $E(n)$ with optimal hop number n as well as corresponding r_i under constraint conditions like $\sum_{i=1}^{n} r_i = d$ and hardware parameters listed in Table 3.

4.2.2 Determination of transmission manner

First, we will deduce the critical distance threshold d_c above which sensor node will use multi-hop transmission. Or else, it will use direct transmission.

When the source to sink node distance $d < d_0$, it is easy to prove that $E(n)$ in Eq. (4.13) is a monotonously increasing function under parameters in Table 3. So, single hop transmission ($n = 1$) is always more energy efficient than multi-hop transmission ($n \geq 2$).

When the distance $d \in (d_0, 2d_0)$, we can either use direct transmission or 2-hop transmission manner. Let:

$$f(d) = E_{Direct} - E_{Multi-hop}(2) \geq 0$$

so:

$$f(d) = (E_{elec} + \varepsilon_{mp} \cdot d^4) - (3E_{elec} + \varepsilon_{fs} \cdot d^2 / 2)$$
$$= \varepsilon_{mp} \cdot d^4 - \varepsilon_{fs} \cdot d^2 / 2 - 2E_{elec} \geq 0. \quad (4.14)$$

Eq. (4.14) will always hold true when:

$$d \geq d_c = \sqrt{\frac{\varepsilon_{fs}/2 + \sqrt{\varepsilon_{fs}^2/4 + 8\varepsilon_{mp} \cdot E_{elec}}}{2 \cdot \varepsilon_{mp}}}, \quad (4.15)$$

and the critical distance $d_c \approx 104$ here.

Thus, if the distance $d_0 < d \leq d_c$, we will still choose direct transmission with multi-path model. If $d > d_c$, we will choose multi-hop transmission. Table 5 lists the determination of transmission manner under different source to sink node distance d.

Table 5 Determination of transmission manner

d	Direct Transmission	Multi-hop Transmission
$d < d_0$	√	
$d_0 \leq d \leq d_c$	√	
$d_c < d$		√

4.2.3 Determination of the optimal hop number

For a given source to sink node distance d ($d = \sum_{i=1}^{n} r_i$), the latter pat in Eq. (4.13) $\sum_{i=1}^{n} r_i^{\alpha}$ has a minimal value when $r_1 = r_2 = \ldots = r_n = d/n$. Finally, the total energy consumption $E(n)$ is equal to:

$$E(n) = (2n-1) \cdot E_{elec} + \varepsilon_{amp} \cdot n \cdot (d/n)^{\alpha}, \quad (4.16)$$

Eq. (4.16) has the minimum when $E^{'}(n) = 0$ or:

$$2E_{elec} + \varepsilon_{amp} \cdot (1-\alpha) \cdot (d/n)^{\alpha} = 0,$$

Finally, we can get the optimal theoretical hop number as:

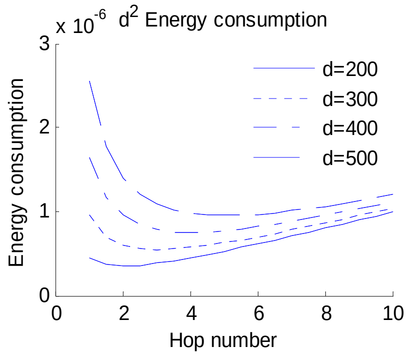
$$n^*_{opt} = d \cdot (\varepsilon_{amp} \cdot (\alpha - 1) / 2E_{elec})^{1/\alpha}. \tag{4.17}$$

and the corresponding optimal individual distance as:

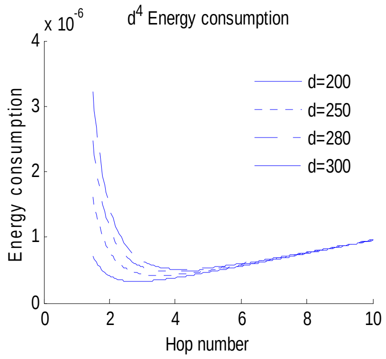
$$r^*_i = d / n^*_{opt} = (2E_{elec} /(\alpha - 1) \cdot \varepsilon_{amp})^{1/\alpha}. \tag{4.18}$$

Therefore, given the source to sink node distance d as well as the hardware parameter values in Table 3, we can get the minimal total energy consumption $E(n^*_{opt})$ from Eq. (4.16). Taking free space model (d^2) as an example, the minimal total energy consumption along the one dimensional multi-hop route can be achieved when $n^*_{opt} = \sqrt{\varepsilon_{fs} / 2 \cdot E_{elec}} \cdot d$ and the corresponding optimal intermediate distance is $r_i = d / n^*_{opt} = \sqrt{2 \cdot E_{elec} / \varepsilon_{fs}} = 100$ based on the values in Table 3. Similarly, we can get $n = n^*_{opt} = (3 \cdot \varepsilon_{mp} / 2 \cdot E_{elec})^{1/4} \cdot d$ for multi-path model (d^4) with each individual distance $r_i = d / n^*_{opt} = (2 \cdot E_{elec} / 3 \cdot \varepsilon_{mp})^{1/4} \approx 71$. Here, we find that the optimal individual distance r_i is only related with the hardware parameters and it is not related with d. In other words, each node can make local decision to choose its optimal next hop neighbor without knowing the distance between itself and sink node.

Fig. 15 shows the energy consumption under both free space and multi-path energy models. Given the source to sink node distance d and the hardware parameters in Table 3, we can equally divide d into n pieces with n nodes placed along d. We can see that there exits an optimal hop number with minimal energy consumption in Fig. 15, which is consistent with Eq. (4.16).



(a) free space model



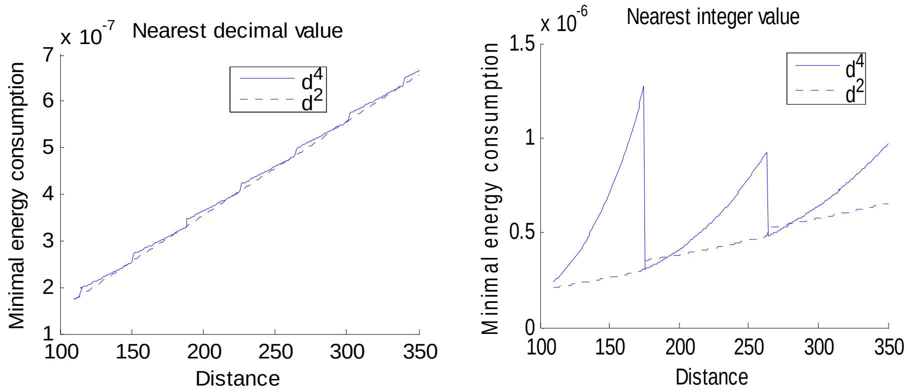
(b) multi-path model

Fig. 15. Energy consumption under two models

From Fig. 15 (a) we can see that the larger d is, the larger optimal hop number will be since the corresponding optimal intermediate distance is kept as a constant (as we mentioned in the previous paragraph). Also, the larger d is, more energy will be consumed on average with the same hop number since the average individual distance is larger. However, it can also be seen that more energy can be saved through multi-hop transmission rather than through direct transmission as d increases. Fig. 15 (b) shows the case under multi-path model. Similarly, the larger d is, the larger corresponding optimal hop number will be and the intermediate distance r_i is kept as a constant.

However, n_{opt}^* can not be obtained in Eq. (4.17) if we further consider the constraint condition $r_i < d_0$ when $\alpha = 2$, since $r_i = 100 > d_0 \approx 87.7$. It is the same when $\alpha = 4$ under constraint condition $r_i \geq d_0$. Thus, we will choose the nearest integer of n_{opt}^* in Eq. (4.17) which satisfies $r_i < d_0$ or $r_i \geq d_0$. We call it sub-optimal hop number n_{opt} in this thesis. With different hardware parameters and distance d, the optimal hop number and the corresponding r_i will be different. The values of these hardware parameters are determined by factors like electronic circuit, antenna height, receiver sensitivity etc. [33].

Fig. 16 shows the minimal energy consumption $E(n)$ under free space model and multi-path model with different source to sink node distance d by considering the constraint condition $r_i < d_0$ or $r_i \geq d_0$. In Fig. 16 (a), the optimal hop number is not an integer value but the nearest decimal value which satisfies constraint condition. In Fig. 16 (b), the optimal number is chosen as the nearest integer (we call it the sub-optimal hop number n_{opt} in this thesis) which can be applied to practical sensor network situation.



(a) nearest decimal value (b) nearest integer value

Fig. 16. Energy consumption under constraint conditions

From Fig. 16, we find that in most of the time, free space model consumes less energy than multi-path model. Especially, for the practical sensor network case when the hop number is an integer value (Fig. 16 (b)), free space model is usually much more energy efficient than multi-path model. For example, when $d = 160$, 2-hop free space transmission is more energy efficient than direct multi-path transmission. And when $d = 240$, 3-hop free space transmission with $r_i = 80$ is more energy than 2-hop multi-path transmission with $r_i = 120$. It is worth noting that the energy consumption for multi-path model will reduce sharply around distance $d \geq N \cdot d_0$ (N is an integer here). That is because the individual distance is further divided into smaller multi-path distances with r_i larger and close to d_0, so the overall energy consumption is reduced. However, it is very hard (if not impossible) to find such intermediate nodes with r_i larger and close to d_0 under practical sensor network. Therefore, free space model is more practical to implement and the energy difference is almost neglectable.

Table 6 and Table 7 provide several intuitive illustrations about the energy consumption under different hop number which is depicted in Fig. 16 (b). Table 6 shows the cases when free space model is more energy efficient than multi-path model, which happens most of the time. Taking $d = 240$ as an example, when the source node has 2000-bit message to transmit over distance d, it can choose either direct transmission or 2-hop multi-path transmission with $E(1)$ and $E(2)$ equal to $43.6 \times 10^{-7} J$ and $6.9 \times 10^{-7} J$ respectively. It can also choose 3-hop or 4-hop free space model with $E(3)$ and $E(4)$ equal to $4.4 \times 10^{-7} J$ and $4.9 \times 10^{-7} J$ respectively. It is obvious that free space model is much more energy efficient than multi-path model. Another example is also given when $d = 300$. We can also see the difference of energy consumption under different hop number between free space and multi-path model clearly.

Table 6 Energy consumption under different hop number (a)

d_i (m)	240*1	120*2	80*3	60*4	40*6
$E(10^{-7} J)$	43.6	6.9	4.4	4.9	6.5
d_i (m)	300*1	150*2	100*3	75*4	60*5
$E(10^{-7} J)$	105.8	14.6	6.4	5.8	6.3

Table 7 shows the cases when multi-path model is more energy efficient than free space model which happens occasionally around distance $d \ge N \cdot d_0$ (N is an integer), as we mentioned and explained before. Taking $d = 180$ in Table 7 as an example, the 2-hop multi-path transmission with $r_i = 90$ is more energy efficient than 3-hop free space transmission with $r_i = 60$ at the same packet length of 2000-bit. Also, when $d = 270$, 3-hop multi-path transmission is more energy efficient than 4-hop free space transmission. This is because the individual distance $r_i = 90$ under multi-path model ensures a near optimal energy consumption performance. Also, we find that the difference of energy consumption under these two models is very small and even neglectable. Considering the practical sensor network where sensor nodes are randomly deployed, it is easier to find $n+1$ multi-hop route under free space model than to find n-hop route under multi-path model.

Table 7 Energy consumption under different hop number (b)

d_i (m)	180*1	90*2	60*3	45*4	30*6
$E(10^{-7} J)$	14.1	3.2	3.6	4.3	6.0
d_i (m)	270*1	135*2	90*3	68*4	54*5
$E(10^{-7} J)$	69.6	10.1	5.1	5.3	6.0

In summary, we can either use n_1-hop free space model with each intermediate distance r_1 or use n_2-hop multi-path model with each intermediate distance r_2 for the same d,. Here, $r_1 < d_0 < r_2$ and $n_1 \cdot r_1 = n_2 \cdot r_2 = d$. Based on the analysis in Fig. 16, we will always choose n_2-hop free space model in this thesis since free space model is more energy efficient in most cases. Even though it consumes a little more energy than multi-path model when $d \approx N \cdot d_0$, the difference is neglectable. Besides, it is hard to find such n_1 intermediate nodes under practical sensor network.

4.2.4 Determination of the sub-optimal hop number

We can not use the theoretical optimal hop number and the corresponding intermediate distance directly for three reasons. First, we have to consider the constraint conditions like $r_i < d_0$ or $r_i \geq d_0$. Secondly, the optimal hop number should be an integer value rather than a decimal value under practical sensor network environment. Third, it is very hard (if not impossible) to find such n^*_{opt} optimal intermediate nodes which equally divide the source to sink line under practical sensor network. Thus, we have to find the sub-optimal hop number n_{opt} as well as corresponding intermediate nodes under real sensor network.

In this section, we will try to provide a practical selection criterion of the sub-optimal hop number and intermediate distance based on our experimental simulations and analysis.

Table 8 gives the empirical selection criterion of the sub-optimal hop number based on our extensive experiments. It is worth mentioning that this is not the optimal solution since no global information about network topology is used and it is only based on local information like relative distance to its neighbors.

Table 8 Selection criterion of the sub-optimal hop number

d	r_i	Hop Number
$(0, d_c)$	$r_1 < d_c$	1
$[d_c, 2d_0)$	$r_1, r_2 < d_0$	2
$\vdots$	$\vdots$	$\vdots$
$[(n-1)d_0, nd_0)$	$r_1, \cdots, r_n < d_0$	n

Given the source to sink node distance d as well as the hardware parameter values, we can first determine the transmission manner as is provided in Table 5. If multi-hop transmission is used, we will always choose free space model based on the analysis and comparison with multi-path model above. In order to meet the constraint condition $r_i \le d_0$, we will try to find n-hop route instead of ($n-1$)-hop route for the distance $(n-1)d_0 \le d < nd_0$ which is listed in the last row of Table 8. This is because the source node can not easily find such $n-1$ intermediate nodes with $r_i \approx d_0$ under real sensor network, especially under sparse sensor network. Taking $d = 270$ and $d_0 = 90$ as an example, it is not easy to find 3-hop route with each $r_i \approx 90$. Instead, we can easily find some 4-hop route with $r_i \approx 70$ which consumes a little more energy than 3-hop case. The energy difference is almost neglectable, as can be seen from Table 7. Thus, for distance $(n-1)d_0 \le d < nd_0$, we will determine the integer value of the sub-optimal hop number as $n_{opt} \in (d/d_0, d/d_0 + 1]$ which is deduced from the last row in Table 8.

For the selection of intermediate nodes or distances, it is based on the following three criteria. First, each of the intermediate distance should be larger or equal to d/n_{opt} under real sensor network. Second, the intermediate should be as close to the direct line connecting source and sink node as possible. In this way, the resulting average hop number might not increase. Finally, a node should choose its next hop node which is closer to sink node than itself. In other words, progress should be made toward sink node under each hop. If there is no such neighboring node under sparse network, it will simply choose its neighbor which is closest to sink node as its next hot node.

In the future, we can consider the residual energy of the intermediate nodes during the selection of next hop node. We will avoid using those nodes with little remaining energy to forward the message and they only use their energy when they have their own data to transmit.

4.3 HEAR Algorithm

HEAR algorithm is a distributed and localized algorithm for practical sensor network, which combines the general routing mechanism with hop-based nature during routing process in WSNs. It does not need the whole network knowledge such as the location of all sensor nodes. It only needs the relative distance to its neighbors and to the sink node. Each sensor node has two tables. One is the routing table which contains information like source node, previous node, next node, destination node and TTL (time to live) etc. in the header of each packet. Another table is called neighboring table which contains relevant information about its neighbors like distance between them, distance to sink node, residual energy etc. Thus, each node can make intelligent decision of the next hop node locally based on our HEAR algorithm and the algorithm is easy to implement for practical engineering applications.

Our HEAR algorithm consists of two phases which are route setup phase and route maintenance phase. Similar to the wok in [41] which tries to build a chain to transmit fused data to the sink node, here we focus on building a multi-hop route with n_{opt} intermediate nodes and individual distances $r_i \approx d / n_{opt}$ under practical sensor network from hop number point of view. Once there is a link failure, we will either initiate a local link repair process or restart a new route setup phase during route maintenance phase.

The key strength of HEAR algorithm is that given the hardware parameters as well as the distance from source to the sink node d, we can determine an energy efficient multi-hop route from hop number point of view. By carefully selecting the n_{opt}-hop route with n_{opt} intermediate nodes along the route, we can largely reduce the energy consumption as well as prolong the network lifetime. In the mean time, the hot spot phenomena can also get alleviated according to the nature of hop-based routing mechanism.

4.3.1 Basic assumptions

We make the following basic assumptions in this thesis:

1) All sensor nodes are stationary and homogenous;

2) All sensor nodes can adjust their power levels based on distance;

3) All sensor nodes know the distance to their neighbors and to sink node;

4) The communication links are symmetric;

5) There is no confliction with underlying MAC layer protocols;

6) There is no big obstacle between source and sink node.

Here, we do not consider mobile sensors or sink nodes and we suppose that all sensor nodes have the same capability in term of processing, communication and power supply etc. It is practical for each sensor to adjust its power level, which has been proved by the successful application of MICA2 [14]. Beside, the Berkeley Motes have in total 100 power levels [18]. The relative distance information can be obtained either through certain positioning or localization algorithms like triangulation algorithm [114] based on received signal strength or through GPS devices installed on several specific sensor nodes (not all the sensor nodes are needed to install GPS devices). Since the sensor nodes are static, there is no need to update the location or relative distance information. Thus, the overhead of obtaining and maintenance relative distance is almost neglectable. We assume symmetric link so that backward routing is not necessary during HEAR routing process. The general support from MAC layer is assumed to be available to ensure the quality of communication link. Finally, we assume there is no big obstacle. Or else, our HEAR algorithm can not find suitable next hop node which might be behind obstacle.

4.3.2 Route setup phase

Let us consider a sensor network with N stationary nodes randomly deployed in the monitoring area A. Once a source node has data to report to sink node, it will try to set up a route from source to sink node as follows.

First, the source node will determine whether to use direct transmission or multi-hop transmission based on the determination criterion in Table 5. If the distance $d \le d_c + \Delta$, it will choose direct transmission which is more energy efficient. If $d > d_c + \Delta$, it will choose multi-hop transmission. It is worth noting that d_c is a theoretical value of the threshold distance and sometimes direct transmission is also more energy efficient than multi-hop transmission even when $d_c < d \le d_c + \Delta$ under practical network environment. For example, when $d = 120$, it is very hard to find a 2-hop route with $r_1 = r_2 = 60$. Thus, direct transmission is better than 2-hop transmission with $r_1 = 65, r_2 = 71$ under practical sensor network. The value of Δ is dependant on network density as well as hardware parameter in Table 3. We set $\Delta \in [20,40]$ in this thesis.

If $d > d_c + \Delta$, source node will then determine the sub-optimal hop number n_{opt} and corresponding intermediate nodes. Here, we say sub-optimal because our algorithm is a localized algorithm and each node does not know the whole network topology information. Also, the theoretical optimal hop number n_{opt}^* can not be used directly since we have to consider the constraint conditions, the integer value of hop number and the practical random sensor network topology. Therefore, we can only get the sub-optimal hop number. Taking $d = 180$ as an example, we first get $n_{opt} \in (180/87.7, 180/87.7+1]$ from Table 8. So, the final sub-optimal hop number is chosen as $n_{opt} = 3$. Although 2-hop transmission with $r_1 = r_2 = 90$ is a little more energy efficient than 3-hop transmission with $r_1 = r_2 = r_3 = 60$ (see Table 7), it is impossible to find such intermediate nodes with $r_1 = r_2 = 90$ under real sensor network. Instead, we prefer to choose 3 intermediate nodes with $r_1 = 60, r_2 = 65, r_3 = 70$ which are easy to find. That is why we provide selection criterion of the sub-optimal hop number in Table 8. From the simulation part, we can see that our empirical selection criterion of sub-optimal hop number is very simple and effective.

After determination of the sub-optimal hop number n_{opt}, the source node will choose a set of its neighbors with distance $d_i \in [d / n_{opt}, d / n_{opt} + \Delta]$ as candidates of its next hop. Finally, the neighbor node which is closest to the sink node will be chosen as the next hop.

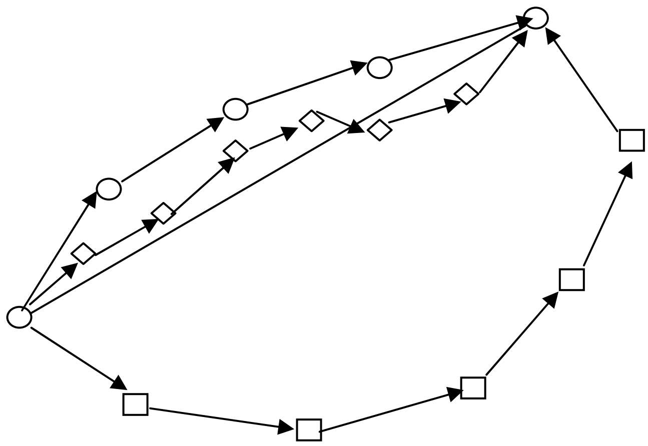


Fig. 17. Illustration of the next hop node selection criteria

Fig. 17 shows an illustration of next hop node selection criteria in HEAR. Once source has data to send, it will choose its next hop node based on different routing criteria. The next hop selection criterion of HEAR is the topside one with circles, where the hop number is 4 with proper intermediate distances. Here we can see that our selection criteria of next hop are twofold. First, the distance to next hop should be equal or larger than d / n_{opt}. Or else, it might cause an increased multi-hop number with more energy consumption during routing process. As we can see from the middle multi-hop route with diamonds in Fig. 17, the hop number is 6 if the individual distance is less than d / n_{opt}.

Thus, more energy is caused therein. Second, we next hop should be the closest one to sink node. In other word, progress should be made toward sink node during each hop routing. Or else, the next node with $d_i \in [d / n_{opt}, d / n_{opt} + \Delta]$ could be far away from the direct line from source to sink node. Consequently, an increased hop number and more energy consumption can also be caused. The bottommost multi-hop route shows this case in Fig. 17. It is worth emphasizing that if there is no such neighboring node with $d_i \in [d / n_{opt}, d / n_{opt} + \Delta]$ under very low density network, we will simply choose all its neighbors as candidates and finally choose the one closest to sink node as next hop. In such case, successful packet delivery or packet reachability between source and sink node has higher priority than energy efficiency.

Table 9 Node 1's neighboring table

ID	Dist. to BS	Dist. between them	Next hop candidate	……..
2	170	30	N	
3	200	70	Y	
4	150	65	Y	
5	145	71	Y	
6	130	83	Y	
7	90	120	N	

Table 9 is the neighboring table inside node 1 which gives an example of the selection criteria of next hop node. Since the distance between node 1 and BS is 180, the final sub-optimal hop number is 3 based on Table 8. If we set $\Delta = 30$, the neighboring nodes with relative distance $d_i \in [60, 60 + 30]$ are chosen as candidates of the next hop nodes of node 1. At last, node 1 will choose node 6 as l next hop since node 6 is closest to BS..

When the next hop node is chosen, the source node will send a short RREQ (Route Request) message to the next hop directly through unicast. Once the neighbor node receives this RREQ message, it will send an ACK (acknowledge) message to its previous (source) node. Then, it will add its own location information into the RREQ message and send it to its next hop neighbor in an iterative manner like its previous node. Finally, the RREQ message will reach sink node with complete route information inside the RREQ message and a RREP (Route Reply) message will be sent back in a reverse way by sink node to the source node based on the assumption of symmetric link.

The traffic can get started once the source node gets RREP message with complete route information. After the traffic session is closed, each node on the route will update its routing table and neighboring table. For example, if there are some nodes dying out of energy, their relevant neighboring nodes will delete them from their neighboring table. Or if there is some new nodes joining the network (like mobile nodes), the relevant neighboring table and routing table should get updated in time.

During routing process, each of the packets to be sent has the following message structure, as is illustrated in Table 10. Here, "Type" designates the property of message which is either control message or data message. If it is control message, the packet length is short and small amount of energy is needed. If it is data message with long data length, more energy is necessary and the data information is attached in the latter part of message structure. The "Dest_Addr." can be neglected if there is only one sink node. If there are several sink nodes, it is necessary to specify to which sink node (i.e. destination) message is sent.

Table 10 Message structure

Type	Source_ Addr.	Previous_ Add.	Next_ Addr.	Dest._ Addr.	TTL	Data_ length	⋯ …

The whole route setup phase can be summarized as the following 4 steps:

Step 1: The source node will first determine whether to use direct transmission or multi-hop transmission as well as the hop number based on Table 5;

Step 2: If the source node uses direct transmission, the data will be sent directly from source to the sink node. If multi-hop transmission is used, it will determine its next hop from hop-based aspect as follows:

Step 2.1: It will first choose a series of its neighbors with distance $d_i \in [d / n_{opt}, d / n_{opt} + \Delta]$ which are also nearer to sink node than itself as the next hop candidates. If there is no such neighbor under sparse network, it will treat all its neighbors as its next hop candidates;

Step 2.2: It will finally choose the one closest to sink node as the next hop;

Step 2.3: It will then send a RREQ message directly to the final next hop node containing its location;

Step 3: Once the next hop neighbor receives the RREQ, it will send an ACK message to the previous node and then determine its next hop in an iterative manner above. Afterwards, the RREQ message will be sent with its own location information inside;

Step 4: Finally, the RREQ message will reach the sink node and a RREP message is sent back by sink node to the source node. If there is link failure, a RERR message will be sent to the source node and the route maintenance phase will be initiated.

It is worth mentioning that we can also consider factor like remaining energy during hop-based routing process. For example, we can choose the candidate with maximum residual energy as next hop in Step 2.2. In that case, the network lifetime can get further prolonged and the possibility of link failure can also get reduced. We treat this as one of the future works since our primary concern is hop number in this thesis.

From the four steps in route setup phase above, we can see that most of the computational work is done inside each sensor node due to the fact that energy consumption during processing process is much smaller than that during communication process. The decision of the next hop is made locally without global knowledge about the whole network. Thus, our HEAR algorithm is a distributed and localized routing algorithm.

4.3.3 Route Maintenance Phase

If a node does not receive an ACK message from its next hop neighbor within certain TTL (time-to-live) time, a link failure will be detected and the route maintenance phase will be initiated. A link might fail due to reasons like node energy drainage, physical damage, interference, attack or node mobility etc.

If the source node detects a link failure to its next hop, it will first delete that node from its routing and neighboring table and then restart the route setup phase by choosing another appropriate next hop neighbor. If an intermediate node detects a link failure, it will first attempt a local link repair process. Namely, it will choose another proper neighbor from its neighboring table in a similar way like Step 2. This local repair process will last for certain time until either an ACK message is received or time is expired.

If no ACK message is received by intermediate node, a RERR (route error) message will be sent from the intermediate node to source node in a backward way based on the route information stored in the RREQ message. Finally, this broken link will be deleted from source and relevant intermediate nodes and both the routing table and neighboring table will be updated. Finally, a new route setup phase will be initiated by source node. With the help of local repair, end to end latency and communication overhead can get reduced.

It is worth mentioning that the possibility of link breakage is usually very low since we do not consider node mobility, interference, physical damage or confliction with MAC layer protocols in this thesis.

4.3.4 Routing workflow

Fig. 18 illustrates the workflow of our HEAR algorithm which consists of two phases. On the left side with light orange box is the route setup phase and on the right side is the route maintenance phase.

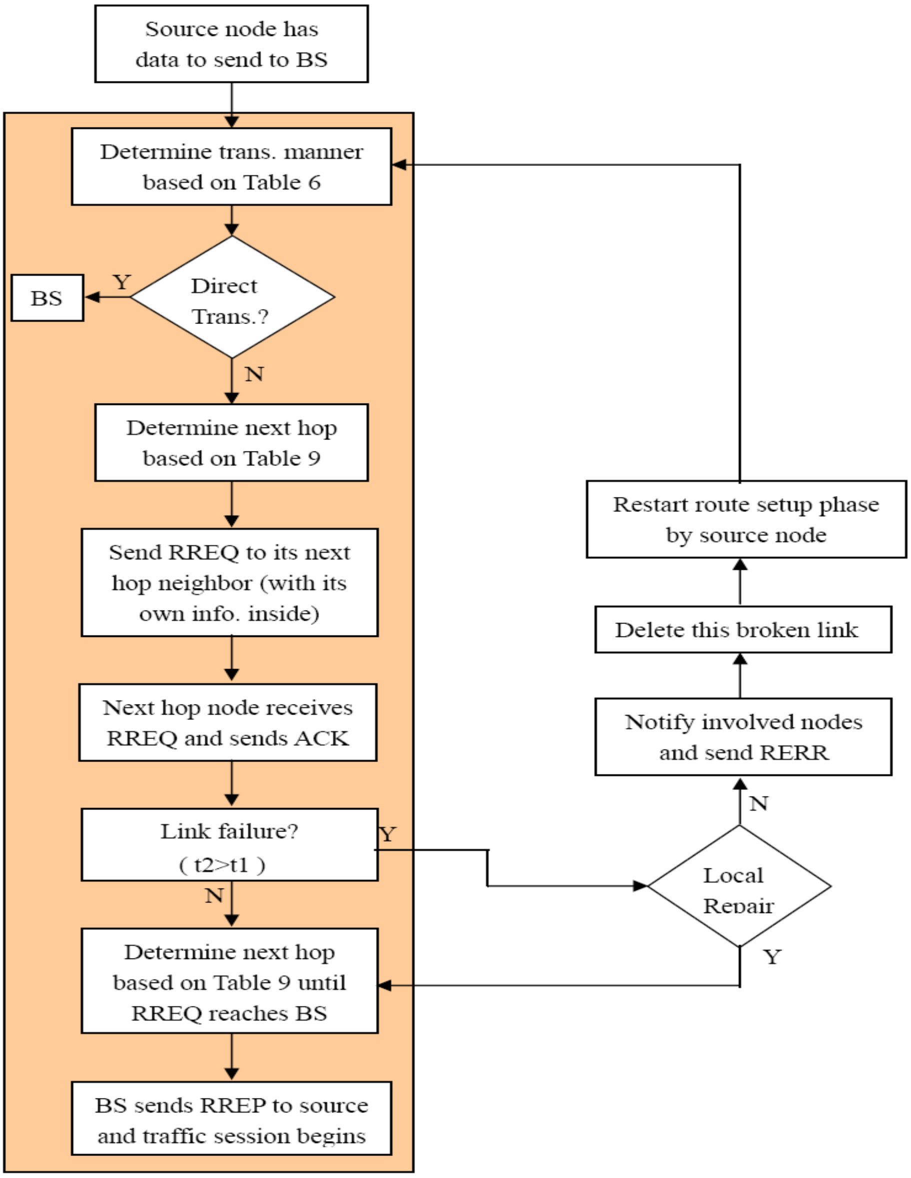


Fig. 18. HEAR algorithm workflow

From Fig. 18 we can see the routing workflow of our HEAR algorithm very clearly. Once the source node has data to transmit to a remote base station (BS) or sink node, it will first determine the transmission manner (direct or multi-hop transmission) based on Table 5. If the distance $d < d_c$, it will decide to transmit its data directly to BS. Or else, it will use multi-hop transmission. The selection of next hop node is based on the criterion in Table 8. Next, a RREQ message is sent to that specific net hop neighbor with its own location information inside RREQ. Once the next hop node receives the RREQ message, it will send back an ACK message to confirm the reception of RREQ message. Afterwards, the next hop node will continue to find its own next hop neighbor in an iterative way until the RREQ message finally reaches BS. At last, a RREP message is sent back by BS to the source node along the reverse route. The traffic session will start by source node afterward.

If the ACK message is not received within certain time, a link failure is detected. Then a local repair process will first be initiated. If the node can find an alternative next hop node, it will determine its next hop in a similar way like Step 2 in section 4.3.2 above. Or else, it will notify all the involved nodes about the failure of this link. So, this broken link will be deleted by all involved nodes from their routing table and neighboring table. Later on, they will avoid using this link again. Finally, the source node will restart the route setup phase with an increased end to end delay and more energy consumption.

It is worth noting that we mainly focus on studying the relationship between energy consumption and hop number in this thesis. We try to provide energy efficient routing algorithms rather than a routing protocol. So, we will not consider more factors like the format of different ACK, RREQ, RREP and RERR messages, the definition of different time unit, the detail information of data format inside the routing table and neighboring table in this thesis.

4.3.5 Algorithmic process

The algorithmic process of HEAR is consisted of three processes which are initialization process, main process and finalization process. In the following, we will introduce each of them in detail.

Fig. 19 shows the initialization process where relevant models in section 4.1 are initialized. The definition of each parameter can be found in section 4.1. Beside, we need to initialize the relative distance between each neighbors (Distance (i, j)) as well as each individual distance to the BS (DistToBS(i)).

I. Initialization process

1. Network model: [X, Y], N, R, BS, Δ

2. Energy model: E_{ini}, k, d_c

3. Propagation model: E_{elec}, E_{amp}

4. Traffic model: sequenced [1..N] or randomized [1..N]

5. Distance (i, j)

6. DistToBS (i)

Fig. 19. Initialization process of HEAR algorithm

Fig. 20 shows the main process of HEAR algorithm under time-driven traffic model. Here, each sensor node i will take turn to send its data to BS through direct or multi-hop transmission. Fig. 20 includes three important functions, namely the determination of transmission, optimal hop number as well as the final next hop, which is corresponding to line 2, 7 and 8. It is easy to determine the transmission manner by comparing the critical distance d_c with the relative distance to BS. The deduction of optimal hop number is based on the analysis of energy model and propagation model, which is explained in section 4.2.3 and 4.2.4. Finally, the selection of the final next hop is given in section 4.3.2 (Fig. 17). Until now, we have obtained the single hop or multi-hop route for each of the sensor node. Then, we can calculate the corresponding distance (Dist(n)) for each route as well as the hop number (HopNum(n)). Finally, we can calculate the energy consumption (*Econ(n)*) for each node during the routing process. Given the initial energy E_{ini}, we can easily get the remaining energy in line 13.

It is worth noting that the main process is similar for event-driven traffic model. Rather than using a sequenced [1..N] in previous Fig. 19, we can generate a randomized sequence [1..N] during the initialization process.

```
II.  Main process
Repeat
  1.  n=1; i=n; Route(n)=[empty]
  2.  While (DistToBS(n) < d_c )
  3.      DirectTrans.(i)
  4.      Route(n)=[i]
  5.  Else
  6.      Route(n)=[Route(n), i]
  7.      OptimalHopNum(i)
  8.      j=OptimalNextHop(i)
  9.      i=j
  10. Dist(n)
  11. HopNum(n)
  12. Econ(n)
  13. Erem(n)=Eini(n)-Econ(n)
  14. n=n+1
  Until  n=N
```

Fig. 20. Main process of HEAR algorithm

During the finalization process in Fig. 21, we will repeat the main process above until one of the nodes die out of battery. The network lifetime is viewed as the time when the first node dies out of energy. Finally, we can calculate the network lifetime as well as draw some plots about the distribution of energy consumption. We can also easily get the distribution of remaining energy so as to study the hot spot phenomenon.

III. Finalization process

```
NetLifetime=0
While Min(Erem(1..N))>0
    Main process
    NetLifetime=NetLifetime+1
End
Plot(1..N, Econ(1..N))
Plot(1..N, Erem(1..N))
Plot(NetLifetime)
```

Fig. 21. Finalization process of HEAR algorithm

In this chapter, we propose a Hop-based Energy Aware Routing (HEAR) algorithm for WSNs, which is the focus of this thesis. We first determine the transmission manner as well as the theoretical optimal hop number under one dimensional linear network. Then, we extend the result and propose an empirical selection criterion of the sub-optimal hop number under practical sensor network. Based on our extensive simulation and analysis, we find that energy consumption during routing process can be reduced from hop-based point of view and we propose our HEAR algorithm with detail explanation and workflow.

We can see that our HEAR algorithm has the following features:

- Suitable to random and dynamic network
- Distributed and localized
- Hop-based
- Energy efficient and energy balancing
- Simple to be implemented

Chapter 5 Performance Evaluation

In this chapter, we provide extensive simulation results and comparisons of the performance between our HEAR algorithm and five other popular routing algorithms like direct transmission, greedy, maximal remaining energy as well as LEACH and HEED algorithms in WSNs.

Simulations are done under various network environments with different factors such as node number, transmission radius, BS location, network scale, traffic pattern as well as network structure (flat and hierarchical). We mainly study the performance of energy consumption, hop number, network lifetime, packet reachability as well as hot spot phenomenon in this chapter.

5.1 Simulation environment

For performance analysis and comparison, we use MATLAB simulator [110]. As is shown in Table 11 and Fig. 22, there are 80 to 500 sensor nodes randomly deployed in a WSN area ranging from $200 \times 200\, m^2$ to $800 \times 800\, m^2$. The sink node (or BS) is placed either inside or outside the WSN area. The transmission radius can be adjusted from 80 to 300 meters depending on the density of network as well as the location of sink node.

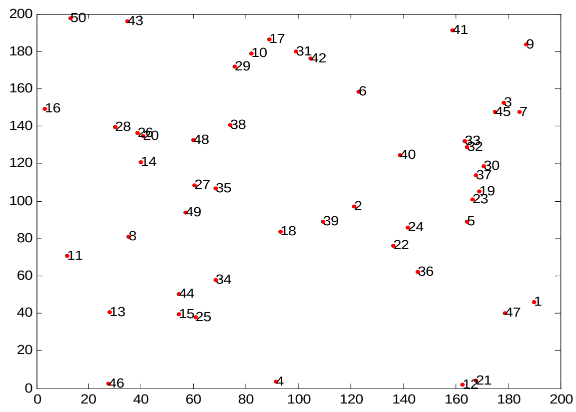


Fig. 22. Sensor network simulation environment

Table 11 Simulation environment

Parameter	**Value**
Network size	$[100\times 100, 800\times 800]\, m^2$
Node number	[80, 500]
Trans. radius	$[80, 300]\, m$
Sink node location	Inside or outside
Data length	2000 bits
Initial energy	2 J
E_{elec}	50 nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^4
d_0	$\sqrt{\varepsilon_{fs}/\varepsilon_{mp}} \approx 87.7m$

We will first study the performance under time-based traffic model in HEAR algorithm. In each round, sensor node will take turn to transmit a 2000 bits message to the sink node using either direct transmission or multi-hop transmission based on different routing algorithms. In multi-hop transmission case, the intermediate nodes will also consume additional energy to forward the message. After that, we will use event-based traffic model where each sensor node is randomly chosen to send its data to sink node, which is more similar to practical sensor network.

5.2 Algorithms to compare

We compare our HEAR algorithm with the following five popular routing algorithms in WSNs. The first three routing algorithms are used in flat structure network while the last two algorithms are used in hierarchical structure network.

A) **Direct transmission algorithm**: Each node will transmit its data directly to the sink node supposing that its transmission radius is large enough. This transmission manner is suitable for small scale network where the average source to sink node distance is relatively small. For example, the authors in LEACH [32, 33] and PEGASIS [41] mainly use direct transmission under their small scale network.

B) **Greedy algorithm:** Each node will choose one of its neighbors as the next hop which is closest to the sink node. The essence of this algorithm is to make the best progress (greedy) toward the sink node during each hop [47]. Usually, the average hop number is small while the average individual distance is long which causes more and unbalanced energy consumption. It can have a good energy consumption performance if the transmission radius is properly chosen.

C) **Maximal remaining energy (MRE) algorithm**: Each node will choose one of its neighbors with maximal remaining energy as the next hop node [59]. In some of its variant algorithms, the factor of distance is considered. For example, each node will also try to make progress toward sink node during MRE routing process. In this thesis, we simulation MRE algorithm by considering both the factor of residual energy and distance.

D) **LEACH algorithm**: It consists of route set-up phase and route steady-state phase. During set-up phase, the cluster will be formed with 5% cluster head nodes as well as other ordinary members. The cluster heads are randomly chosen in turn by comparing its random number with a threshold value [32, 33]. During route steady-state phase, each cluster head will transmit its fused data directly to the remote sink node outside.

E) **HEED algorithm**: It periodically selects cluster head based on a hybrid of node residual energy and a secondary parameter such as node proximity to its neighbors or node degree [48]. Node with more residual energy will have a higher probability to be chosen as cluster head. It does not need global knowledge and the message overhead is low therein.

5.3 Simulation results

5.3.1 Energy consumption

In this section, we will study the performance of average energy consumption under different transmission radius R, different source to BS distance d, different node number N, different BS location, different network scale as well as different traffic pattern.

a) Under different transmission radius

We first study the influence of transmission radius R on energy consumption since different routing algorithms will choose the next hop node based on their next hop selection criteria. Thus, the performance of energy consumption changes a lot under different transmission radius.

The simulation environment is that there are 300 nodes randomly deployed in a $300 \times 300\,m^2$ area with BS placed in the middle of the area. The data length is 2000 bits and each node takes turn to send its data to BS based on different routing algorithms. We set $d_c = 120$ and $\Delta = 20$ in HEAR algorithm.

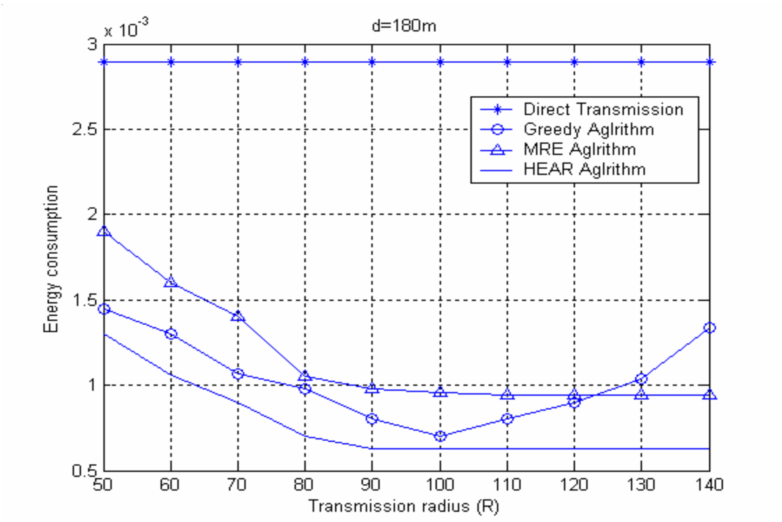


Fig. 23. Energy consumption under different R

We first choose one communication link with specific $d = 180m$ to study the total energy consumed along the link under different routing algorithms. From Figure 23 we can see that direct transmission always consumes the largest amount of energy since it utilizes the multi-path energy model with average long distance. There is no variation in energy consumption value since the hop number as well as distance is fixed in direct transmission algorithm.

For the max-remaining energy algorithm, the node chooses its next hop based on the remaining energy which is irrelevant to distance distribution. As the transmission radius increases, there will be more candidates with larger residual energy. Thus, there is a trend that the energy will decreases as R increases. When R is large enough (like $R > 120$), there is no variation since each node can find its neighbor with largest residual energy. Thus, the energy consumption does not change as R keeps on increasing.

For the greedy routing algorithm, we can see that the hop number is large when R is small, which causes more energy consumption. As R increases, it will prefer to choose the next hop with distance $r_i \approx R$ to get close to the BS (greedy). Thus, the energy consumption decreases as R increases. It gets the best performance of energy consumption at $R = 100$. This is because the individual distance is close to the critical distance d_c which ensures desirable energy consumption. As R continue to increase, the energy consumption for greedy algorithm increases since larger distance will be chosen, causing more and unbalanced energy consumption.

For our HEAR algorithm, it consumes the least energy since it always tries to divide d into several pieces with similar distances. Taking $R = 60$ as an example, it can find a 4-hop multi-path with $d_i \approx 45$. When $R \geq 90$, there is a guarantee that our HEAR can always find a 3-hop route with each individual distance $d_i \approx 60$ which is very energy efficient. Thus, there is no variation of energy consumption value as R increases from 90 to 140 for HEAR algorithm.

It is worth noting that $R \in [90,120]$ can ensure desirable energy consumption performance for three routing algorithms except direct transmission algorithm. If R is too large, it will cause other issues like more interference, larger routing table and more control overhead etc.

b) Under different source to BS distance

In Fig. 23, we study the energy consumption on one communication link with $d = 180m$. Now, we study energy consumption on different communication links. The simulation environment is the same as Fig. 23 and we set $R = 110$.

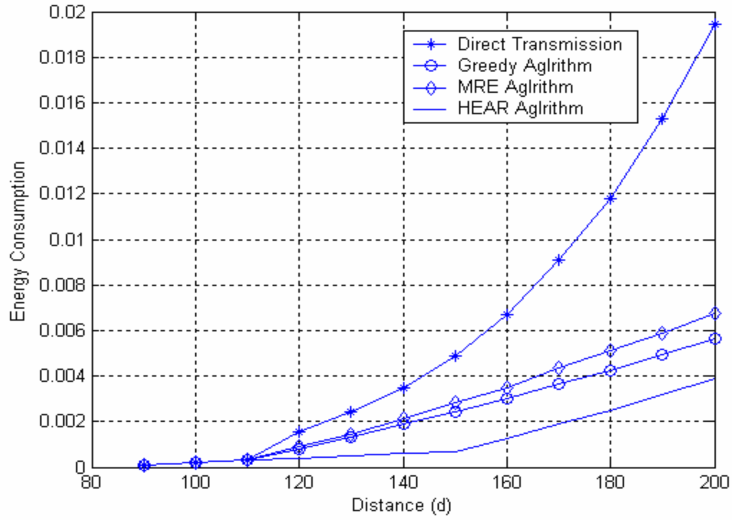


Fig. 24. Energy consumption under different d

Fig. 24 shows the energy consumption under different source to BS distance. We can see that when $d \le R = 110$, direct transmission manner can be chosen by all these 4 routing algorithms and they have almost the same energy consumption which is also very small. When $d > 110$, direct transmission is not possible for the other 3 routing algorithms except direct transmission. Direct transmission consume the largest energy since multi-path model is used under which power attenuates in the fourth order of distance. The performance of MRE and greedy algorithms are in the middle while our HEAR algorithm consumes the least energy. The reason is the same as in Fig. 23.

c) Under different node number

In Fig. 25, we study the energy consumption under different node number N. The simulation environment is the same as Fig. 23 and 24 where there are 300 nodes randomly placed in a $300 \times 300\, m^2$ area. Here, the node number will change from 100 to 300.

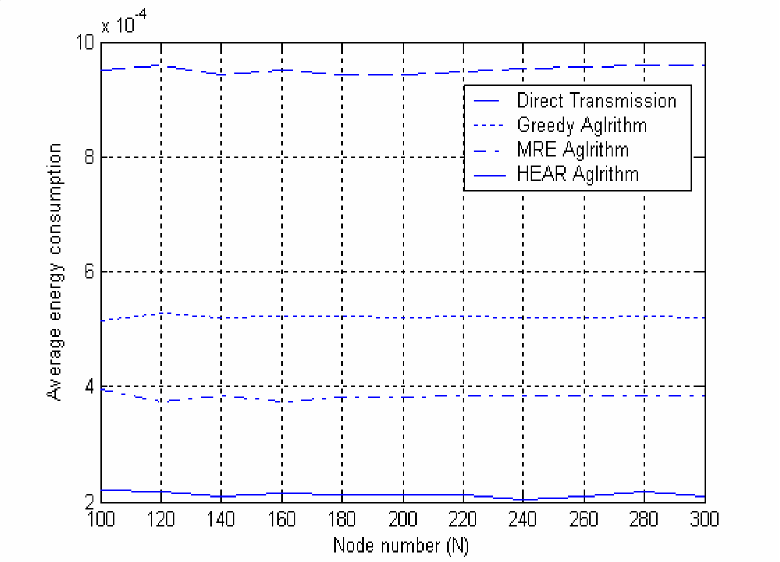


Fig. 25. Energy consumption under different N

From Fig. 25 we find see a similar energy distribution for different routing algorithms as in Fig. 24. And the direct transmission consume the largest energy while our HEAR algorithm consumes the least average energy. Greedy and MRE algorithms are in the middle. We can see that the variation or fluctuation of the average energy consumption becomes smaller as N increases. This shows the essence of energy consumption for each routing algorithm. For example, due to the essence of greedy routing algorithm, each node will choose its neighbor with distance $r_i \approx R$ which causes reduced energy consumption since $R = 110$ here. For our HEAR algorithm, it can always find the sub-optimal hop number and intermediate nodes as N increases.

d) Under different BS location

In Fig. 26, we study the energy consumption under different BS location. The simulation environment is the same as Fig. 23 to 25 where there are 300 nodes randomly placed in a $300 \times 300\, m^2$ area. The data length is 2000 bits and we set $R = 110$ here. Here, the BS will change its position along the diagonal line from position (0, 0) to (300, 300) with each step of 10 units on x or y axis.

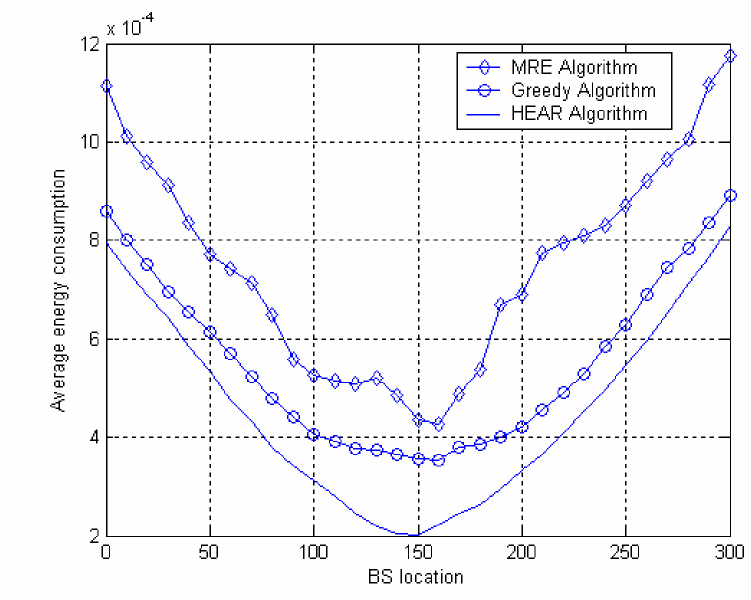


Fig. 26. Energy consumption under different BS location

From Fig. 26 we find that the distribution of energy consumption for the 3 algorithms is almost symmetric based on line $x = 150$ and the minimal energy consumption can be achieved if BS is placed at (150, 150) (middle of WSN). It is easy to under the symmetry property from energy consumption model since the average energy consumption $E_{avg} \propto \frac{1}{N}\sum_{i=1}^{N}(k \cdot E_{elec} + k \cdot d_i^{\alpha})$ where $\sum_{i=1}^{N} d_i^{\alpha}$ tends to get the minimum value when BS is located at the center of network area. It is worth noting that we do not compare with direct transmission since its energy consumption is relatively large. Here, its average energy consumption is in the rage of $[8.91 \times 10^{-4}, 1.35 \times 10^{-2}]$.

e) Under different network scale

Next, we study the energy consumption under different network scale. Fig. 27 shows a small scale network where there are 100 nodes randomly deployed in $100 \times 100\, m^2$ area. The BS is located at (50, 125) and we set $R = 50$, $d_c = 120$ and $\Delta = 20$. Here, we can see that direct transmission has a better energy consumption performance than greedy and MRE algorithms. This is because the average source to sink node is relatively small. Therefore, direct transmission can be more energy efficient than multi-hop transmission with many hops when R is small. However, our HEAR will adaptively choose its transmission. Thus, it still has the best performance.

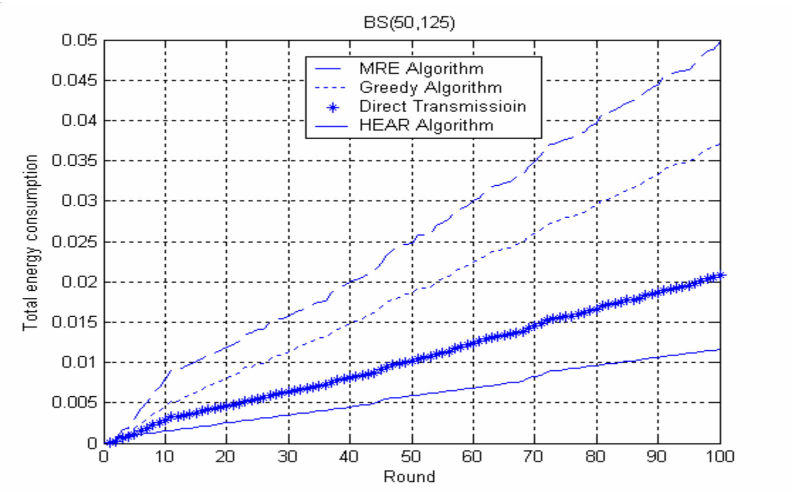
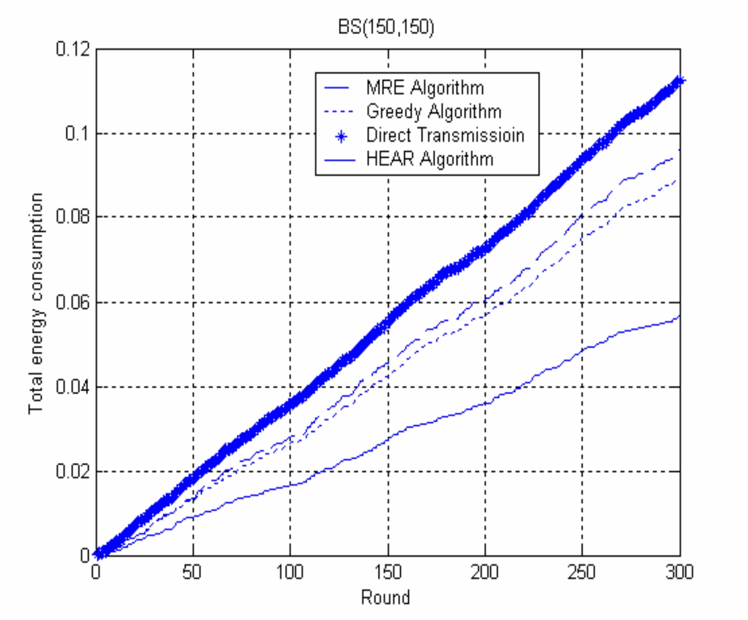
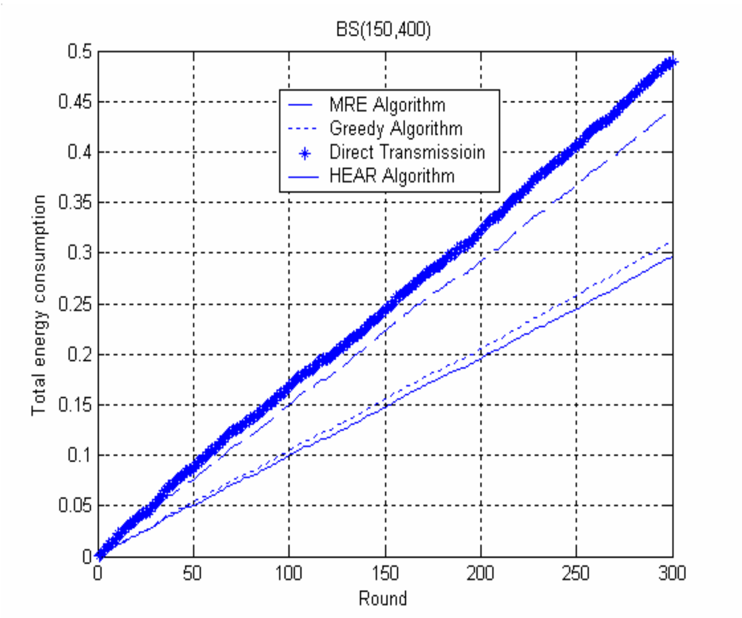


Fig. 27. Total energy consumption under small scale network

Fig. 28 shows a similar case under large scale network where there are 300 nodes randomly deployed in $300 \times 300\, m^2$ area. BS is located either at (150, 150) (Fig. 28 (a)) or at (150, 400) (Fig. 28 (b)). We set $R = 130$, $d_c = 150$ and $\Delta = 20$. We find that the performance of direct transmission decreases as network scale increases and it has the largest energy consumption in Fig. 28. It is worth noting that as network scale continue to increase or when the BS is located outside network area, more energy is needed to send data from source to BS since the average source to BS distance becomes larger.



(a) BS placed inside



(b) BS placed outside

Fig. 28. Total energy consumption under large scale network

f) Under different traffic pattern

In the previous scenarios from a) to e), we only consider the traffic pattern when each node takes turn to send their data to BS based on different routing algorithms. There, the traffic pattern can be viewed as time-based since each of the sensors has change to send their data at different time interval (round). Here, we will consider another type of event-based traffic pattern where the node is randomly chosen to send its data to sink node. In other words, some nodes may have more chances or probability to send the data while other nodes might be in idle state.

In Fig. 29, we first study the average energy consumption for 4 algorithms under 100 various network topologies. The simulation environment is the same as Fig. 25 and 26 where there are 300 nodes randomly placed in a $300 \times 300\, m^2$ area. The data length is 2000 bits and each node is randomly chosen to transmit its data to the BS. We set $R = 110$, $d_c = 150$ and $\Delta = 20$ here.

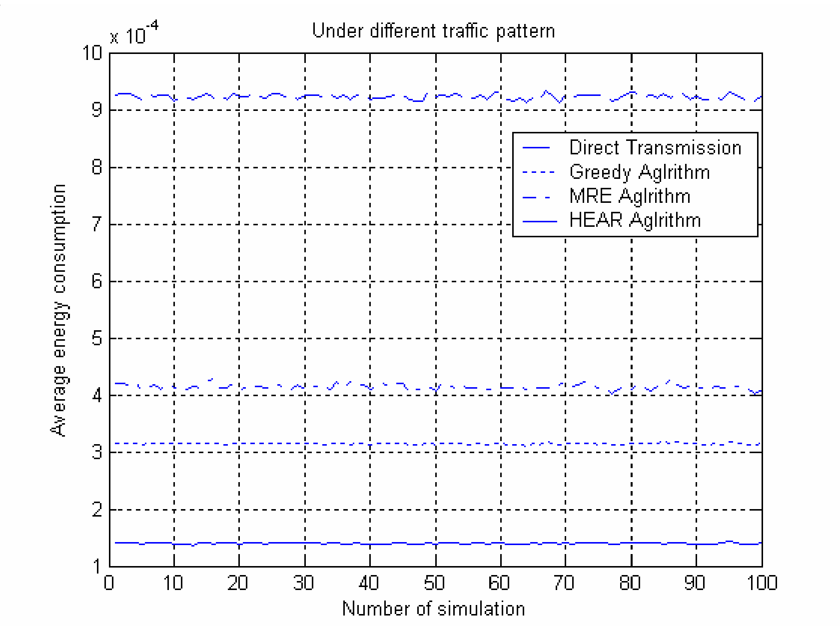


Fig. 29. Average energy consumption under different traffic pattern

It is worth emphasizing that Fig. 29 is very similar to Fig. 25 in the average energy consumption performance for 4 routing algorithms. This is determined by the intrinsic nature of each routing algorithm.

Fig. 30 shows the average energy consumption under different packet size when each node is randomly chosen to send their data to BS. The simulation environment is the same as Fig. 29 where packet size changes from 500 bits to 200 bits with 10 bits increase each step.

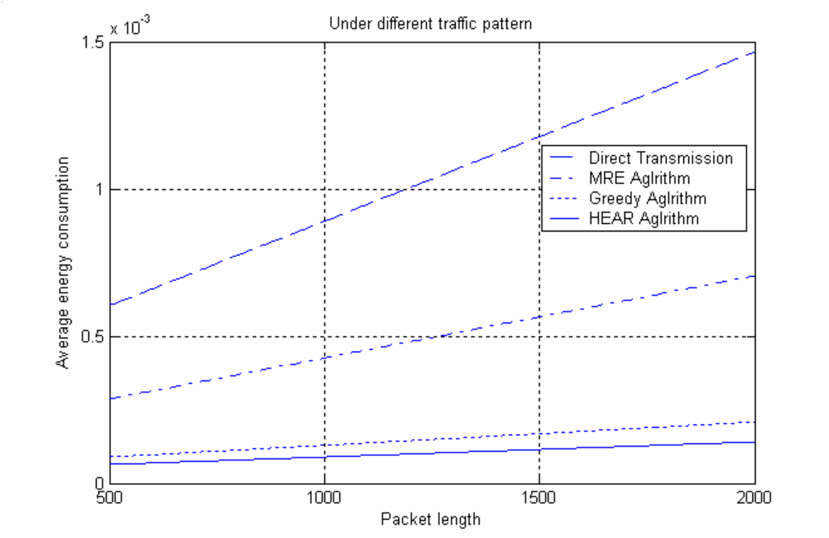


Fig. 30. Average energy consumption under different packet length

From Fig. 30 we can see that energy consumption difference becomes larger as packet length increases. It is worth noting that greedy and HEAR algorithm consume much less energy than the other two algorithms. HEAR has a factor about 5 to 10 times more energy reduction than the other routing algorithms.

From the study of energy consumption in this section, we find that direct transmission algorithm almost consumes the largest amount of energy, especially when the network scale is large. However, it is worth noting that direct transmission also has the following advantages. First of all, it may be more energy efficient that MRE or other routing algorithm under small scale networks (like LEACH), as is seen in Fig. 27. Secondly, when the hardware circuit or modules consume a large volume of energy, routing over many short hops may consume more energy than direct transmission. So, we will prefer to use direct transmission there. Third, direct transmission has better performance of route delay, packet delivery and throughput. When there is QoS requirement on these factors, direct transmission is preferred. Finally, direct transmission may be more energy efficient in some other wireless networks such as cellular phone network, satellite network or Wireless Local Area Networks (WLAN) [116]. Therefore, it is a wise choice to combine multi-hop transmission with direct transmission during the routing process and our HEAR algorithm also adopts direct transmission when the relative distance is small.

5.3.2 Hop number

Similar to the analysis of energy consumption, here we also study the hop number performance under different network topology, different transmission radius as well as different BS location.

a) Under different network topology

Fig. 31 shows the performance of average hop number under different network topologies for 4 routing algorithms. The simulation environment is similar to Fig. 25, 26 and 29 where there are 300 nodes randomly placed in a $300 \times 300\, m^2$ area with BS placed at (150, 150). The data length is 2000 bits and we set $R = 110$, $d_c = 130$ and $\Delta = 20$. The traffic pattern is time-based where each node takes turn to send its data to BS. Simulation is done for 100 times under various sensor network topologies.

From Fig. 31 we can see that direct transmission has the best performance of average hop number which is equal to 1. Here we assume the transmission radius is large enough so that each node can reach BS directly. Our performance of HEAR algorithm is close to direct transmission while greedy and MRE have a worse hop number performance. The reason is similar to energy consumption.

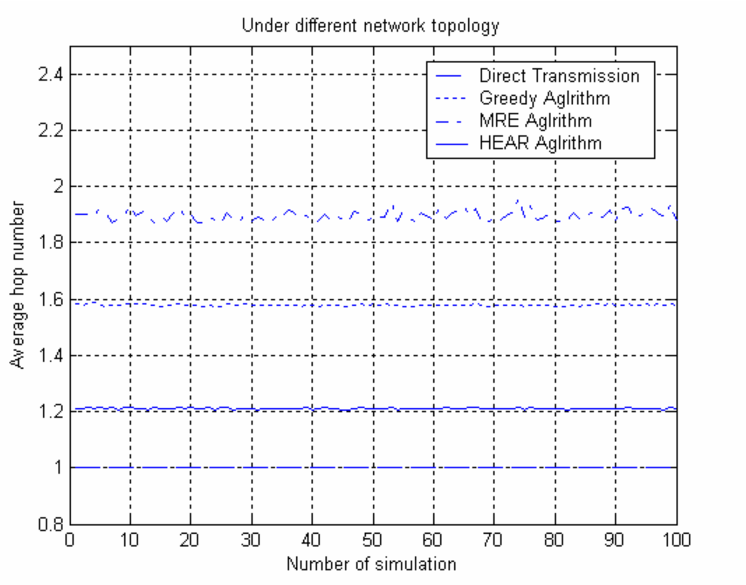


Fig. 31. Hop number under different network topology

b) Under different transmission radius

Fig. 32 shows the average hop number for 4 routing algorithms under the same simulation environment as Fig. 31 where there are 300 nodes randomly placed in a $300 \times 300\, m^2$ area with BS placed at (150, 150). The data length is 2000 bits and we set $R = 110$, $d_c = 130$ and $\Delta = 40$. Here, the transmission radius R changes from 50 to 140 meters.

We can see from Fig. 32 that the average hop number decreases as the transmission radius increases. Greedy and HEAR algorithms have almost the same performance when $R \leq 100$. This is because direct transmission is more energy efficient when the relative distance $d < d_c \approx 104$. Thus, nodes tend to choose their neighbors which is closest to BS with the largest distance when $R \leq 100$ under HEAR algorithm. Here, the essence of these two routing algorithms is almost the same. When $R \geq 140$, greedy algorithm has a better performance than HEAR at the cost of more energy in section 5.3.1.

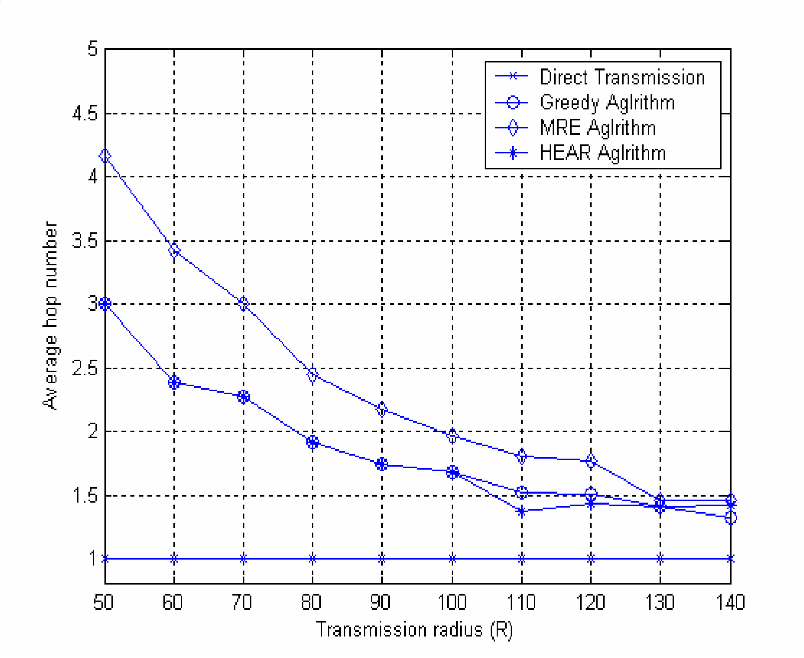


Fig. 32. Hop number under different transmission radius

c) Under different BS location

Fig. 33 shows the average hop number for 4 routing algorithms under the same simulation environment as Fig. 31 and 32 when BS moves along $x = 150$ with step size of 30 (i.e. (150, 0), (150, 30)… (150, 390)).

From Fig. 33 we can see that it is nearly symmetric based on line $x = 150$ as BS moves from (150, 0) to (150, 390), which is similar to Fig. 26. When BS moves from (150, 150) to (150, 390), the average hop number increases since the average source to BS distance is getting larger. MRE algorithm does not have smooth hop number performance due to its intrinsic routing nature.

It is worth noting that we do not compare the performance of hop number under different node number and different traffic pattern. This is because the trend of average hop number distribution for 4 algorithms will not change. The traffic pattern does not affect the value of hop number and there will be less variation of the average hop number as node number N increases.

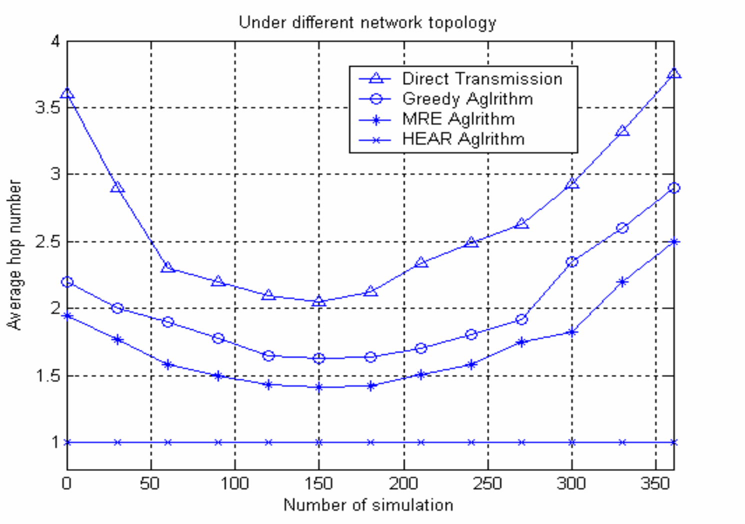


Fig. 33. Hop number under different BS location

5.3.3 Network lifetime

We first study the average network lifetime under 100 different network topologies, as is shown in Fig. 34. The simulation environment is that there are 300 nodes randomly placed in a $300 \times 300\, m^2$ area with BS placed at (150, 150). Each node will take turn to send a 2000 bits message to BS with initial energy of 2 Joule. Here, we set $R = 110$, $d_c = 130$ and $\Delta = 20$.

From Fig. 34, we can see that our HEAR has the longest lifetime while direct transmission algorithm has the worst average network lifetime. The reason lies in the average energy consumption by each of them, which we have explained before. It is worth noting that our HEAR has a factor of 2 to 4 times longer network lifetime than the other 3 routing algorithms.

The average network lifetime give us an intuitive feeling about the average operating time of a network under different routing algorithms, network scale and traffic patterns. Next, we will compare the lifetime which is defined as the time since the first node dies out of energy. This definition is more reasonable since it might cause network partition or isolated area quickly after the first node dies [2, 27, 28].

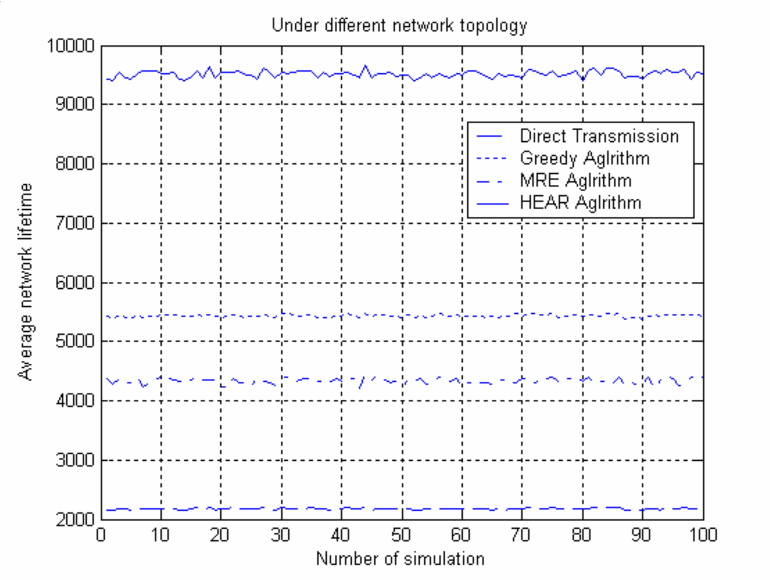


Fig. 34. Network lifetime under different network topology

In the following Fig. 35 and 36, we study the network lifetime under a similar network environment where there are 300 randomly placed in a $500 \times 500\, m^2$ area with BS placed at (250, 250). Each node will take turn to send a 2000 bits message to BS with initial energy of 2 Joule. We set $R = 110$, $d_c = 130$ and $\Delta = 40$ here.

As can be seen from Fig. 35, the network lifetime usually decreases with R since more energy will be consumed on average. Greedy algorithm has a longer lifetime when $R \approx 110$. Because it tends to choose the next hop node with distance near R and $R = 110$ is near the critical distance d_c with better energy efficiency, as we have explained before. When $R \leq 90$, the lifetime of HEAR is relatively shorter because the sub-optimal hop number can not be met and larger hop number is needed. For example, we will choose 2-hop routing instead of direct transmission when $d = 102$ which causes more energy consumption. The performance of MRE algorithm is worse than direct transmission sometimes because there may be such route with too many hops which causes more energy consumption.

The network lifetime of our HEAR is about 6.5 times longer than direct transmission in Fig. 35 and it is 14 times in Fig. 36. When $R \geq 150$, HEAR has a factor of 1.9 and 6.5 times longer lifetime than greedy and MRE algorithm in Fig. 35. And this ratio is about 2.3 and 4.3 in Fig. 36.

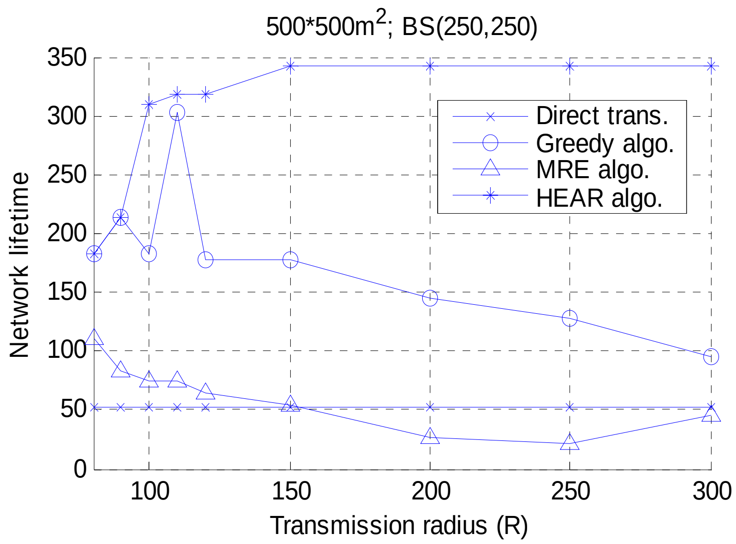


Fig. 35. Network lifetime with BS placed inside

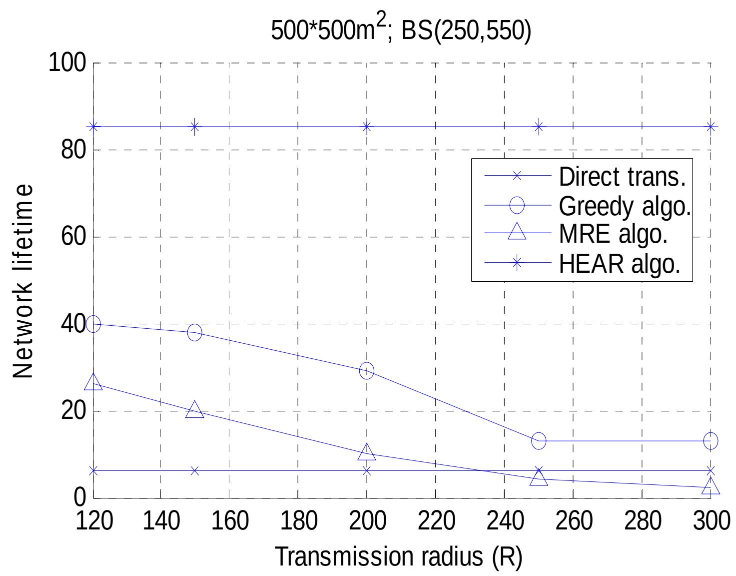


Fig. 36. Network lifetime with BS placed outside

From Fig. 35 and 36, we also observe that:

A) $R \in [110,130]$ can ensure desirable energy efficiency of HEAR because it ensures that corresponding intermediate distance with sub-optimal hop number can be found under practical sensor network environment. If R is too large, it will cause larger interference and unnecessary communication overhead which is not desirable.

B) When sink node is placed outside the monitoring area, it will cause an increased average source to sink node distance. So, the average energy consumption will be increased and network lifetime will be reduced largely. In Fig. 35 and 36, the network lifetime difference for direct transmission is about 9 times and it is 4 times for HEAR algorithm.

In this section, we only study the network lifetime for 4 routing algorithms under different network topology, different transmission radius and different BS location. We do not study the relationship with node number as well as traffic pattern since the trend of average network lifetime will not change, as we have explained before.

5.3.4 Packet reachability

The motivation to study the performance of packet reachability is to see the performance of packet delivery ratio under different network density, especially when the network density is low. Here, packet reachability is defined as the percentage of nodes which can successfully send their packets to the sink node. We define a low density network where there are 50 to 100 sensor nodes randomly deployed in an $800 \times 800\, m^2$ network and the sink node is placed in the center of the network. The maximum transmission radius R is set as 110, 120, 130 and 140 meters which represents various network topologies.

Table 12 gives several network metrics under very low density network topologies when N=50. Here, isolated node means the node which can not reach the sink node through its neighbors. Void node means the node which can not forward the data to its neighbors according to greedy algorithm. In other words, it has no neighboring node which is closer to sink node than itself.

Table 12 Network metrics under various topologies

R	110	120	130	140
Isolated nodes	13	12	8	0
Void nodes	5	3	1	0
Avg. neighbor	3	3.5	4	4.6
HEAR failed nodes	17	14	11	0

We can see from Table 12 that the average neighbor number increases with R. We also found that low packet reachability is mainly caused by isolated node with no neighbors or several isolated nodes which form an isolated area under very low density network. Also, void nodes [61, 115] can cause low packet reachability since it will send its data to the neighbor which is further to the sink node than itself. Sometimes, the ordinary nodes which are connected or routed through void nodes can also cause packet delivery failure or low packet reachability.

It is worth noting that under medium or high density random sensor network, the average neighbor number is usually above 15 and the packet reachability is above 95%. In Fig. 23-36, the average neighbor number is usually above 20. Therefore the packet reachability is always 100%. The average neighbor number is about 13 in [61, 115] and the packet reachability of our HEAR is always 100% under their application environment. That is why we illustrate a low density network here to study the performance of packet reachability. Also, we find that high network density and even node distribution can ensure better performance of packet reachability. Taking uniform node distribution as an example, the packet reachability is always 100% since all nodes are well connected and there are no isolated or void nodes. From Table 12 and Fig. 37, we can see that HEAR algorithm can achieve desirable packet reachability even under very low density network.

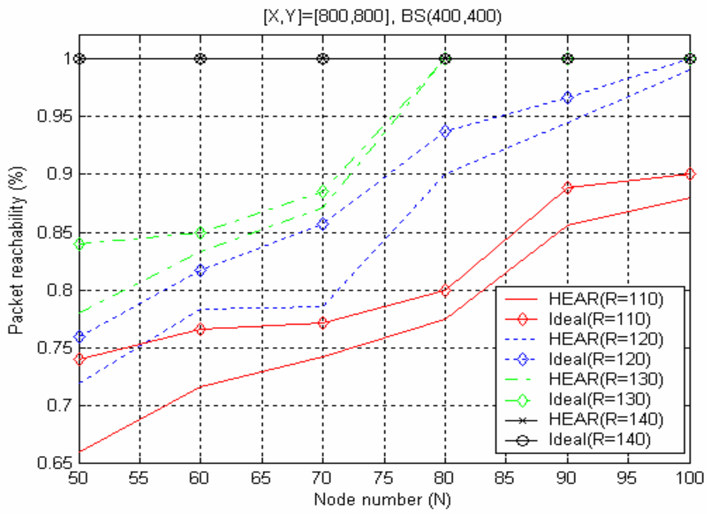


Fig. 37. Packet reachability

We compared our HEAR algorithm with flooding algorithm in Fig. 37. The flooding algorithm is viewed as the ideal algorithm since it can guarantee the highest packet reachability. We found that for the same node number N, packet reachability increases with R, which is also explained in Table 12. For the same R, the packet reachability increases with node number N.

It is worth noting that packet reachability is dependant on the random network topology under practical sensor network. Sometimes, a high node number and R may also cause low packet reachability due to the existence of isolated or void nodes. HEAR algorithm has high packet reachability under medium or high density networks. It can also guarantee desirable packet reachability even under very low density sensor network

5.3.5 Comparison with LEACH and HEED

We make simple comparison between our HEAR algorithm and other two hierarchical routing algorithms which are LEACH and HEED in the aspects of average energy consumption and network lifetime. The clustering and radio parameters are the same as [32, 48]. It is worthy noting that we do not consider data fusion, which is an important advantage of clustering algorithms in this thesis. In the near future, we can compared our clustered HEAR with LEACH and HEED algorithm under the same advantage of data fusion technique. We believe that more energy can be saved since both the number of transmission and data length is largely reduced.

We consider the following 4 scenarios:

- **Scenario 1**: In a $200 \times 200\, m^2$ network, there are 100 sensor nodes with sink node at (100, 200).
- **Scenario 2**: In a $500 \times 500\, m^2$ network, there are 300 sensor nodes with sink node at (250, 250).
- **Scenario 3**: In a $500 \times 500\, m^2$ network, there are 300 sensor nodes with sink node at (250, 550).
- **Scenario 4**: In a $800 \times 800\, m^2$ network, there are 500 sensor nodes with sink node at (400, 800).

From Table 13 we can see that the average energy consumption of LEACH and HEED increases with the network scale as well as source to sink node distance. Our HEAR algorithm has a very desirable performance due to its hop-based nature. We can also see that the performance of HEED is better than LEACH, which consists with [48]. The difference between them becomes larger as network scale and source to sink node distance increases. The main reason is that LEACH uses direct transmission from each cluster head to the sink node while HEED uses multi-hop transmission between cluster heads and the sink node. Our HEAR algorithm has even more advantage over HEED for two reasons. First, the cluster heads in HEED are well distributed in terms of remaining energy rather than geographic location. In fact, the distance between ordinary nodes and cluster head as well as between cluster heads is randomly distributed in HEED. However, each multi-hop distance is carefully chosen based on theoretical deduction in HEAR. Second, there is additional clustering overhead like control message and energy consumption in HEED.

Table 13 Average energy consumption (J) under 4 scenarios

Scenario / Algorithm	1	2	3	4
LEACH	0.0013	0.0060	0.0676	0.2664
HEED	0.0010	0.0027	0.0272	0.0847
HEAR	0.0004	0.0007	0.0020	0.0029

From Table 14, we can draw similar conclusion of average network lifetime for three algorithms. The performance of network lifetime decreases with network scale as well as source to sink node distance. Our HEAR algorithm has about 2 to 10 times longer lifetime than LEACH and HEED. Since the nodes with high residual energy have a high probability to be chosen as cluster heads in HEED, the nodes with low residual energy can get protected from dying quickly. Thus, the network lifetime of HEED is longer than LEACH which chooses cluster head randomly. Due to the same reasons as average energy consumption above, our HEAR algorithm has better performance than HEED. It is worth noting that network lifetime can get further prolonged if we consider residual energy during the selection of next hop node, as is mentioned before.

Table 14 Average network lifetime under 4 scenarios

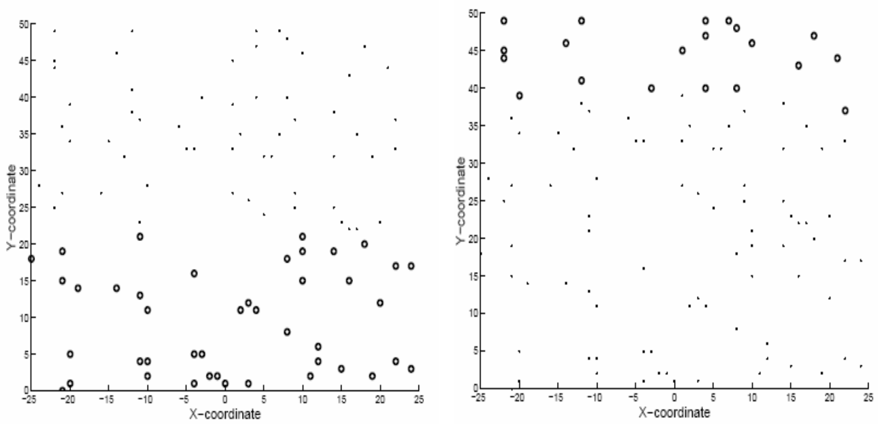
Scenario / Algorithm	1	2	3	4
LEACH	476	256	23	7
HEED	537	458	93	11
HEAR	769	667	294	17

The authors in [48] demonstrated the superiority of their proposed HEED algorithm over LEACH [32]. In this thesis, our HEAR algorithm has a better performance than HEED. From network structural aspect, HEAR is suitable to flat sensor network while HEED is applicable to hierarchical network structure since clustering algorithm is adopted therein. From algorithmic aspect, HEAR is hop-based routing algorithm which is distance aware. On the other hand, HEED is maximal residual energy based routing algorithm which has a secondary factor of node degree. Thus, each individual node during multi-hop routing in HEAR has almost similar energy consumption and they are physically evenly placed. However, both the cluster head and the ordinary sensor node in HEED are not physically even distributed due to the nature of maximal residual energy routing algorithm. More specifically, the cluster heads chosen in HEED has the largest residual energy on average, but they are placed randomly in sensor network. Usually, more and unbalanced energy is caused therein. In conclusion, our HEAR algorithm has a better performance than HEED both in the energy consumption and lifetime. It is worthy emphasizing that we can introduce the cluster-based HEAR algorithm with evenly placed cluster heads in the future, which will have a better performance of energy consumption and lifetime.

5.3.6 Hop spot phenomenon

Finally, we study the hop spot phenomenon since it can cause short network lifetime. The following Fig. 38 is an example of hop spot phenomenon which is illustrated in LEACH [32, 33].

The network environment is that there are N sensor nodes (dots and circles) randomly placed in a ([-25, 25, 0, 50]) area with BS placed at (0, -100). Here, dot means dead node and circle means node alive. So, nodes far away from BS will die quickly if direct transmission is used, which is the case in Fig. 38 (a). On the other hand, nodes close to BS will die quickly if multi-hop transmission is used, which is the case in Fig. 38 (b).



(a) hot spot nodes under direct trans. (b) hot spot nodes under multi-hop trans.

Fig. 38. Hop spot phenomenon

Even though our HEAR algorithm can alleviate the hop spot phenomenon, it can not thoroughly solve this problem. As can be seen from Fig. 39, there are some hop spot nodes (red circle nodes) under HEAR algorithm with BS placed either inside or outside the sensor network area.

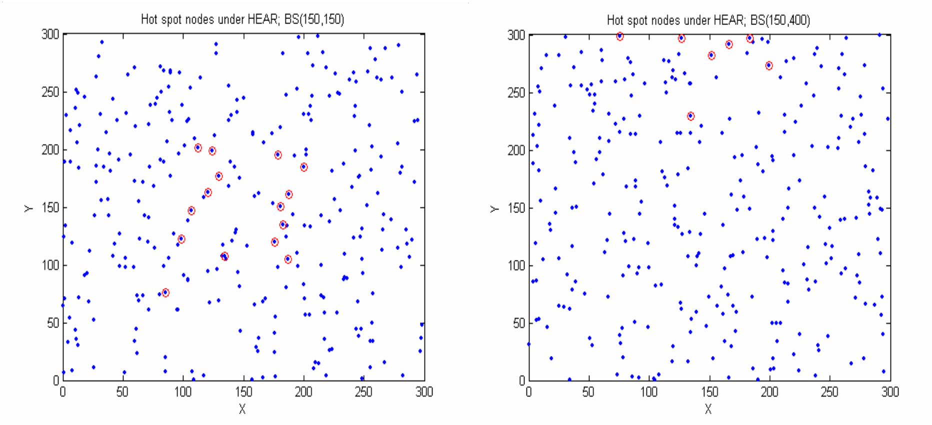


Fig. 39. Hop spot nodes under HEAR algorithm

From the left side picture in Fig. 39, we can see that the hot spot nodes are around BS which is at (150, 150). Even though there are some nodes which are closer than them, but they are not the hot spot nodes since we choose proper nodes with certain distance from BS under HEAR algorithm. It is the same with the right side picture in Fig. 39 where BS is at (150, 400). This is the difference between our HEAR algorithm and other algorithms in Fig. 38.

5.4 Discussion

Once the hardware parameters and distance d are given, the optimal and sub-optimal hop number as well as the corresponding intermediate distances can be determined based on the theoretical and experimental analysis above. The hardware parameters are determined by factors like electronic circuit, antenna height and receiver sensitivity etc [33]. Different set of parameters can cause different optimal hop number as well as intermediate distances. For example, direct transmission is always more energy efficient than multi-hop transmission in [32] with the hardware parameter value $\varepsilon_{fs} = 100\, pJ / bit / m^2$. Some authors use different value of the hardware parameters in their paper. However, we can determine the sub-optimal hop number and the intermediate nodes via the same methodology regardless of the parameter values.

Our HEAR algorithm can not only provide an effective sub-optimal hop number selection criterion under practical sensor network but also can alleviate the hot node phenomena. As we can see, the average energy consumption of HEAR algorithm is much smaller than the other flat and hierarchical routing algorithms. Thus, for the nodes far away from sink node, their average energy consumption is can be greatly reduced via multi-hop routing process. Even for the nodes near sink node, we will choose a few of them which are placed along the multi-hop route from source to sink node with proper intermediate distances. If we consider node remaining energy in the future, HEAR algorithm can further prolong the network lifetime.

It is worthy emphasizing that the optimal or sub-optimal hop number is deduced with an objective to optimize the total energy consumption along multi-hop route. The time-based or event-based traffic model does not influence network lifetime very much. To further prolong network lifetime, we can optimize each individual distance so that each node consumes the same amount of energy under different traffic models. Usually, more energy is consumed on average, but hop spot nodes can save their energy at the cost of more energy consumption by nodes far away from sink node. Besides, we can also build clustered HEAR algorithm which consists of direct transmission routing inside each cluster with shorter distance and our hop-based routing between cluster heads with longer distance. We treat these two issues as our future work.

HEAR algorithm will also introduce some degraded performance. First, it assumes that each node knows its the relative distance to its neighbors as well as to the sink node. Even though it is possible and practical through localization or positioning algorithms, it will introduce more control overhead which we do not analyze here. Second, HEAR is a tradeoff between direct transmission and too many short hop transmission in terms of hop number. Therefore, the link delay might become longer than some other algorithms like direct transmission or greedy transmission sometimes since the average hop number is longer. This is the cost of improved performance in energy efficiency. Third, HEAR may be out of function under very low density network or when there are big obstacles. In that case, the proper next hop node with distance $d_i \in [d/n_{opt}, d/n_{opt} + \Delta]$ may not be found and the final route length from source to sink node could be several times larger than the direct distance between them, which will cause more energy consumption. However, our HEAR can still find the detour route even though the final hop number is larger than n_{opt} hops. In one word, HEAR can improve the performance of energy consumption, network lifetime as well as alleviate hot spot phenomenon without sacrificing too much of the other network performance like control overhead, link delay.

The scheme of HEAR algorithm can be adopted by other routing protocols for WSNs. It is a simple distributed and localized algorithm. No global knowledge is needed and each node can make intelligent local decisions based on its routing and neighboring table. It is similar to [41] since a chain-like multi-hop route is built therein.

From the performance comparison between our HEAR algorithm and five other popular routing algorithms for WSNs above, we can summarize each of their performance in Table 15.

Table 15 Performance comparison between different algorithms

Performance / Algorithm	Energy Consumption	Network lifetime	Hop Number
Direct Trans.	Bad	Bad	Best
MRE	Normal	Normal	Bad
Greedy	Normal	Normal	Better
LEACH	Better	Better	Better
HEED	Better	Better	Normal
HEAR	Best	Best	Better

In this chapter, we compare the performance of our HEAR with other five routing algorithms in Table 15 above in terms of energy consumption, hop number, network lifetime and packet reachability. We also study the hot spot nodes phenomenon. From extensive simulation results, we can see that our HEAR has the best performance of energy consumption and network lifetime. The hop number performance is secondary to direct transmission and LEACH. The packet reachability is 100% under most of the environment when network density is medium or high. Even under very low network density, HEAR can achieve desirable performance. Finally, HEAR can also alleviate the hop spot phenomenon.

Chapter 6 Conclusions and future work

In this thesis, we propose a Hop-based Energy Aware Routing (HEAR) scheme for WSNs. Our objective is to prolong network lifetime of WSNs by reducing and balancing energy consumption during routing process from hop number point of view.

Due to the fact that the factor of hop number plays an important role on many network metrics such as energy consumption, hop number, latency, interference, routing overhead etc. and hop-based routing for WSNs is not well addressed, we first study the hop-based energy consumption performance under one dimensional sensor network. We deduce the selection of transmission manner, the optimal and the sub-optimal hop number as well as the proper intermediate nodes under both one dimensional and practical sensor network.

We then propose our HEAR algorithm which combines the general routing mechanism with hop-based nature during routing process in WSNs. The routing phase consists route setup phase and route maintenance phase. Each node has two tables which are routing table and neighboring table and each node can make local decision of its next hop during routing process without knowing the whole network knowledge. From the detailed explanations and numerical illustrations we can see that our HEAR algorithm is a simple, distributed and localized routing algorithm which can be easily implemented for the practical engineering applications.

Finally, we compare the performance between our HEAR and other five routing algorithms which are direct transmission, greedy, MRE, LEACH and HEED algorithms. Extensive simulations and comparisons are done under different network factors like node number, transmission radius, BS location, network scale, traffic pattern as well as network structure (flat and hierarchical). We find that our HEAR has a better performance than the others in terms of energy consumption, hop number, network lifetime etc.

In the near future, we plan to continue our HEAR algorithm from the flowing aspects. First, we will consider the factor of residual energy for each node during the selection of next hop node. Second, we will introduce the clustering mechanism with data fusion. Third, we plan to use different distances for individual nodes so that each node consumes same amount of energy. Based on these three methods above, the network lifetime can be further prolonged without sacrificing much of the other network performance. Also, we plan to study other network metrics related with hop number and try to address some issue from probability point of view.

Bibliography

[1] M. Weiser, "The computer for the twenty-first century," Scientific American, 265(3), 1991, pp.94-104.

[2] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam and E. Cayirci, "A survey on sensor networks," IEEE Communications Magazine, August 2002.

[3] D. Estrin, R. Govindan, J. Heidemann, and S. Kumar, "Next century challenges: scalable coordination in sensor networks," Proc. IEEE/ACM MobiCom Conference, 1999, pp.263–270.

[4] D. Estrin, L. Girod, G. Pottie and M. Srivastava, "Instrumenting the world with wireless sensor networks," Proc. International Conference on Acoustics, Speech, and Signal Processing, 2001, pp.2033–2036.

[5] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler and K. Piste, "System architecture directions for network sensors," Proc. International Conference on Architectural Support for Programming Languages and Operating Systems, 2000.

[6] G. J. Pottie and W. J. Kaiser, "Wireless sensor networks," Communications of the ACM, vol. 43, May 2000, pp.51–58.

[7] H. Qi, S. S. Iyengar, K. Chakrabarty, "Distributed sensor networks- a review of recent research," Journal of the Franklin Institute, vol. 338, 2001, pp.655–668.

[8] L. Schwiebert, S.D.S. Gupta and J. Weinmann, "Research challenges in wireless networks of biomedical sensors," Proc. IEEE/ACM MobiCom, 2001, pp.151–165.

[9] S. Tilak, N. B. Abu-Ghazaleh and W. B. Heinzelman, "A taxonomy of wireless micro-Sensor network models," ACM Mobile Computing and Communications Review, 6(2), 2002.

[10] Chee-Yee Chong and Kumar, S.P., "Sensor networks: Evolution, opportunities, and challenges," in the Proceedings of IEEE, August 2003.

[11] A. Arora, et al., "A line in the sand: a wireless sensor network for target detection, classification, and tracking," Computer Networks, 46(5):605-634, 2004.

[12] J. Burrell, T. Brooke, and R. Beckwith, “Vineyard computing: sensor networks in agricultural production,” IEEE Pervasive Computing, 3(1):38-45, Jan-Mar, 2004.

[13] K. Chintalapudi, T. Fu, J. Paek, N. Kothari, S. Rangwala, J. Caffrey, R. Govindan, E. Johnson, and S. Masri, “Monitoring civil structures with a wireless sensor network,” IEEE Internet Computing, 10(2):26-34, 2006.

[14] J. Hill and D. Culler, “Mica: a wireless platform for deeply embedded networks,” IEEE Micro, 22(6):12-24, Nov. 2002.

[15] A. Mainwaring et al., “Wireless Sensor Networks for Habitat Monitoring,” in the Proc. of ACM International Workshop on Wireless Sensor Networks and Applications, Sept., 2002.

[16] Crossbow Technology Inc. http://www.xbow.com.

[17] G. J. Pottie and W. J. Kaiser, “Embedding the internet: wireless integrated network sensors,” Communications of the ACM, 43(5):51–58, May 2000.

[18] Tinyos, University of California at Berkeley, http://www.tinyos.net.

[19] D. Goense, J. Thelen, and K. Langendoen, “Wireless sensor networks for precise Phytophthora decision support,” in the 5th European Conference on Precision Agriculture (5ECPA), Sweden, June 2005.

[20] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris, “Span: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks,” ACM Wireless Networks, Vol. 8, No. 5, 2002.

[21] Y. Xu, J.Heidemann and D. Estrin, “Adaptive energy-conserving routing for multihop ad hoc networks,” Research report, USC/Information Sciences Institute, 2000.

[22] Y. Xu, J. Heidemannn, and D. Estrin, “Geography-informed energy conservation for ad hoc routing,” Proc. of the Seventh Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 2001), Rome, Italy, July 2001.

[23] Josh Broch, David B. Johnson, and David A. Maltz, “The Dynamic Source Routing (DSR) Protocol for Mobile Ad Hoc Networks,” Internet-Draft, draft-ietf-manet-dsr-00.txt, March 1998.

[24] Charles Perkins, “Ad Hoc On Demand Distance Vector (AODV) routing,” Internet-Draft, draft-ietf-manet-aodv-00.txt, Nov. 1997.

[25] C. E. Perkins and P. Bhagvat, “Highly Dynamic Destination Sequenced Distance Vector Routing (DSDV) for Mobile Ad hoc Networks,” Computer Communications, Oct. 1994.

[26] J. Broch, D. Maltz, D. Johnson, Y. Hu, and J. Jetcheva, “A Performance Comparison of Multi-hop Wireless Ad hoc network routing protocols,” Proc. of the 4th ACM International Conference on Mobile Computing and Networking (Mobilecom’98), Oct. 1998.

[27] K. Akkaya, M. Younis, “A Survey on Routing Protocols for Wireless Sensor Networks,” Elsevier Ad Hoc Network Journal, vol 3, 2005, pp.325-349.

[28] Al-Karaki, J. N. and A. E. Kamal, "Routing Techniques in Wireless Sensor Networks: A Survey," IEEE Wireless Communications, 11(6), Dec., 2004.

[29] K. Sohrabi, et al., "Protocols for self-organization of a wireless sensor network,” IEEE Personal Communications, 7(5):16-27, October 2000.

[30] Haenggi, M., “Twelve reasons not to route over many short hops,” in the proceedings of the 60th IEEE Vehicular TEchnology Conference (VTC), Sep. 2004, pp.3130-3134.

[31] W. B. Heinzelman, J. Kulik and H. Balakrishnan, “Adaptive protocols for information dissemination in wireless sensor networks,” Proc. IEEE/ACM MobiCom Conference, 1999, pp.174–185.

[32] W. B. Heinzelman, A. Chandrakasan and H. Balakrishnan, “An application-specific protocol architecture for wireless microsensor networks,” IEEE Transactions on Wireless Communications, vol.1, 2002, pp.660–670.

[33] W.B. Heinzelman, “Application-specific protocol architecture for wireless networks,” Ph.D. dissertation, MIT, 2000.

[34] W. B. Heinzelman, A. Chandrakasan and H. Balakrishnan, “Energy-efficient communication protocol for wireless micro sensor networks,” Proc. 33rd Annual Hawaii International Conference on System Sciences, 2000.

[35] W. Heinzelman, A. Sinha, A. Wang, and A. Chandrakasan, “Energy-Scalable Algorithms and Protocols for Wireless Microsensor Networks,” Proc. of the

International Conference Acoustics, Speech, and Signal Processing (ICASSP’00), June 2000.

[36] C. Intanagonwiwat, R. Govindan and D. Estrin, “Directed diffusion: A scalable and robust communication paradigm for sensor networks,” Proc. of the 6th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom'00), Boston, MA, August 2000.

[37] C. Intanagonwiwat, R. Govindan, D. Estrin, J. Heidemann, F. Silva, “Directed diffusion for wireless sensor networking,” IEEE/ACM Transactions on Networking, 11(1):2-16 , Feb. 2003.

[38] Joanna Kulik, Wendi Heinzelman, Hari Balakrishnan, “Negotiation-based protocols for disseminating information in wireless sensor networks,” ACM Transaction on Networking, Volume 8, Issue 2/3, March-May 2002.

[39] Fan Ye, Haiyun Luo, Jerry Cheng, Songwu Lu, Lixia Zhang, “Sensor Networks: A two-tier data dissemination model for large-scale wireless sensor networks,” Proc. of the Eighth Annual ACM/IEEE International Conference on Mobile Computing and Networks (MobiCOM 2002), Sept 2002.

[40] N. Heo and P. K. Varshney, “A Distributed self spreading algorithm for mobile wireless sensor networks,” Proc. IEEE Wireless Communications and Networking Conference, 2003.

[41] S. Lindsey and C. S. Raghavendra, “PEGASIS: power-efficient gathering in sensor information systems,” Proc. IEEE Aerospace Conference, vol. 3, 2002, pp.1125–1130.

[42] F. Ye, S. Lu, L Zhang, “GRAdient Broadcast: A Robust, Long-lived, Large Sensor Network,” http://irl.cs.ucla.edu/papers/grab-tech-report.ps, 2001.

[43] I. Stojmenovic and X. Lin, “Power Aware Distributed Routing in Ad Hoc Wireless Networks,” University of Ottawa, TR-98-11, December 1998.

[44] I. Stojmenovic and X. Lin, “GEDIR: Loop-Free Location Based Routing in Wireless Networks," in International Conference on Parallel and Distributed Computing and Systems, Boston, MA, USA, Nov., 1999.

[45] Ivan Stojmenovic and Xu Lin, “Power-aware Localized Routing in Wireless Networks,” in IEEE Transactions on Parallel and Distributed Systems, Nov., 2001, pp.1121-1133.

[46] R. Jain, A. Puri, and R. Sengupta, “Geographical routing using partial information for wireless sensor networks,” IEEE Personal Communications, 8(1), 2001.

[47] G. Xing, C. Lu, R. Pless, and Q. Huang, “On Greedy Geographic Routing Algorithms in Sensing-Covered Networks,” ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), Tokyo, Japan, 2004.

[48] O. Younis, et. al., “HEED: A Hybrid, Energy-Efficient, Distributed Clustering Approach for Ad Hoc Sensor Networks,” IEEE Transactions on Mobile Computing, 3(4), 2004, pp.660-669.

[49] K. Akkaya and M. Younis, “An Energy-Aware QoS Routing Protocol for Wireless Sensor Networks,” in the Proceedings of the IEEE Workshop on Mobile and Wireless Networks (MWN 2003), Providence, Rhode Island, May 2003.

[50] V. Rodoplu and T.H. Ming, “Minimum energy mobile wireless networks,” IEEE Journal of Selected Areas in Communications, Vol. 17, No. 8, 1999, pp.1333-1344.

[51] L. Li and J. Y Halpern, “Minimum energy mobile wireless networks revisited,” in the Proceedings of IEEE International Conference on Communications (ICC’01), June 2001.

[52] C. Efthymiou, S.Nikoletseas, J.Rolim, “Energy Balanced Data Propagation in Wireless Sensor Networks,” Wireless Networks, Special Issue: Selected Papers from WMAN’04, Vol. 12, No. 6, 2006, pp.691-707.

[53] Fedor, Szymon; Collier, Martin, “On the Problem of Energy Efficiency of Multi-Hop vs One-Hop Routing in Wireless Sensor Networks,” the 21st International Conference on Advanced Information Networking and Applications Workshops (AINAW), May 2007, pp.380-385.

[54] A. Manjeshwar and D. P. Agrawal, “TEEN: A Protocol for Enhanced Efficiency in Wireless Sensor Networks,” in the Proceedings of the 1st International Workshop on Parallel and Distributed Computing Issues in Wireless Networks and Mobile Computing, San Francisco, April 2001.

[55] A. Manjeshwar and D. P. Agrawal, “APTEEN: A Hybrid Protocol for Efficient Routing and Comprehensive Information Retrieval in Wireless Sensor Networks,” in the Proceedings of the 2nd International Workshop on Parallel

and Distributed Computing Issues in Wireless Networks and Mobile computing, Ft. Lauderdale, FL, April 2002.

[56] B. Krishnamachari, D. Estrin, S. Wicker, “Modeling Data Centric Routing in Wireless Sensor Networks,” in the Proceedings of IEEE INFOCOM, New York, NY, June 2002.

[57] D. Braginsky and D. Estrin, “Rumor Routing Algorithm for Sensor Networks,” in the Proceedings of the First Workshop on Sensor Networks and Applications (WSNA), Atlanta, GA, October 2002.

[58] C. Schurgers and M.B. Srivastava, “Energy efficient routing in wireless sensor networks,” in the MILCOM Proceedings on Communications for Network-Centric Operations: Creating the Information Force, McLean, VA, 2001.

[59] An Kyu Hwang, Jae Yong Lee and Byung Chul Kim, “Design of Maximum Remaining Energy Constrained Directed Diffusion Routing for Wireless Sensor Networks,” the International Conference on Computational Science and Its Applications (ICCSA 2006), 2006.

[60] M. Youssef, M. Younis and K. Arisha, “A constrained shortest-path energy-aware routing algorithm for wireless sensor networks,” in the Proceedings of the IEEE Wireless Communication and Networks Conference (WCNC 2002), Orlando, FL, March 2002.

[61] Karp, B. and Kung, H.T., “GPSR: Greedy Perimeter Stateless Routing for Wireless Networks,” in the Proceedings of the Sixth Annual ACM/IEEE International Conference on Mobile Computing and Networking (MobiCom 2000), Boston, MA, August 2000, pp. 243-254.

[62] J. H. Chang and L. Tassiulas, “Maximum Lifetime Routing in Wireless Sensor Networks,” in the Proceedings of the Advanced Telecommunications and Information Distribution Research Program (ATIRP'2000), March 2000.

[63] M. Chu, H. Haussecker, and F. Zhao, “Scalable Information-Driven Sensor Querying and Routing for ad hoc Heterogeneous Sensor Networks,” the International Journal of High Performance Computing Applications, Vol. 16, No. 3, August 2002.

[64] R. C. Shah and J. Rabaey, “Energy Aware Routing for Low Energy Ad Hoc Sensor Networks,” IEEE Wireless Communications and Networking Conference (WCNC), March 2002.

[65] T. He et al., "SPEED: A stateless protocol for real-time communication in sensor networks," in the Proceedings of International Conference on Distributed Computing Systems, May 2003.

[66] W. Ye, J. Heidemann, and D. Estrin, "An Energy-Efficient MAC Protocol for Wireless Sensor Networks," in the Proceedings of the 21st International Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM), New York, 2002.

[67] A. Woo and D. Culler, "A Transmission Control Scheme for Media Access in Sensor Networks," in the Proceedings of the 7th Annual ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom'01), Rome, Italy, July 2001.

[68] T. Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," in the first ACM Conf. on Embedded Networked Sensor Systems (SenSys 2003), USA, Nov. 2003.

[69] D. Hall, "Mathematical Techniques in Multisensor Data Fusion," Artech House, Boston, MA, 1992.

[70] L. Klein, "Sensor and Data Fusion Concepts and Applications," SPIE Optical Engr Press, WA, 1993.

[71] S. Lindsey, C. S. Raghavendra and K. Sivalingam, "Data Gathering in Sensor Networks using the Energy*Delay Metric," in the Proceedings of the IPDPS Workshop on Issues in Wireless Networks and Mobile Computing, San Francisco, CA, April 2001.

[72] Yan Yu, Ramesh Govindan, Deborah Estrin, "Geographical and Energy Aware Routing: a recursive data dissemination protocol for wireless sensor networks," UCLA Computer Science Department Technical Report UCLA/CSD-TR-01-0023, May 2001.

[73] Wensheng Zhang; Guohong Cao; La Porta, T, "Data dissemination with ring-based index for wireless sensor networks," in the Proceedings of the 11th IEEE International Conference on Network Protocols, Nov. 2003.

[74] K. Kalpakis, K. Dasgupta and P. Namjoshi, "Maximum lifetime data gathering and aggregation in wireless sensor networks," in the Proceedings of IEEE International Conference on Networking (NETWORKS '02), Atlanta, GA, August 2002.

[75] K. Dasgupta et al., "An efficient clustering-based heuristic for data gathering and aggregation in sensor networks," in the Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC'03), New Orleans, Louisiana, March 2003.

[76] Jamal N. Al-Karaki, A.E. Kamal, "On the Correlated Data Gathering Problem in Wireless Sensor Networks," in the Proceedings of the 9th IEEE Symposium on Computers and Communications, Alexandria, Egypt, July 2004.

[77] Ossama Younis, Marwan Krunz, and Srinivasan Ramasubramanian, "Node Clustering in Wireless Sensor Networks: Recent Developments and Deployment Challenges," IEEE Network (special issue on wireless sensor networking), 20(3):20-25, May 2006.

[78] S. Bandyopadhyay, E. Coyle, "An Energy Efficient Hierarchical Clustering Algorithm for Wireless Sensor Networks," in the Proceedings of INFOCOM 2003, pp.1713-1723.

[79] Wang Jin, Shu Lei, Jinsung Cho, Young-Koo Lee, Sungyoung Lee, Yonil Zhong, "A Load-balancing and Energy-aware Clustering Algorithm in Wireless Ad-hoc Networks," in the first International Workshop on RFID and Ubiquitous Sensor Networks, 2005, pp.1108-1117.

[80] Q. Li and J. Aslam and D. Rus, "Hierarchical Power-aware Routing in Sensor Networks," in the Proceedings of the DIMACS Workshop on Pervasive Networking, May 2001.

[81] M. Younis, M. Youssef and K. Arisha, "Energy-Aware Routing in Cluster-Based Sensor Networks," in the Proceedings of the 10th IEEE/ACM International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems, October 2002.

[82] C. Lin and M. Gerla, "Adaptive Clustering for Mobile Wireless Networks," IEEE Journal on Selected Areas in Communications, Sept. 1997.

[83] Georgios Smaragdkis, Ibrahim Matta and Azer Bestavros, "SEP: A Stable Election Protocol for clustered heterogeneous wireless sensor networks," Proc. of the Int'l Workshop on SANPA, 2004.

[84] S.Bandyopadhyay, E.J.Coyle, "Minimizing communication costs in hierarchically clustered networks of wireless sensors," Computer Networks, 44(1):1-16, 2004.

[85] S. Bandyopadhyay and E. J. Coyle, “An energy efficient hierarchical clustering algorithm for wireless sensor networks,” in the Proceedings of the IEEE Conference on Computer Communications (INFOCOM), 2003.

[86] J. Deng, Y. S. Han, W. B. Heinzelman, and P. K. Varshney, “Scheduling Sleeping Nodes in High Density Cluster based Sensor Networks,” ACM/Kluwer Mobile Networks and Applications (MONET) Special Issue on Energy Constraints and Lifetime Performance in Wireless Sensor Networks, 2005.

[87] Yun Wang, Demin Wang, Weihuang Fu, and Dharma P. Agrawal, “Hops-based Sleep Scheduling Algorithm for Enhancing Lifetime of Wireless Sensor Networks,” Proc. of IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS), Canada, 2006, pp.709-714.

[88] Xiaoling Wu, Jinsung Cho, Brian J. d'Auriol, and Sungyoung Lee, “Sleep Nodes Scheduling in Cluster-based Heterogeneous Sensor Networks Using AHP,” Proc. of the International Conference on Embedded Software and System, May 2007.

[89] M. Dong, K.Yung, and W. Kaiser, “Low Power Signal Processing Architectures for Network Microsensors,” in the Proceedings of International Symposium on Low Power Electronics and Design, August 1997, pp.173-177.

[90] S. Meguerdichian, F. Koushanfar, M. Potkonjak, and M. B. Srivastava, “Coverage problems in wireless ad-hoc sensor networks,” Proc. IEEE Conference on Computer Communications (INFOCOM), Apr. 2001, pp.1380-1387.

[91] S. Shakkottai, R. Srikant, and N. Shroff, “Unreliable sensor grids: coverage, connectivity and diameter,” Proc. IEEE Conference on Computer Communications (INFOCOM), San Francisco, Vol. 2, Mar./Apr. 2003, pp.1073-1083.

[92] Seapahn Megerian, Farinaz Koushanfar, Miodrag Potkonjak, and Mani B. Srivastava, “Worst and best-case coverage in sensor networks,” IEEE transactions on mobile computing, 4(1):84-92, 2005.

[93] A. Perrig, R. Szewzyk, J.D. Tygar, V. Wen, and D. E. Culler, “SPINS: security protocols for sensor networks,” Wireless Networks, Vol(8), 2000, pp.521-534.

[94] Karlof, C. and Wagner, D., "Secure Routing in Wireless Sensor Networks: Attacks and Countermeasures," in the Proceeding of the first IEEE International Workshop on Sensor Network Protocols and Applications (SPNA), AK, USA, May 2003, pp.113-127.

[95] Lee, S.B; Choi, Y.H, "A secure alternate path routing in sensor networks," Computer Communication, 30(1):153-165, 2006.

[96] Y. Zou and K. Chakrabarty, "Energy-aware target localization in wireless sensor networks," Proc. IEEE Interantional Conference on Pervasive Computing and Communications, 2003, pp.60–67.

[97] Y. Zou and K. Chakrabarty, "Target localization based on energy considerations in distributed sensor networks," Ad Hoc Networks, vol. 1, 2003, pp.261–272.

[98] N. Bulusu, J. Heidemann, V. Bychkovskiy, and D. Estrin, "Density-adaptive beacon placement algorithms for localization in ad hoc wireless networks," in IEEE Infocom, New York, June 2002.

[99] N. Bulusu, J. Heidemann, D. Estrin, "GPS-less low cost outdoor localization for very small devices," Technical report, University of Southern California, April 2000.

[100] A. Savvides, C-C Han, aind M. Srivastava, "Dynamic fine-grained localization in Ad-Hoc networks of sensors," in the Proceedings of the Seventh ACM Annual International Conference on Mobile Computing and Networking (MobiCom), July 2001, pp.166-179.

[101] S. Capkun, M. Hamdi, J. Hubaux, "GPS-free positioning in mobile ad-hoc networks," in the Proceedings of the 34th Annual Hawaii International Conference on System Sciences, 2001 pp.3481-3490.

[102] N. Bulusu, D. Estrin, L. Girod and J. Heidemann, "Scalable Coordination for wireless sensor networks: Self-Configuring Localization Systems," in the Proceedings of the Sixth International Symposium on Communication Theory and Applications, July 2001.

[103] Ahmed N., Kanhere S. and Jha S., "The Holes Problem in Wireless Sensor Networks: A survey," Mobile Computing and Communications Review, 9(2):4-18, 2005.

[104] S. Tilak et al., “A Taxonomy of Wireless Microsensor Network Models,” in ACM Mobile Computing and Communications Review (MC2R), June 2002.

[105] Eugene Shih, et al., “Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks,” in the Proceedings of the 7th Annual ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom'01), July 2001.

[106] H. Zimmermann, “OSI Reference Model- The ISO Model of Architecture for Open Systems Interconnection,” IEEE Transactions on Communications, 28(4), April 1980.

[107] G. G. Finn, “Routing and addressing problems in large metropolitan-scale internetworks,” USC ISI Report ISI/RR-87-180, 1987.

[108] J. Razavilar, F. Rashid-Farrokhi, and K. Liu, “Software Radio Architecture with Smart Antennas: A Tutorial on Algorithms and Complexity,” IEEE Journal on Selected Areas in Communications, 17(4):662-676, April 1999.

[109] T. Rappaport, “Wireless Communications: Principles & Practice,” Prentice-Hall, Inc., New Jersey, 1996.

[110] MATLAB, http://www.mathworks.com/.

[111] J. Deng, “Multi-hop/Direct Forwarding (MDF) for Static Wireless Sensor Networks,” ACM Transactions on Sensor Networks, 5(4), November 2009.

[112] Chunlai Chai, “Efficient Intelligent Localization Scheme for Distributed Wireless Sensor Networks,” Journal of Computers, Vol.4, No.11, November 2009.

[113] Duc-Dzung Nguyen, Myungchul Kim, Le Quy Loc, Pham Tuan Tu, “A Hop-Based Routing Scheme for MANETs,” 5th IEEE Consumer Communications and Networking Conference (CCNC), 2008.

[114] S. Vural, E. Ekici, “Hop-distance based addressing and routing for dense sensor networks without location information,” Ad Hoc Networks, 5(4), 2007, pp. 486-503.

[115] Brad Nelson Karp, “Geographic Routing for Wireless Networks,” Ph.D. Dissertation, Harvard University, USA, October 2000.

[116] A. Ephremides, “Energy concerns in wireless networks,” IEEE Wireless Communications, August 2002, pp. 48-59.

[117] Trong Thua Huynh, Choong Seon Hong, "An Energy Delay Efficient Multi-Hop Routing Scheme for Wireless Sensor Networks," IEICE Transaction on Information and Systems, pp.1654-1661, May 2006.

[118] Md. Abdur Razzaque and Choong Seon Hong, "Analysis of Energy-Tax for Multipath Routing in Wireless Sensor Networks," Annals of Telecomm., May 2009.

List of publications

Journals

[1] Kwang-Cheng Chen, Bilge Kartal Cetin, Yu-Cheng Peng, Neeli Prasad, Jin Wang, Songyoung Lee, "**Routing for Cognitive Radio Networks Consisting of Opportunistic Links**," Wireless Communications and Mobile Computing, Wiley Journal (SCI), 2009.

[2] Jin Wang, Jinsung Cho, Sungyoung Lee, Kwang-Cheng Chen, Young-Koo Lee, "Hop-based Energy Aware Routing Algorithm for Wireless Sensor Networks," IEICE Transaction on Communication (SCI), Vol. E93-B, No. 02, pp -, Feb. 2010.

Conferences

[1] Wang Jin, Shu Lei, Jinsung Cho, Young-Koo Lee, Sungyoung Lee, Yonil Zhong, "A Load-balancing and Energy-aware Clustering Algorithm in Wireless Ad-hoc Networks," The 1st International Workshop on RFID and Ubiquitous Sensor Networks (USN'2005), Japan, Dec., 2005, pp.1108-1117.

[2] Shu Lei, Wang Jin, Xu Hui, Jinsung Cho and Sungyoung Lee, "Connecting Sensor Networks with TCP/IP Network," International Workshop on Sensor Networks (IWSN'06) in conjunction with APWeb 2006, Harbin, China, 2006.

[3] Xiaoling Wu, Shu Lei, Wang Jin, Jinsung Cho and Sungyoung Lee, "Energy-efficient Deployment of Mobile Sensor Networks by PSO," the International Workshop on Sensor Networks (IWSN'06) in conjunction with APWeb, Harbin, China, 2006.

[4] Jin Wang, Brian J. d'Auriol, Young-Koo Lee, Sungyoung Lee, "A Swarm Intelligence inspired Autonomic Routing Scenario in Ubiquitous Sensor Networks," the International Conference on Multimedia and Ubiquitous Engineering (MUE 2007), Seoul, Korea, April 2007, pp.745-750.

[5] Jin Wang, Brian J. d'Auriol, Xiaoling Wu, Young-Koo Lee, Sungyoung Lee, "Energy Consumption of Swarm Intelligence inspired Routing Algorithms in MANETs," International Conference on Multimedia and Ubiquitous Engineering (MUE 2007), Seoul, Korea, April 2007, pp.803-806.

[6] Jin Wang, Brian J. d'Auriol, Young-Koo Lee, Sungyoung Lee, “Study on Routing Related Energy Consumption Problem in Wireless Sensor Networks,” in Proceedings of The 27th KIPS Spring Conference, Kyungwon University, Seoul, Korea, May 2007.

[7] Jin Wang, Yu Niu, Jinsung Cho, Sungyoung Lee, “Analysis of Energy Consumption in Direct Transmission and Multi-hop Transmission for Wireless Sensor Networks,” the Third IEEE/ACM International Conference on Signal-Image Technology and Internet based Systems (SITIS'07), Shanghai, Dec. 2007, pp.254-259.

[8] Jin Wang, Jinsung Cho, Sungyoung Lee, “Experimental Study of Energy Consumption in Direct Transmission and Multi-hop Transmission for Wireless Sensor Networks,” the IEEE International Conference on Networking, Sensing and Control (ICNSC'08), April 2008.

[9] Yu Niu, Brian J. d’Auriol, XiaolingWu, Jin Wang, Jinsung Cho, Sungyoung Lee, “Selective Pulse Coupling Synchronicity for Sensor Network,” the Second International Conference on Sensor Technologies and Applications SENSORCOMM 2008 - Cap Esterel, France, August 2008.

[10] Jin Wang, Jinsung Cho, Sungyoung Lee, “A Hop-based Energy Aware Routing Algorithm for Wireless Sensor Networks,” the First China-Korea Wireless Sensor Network Workshop (CKWSNW’08), Chongqing, China, Oct., 2008.

[11] Jin Wang, Young-Koo Lee, “Determination of the Optimal Hop Number for Wireless Sensor Networks,” the 2009 International Conference on Computational Science and its Applications (ICCSA'09), Yongin, Korea.

[12] Jin Wang, Sungyoung Lee, “A Performance Comparison of Swarm Intelligence Inspired Routing Algorithms for MANETs,” the 2009 International Conference on Computational Science and its Applications (ICCSA'09), Yongin, Korea.

List of abbreviations

AODV	Ad hoc On-demand Distance Vector
ADC	Analog-to-Digital Converter
a.k.a	also known as
ACK	Acknowledge
API	Application Programming Interface
BS	Base Station
CH	Cluster Head
DD	Directed Diffusion
DoS	Denial of Service
DSDV	Destination-Sequenced Distance Vector
DSR	Dynamic Source Routing
EEG	Electroencephalogram
GAF	Geographic Adaptive Fidelity
GPS	Global Position System
GPSR	Greedy Perimeter Stateless Routing
GRAB	GRAdient Broadcast
HEAR	Hop-based Energy Aware Routing
HEED	Hybrid, Energy-Efficient, Distributed
ID	Identification
ISM	Industrial, Scientific and Medical

IT	Information Technology
LEACH	Low Energy Adaptive Clustering Hierarchy
LOS	Line of Sight
MAC	Medium Access Control
MANETs	Mobile Ad hoc NETworks
MECN	Minimum Energy Communication Network
MEMS	Micro Electro-Mechanical Systems
MRE	Maximal Remaining Energy
MTE	Minimum Transmission Energy
OSI	Open Systems Interconnection
PDAs	Personal Digital Assistants
PHY	Physical
PEGASIS	Power Efficient GAthering in Sensor Information Systems
QoS	Quality-of-Service
RREP	Route Reply
RREQ	Route Request
RERR	Route Error
SPIN	Sensor Protocols for Information via Negotiation
TDMA	Time Division Multiple Access
TTL	Time-to-Live
TTDD	Two-Tier Data Dissemination
WSNs	Wireless Sensor Networks