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Energy-balanced parameter-adaptable cooperative protocol (EBPACP) design in wireless sensor networks

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ENERGY-BALANCED PARAMETER-ADAPTABLE COOPERATIVE PROTOCOL (EBPACP) DESIGN IN WIRELESS SENSOR NETWORKS

by

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Abstract

The performance of WSNs is adversely affected by the radio irregularity and fading effect. Cooperative transmission has been proven to be an effective way to combat the impacts of fading by obtaining diversity gains and therefore reduces the transmit energy. Meanwhile, some sensor nodes have heavier burden than the others and the energy imbalance problem remains harmful to the system lifetime. How to efficiently incorporate cooperative transmission into WSNs and balance energy are the subjects of this thesis. In our research, we proposed an energy-balanced parameter-adaptable cooperative protocol (EBPACP) for cluster-based WSNs. Since the design of WSNs is highly dependent on application scenarios, we analyzed the effects of the system parameters and found a unified criterion to summarize the effects. With this knowledge, a preferred scheme of cooperative transmission is chosen to reduce energy consumption. How to form clusters, build up cooperative relationships and transmit data to the BS are explored in detail in the thesis. We use the idea of weighted distance to adjust the size of the cluster. Thus energy consumption is balanced by adjusting energy dissipated inside and outside of the clusters. Sensor nodes consuming higher energy in outside-cluster communication form smaller clusters. In this thesis, EBPACP is mainly discussed in single-hop systems and it can be extended to multi-hop systems. Simulation results have shown that the proposed EBPACP provides good system performance in terms of energy efficiency and energy balance.

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Abbreviation List

ADC	Analog to digital convertor
AWGN	Additive white gaussian noise
BS	Base station
CDMA	Code division multiple access
CSMA	Carrier sense multiple access
DAC	Digital to analog convertor
EBPACP	Energy-balance parameter-adaptable cooperative Protocol
IFA	Intermediate frequency amplifier
LEACH	Low energy adaptable clustering hierarchy
LNA	Low noise amplifier
MIMO	Multi-input multi-output
MISO	Multi-input single-output
SBTD	Stochastic based traffic distribution
SIMO	Single-input multi-output
SISO	Single-input single-output
SNR	Signal to noise ratio
STBC	Space time block coding
TDMA	Time division multiple access
PAR	Peak to average ratio
PSD	Power spectral density
QoS	Quality of service
RP	Reference point
WSN	Wireless sensor network

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Chapter 1

Introduction

A Wireless Sensor Network (WSN) is a wireless network consisting of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions. There are different kinds of sensor nodes that collect the information about magnetic, thermal, visual, infrared, acoustic and radar, which are able to monitor a wide variety of ambient conditions [1].

In WSNs the sensors need not to be pre-determined or engineered, which allows random deployment and applications in inaccessible terrains. Moreover, sensor nodes have onboard processors which enable local data processing and transmit only required information to the Base Station (BS). At the same time, the rapid advances in the hardware of sensors have greatly reduced the cost of sensor nodes and made the dense-deployment of sensor nodes possible. The concepts of micro-sensing and wireless connection of these nodes promise many new application areas. In other words, all these features have addressed a wide range of potential applications of WSNs.

Originally WSNs are motivated by military applications such as battlefield surveillance and enemy tracking. Now the applications of WSNs expand to many other fields, far beyond its original motivation. In terms of scenarios where WSNs are applied, the applications can be categorized as follows: military, environmental, health, home and commercial applications.

Thanks to the promising potential that WSNs have demonstrated, the market of WSNs is undergoing its first stage of development and is ready to realize its full potential in the following years. Much research attention has been attracted into this field to fulfill the promising potential of WSNs. Since WSNs are application-specific, they involve both software and hardware and also use protocols that are related to both application and the wireless network. Efforts in software, hardware as well as protocols and standards have been made to target at maximizing the performance of WSNs for a specific application.

In this chapter, an introduction about WSNs is presented to give an overview about WSNs. We will introduce the features, applications, design targets, metrics, limitations and challenges in WSNs. These factors also serve as design guidelines of protocols for WSNs.

1.1 Wireless Sensor Node Components

A wireless sensor node consists of four basic components, as shown in Figure 1.1:

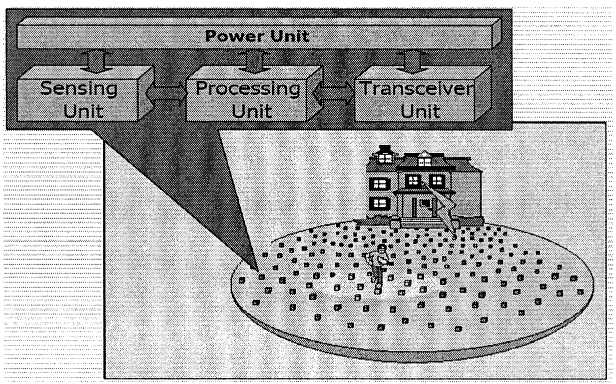

Figure 1.1: Sensor node components

- Sensing Unit: This unit usually contains two subunits: sensor nodes and analog to digital converters (ADCs). The analog signals produced by the sensor based on the observed phenomenon are converted to digital signals by the ADC and then fed into the processing unit.

- Processing Unit: This unit is usually associated with a small storage unit. It manages the procedures that make the sensor node collaborate with the other nodes to carry out the assigned sensing tasks.

- Transceiver Unit: This unit connects the node to the network.

- Power Unit: This unit supplies the other units of the sensor nodes with energy and may be supported by a power scavenging unit like solar cells. Limited by the size of sensor nodes, the power units should meet the size limitation.

Sensor nodes may contain other units according to the application scenarios. For example, some routing protocols require nodes to have location information and thus it is common for the sensor nodes to equip a location finding system. However, all these units should fit into a small package and be adapted to the environment. Since it is not applicable to recharge the nodes in most of the applications, all units of the nodes should be power efficient to work as long as possible.

1.2 WSN Structure

WSNs are designed to fulfill certain tasks for a specific application, such as to monitor temperature, humidity and pressure in an area of interest. Usually there are requirements on the system performance and cost. How are WSNs organized to fulfill the tasks and provide required services? The following gives the structure of a WSN:

- Infrastructure: The sensor nodes and their current deployment status constitute the infrastructure of WSNs. The infrastructure is influenced by two factors: the characteristics of the sensors and the deployment strategies. The sensor characteristics include sensing accuracy, battery life and transmission range. The deployment strategies include the density and mobility of the sensor nodes. Both of the sensor characteristics and deployment strategies have a great impact on the infrastructure.

- Network Protocol: The network protocol is how sensor nodes communicate with each other and how the sensing information is transmitted to the observer or Base Station (BS). The network protocol should be designed to meet the application and energy requirements.

- Observer/Base Station: All the data are transmitted to the observer or BS for further analysis. The BS is usually considered powerful in terms of more transceivers and more powerful data processing ability. It receives data from the sensors, makes a decision to filter out the useful information according to the application and then takes measures.

Designers of WSNs can cut off the three organizational levels to achieve optimized performance. For instance, the deployment of the sensor nodes can reflect the interests of observer to some extent. Such a deployment strategy incorporates application knowledge in the infrastructure design. In some other cases, the application knowledge will play a key role in the network protocol design. For example, priority might be given to those data that observers are interested by giving priority in forwarding and using redundancy to increase the chance of reception. Most of the research in WSNs focuses on the network protocol design which is responsible for supporting all the communication, both among sensor nodes and between the sensor nodes and the observer. The performance of the protocol will be highly influenced by the network dynamics as well as by the specific data delivery model employment. In other words, the design of the protocol is highly dependent on the network scenarios. The classification of sensor network scenarios is given in the following section.

1.3 WSN Scenarios

The design of WSNs is very sensitive to application scenarios. Different application scenarios call for different considerations and pose different opportunities to maximize system performances. Communication protocols for WSNs have to render appropriate support to different network scenarios. The following gives a classification of WSN application scenarios.

- Source and Sink Types: The sources are entities in the network which can be a sensor node that provides information sensed from the environment or an actuator node that provides feedback about an operation. For the sink, on the other hand, is an entity where the information is required. Basically there are three types of sink. A sink could be just another sensor node/actuator in the network. It could also be an actual device, for example, a hand-held or a PDA used to interact with the sensor network. The last type of sink is a gateway to another larger network such as the Internet.

- Network Types: In respect of routing, there are single-hop network and multi-hop network. Limited by the batteries and the connectivity range of sensor nodes, direct transmission between sensor nodes and receiver are not always possible. To overcome the limitation of distances, sensor nodes could take multi-hops to deliver the data packets to the BS. The concept of multi-hop is particularly attractive in WSNs since sensor nodes themselves can perform as relay nodes instead of adding additional equipments. Moreover, even it is within the connectivity range of the sensor nodes, it is more energy efficient to use multi-hop since long distance data transmission is much more energy consuming than local data transmission. On the other hand, whether multi-hop or direct transmission should be carefully chosen since multi-hop introduces extra expenses in control overheads and circuit energy consumption. From the perspective of sensor node types, there are homogeneous and heterogeneous WSNs. Homogeneous WSNs are composed of the same type of sensor nodes which have the same power supply and data processing abilities. Heterogeneous WSNs consist of mainly normal sensor nodes as well as some super nodes which may either possess more energy supply or data processing ability to take more responsibilities.

- Three Types of Mobility: In the application of sensor networks, there are basically three types of mobility: node, sink and event mobility.

  Node Mobility: The wireless sensor nodes themselves can be mobile. Such kind of mobility is quite application dependent. Node mobility is necessary only in some scenarios like livestock surveillance. In the case of node mobility, the network has to reorganize itself frequently enough to be able to function correctly. There is a trade-off between the speed of node movement and the energy required to maintain a desirable level of functionality in the network.

  Sink Mobility: The information sinks can be mobile. For example, a human user requested information via a PDA while walking in an intelligent building. In simple cases, the mobile sink can receive the information from network at one point and complete the interaction before moving on. But in other complicated cases, consecutive interactions between sink and network will take place and be treated as separate and unrelated request. The network, with the assistance of the mobile sink, must make provisions that the information reaches the sink despite of its movement.

Event Mobility: The cause of the events or the objects to be tracked can be mobile like event detection. In these applications, it is important to make sure that the observed events are covered by a sufficient number of sensor nodes all the time. The sensor nodes around the object will wake up and send information to the Sink. When the object moves away, the nodes go back to sleep mode.

1.4 WSN Characteristics and Performance Merits

Same as traditional wireless networks, WSNs also use radio broadcasting to transmit information instead of wires. Thus the typical challenges in wireless network still remain in the design of WSNs. The feature of unstable wireless channel also affects WSNs and a trade off between power and quality of service (QoS) is required in the design of WSNs as well. However, WSNs distinguish themselves from traditional wireless networks in the following ways:

- Energy Driven: Different from traditional networks which aim to achieve high QoS, WSNs must focus on power conservation and energy efficiency. As shown in Figure 1.1, sensing, processing and transceiver units are all supported by the power unit. Due to the size limitation of sensor nodes, it is impossible to equip a large power supply. However, for some applications, like battlefield surveillance or mine monitor, it is very expensive or impossible to recharge or replace the batteries of sensor nodes. From this point of view, the design of WSNs should focus on energy efficiency and prolonging the lifetime of WSNs.

- Application Sensitive: The applications for which WSNs are used has a great impact on the design. Designs for delay-sensitive applications and non-delay-sensitive applications are quite different. The latter allows data aggregation inside networks. Furthermore, for different types of mobility as mentioned in section 1.3, the network should be designed to support different forms of mobility.

- Dense deployment: Cheap hardware of sensors makes it possible for densely deployment in the area of interest. Randomly and densely deployment of sensor nodes result in highly correlation among the traffic sent to the BS. Thus data aggregation is preferred in WSNs to eliminate data redundancy and reduce the amount of data that needs to be sent to the BS. A tremendous energy saving can be promised by data aggregation under some protocols and application scenarios.

All these features add into the design of WSNs some different elements from traditional networks and need to be taken into account in the design of WSNs. How to optimize network performance and how to choose a protocol that supports a given application well? These questions lead to the general merits of the performance of WSNs. However, considering the large variety of application scenarios, it is not possible to render to a simple answer but some aspects are fairly evident.

- Quality of service (QoS): Generally speaking, the quality requirements for WSNs are relatively low compared to conventional communication networks and highly dependent on the application scenarios. Higher quality of service results in more power consumption. If given the same power consumption for the same service, protocols which provide better QoS are preferred.

- Energy efficiency: Since energy is a precious resource in WSNs, much research has been done to improve the energy efficiency. Generally the measurements of energy efficiency are based on the following aspects: energy per correctly received bit, energy per reported event, delay/energy tradeoffs and network lifetime.

- System lifetime: A precise definition of the system lifetime depends on the application. Some definitions of wireless network lifetime are given in the following [3].

  1. Define lifetime as the time of the first node's failure.
  2. Define lifetime as the time of a certain fraction of surviving nodes in the network.
  3. Define lifetime in terms of the number of alive flows.
  4. Define lifetime as the time of the first loss of coverage.

  The first two are used more often in the research of WSNs. In this thesis we use the second definition of lifetime: the time of a certain fraction of surviving sensor nodes.

- Latency: The time delay between the moment something is initiated and the moment it is reported to the observer.

- Scalability: The ability to maintain the performance characteristics irrespective of the size of the network is referred to as scalability. Considerable research has been done to highly scalable protocols. Architectures and protocols should apply appropriate solutions for scalability rather than trying to be as scalable as possible.

- Robustness: The sensor network is expected to maintain its function despite some of the sensor nodes in the network running out of energy or the environment changing.

1.5 Development of WSNs

As early as the Cold War, the Sound Surveillance System (SOSUS) was deloyed at strategic locations to detect and track quiet Soviet submarines. Afterwards, some more sophisticated acoustic networks have been developed. These networks perform data processing at different levels and human operators lead a key role in the system [1].

The Distributed Sensor Networks (DSN) program at the Defense Advanced Research Projects Agency (DARPA) started the development of modern WSNs around 1980. The technology components for DSN were identified in the workshop in 1978. They included

Table 1.1: Generation of sensor nodes [1]

	1980-1990	2000-2003	current
Manufacture	Custom contractors, e.g. for TRSS	Commercial companies: Crossbow, Ember, Sensoria	Crossbow, Dust....
Size	Large shoe box and up	small shoe box	match box and coin size
Weight	Kilograms	Grams	Negligible
Node architecture	separate sensing, processing and communication	Integrated sensing, processing and communication	Integrated sensing, processing and communication
Topology	Point-to-point, star	Client server, mesh, peer-to-peer	peer-to-peer
Power supply lifetime	large batteries, hours, days and longer	AA batteries; days and weeks	Solar, months to years

sensors (acoustic), communication (high-level protocols that link processors working on a common application in a resource-sharing network), processing techniques and algorithms (including self-location algorithms for sensors), and distributed software (dynamically modifiable distributed systems and language design). By the end of 1980s, researchers from different institutes had achieved accomplishments in those research targets.

In 1980s and 1990s, the military sensor networks collected information through relatively large number of sensor nodes. The sensor network improved the detecting and tracking performance by multiple observations, geometric and phenomenological diversity, extended detection range and faster response time. Also the cost of deployment was reduced by using commercial networks and common network interfaces.

In the 21st century, the advances in computing and communication have addressed great development in sensor network research. DARPA started another research program to leverage the latest technological advances. The two main goals of this research focus on new networking techniques and network information processing.

With the development in the hardware, software and network technologies, current WSNs

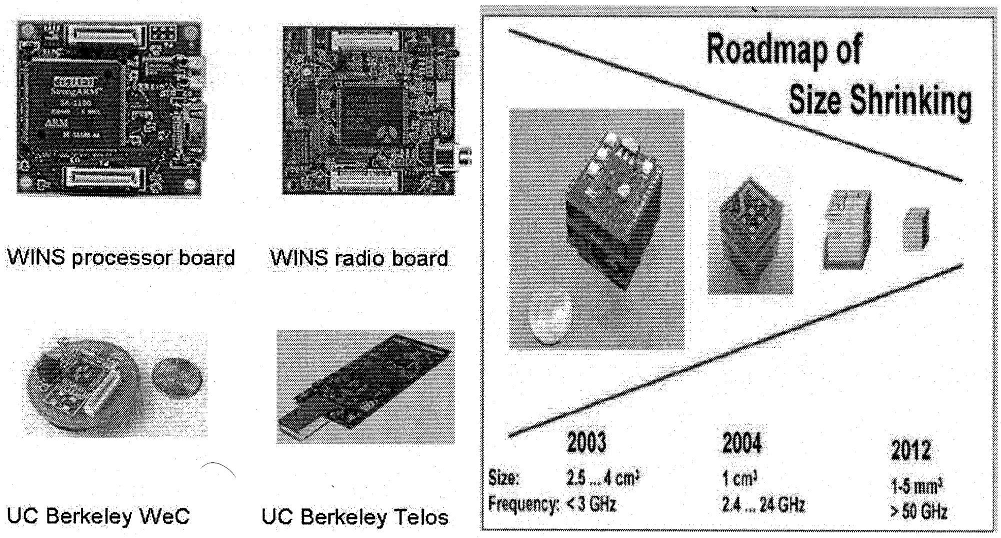

Figure 1.2: Road map of size shrinking

are used in various fields and perform functions that were not even dreamed of 20 years ago. Not only institutions but also commercial companies like Ember, Crossbow and Sensoria are building and deploying small sensor nodes and systems. Table 1.1 presents the generation of sensor nodes. Figure 1.2 shows the development in the size of the sensor nodes.

1.6 Challenges

The wide range of current and potential applications of WSNs calls for more research attention to improve the WSNs performance in all aspects from hardware to protocol design. However, designers are challenged by some issues like the unstable status of the wireless channel and energy imbalance problem. Tradeoffs among energy efficiency, latency, QoS are made to obtain a better global performance. The general research challenges in WSNs arise primarily due to the energy constraint and application oriented feature. The challenges of WSNs can be grouped as below.

- Energy constraints
- Unpredictability
- High density/scale

- Real-time
- Security

WSNs are expected to work for a long time but this is constrained by the energy resource. Generally sensor nodes are limited by size and cannot be equipped with large batteries. Therefore, all the designs of WSNs should satisfy the requirements of energy conservation. However, due to the wireless broadcasting feature, signals suffer from fading effects and much transmit power is required to guarantee a certain power level at the receiver. Thus energy efficient transmission schemes are crucial in WSNs. One of the research challenges in WSNs is to design an efficient transmission scheme that will reduce energy consumption without loss of BER performance. On the other hand, WSNs work as a whole system to fulfill tasks, thus the design of WSNs should take all aspects into consideration. Even though the transmission scheme reduces the energy consumption and the whole system power consumption is minimized, it might stop working properly if some sensor nodes run out of energy while others still have a lot remaining energy. This is possible if WSNs are not well designed and some sensor nodes have a much higher burden and run out of energy earlier than others and shorten the system lifetime as a result. Hence, energy balance is also an important factor in the design of WSNs.

As an efficient way to combat fading effect in wireless communication, diversity has been incorporated into WSNs to reduce energy consumption in the form of user cooperation. But how to efficiently apply cooperative transmission as well as to balance energy and how the system parameters affect the design of the transmission scheme remain as challenges in WSNs.

1.7 Outline

To meet the challenges pointed out in the previous section, energy efficiency and energy balance of WSNs are the main design goals in our research. In this thesis, cooperative transmission scheme is incorporated into cluster-based WSNs with energy balance considerations.

The effects of system parameters are thoroughly investigated in the pursuit of finding out the essence that determines the selection of cooperative transmission schemes. A unified criterion to choose cooperative transmission scheme under different system parameters is first proposed and an energy-balanced parameter-adaptable cooperative protocol is investigated.

The contribution of this thesis is that the impacts of parameters on the selection of cooperative transmission scheme is analyzed thoroughly. The criterion to select proper cooperative transmission scheme irrespective of the impacts of a single parameter is first proposed and an cooperative protocol for WSNs with energy balance considerations is proposed and investigated. The proposed protocol provides WSNs better performance in terms of energy balance and energy efficiency.

The rest of the thesis is organized as below:

- Chapter 2 introduces the background knowledge and evaluates the related work on the topic of energy-efficiency and energy-balance in WSNs.
- Chapter 3 analyzes the energy consumption in WSNs with cooperation, explores in depth about what parameters and how they influence the selection of transmission scheme. At the end of Chapter 3, a unified criterion that is essential to the selection of cooperation scheme in WSNs is proposed. Based on the conclusion in Chapter 3, an Energy-Balanced Parameter-Adaptable Cooperative Protocol (EBPACP) for WSNs is designed.
- Chapter 4 describes in detail the operation of the proposed EBPACP.
- Chapter 5 analyzes the energy consumption using EBPACP and presents the simulation results.
- Chapter 6 concludes this thesis and points out the future work.

Chapter 2

Background and Related Literatures

As mentioned in section 1.4, energy is a precious resource in WSNs. Therefore, different from traditional wireless networks which aim at high QoS, WSNs should be designed to be energy efficient and prolong the system lifetime as much as possible. How to design an energy-efficient WSN as well as fulfill the mission is a rich topic which attracts a lot of research interests. Much effort has been done in this area from different perspectives including organizations of system infrastructure [4, 5], transmission schemes [6, 7], routing [8, 9] as well as strategies for nodes deployment such as [10, 11]. Since energy efficiency is such a rich topic that it is impossible to cover all aspects in one research work, we mainly focus our effort on two aspects: infrastructure of the WSNs and transmission schemes. In our work, we organize the whole sensor network by grouping the sensor nodes into clusters and apply cooperative transmission to save energy.

Since WSNs share some common characteristics with traditional wireless networks and also remain some distinguished features of their own, designers of WSNs should not only reap the technical achievements in wireless networks but also apply novel ideas adapted to the features of WSNs.

One common feature of WSNs and other wireless networks is that the system performance is greatly affected by the instable of wireless channel. The wireless channel exhibits fading of different scales, from free space to the more volatile multi-path fading which greatly corrupts the received signal and degrades the system performance if left untreated. The model of free space propagation treats the region between receiver and transmitter as obstacle free, which indicates a clear, unobstructed line-of-sight path between them. Satellite communication systems and microwave line-of-sight radio links typically undergo free space. However, in some more practical cases, signal propagation takes place in the atmosphere near the ground. The signals have to go through multiple reflection paths to reach the receiver, which results in the fluctuations in amplitude, phase, and angle of arrival of the received signal. Although wireless channels are adversely affected by the fading effect, this feature presents the system designers both challenges and opportunities. Diversity emerges as an effective way to combat the fading effects and provides an opportunity for WSN designers to satisfy QoS requirement without much increase in transmit power. How to efficiently employ diversity in WSNs has emerged as a hot research topic in recent years.

Although diversity improves the system performance in terms of combating the fading effects along wireless channels, there exists an energy imbalance problem resulted from the network structure. If the nodes transmit information directly to the BS, those nodes far from the BS may drain out of battery much earlier than nodes close to the BS because much more energy is required to compensate for the long distance loss. On the other hand, in WSNs where multi-hop is adopted, sensor nodes close to the BS have a much heavier burden than nodes far from the BS. As mentioned in section 1.6, the energy imbalance problem is also a major factor that degrades the performance of WSNs and calls for appropriate measures to combat with.

There are many research topics in energy efficient design in WSNs. However, in our work, we focus on two aspects: the cluster structure from the network organization point of view and the cooperative transmission from the perspective of data transmission scheme. In this chapter, the background about the cluster structure, cooperative transmission in WSNs and energy imbalance problem are presented as well as related work in these fields, and then followed by the motivation of our work.

2.1 Energy Efficiency

2.1.1 Cluster Infrastructure

With the reduction of the cost of sensor nodes, dense deployment is more and more common in WSN application. Data from adjacent sensor nodes are highly correlated, but the observer only requires a high level description of the events occurring in the environment. The nodes can collaborate locally to reduce data that need to be transmitted to the observer. Highly correlation among data suggests the use of clustering infrastructure that allows adjacent nodes to remove the redundant data.

Among the work of cluster-based WSNs, LEACH (Low Energy Adaptable Clustering Hierarchy) [4] is one of the most fundamental and elegant protocol frameworks in literature. Much of the later work on WSNs either adopts LEACH protocol as a basis or makes modifications to LEACH to improve system performance. The operation of LEACH is divided into rounds which have two phases: the set-up phase and steady state phase. In the set-up phase, cluster heads are elected and clusters are organized. The cluster heads are selected based on a pre-defined probability related to the remaining energy. Sensor nodes with higher remaining energy are more likely to be selected as cluster heads since being cluster heads is much more energy consuming than normal nodes. Once the cluster heads are chosen, the other non-cluster head nodes choose the closest cluster head to join. After several interactions between sensor nodes and cluster heads, the clusters are formed. Each cluster head will create a Time Division Multiple Access (TDMA) schedule for its member nodes to transmit data. The set-up phase is over and then followed by the steady phase which is composed of frames. During one frame, sensor nodes collect data from environment, send them to their cluster heads during the allocated time slots and then turn to sleep mode to save energy. After collecting all the data from sensor nodes, cluster heads aggregate the data. Cluster heads communicate with the BS using a fixed spreading code and a Carrier Sense Multiple Access (CSMA) approach. When a cluster head has data to send, it will sense the channel to see if any other node is transmitting using the BS spreading code. If so, the cluster head waits until the BS is available. Otherwise, it will send the data using the spreading code. Once the cluster head has sent data to the BS, it will begin another frame. The steady phase will last until the end of a round. The system will go back to the set-up phase again. The role of cluster heads is rotated among sensor nodes to avoid heavy burden on any specific sensor nodes, and therefore, energy is to some extent balanced.

The cluster structure formed in LEACH has been widely employed and further improved by later research, for example [12–14]. A judicious cluster formation will benefit the system performance greatly in terms of energy efficiency.

2.1.2 Cooperative Transmission

If only an ideal additive white Gaussian noise (AWGN) channel and an interference-free system is considered, the primary factor that degrades the system performance is the thermal noise generated in the receiver. However, in most cases, the external interference received by the antenna overwhelms the thermal noise. For practical channels, signal propagation suffers from fading of different scales. A comparison of bit error rate (BER) versus signal to noise ratio (SNR) for AWGN and Rayleigh fading channels is shown in Figure 2.1.

From Figure 2.1, we observe that to achieve the same BER, Rayleigh fading channel requires much higher SNR compared with AWGN channel. For example, for a targeted BER of 0.001 when BSPK is used, a SNR of 6.8 dB for AWGN is needed while 24 dB for Rayleigh fading channel. This means to provide the same accuracy of service, about 53 times more energy is required under Rayleigh fading channel than under AWGN channel.

Diversity has been proven to be an effective way to combat the fading effects [15]. There are a wide range of diversity implementations, many of which are very practical and provide wireless link improvement at relatively low cost. The diversity techniques including space, frequency, polarization and time diversities [2].

In short, the diversity techniques in wireless communication improve the reliability of message signal by utilizing two or more communication channels with different characteristics and provide the observer several replicas to make a better decision. The advantage of

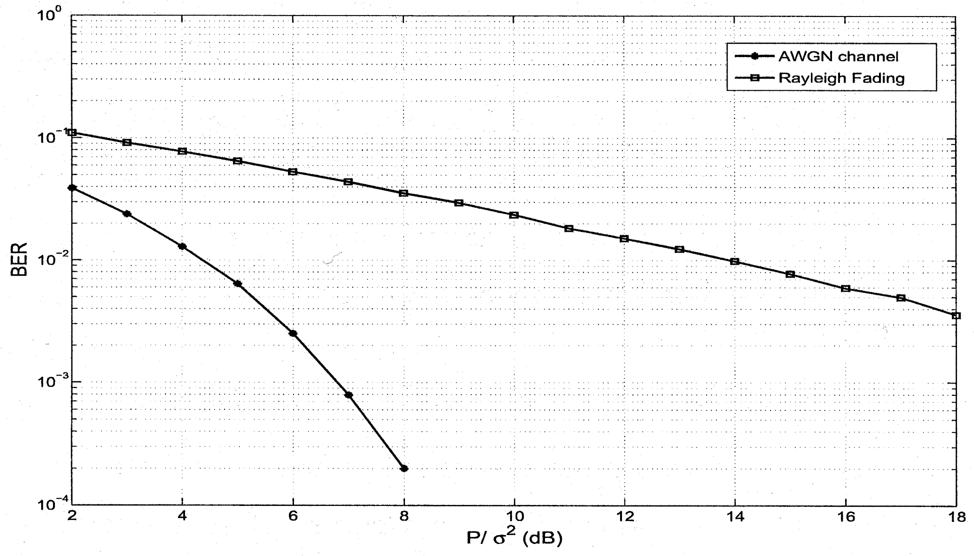

Figure 2.1: Comparison of BER vs. SNR for AWGN and Rayleigh fading channels [15]

diversity is shown in Figure 2.2. Diversity at the transmitter of an order of two is compared with non-cooperation scheme under Rayleigh fading channel. We observe from Figure 2.2 that for the same BER (e.g. 0.001), the SNR required for second-order transmit diversity (14 dB) is much less than that for no diversity (24 dB). The improvement in BER performance is evident when diversity is used given a certain power. From another perspective, for a targeted BER, much less transmission power is required for transmission with diversity than transmission without diversity.

As a type of space diversity techniques, multi-input multi-output (MIMO) technique emerges as a new trend by providing the system space diversity and benefiting the system performance in terms of higher capacity and higher data rate. MIMO technology has gone through significant development in recent years as shown in Figure 2.3.

Although space diversity is an obvious advantage for a cellular Base Station, it is impractical for WSNs since the sensor nodes are limited by the size. It is luxurious for sensor nodes to equip more than one antenna to obtain diversity gains. Thus a concept called cooperative transmission emerges and allows the single antenna mobiles to reap some of the benefits of MIMO systems. Cooperative transmission is capable of addressing the spatial

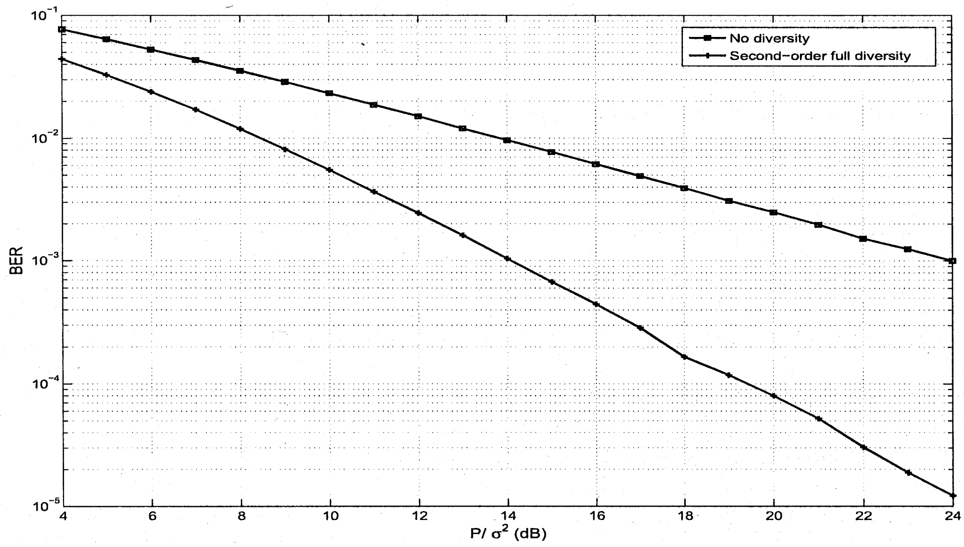

Figure 2.2: Comparison of BER vs. SNR for non-cooperation and second order cooperation under Rayleigh fading channels [15]

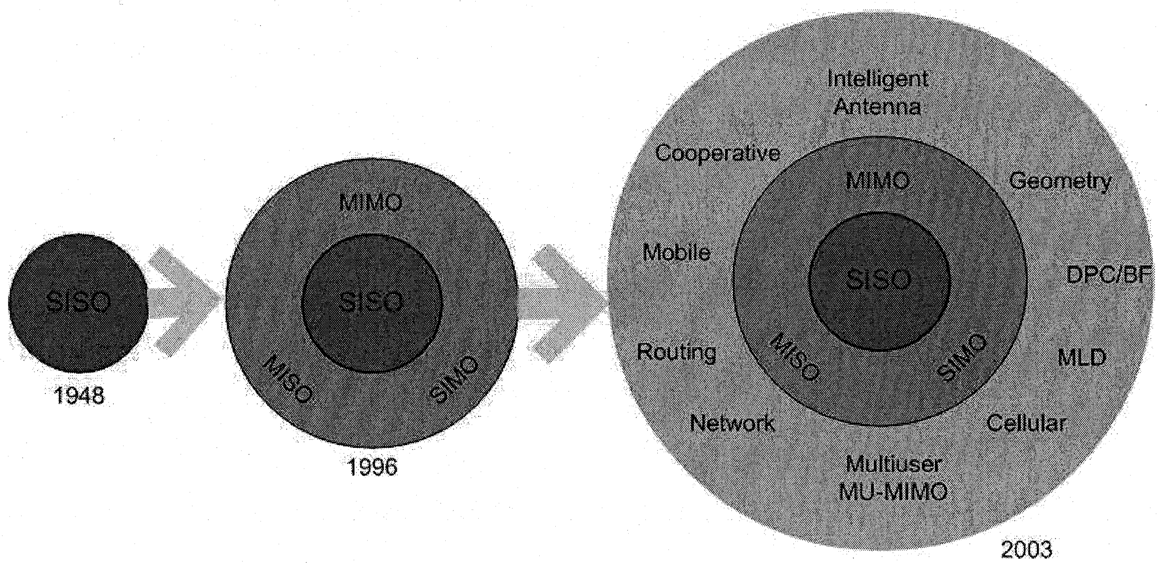

Figure 2.3: The development of MIMO technology

correlation and complexity issues inherent in MIMO systems by uniting some single antenna users, sharing their antennas and providing different channels. Figure 2.4 shows an example of two users transmitting to the destination in a cooperative manner. Different from relay model, cooperative users have their own information while serving as relays for their partners. As in [16, 17], each user firstly sends its data to the destination. Due to the broadcast feature of wireless communication, the other user can overhear the information sent by its neighbors. At the second stage, each user sends the overheard data to the destination for its partners. At the destination, it receives several different replicas from independent channels and can make a judicious decision about what is transmitted, and therefore diversity gain is achieved. There are mainly three types of cooperation [18]:

1. Detect and forward: A user attempts to detect the partner's bits and retransmits the detected bits.

2. Amplify and forward: A user amplifies the overheard data of its partner and retransmits them to the destination.

3. Coded cooperation: Different portions of each user's code word are sent via independent fading paths. It is a combination of cooperation and channel coding.

Cooperation addresses an advantage of combating fading effect by achieving diversity without extra antennas, which prompted the interest of incorporating cooperation into WSN design to improve the performance. Due to the unique features of WSNs we pointed out in Chapter 1, cooperation is a good fit to meet the challenges of WSN design. The following section will present some recent literature on the topic of cooperative communication in WSNs.

2.1.3 Related Work

Transmit diversity has been studied extensively as a method of combating impairments in wireless fading channels. It is pointed out in [19] that a MIMO system may support higher data rate without increasing transmission power. From another perspective, MIMO

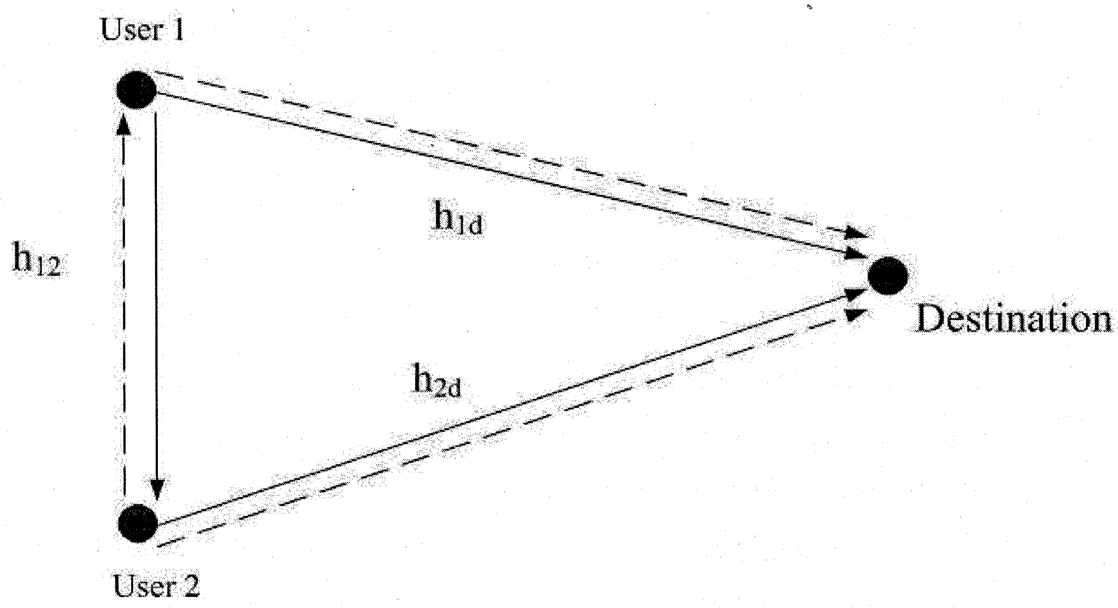

Figure 2.4: An example of cooperative communication

system requires less energy than SISO for the same throughput. Alamouti discovered a remarkable space time block coding (STBC) scheme for transmission that can achieve full diversity with two antennas [20]. This scheme supports maximum likelihood detection based on linear processing at the receiver. The simple structure and linear processing of Alamouti construction makes it an attractive scheme. This scheme was later generalized in [21] to an arbitrary number of antennas. However, in these schemes, multiple antennas are required, which is not practical for small-size users that can only afford one antenna. Cooperative transmission emerges as a way to help single antenna users to reap the benefits of diversity.

The basic idea of cooperative transmission dates back to 1979 in the groundbreaking work of Cover and Gamal in [22]. The authors analyzed the capacity of a three-node network including a source, relay and destination. Most of the ideas in the later literature on cooperative transmission were first proposed there. Cover and Gamal's work mainly focused on the capacity analysis in AWGN channel, while in practical case, signal propagation suffers from fading effects.

Sendonaris et al. implemented cooperative diversity in a wireless setting in [16, 17]. They used a basic model as shown in Figure 2.4 where Rayleigh fading channel between two nodes and AWGN at the receiver were assumed. They examined in CDMA system the case of channel phase information being available to transmitters. They demonstrated that cooperative diversity not only increases the sum-rate over non-cooperative transmission, even though inter user channel is noisy, but also promises a more robust system where users' achievable rates are less susceptive to channel variations.

Sendonaris et al.'s work in [16, 17] demonstrated the potential and advantages of cooperation in resource limited systems which inspired much of the recent activities in this area. Single-antenna users share their antennas to form a virtual MIMO system to generate space diversity to combat fading effect without extra equipment or much overhead. Due to its potential to improve system performance in terms of energy efficiency, channel capacity and QoS, cooperative transmission has been widely researched with an attempt to contribute to WSNs as in [23–28].

A closer look at energy comparison of MIMO and SISO techniques in WSNs was taken in [6]. The application of cooperative MIMO techniques in WSNs is considered based on overall energy consumption. The authors proved that there is a threshold of transmit distance, beyond which MIMO system is more energy efficient than SISO systems even though extra circuit energy consumption for MIMO is taken into consideration. MIMO system is then introduced into WSNs. Sensor nodes at the transmitter side firstly share their information with each other and then encode all the data into Alamouti codes to transmit to the destination. The simulation results show that if the long-haul transmit distance is larger than a certain threshold, a tremendous energy saving is promised by cooperative transmission.

Since cluster structure has been proven to be energy efficient, effort has been made to incorporate cooperation into cluster structure. The authors in [29] combined cluster structure and cooperative transmission together and studied the associated overhead. The synchronization problem is also addressed in his work. Although cooperative transmission has been studied mostly under assumption of perfect synchronization, the proposed virtual MIMO scheme based on STBC uses two [30] and more [29] cooperative sensors to provide diversity in WSN without antenna or transmission synchronization. Li also pointed out it is possible to achieve relatively low or negligible overhead in a cooperative WSN in [29].

In [7], the authors proposed a cluster-based cooperative MIMO scheme, which is called MIMO LEACH in the rest of this thesis, to reduce adverse impacts resulted by radio irregularity and fading in multi-hop WSNs. The sensor nodes are firstly grouped into clusters according to geographic locations. A cluster head is chosen based on the energy level in each cluster. The cluster heads collect data from the sensor nodes, aggregate the data and send back to the cooperative nodes. Then the cooperative nodes send the aggregated data using Alamouti or STBC code to the BS through multiple hops. The criterion to choose the cooperative nodes is also given. The authors formulated an optimization model to minimize the system energy based on the energy consumption model developed in [7]. Preferred number of cooperative nodes and number of multiple hops are found based on the optimization model. Simulation results exhibit that MIMO LEACH can effectively save energy and prolong network lifetime.

A semi-analytical method was developed in [23] to obtain the energy consumption of both virtual-MIMO-based and SISO-based sensor networks taking into account the effect of extra training overhead required in MIMO systems. The energy and delay efficiencies of the virtual-MIMO-based sensor network compared to a traditional SISO-based sensor network were computed using the techniques developed in this paper for different channel propagation conditions. The simulation results show that even with extra training overhead of MIMO systems, the virtual-MIMO-based networks can provide significant energy savings if judicious system parameters are used.

Besides the work of how to achieve good performance in cooperative WSNs, effort has been made on the selection of optimal cooperative scheme based on different scenarios like transmit distances. In [31], an optimal selection of cooperative MIMO schemes is proposed based on the energy consumption for different transmit distances. STBC codes are used to achieve maximum diversity for a given number of transmit and receive antennas. However, in [31] the authors only take the impact of transmit distances into consideration. A more thorough research is given in [24] on the topic of when cooperation has a better performance in WSNs. The total power required for a certain QoS requirement serves as system performance metric. Both analytical and numerical results reveal that there is a distance threshold, above which cooperative transmission is more beneficial than direct transmission while below the threshold direct transmission is more preferable. Impacts of parameters such as power amplifier efficiency are analyzed as well. However, the work of [24] stopped at the surface about how a single parameter changes the advantages of protocols and the analysis is limited to cooperation between two nodes. In case of two or more parameters change, the selection of the proper cooperative scheme remains unexplored.

2.2 Energy Balance in WSNs

Energy efficient protocol is important to the lifetime of WSNs, but it is not the only metric in the design of WSNs. There are other factors that should be taken into consideration such as energy balance. Although WSNs focus on whole system performance, the fairness among sensor nodes are not negligible [32–34]. It is important to distribute processing and communication activities evenly among the sensor nodes. Although the definitions of system lifetime vary with the application, the energy imbalance among sensor nodes will have an adverse impact on the system lifetime no matter what definitions are used and needs to be treated properly.

2.2.1 Overview

Heavy communication or processing burden in some of the sensor nodes may cause those nodes die early and therefore shorten the system lifetime. However, in most cases, it is unavoidable that some nodes take on more responsibility. In different application scenarios and protocols, there exists an energy imbalance problem as summarized in the following:

- **direct transmission WSNs:** No matter what kind of signal propagation model is used, the longer transmit distance is, the more transmit energy is required to communicate with the destination. If all the nodes communicate with the BS directly as shown in Figure 2.5, those sensor nodes far from the BS may run out of energy much

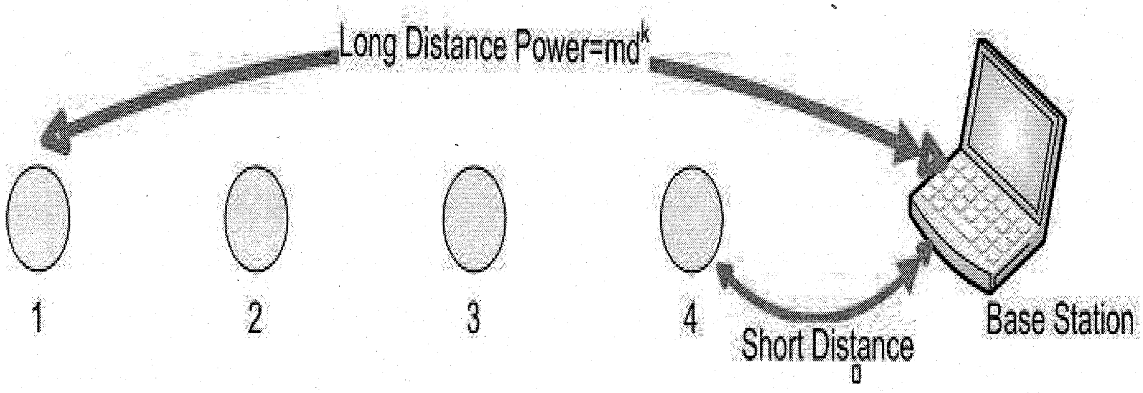

Figure 2.5: Energy imbalance problem for direct transmission

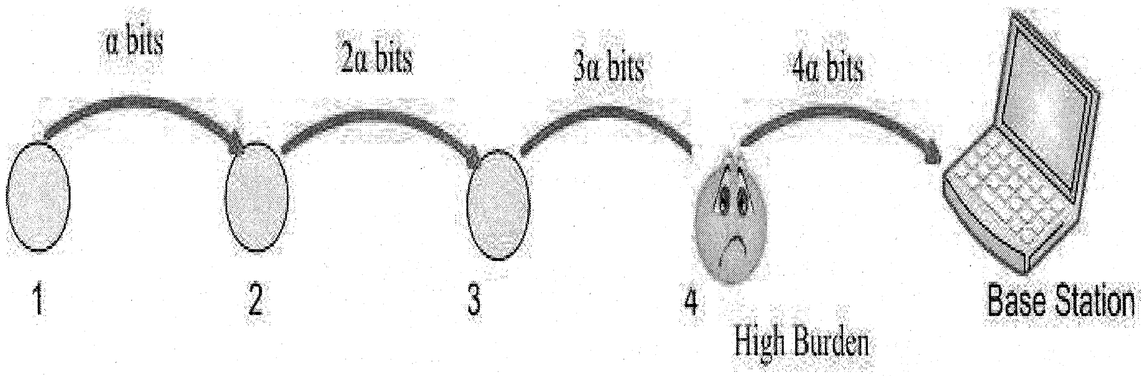

Figure 2.6: Energy imbalance problem for multi-hop transmission

quickly than those nodes close to the BS. If the lifetime of WSNs is defined as the running time until the first or a small fraction of the sensor nodes die, it may turn out that the WSNs stop working although most of the nodes close to the BS still have much remaining energy.

- **multi-hop transmission WSNs:** Multi-hop transmission serves as an effective way to avoid long-haul transmission which is quite energy consuming. However, it brings in new energy imbalance problem. In multi-hop WSNs, sensor nodes close to the BS receive data from nodes far from the BS and relay them to the BS. They consume much more energy than the distant nodes as shown in Figure 2.6. Multi-hop shifts the high burden from distant nodes to close nodes, which also leads to an energy imbalance problem.

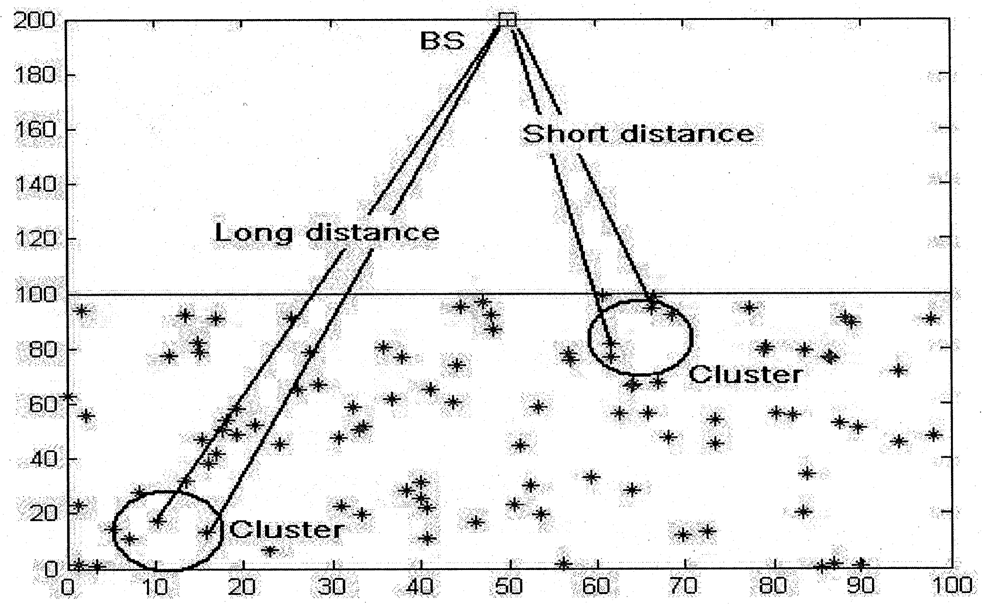

Figure 2.7: Energy imbalance problem for cluster-based WSNs

- **cluster-based WSNs:** In cluster-based WSNs, sensor nodes are grouped into local clusters and a cluster head is assigned to each cluster. Each cluster head collects data from its members, aggregates the data and then sends them to the BS. Cluster infrastructure takes advantage of data aggregation and significantly reduces the data transmitted through long distance to the BS. The cluster heads take most of the responsibilities such as data receiving, processing and transmitting. Although the roles of cluster heads are rotated among sensor nodes to balance the energy consumption, the energy imbalance problem caused by the differences in distance to the BS still exists. Since in most of cluster-based WSNs, self-configured clustering is applied, another factor that might result in energy imbalance is unequal cluster size. Nodes in the distant area drain out of energy earlier than those close to the BS. Cluster heads with more member nodes in their clusters consume more energy than their peer cluster heads which are of the same distance to the BS but with smaller cluster size. Figure 2.7 shows the energy imbalance problem in clustered-based WSNs.

- **cooperative WSNs:** As pointed out in [35], cooperative transmission contributes to the WSNs not only in the aspect of energy saving but also in energy balance. The differences in transmit energy between distant nodes and close nodes are reduced by cooperative transmission. However, the disparity still exists and will result in distant nodes running out of battery power faster. The same as cluster-based WSNs, the energy imbalance resulted from distance differences can not be eliminated and remain a threat to the system lifetime.

2.2.2 Related Work

In the previous section, it is shown that energy imbalance problem exists in different protocols and scenarios. Since the system lifetime is an important yardstick to measure the performance of system, much work has been done with an effort to balance energy consumption among all the sensor nodes in WSNs. Most of the efforts to balance energy are made mainly in two scenarios: chain-based scenario [32–34, 36] and cluster-based scenario [12, 35, 37–40].

In [32], an energy balanced chain was proposed in which the nodes' hop distances are actively controlled. A mathematical model is set up to formulate the preferred hop distances. Numerical results proved the advantage of energy balanced chain over traditional hop by hop transmission. In [33], the authors solved the energy imbalance problem by optimizing both the hop distance and traffic flow. The traffic distribution in this paper is based on stochastic model and therefore called stochastic based traffic distribution (SBTD), which achieves a complete balance by giving each sensor the flexibility of sending the data to the BS through any number of intermediate nodes. In this protocol, each node can choose to send some parts of its information to any intermediate nodes in the direction of the BS while the rest parts of information to the BS directly. Although this protocol balances the energy consumption among nodes, it is not applicable in practical application due to its complexity. The authors in [36] studied the problem of balancing the energy dissipation along multi-hop within a specific latency constraint. The goal of this paper is to balance the energy consumption with a full exploration of energy-latency tradeoffs. In [34], the authors investigate an optimization problem of transmission range distribution with considerations of varying transmission range as a function of distance to the destination and optimally distributing their traffic. Simulation results show that energy balance can only be achieved at the cost that some nodes are not used efficiently.

Besides chain-based WSNs, much effort has been made to balance energy consumption in cluster-based WSNs [12, 35, 37–39]. In [37], a concept called competition range is brought in. Sensor nodes eligible for cluster head compete with each other in its competition range. The competition range is related to the location of the node. In this way, unequal-sized clusters are set up in WSNs. Nodes far from the BS are grouped into relatively smaller cluster so that the cluster head spends less energy in data receiving and aggregating. The energy saved from local data processing will compensate for the energy spent on long-haul data transmission. On the other hand, authors in [12] applied multi-hop in WSNs so that the conclusion is quite different. Since multi-hop is applied in cluster-based WSNs, clusters close to the BS have heavier burden to relay information to the BS. Thus the competition range is smaller for those nodes close to the BS, which is opposite to the conclusion in [37]. In [35], cooperation is applied in WSNs, where the energy imbalance problem is relieved. Unequal cluster size is applied to further balance the energy consumption.

2.3 Motivation

Since cooperation brings to WSNs significant improvements in performance at relatively low cost, it has been widely investigated that how cooperation benefits WSNs most. Research in cooperative transmission covers wide topics such as the performance of cooperative transmission in multi-hop systems and cluster-based WSNs, tradeoffs of total energy consumption and latency and also whether and how cooperation benefits the system. However, due to the feature of highly application-dependence, the design of WSNs is related to the application scenarios and system parameters like the noise at the receiver, transmit distance and the channel conditions. Although the issue of impacts of parameters has already been addressed in some of the literatures, the research is limited in the effects of transmit distance. How the other parameters like BER requirement and power amplifier efficiency affect the selection of cooperative schemes remains unknown. More work should be done about how cooperation is affected by these parameters and how to design a parameter adaptable WSNs protocol. Moreover, little work has been done on the topic of energy balance in cooperative WSNs. In [39] the energy balance is considered in a cooperative cluster-based WSNs, or namely coalition-based as mentioned in [39], but the authors only carry out numerical analysis. Although cooperation contributes to energy balance to some extent by decreasing the transmit power and share the transmitting responsibility among more nodes as pointed out in [35], the energy imbalance problem resulted from the distance differences to the BS always exists, either for multi-hop or direct transmit.

Our work aims to design a parameter adaptable protocol for WSNs with energy balance considerations. We try to reveal the impacts of system parameters by carrying out a thorough analysis of how system performance changes with parameters. The results of what parameters and how they affect system performance will serve as a design guideline and lead to a judicious design of WSNs, such as when and how to cooperate in WSNs. Also, energy balance is a main consideration in our design. As pointed out in [34], energy balance can only be achieved at the expense that some of the sensor nodes are not efficiently used, which indicates a loss of overall energy efficiency. Therefore, in our work, we try to reduce the energy consumption differences among sensor nodes instead of absolute energy balance for each node.

Chapter 3

Energy and Analysis of Parameters Impacts

3.1 Energy Model

There has been a significant amount of research in the area of low-energy radios. Different assumptions about the radio characteristics, including energy dissipation in the transmitting and receiving models, will change the advantages of different protocols. Therefore, the application environment has a significant impact on the design of WSNs. In [6], the authors show that MIMO is not always beneficial to the system. Only when the transmit distance exceeds a certain threshold, will the energy saving promised by MIMO compensate for the extra energy spent on the circuits. In that case, MIMO is a judicious choice. It should be addressed that energy consumption in circuits and radio broadcasting has a significant impact on whether or when MIMO outperforms SISO. Therefore a precise energy model is essential in WSNs design to give accurate calculations about the energy consumption. In the following, the energy model used in this thesis is described in detail.

In the literature on the topic of WSNs design or study, there are mainly two energy models: first order radio model as applied in [4] and the other one proposed in [41] which is referred as block energy model in this thesis. The first order radio model is widely used in energy-related research in WSNs such as [12, 32, 34, 37–39]. However, in later literature that is related to cooperative transmission, block energy model is used more often such as [6,7,24,31,35,42]. In our research, we use the block energy model as a basis to analyze energy consumption in WSNs.

Block energy model uses link margin theory and breaks transceiver circuits into blocks to analyze energy consumption. Figures 3.1 and 3.2 show the signal path at transmitter and receiver respectively. The abbreviations and notations used in these figures are given in Table 3.1.

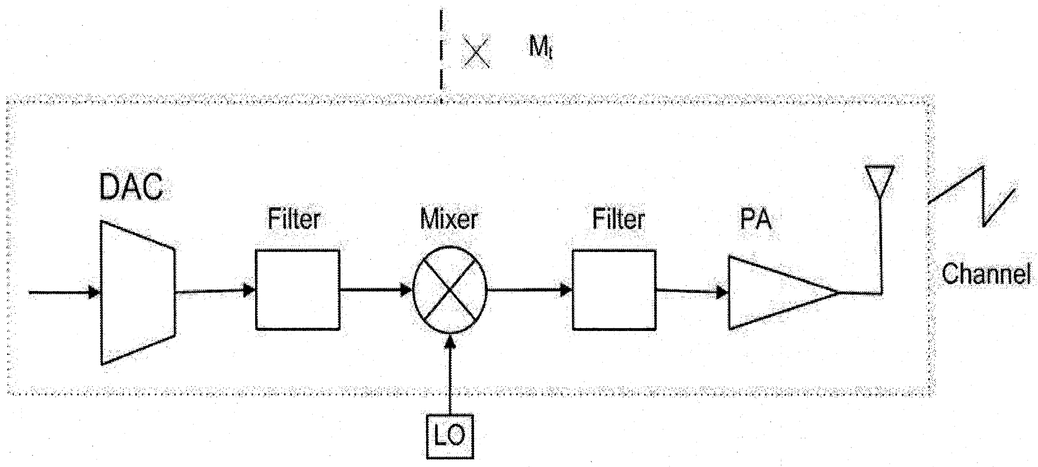

Figure 3.1: Transmitter circuit block

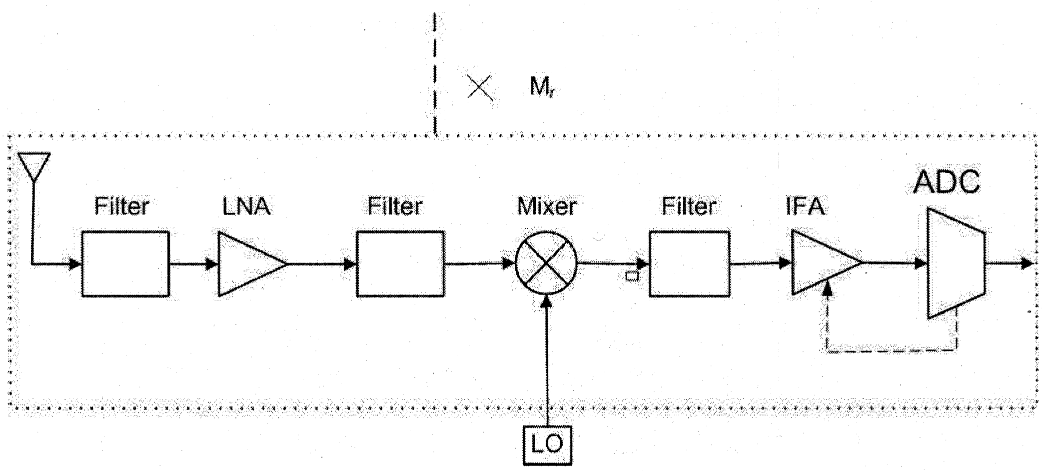

Figure 3.2: Receiver circuit block

For the signal at the transmitter, it goes through digital to analog convertor (DAC), filter, mixer, power amplifier and then broadcasts in wireless channel to reach the receiver.

Table 3.1: Abbreviations and notations in transceiver circuit blocks

Abbreviation	Meaning	Notation of Power consumption
DAC	digital to analog converter	P_{DAC}
PA	power amplifier	P_{amp}
LNA	lower noise amplifier	P_{LNA}
IFA	intermediate frequency amplifier	P_{IFA}
ADC	digital to analog converter	P_{ADC}
Filter	filter	P_{filt}
Mixer	mixer	P_{mix}
LO	Local Oscillator	
M_t	number of transmitter antenna	
M_r	number of receiver antenna	

At the receiver side, signal goes through filter, low-noise amplifier (LNA), mixer, intermediate frequency convertor and analog to digital amplifier (ADC). The power dissipated in transmitter and receiver circuits is given as

$$P_{ct} = P_{DAC} + P_{mix} + P_{filt} + P_{syn} \tag{3.1}$$

$$P_{cr} = P_{LNA} + P_{mix} + P_{IFA} + P_{filt} + P_{ADC} + P_{syn} \tag{3.2}$$

where P_{syn} is the power consumption at frequency synchronizer. Let P_{amp} denote the power consumption at power amplifier and P_{out} denote transmit power after power amplifier, the relationship between them is give as

$$P_{amp} = \alpha P_{out} \tag{3.3}$$

where $\alpha = \frac{\xi}{\eta} - 1$ is the efficiency of power amplifier with η the drain efficiency of the RF power amplifier [43] and ξ the peak-to-average ratio (PAR). The PAR is dependent on the modulation scheme and the associated constellation size [44].

Transmit power P_{out} is calculated according to the link budget relationship [2]. It is defined as:

$$P_{out} = P_r \times \frac{(4\pi)^2 d^{\kappa}}{G_t G_r \lambda^2} M_l N_f \tag{3.4}$$

where G_t and G_r are the gains of transmitting and receiving antennas respectively, λ is the wavelength of the carrier signal, κ is the path loss index, d is the distance between transmitter and receiver, M_l is the link margin, N_f is the receiver noise figure defined as $N_f = N_r/N_0$ with N_0 the single-sided thermal noise power spectral density (PSD) at the room temperature and N_r the total effective noise at the receiver input, P_r is the required power per bit at the receiver output for a given bit error rate (BER) requirement which is associated with average signal to noise ratio (SNR). The expression for SNR is different for different propagation models. Under AWGN channel without fading, SNR is written as

$$\bar{\gamma} = \frac{P_r}{BN_0} \tag{3.5}$$

where B is the bandwidth.

Under Rayleigh fading channel, the instantaneous SNR is written as

$$\gamma = \frac{h_i P_r}{BN_0} \tag{3.6}$$

where h_i is power gain for Rayleigh fading channel [45]. It follows exponential distribution with a mean value of H_i. Therefore, the average SNR can be derived as

$$\bar{\gamma} = \frac{H_i P_r}{BN_0} \tag{3.7}$$

Combining (3.5)-(3.7), the required power per bit at the receiver input can be written as

$$P_r = \begin{cases} \bar{\gamma} BN_0 & AWGN \\ \bar{\gamma} BN_0/H_i & Rayleigh \quad fading \end{cases} \tag{3.8}$$

In summary, the energy consumption of transmitting or receiving one bit for a fix-rate system can be obtained as in the following with R_b denoting the bit rate. The calculations of P_{amp}, P_{out}, P_{ct} and P_{cr} can be found from equations (3.1)-(3.8).

$$E_{bt} = \frac{P_{amp} + P_{out} + P_{ct}}{R_b} \tag{3.9}$$

$$E_{br} = \frac{P_{cr}}{R_b} \tag{3.10}$$

When different propagation models and channels are chosen, the required SNR at the receiver and the path loss index κ are different as well. Table 3.2 shows that the threshold of

Table 3.2: Average SNR threshold for AWGN and Rayleigh fading channels

BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}
Rayleigh	14 dB	24 dB	34 dB	44 dB
AWGN	4.3 dB	6.8 dB	8.3 dB	9.5 dB

Table 3.3: Path loss index for different environments [2]

Environment	Path loss index κ
Free Space	2
Urban area cellular radio	2.7-3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

SNR at the receiver varies a lot for the same BER for AWGN and Rayleigh fading channel. Under Rayleigh fading channel, the requirement of SNR at the receiver for the same targeted BER is much higher compared with AWGN channel. The path loss index κ varies with the propagation condition. Table 3.3 shows the path loss index for different environments in log-distance path loss model as an example.

There are several kinds of channels and propagation models which fit in with different application scenarios. The commonly used channel models include Rayleigh fading, Rician fading and AWGN. For the propagation model, free space, two-ray ground propagation and log-distance path loss model are often used. Since the power consumption of sensor nodes is highly dependent on the channel and propagation models, the choice of protocols for WSNs are quite application-dependent. In our research, we assume AWGN channel for local data transmission and Rayleigh fading channel for long-haul data transmission. This is widely adopted in the research as in [6, 7]. In the following section, we will summarize the energy consumption in WSNs where cooperative transmission is involved using this model.

3.2 Energy Analysis with Cooperation

In cooperative transmission, nodes share their information among partners and cooperatively transmit the information to the BS. In this way, diversity gains are achieved so that the SNR threshold for a certain BER requirement at the receiver is reduced. As a consequence, sensor nodes do not need as much power as non-cooperative transmission.

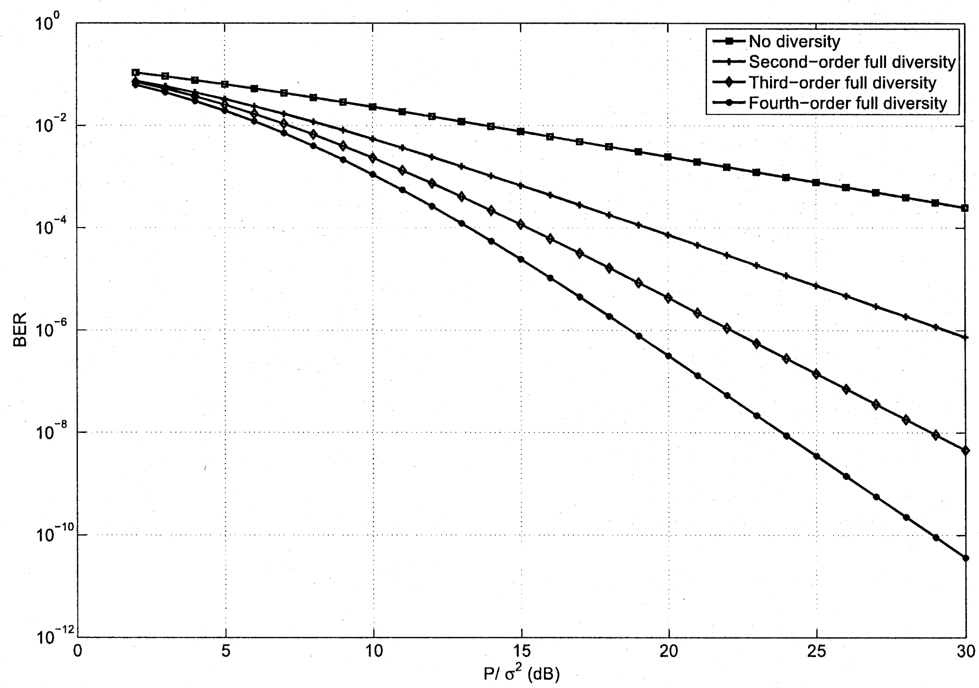

Figure 3.3: Performance of binary signals with diversity (BPSK)

Figure 3.3 shows the BER-SNR relationship for different orders of transmit diversity where BPSK is used. It indicates that the required SNR for a targeted BER decreases greatly with the increase in the number of transmit antennas. Higher order of transmit diversity promises higher BER given the same transmit power, or namely, less power consumption for the same targeted BER performance. But this improvement slows down with the increase in the number of transmit antennas. For example, for a targeted BER of 0.001, second-order transmit diversity requires a SNR of 14 dB while 11 dB and 10 dB for third-order and fourth-order transmit diversity respectively. If we measure the energy saving gain from second-order to third-order as the SNR decrease, which is 3 dB, the energy saving gain from third-order to fourth-order is only 1 dB. By contrast, the energy saving gain from no diversity to second-order transmit diversity is almost 10 dB. But if taking circuit overhead into consideration, it is not always beneficial to increase the number of transmit antennas since circuit energy consumption in receiving and transmitting will increase as a consequence. Only when the energy saved by diversity outweighs the energy dissipated in circuits and other training overhead, is diversity beneficial to the system in terms of energy efficiency.

It is pointed out in [46] that cooperative transmission can achieve full diversity. In [6] and [7], the authors assume full diversity in cooperative WSNs and using Chernoff bound to estimate the required SNR for different orders of cooperation. However, it is also pointed out in [6] that this bound is too loose to give an accurate analysis in cooperative transmission. Therefore, we use numerical results to find the required SNR for different orders of cooperation. We use the energy model mentioned in the previous section and use κth path loss propagation under Rayleigh fading channel. For energy analysis in cooperative transmission, we focus on the total energy dissipation by taking all the cooperative nodes as a whole instead of simply considering energy consumption of a single sensor node. For simplicity, we only consider direct transmission in this thesis, and our work can be extended to multi-hop as well. Since the BS is usually considered as not power-limited, we have not taken the energy consumption at the BS into consideration. Using the equations of (3.9) and (3.10), the energy consumed for transmitting one bit with J cooperative nodes is given as:

$$E_b(J,d) = (1+\alpha)\frac{J\bar{\gamma}(J)(4\pi)^2}{RG_tG_r\lambda^2}N_0M_lN_fd^{\kappa} + \frac{JP_{ct}}{RR_b} + \frac{JP_{cr}}{R_b} \tag{3.11}$$

where J is the number of cooperative nodes and $J = 1$ corresponds to non-cooperative transmission, R_b is bit rate, $\bar{\gamma}(J)$ is the required SNR at the receiver for a targeted BER. The more nodes get involved in the cooperative transmission, the smaller $\bar{\gamma}(J)$ is. R is the code rate defined as $R = F/L$, given F symbols transmitted in L symbol durations. On

Table 3.4: Parameters

$P_b = 10^{-3}$	$N_f = 10\ dB$	$\frac{N_0}{2} = -174\ dBm/Hz$
$G_tG_r = 0.5\ dBi$	$f_c = 2.5\ GHz$	$\alpha = 1.47$
$R_b = 10\ kbps$	$P_{ct} = 98.2\ mW$	$P_{cr} = 112.6\ mW$
$M_l = 40\ dB$	$k = 3$	$R = 0.5$

the other hand, more cooperative nodes indicate more energy consumption in circuits. Thus there exists an optimal number of cooperative nodes which will promise a minimum energy consumption given other parameters fixed.

3.3 Analysis of Parameter Impacts

It is pointed out in [6] that cooperation is not always beneficial to the system performance. When the transmit distance is larger than a threshold, the energy saving promised by cooperation surpasses that dissipated in circuit and cooperation is preferable in terms of energy efficiency. However, transmit distance is not the only parameter that affects the performance of cooperation. From (3.11) we observe that there are many other parameters that affect the performance of cooperation besides distance. Using the parameters listed in Table 3.4, the energy consumption over transmit distance for different numbers of cooperative nodes are presented in Figure 3.4

With the increase of transmit distance, the preferred number of cooperative nodes goes up as well. However, for different parameters the preferred number of cooperative nodes varies a lot even for a fixed transmit distance. The parameters that have effects on the performance of cooperation are listed in the following.

Parameters that affect circuit energy consumption:

- R_b: Bit rate is a system parameter which is basically decided by the symbol rate and bits carried in each symbol. It varies at a wide range of values from 10 kB to 1 MB for different types of application scenarios and sensor nodes. It plays a key role in the energy consumption. As in equation (3.11), it does not change the transmit energy per

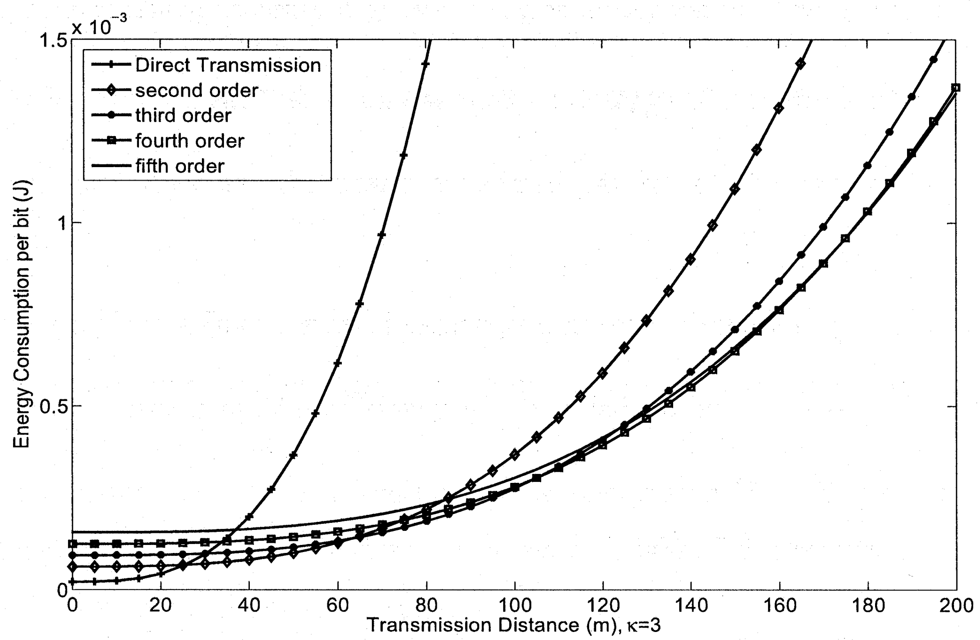

Figure 3.4: Energy consumption over distance for different orders of cooperation

bit but has a significant effect on the receiver energy consumption.

- P_{ct} and P_{cr}: They are the power consumed per bit at the circuit transmitter and receiver.

Parameters that affect transmit energy consumption:

- α: It is the power amplifier efficiency which is defined by $\alpha = \frac{\xi}{\eta} - 1$.

- BER requirement: Though it does not appear in equation (3.11) directly, it determines the threshold of power received at the receiver. Higher BER requirement indicates a higher power threshold at the receiver.

- κ: It is the path loss index during propagation which greatly affects the power loss during propagation. Larger κ corresponds to worse propagation channel condition. To achieve the same power at the receiver, higher transmit power at the transmitter is required for larger κ.

- N_0: It is defined as single-sided power spectral density of the AWGN at the receiver. Its value varies greatly for different scenarios. For instance, it is $-174\ dBm$ in [6] while $-134\ dBm$ in [7]. In case other parameters remain fixed, this $40\ dB$ difference in N_0 significantly changes how cooperative transmission performs.

- h_i: It is the power gain for Rayleigh fading channel. It follows exponential distribution with a mean value of H_i. It affects the value of instantaneous SNR since $\gamma = \frac{h_i P_i}{N_0 B}$. The average SNR can be derived as $\bar{\gamma} = \frac{H_i P_i}{N_0 B}$.

Parameters that affect total consumption:

- J: It is the number of cooperative nodes. It affects both the transmit power and receive power.

- R: It is the code rate. It is defined as F/L where F is the number of symbols and L is the symbol duration. It affects the transmit power and transmitter circuit power. Receiver circuit energy consumption remains unchanged despite the changes of R.

All these parameters play a role in the performance of cooperation. How do those parameters affect system performance? Are they of the same importance? Is there a unified element that summarizes all the impacts? With these questions, we did some simulations to reveal the roles of those parameters in the cooperative performance.

We vary one of the system parameters listed in Table 3.4 but keep the rest of them fixed to observe the impacts of the chosen parameter. The parameters we use are the same as those in [6] and have been widely adopted in the literature.

In order to compare the performance of cooperation, we define Cooperation Gain as a criterion to quantize the performance. Cooperation Gain, denoted as CG, measures the energy saved by cooperation over non-cooperation and is defined as:

$$Cooperation\ Gain\ (CG) = \frac{e_{non} - e_{coop}}{e_{non}} \tag{3.12}$$

where e_{non} is the energy consumption if non-cooperative transmission is used and e_{coop} is the energy consumption if two sensor nodes cooperatively transmit. From the definition of CG

Table 3.5: SNR requirement over Rayleigh fading channel

BER	10^{-2}	10^{-3}	10^{-4}	10^{-5}
Direct	14 dB	24 dB	34 dB	44 dB
J=2	9.5 dB	14 dB	19 dB	24 dB
J=3	8.9 dB	12 dB	15 dB	18.7 dB
J=4	7 dB	11 dB	13.5 dB	16 dB

we observe that CG is a number less than 1 and different ranges of it indicate how the performance of cooperative transmission is when compared with non-cooperative transmission.

- $CG > 0$: Cooperative transmission outperforms non-cooperative transmission.
- $CG = 0$: Cooperative transmission equals to non-cooperative transmission.
- $CG < 0$: Cooperative transmission is worse than non-cooperative transmission.

The parameters we choose are: P_b, κ, R_b, α and σ^2. We are also in pursuit of a high quality, parameter adaptable protocol for WSNs with the knowledge of how those parameters affect the system performance. The following gives the energy consumption with different parameters and how the advantages of cooperative transmission changes with these parameters.

Table 3.5 gives the SNR threshold for different BER requirements with different numbers of cooperative nodes under Rayleigh fading channel. The values in this table are based on numerical simulation. From Table 3.5 we observe that the more stringent BER requirement is, the more transmit power is required at the receiver. And the increase in the number of cooperative nodes decreases the required SNR for a targeted BER. In the simulation, we use the values in Table 3.5 as the required SNR at the receiver to calculate energy consumption in WSNs. The following figures 3.5-3.9 show the impacts of those parameters on the system performance.

Figure 3.5 shows how CG changes with the requirement of BER. CG goes up with the increase of transmit distance apparently. When CG exceed 0, it indicates that cooperation

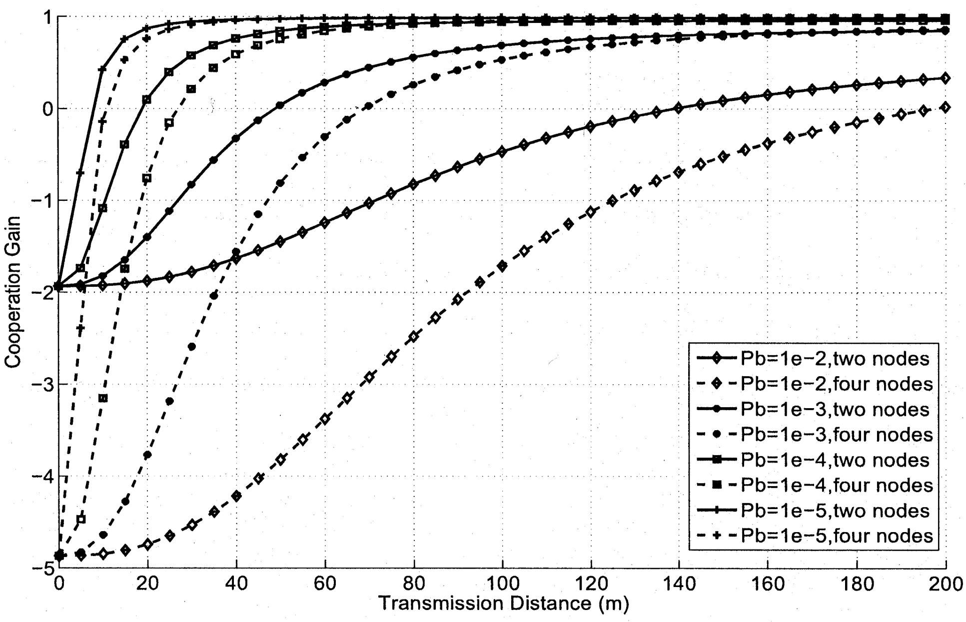

Figure 3.5: The impacts of BER requirements

is more energy efficient than non-cooperative transmission. Higher BER requirement gives priority to cooperative transmission at a relatively shorter distance. The CG of four cooperative nodes is smaller than that of two cooperative nodes when transmission distance is short. But this difference becomes smaller with the increase of transmit distance. When transmit distance exceeds a threshold, four cooperative nodes will outperform two cooperative nodes since the energy saved from cooperation compensates for the energy dissipated in circuits and control overhead.

Bit Rate (R_b) has a significant impact on the energy consumed by the transceiver circuits. As shown in Figure 3.6, less energy per bit is consumed in transceiver circuit for higher R_b, and therefore cooperative transmission is preferred at a relatively short distance.

The path loss index κ mainly depends on the propagation channel and environment. As listed in Table 3.3, κ varies from 2 to 6, which greatly changes the advantages of cooperative transmission and non-cooperative transmission as shown in Figure 3.7.

Figures 3.8 and 3.9 show the impacts of the noise power of the AWGN at the receiver

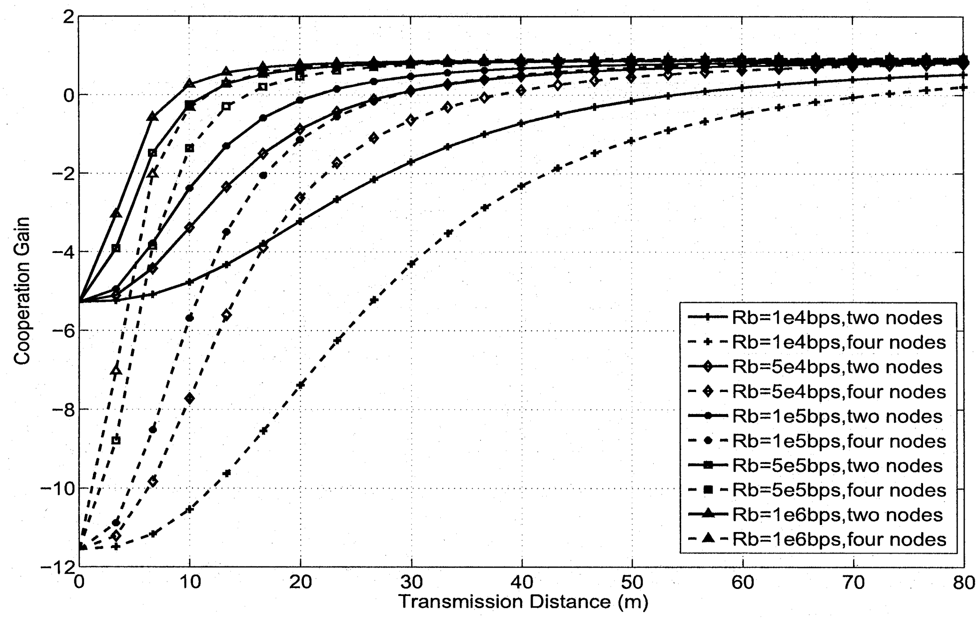

Figure 3.6: The impacts of bit rate

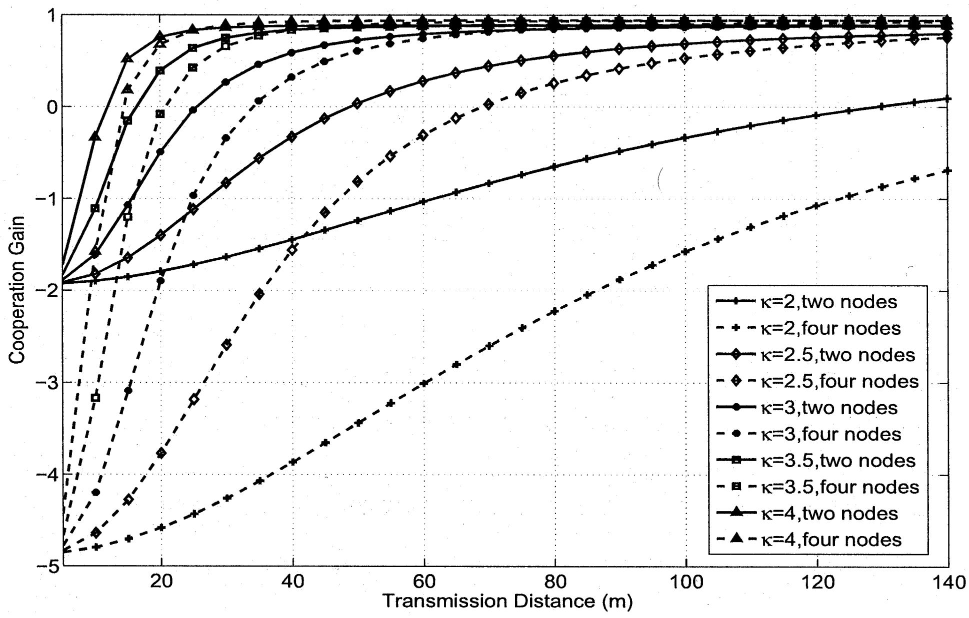

Figure 3.7: The impacts of path loss index κ

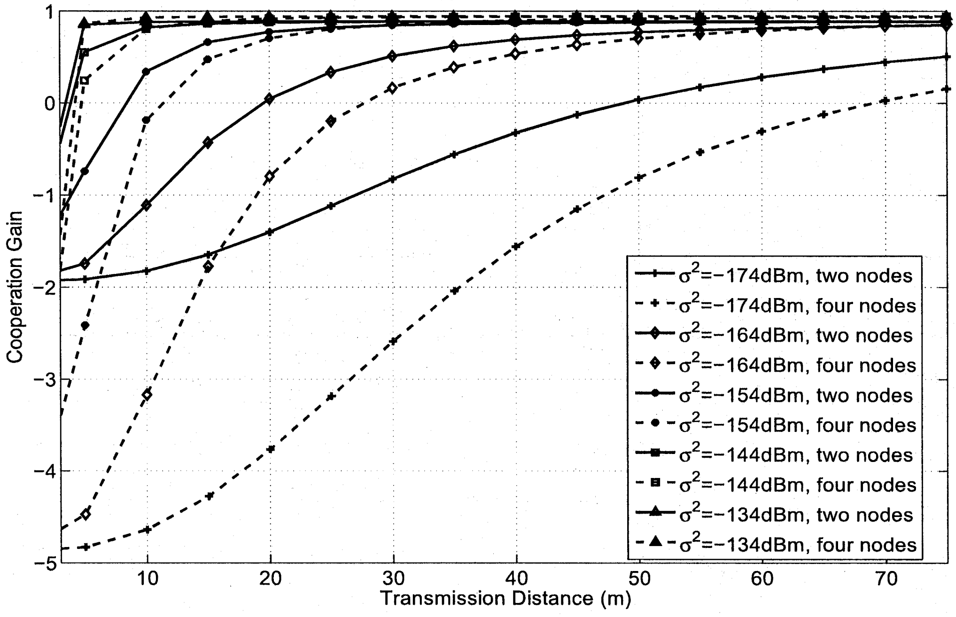

Figure 3.8: The impacts of noise power σ^2

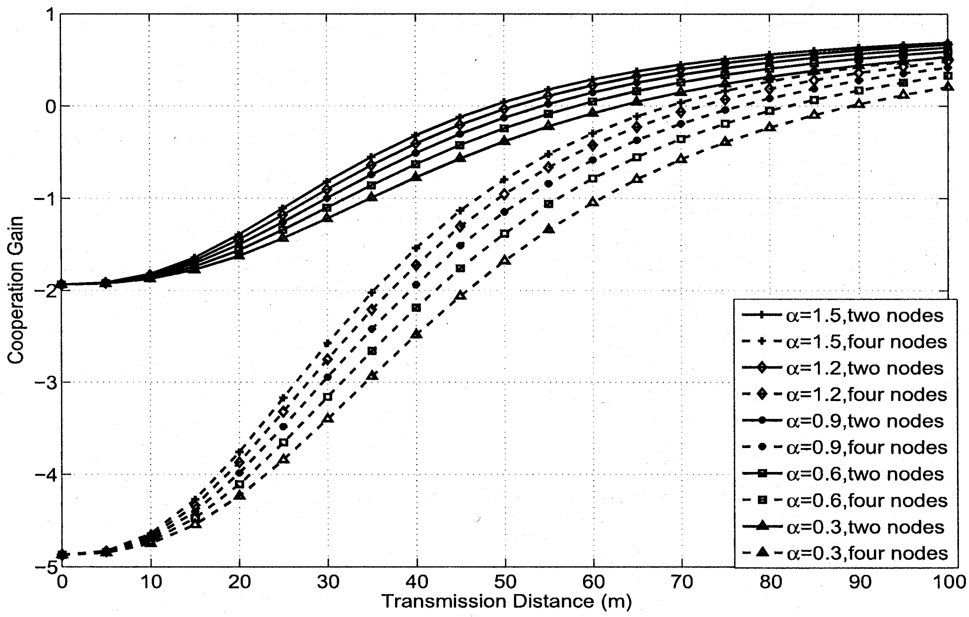

Figure 3.9: The impacts of α

and the power amplifier efficiency at the transmitter respectively.

Although these parameters all affect the advantages of cooperative transmission and non-cooperative transmission, the overall impacts of them are not clear. How is the system performance influenced if two or more parameters change? Is there a unified criterion that can reflect the effects of all the parameters? From the results of Figures 3.5-3.9, we observe that how parameters affect the advantages of cooperation is related to whether they change transmit power or circuit power. If the change of one parameter increases the transmit power, it will stress the advantage of cooperation. On the other side, if the change of the parameter increases circuit power consumption, it stresses the advantage of non-cooperation. Hence it comes to the conclusion that the ratio of transmit power over the circuit power determines whether cooperative transmission outperforms non-cooperative transmission or not. When the circuit power weighs more, the cooperative nodes will add in more circuit power consumption which surpasses the energy saved in transmit power by cooperation. If the transmit power weighs more in the total consumption, energy saved by cooperative transmission will cover extra energy dissipated in circuit consumption.

We define two coefficients: transmit power coefficient C_t and circuit power coefficient C_c. They are related to the transmit power and circuit power respectively and are give as

$$C_t = (1+\alpha)\frac{(4\pi)^2}{RG_tG_r\lambda^2}M_lN_0N_f \quad (3.13)$$

$$C_c = \frac{P_{ct}}{RR_b} + \frac{P_{cr}}{R_b} \quad (3.14)$$

With the definition of C_t and C_c, we rewrite (3.11) as

$$E_b(J,d) = C_tJ\gamma(J)d^{\kappa} + JC_c \quad (3.15)$$

where $J = 1$ denotes direct transmission. In order to explore the performance of cooperation, we simulate the energy consumption from one node transmission to ten nodes cooperative transmission. The ratio of transmit power coefficient C_t over circuit power coefficient C_c varies from 3.5×10^{-7} to 3.5×10^{-2}. Table 3.6 presents the preferred number of cooperative nodes for different transmit distances and ratios of C_t over C_c. It shows that when the

Table 3.6: The optimal number of cooperative nodes

$\frac{C_t}{C_c}$ \ Distance	10 m	20 m	30 m	40 m	50 m	60 m	70 m	80 m	90 m	100 m
3.5×1e-7	1	1	1	1	1	2	2	2	3	4
3.5×5e-6	1	1	1	2	2	2	3	4	4	5
3.5×1e-5	1	1	1	2	2	3	3	4	5	5
3.5×5e-5	1	1	2	2	2	4	4	5	5	5
3.5×1e-4	1	2	2	2	3	4	4	5	5	5
3.5×5e-4	1	2	2	3	3	4	5	5	5	5
3.5×1e-3	1	2	2	3	4	5	5	5	5	5
3.5×5e-3	2	2	2	3	4	5	5	5	5	5
3.5×1e-2	2	2	3	4	4	5	5	5	5	5

transmit power weighs a higher ratio in the total consumption compared with circuit power, more cooperative nodes are preferred. Table 3.6 will serve as a guideline for us to choose the preferred cooperation scheme. The ratio of C_t over C_c can be treated as the unified criterion to choose whether cooperation or not and how many cooperative nodes. In the next chapter, we will present a parameter-adaptive protocol based on this unified criterion.

Chapter 4

Energy-Balanced Parameter-Adaptable Cooperative Protocol (EBPACP) for WSNs

As mentioned in the previous chapter, the ratio of transmit power over circuit power will change the advantage of cooperation and non-cooperation. As a result, whether cooperation or not and how many cooperative nodes are preferred are subject to change with the ratio. This will consequently change the ratio of long-haul transmit power over local transmit power. As in traditional LEACH protocol, the size of cluster is determined mainly by the ratio of power dissipation in long-haul transmission over local transmission. In cooperative WSNs, since the transmit scheme is different from traditional non-cooperative WSNs which are mainly based on LEACH, the design of WSNs has changed as well. New protocols are needed to fit the features of cooperative WSNs about how to determine the number of clusters, how to form the clusters and how to transmit data to the BS. In EBPACP, we will explore the design of a parameter-adaptable protocol in cluster-based cooperative WSNs with energy balance consideration.

EBPACP is a hybrid protocol for WSNs which combines both traditional clustering infrastructure and cooperative transmission into WSNs. Therefore, EBPACP not only remains some traditional ideas of WSNs design but also brings in new elements. Since individual nodes share a lot of common information, it is not necessary to send all the related information to the BS which is quite energy consuming. In most cases, it is necessary to apply local data processing to remove redundant information. Therefore we choose clustering structure as a basis of EBPACP where local data processing is performed and redundant data is removed to save energy used for long-haul communication with the BS. Similar to LEACH, in EBPACP, sensor nodes organize themselves into clusters and each cluster has a cluster head. Sensor nodes firstly transmit data to the cluster head where local data processing is performed according to the application requirements. For the next step, different from LEACH protocol in which the cluster head transmits the processed data to the BS directly, in EBPACP each cluster head will form a cooperative relationship with other cluster heads based on certain criteria and communicate with the BS cooperatively. The operation of EBPACP is divided into rounds with an initial phase at the very beginning of the operation when some global information is shared between the BS and sensor nodes. Each round starts with a set-up stage during which cluster heads are elected, clusters and cooperative relationships are formed. This is then followed by a data transmission stage when the cluster heads collect data from their members, aggregate the data and then communicate with the BS in a manner of cooperation. The operation of EBPACP will be explored in detail in this chapter.

4.1 Initial Stage

After the sensor nodes are deployed randomly in the area of interest, some global information should be shared among the sensor nodes and the BS. At first, the BS keeps broadcasting a welcome message with high power so that all the sensor nodes are able to receive this welcome message. The welcome message includes the location of the BS and a request of location and energy level of each sensor node. The sensor nodes that receive this welcome message will respond to the BS with information of its location and energy level. This stage lasts until the BS no longer receives any information from new member sensor nodes. Then the initial stage ends and the operation stage begins, which is divided into rounds.

4.2 Set-up Stage

The set up stage of EBPACP has three steps: cluster head selection, cluster formation and cooperative relationship buildup. Since WSNs is resources-limited and system lifetime is critical to the performance of WSNs, we target our design at an energy-efficient and energy-balanced network. The set-up stage is important to the whole network performance since a judicious formation of clusters will greatly improve the energy efficiency in WSNs. In EBPACP, we maintain the idea of rotating cluster heads. It balances the energy consumption among all the sensor nodes since they take turns to take the responsibility of cluster heads which is energy consuming. EBPACP further balances the energy for both distant and close sensor nodes with the help of weighted distance which takes factors that influence energy balance into consideration. Moreover, in EBPACP both the cluster formation and cooperative relationship buildup keep energy efficiency as a target with an adaptability to the system parameters.

We assume a network of N sensor nodes randomly distributed in a $M\ m \times M\ m$ area. The definitions of some symbols used in the rest of this chapter are given in the following.

- RP: The notation of reference point. RPs are the centers of equal geographical divisions of a WSN.
- K: The number of clusters in the WSNs.
- $d_{BS}(i)$: The distance of the sensor node i to the BS.
- Node_ID: A number assigned to each sensor node to distinguish from each other. It is a number from 1 to N given N sensor nodes in the WSN.
- Cluster_ID: A number assigned to a cluster to distinguish from each other. Cluster_ID is a number from 1 to K given K the total number of clusters. Since around each reference point a cluster head is selected and a cluster is formed, this Cluster_ID is also the ID of cluster head and reference point of this cluster.

- $d_{rp}(i,k)$: The distance from sensor node i to reference point k.
- $d_{ch}(i,k)$: The distance from sensor node i to cluster head k.
- J: The preferred number of cooperative nodes. In EBPACP, the value of J can be found using the criterion described in Chapter 3.
- $E_{re}(i)$: The remaining energy of sensor node i.
- $E_{BS}(i)$: The energy required for sensor node i to communicate with the BS.

4.2.1 First Stage: Cluster Head Selection

We assume there are K clusters in the WSN. The cluster heads selection should satisfy the requirement of energy efficiency. This means the location of the cluster heads should be as distributed as possible across the whole network so that the expectation of local transmission energy is minimized. On the other hand, the cluster head bears the higher burden of local data collection, aggregation and long-haul communication with the BS. Since it is highly energy consuming to be a cluster head, only sensor nodes with enough energy should be selected as cluster heads. In the original LEACH, the cluster heads are selected based on a probability that is related to the remaining energy E_{re}. However, it is very likely to lead to an undistributed deployment of cluster heads that there are too many cluster heads in one area and few in other areas. Some other schemes are proposed to find a better selection of the cluster heads. For instance, simulated annealing algorithm is used to find K optimal clusters. Some other schemes choose cluster heads based on a random probability or load balance rather than power conservation. These schemes are either too complicated or suboptimal in terms of power conservation. In [40] the idea of reference points is introduced to help find K optimal cluster heads. With the help of reference points, it is possible to meet the requirements that the cluster heads are distributed evenly, the shape of clusters is regular and the sum of power consumption is small. The idea of reference points is illustrated in Figure 4.1. The WSN is divided geographical evenly into K regions and the reference points are the center of each region. Actually these reference points act as the preferred locations of the cluster heads since they are distributed evenly across the WSN and the expectation of the sum of square distances between sensor nodes and the cluster head is minimum [40].

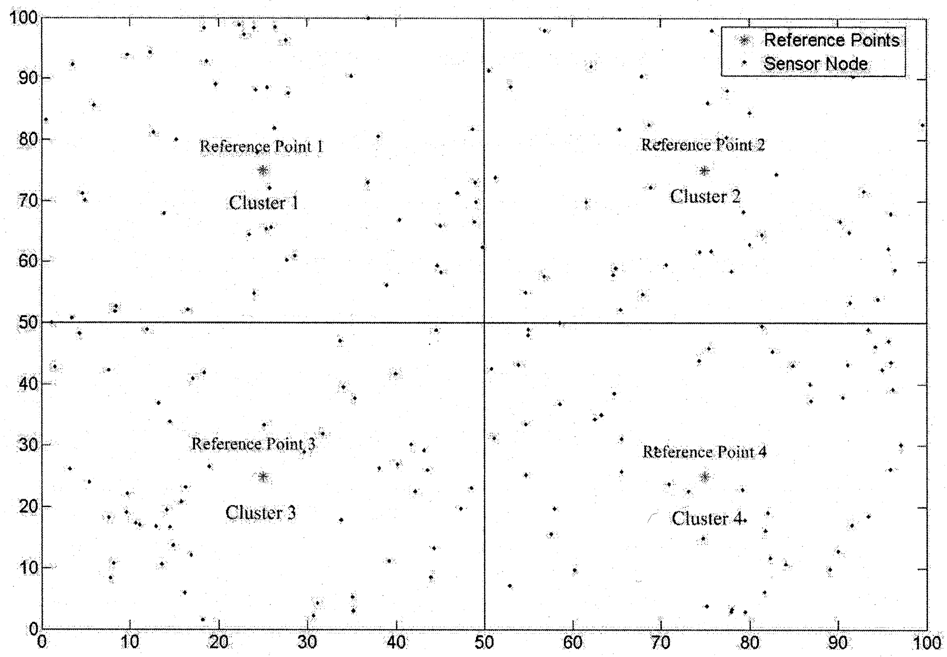

Figure 4.1: Reference points

At the initial stage, the BS sends the location of reference points to all the sensor nodes. Each sensor node calculates its distances to all the reference points. In [40], the BS sorts all the sensor nodes based on the distance of sensor nodes to one reference point and the sensor node nearest to the reference point is preferred to be the cluster head. If the nearest sensor node either has been the cluster head in the previous rounds or is lack of enough energy, then the second nearest one to the reference point is selected. This procedure continues until a qualified sensor node is found for the reference point and then goes on to another reference point. However, whether the sensor node has become a cluster head in the previous rounds or not is not important in the cluster head selection. Our target is to minimize the total energy consumption of the whole network and balance the energy consumption among the sensor nodes, so it is not necessary to make each sensor node become the cluster head the same times. We refine the cluster head selection scheme with the help of competition factor. Since the cluster head is the most energy consuming role and the reference points are located in the preferred locations of cluster heads, we assign each sensor node a competition factor, denoted as $\zeta(i,k)$ for sensor node i to compete to be cluster head around reference point k. The sensor nodes with the highest ζ value for reference point k is selected as the cluster head. The competition factor ζ is defined as:

$$\zeta(i,k) = (0.5 \times \frac{d_{rp}(i,k) - min(d_{rp}(:,k))}{max(d_{rp}(:,k)) - min(d_{rp}(:,k))} + 0.5) \times E_{re}(i) \tag{4.1}$$

where $E_{re}(i)$ is the remaining energy of node i, $min(d_{rp}(:,k))$ and $max(d_{rp}(:,k))$ are the minimum and maximum values of distances from sensor nodes to reference point k. ζ takes both distance to the reference point and remaining energy into consideration. Sensor nodes compete with each other by sending the value of ζ to the BS. The BS decides the cluster head for reference point k by choosing the sensor node with the highest ζ. Then the BS will send back to all the sensor nodes with a small message conveying the information of the node_IDs, cluster_IDs and locations of the cluster heads. After receiving the information from the BS, each sensor node knows whether it is the cluster head or not and then goes to the next stage of cluster formation. The pseudo code of cluster head selection is shown in Figure 4.2.

4.2.2 Second Stage: Geographic Distance Based Cluster Formation

If a sensor node is chosen as a cluster head, it will keep broadcasting an advertisement to the whole network to attract sensor nodes to join it. The broadcast power for this advertisement is the same for all the cluster heads and should be set relatively high so that all the sensor nodes in the network can hear. Since this is a small message, it will not consume much energy. Because the broadcasting power of all cluster heads is the same, the non cluster head sensor nodes can estimate the distances to all cluster heads and keep these distances in $d_{ch}(i,k)$ as sensor node i to cluster head k. Then each sensor node chooses the cluster head closest to it and sends a joining message conveying its node_ID, cluster_ID and location. The cluster

```
Algorithm 1: Cluster Head Selection
1: Elig=ones(1,N);
2: for i=1:N
        for k=1:K
              d_rf(i, k) = distance of node i to reference point k;
        end
   end
3: for i=1:N
      for k=1:K
              ζ(i, k) = (d_rp(i,k) - Min(d_rp(:,k))) / (Max(d_rp(:,k)) - Min(d_rp(:,k)))
      end
   end
4: for k=1:K
      t=1;
      [a b] = sort(ζ(:,k));
      while Elig(b(t)) ! =1
          t = t+1;
          end
      CH = [i, b(t)];
      Elig (b(t)) =1;
  end
```

Figure 4.2: Pseudo code of cluster head selection

head k counted the number of its cluster members $Num(k)$ and the preferred cooperative nodes $J(k)$ at its location and sends these information to the BS. The first step of cluster formation is finished. This stage is the same as traditional LEACH or other cluster-based WSNs that form clusters by their geographic distances.

As pointed out in Chapter 2, although the energy imbalance problem is relieved by cooperative transmission, the energy imbalance problem resulted by different distances from the BS still remains and harms the performance of WSNs. Sensor nodes located far from the BS may die out earlier than those close to the BS since they have to dissipate more energy to communicate with the BS as shown in Figure 2.7. In EBPACP we apply unequal cluster size where the clusters far from the BS is allocated a smaller cluster size so that it spends less energy in receiving or aggregating data, which will compensate for the energy consumed for long-haul communication. On the other hand, the sensor nodes are deployed randomly and it is very likely that sensor nodes are more densely deployed in some ares than other areas. One consequence of this is that some cluster heads have more sensor nodes than others. This kind of unequal cluster size is not desired and we should try to avoid it. Taken these factors into consideration, in the third stage, we form the cluster using weighted distance instead of simply geographic distance, which efficiently relieves the energy balance problem.

4.2.3 Third Stage: Weighted Distance Based Cluster Formation

The basic purpose of weighted distance is to adjust the cluster size to achieve an energy-balanced WSN. Cluster heads having heavier burden in long-haul data transmission form smaller clusters to save energy dissipated in inside cluster data processing. We use the help of weighting factors to form unequal cluster size. The larger the weighting factor is, the longer weighted distance will be. In this way, coefficients will adjust weighted distances from sensor nodes to cluster heads and therefore adjust the size of clusters.

To calculate weighted distances, the BS firstly collects the information of how many sensor nodes are there in each cluster. Then it will calculate the first weighting factor C_1 for all the cluster heads as defined in the following.

$$C_1(k) = \frac{Num(k) - min(Num)}{max(Num) - min(Num)} \tag{4.2}$$

where k is the ID of the cluster, $min(Num)$ and $max(Num)$ are the minimum and maximum numbers of member nodes in clusters. This weighting factor is designed to reduce the different receiving energy of the cluster heads. Since the sensor nodes are randomly distributed in the WSN, there may be some cluster heads with a lot of sensor nodes while some others have relatively few sensor nodes. In this case, clusters with more sensor nodes will have a higher burden on the cluster heads. This kind of unequal cluster size is harmful to the WSN performance and should be avoided. From the definition of parameter C_1, we observe that C_1 is a normalized value from 0 to 1 and $C_1(k) \propto Num(k)$. The more sensor nodes a cluster has, the larger C_1 is.

On the other hand, as we discussed in Chapter 3, the transmit distance to the BS affects the energy balance. Sensor nodes far from the BS dissipate more power in the transmitter to achieve the same SNR at the receiver due to the fact that signal strength attenuates with distance. Therefore, clusters far from the BS prefer a smaller cluster size so that the energy consumed for local data receiving and aggregating are smaller compared with clusters close to the BS. Hence another factor that influences energy balance is the energy consumption differences resulted from the distance. The more energy is consumed to communicate with the BS, the smaller the cluster size should be to save energy consumed in local data processing. Taken this factor into consideration, the other coefficient, C_2, is proportional to the energy consumed to communicate with the BS. The more energy required for long-haul data transmission, the larger C_2 is. The energy to communicate with the BS is dependent on the preferred number of cooperative nodes and the distance to the BS. Firstly we define $KD(k)$ to denote energy consumption to communicate with the BS.

$$KD(k) = \gamma(J(k))d_{BS}(k)^{\kappa} \tag{4.3}$$

where k is the ID of the cluster. Here we use the location of the cluster head to represent the average information of the cluster, which is reasonable since the cluster head is usually located in the middle of the cluster. $d_{BS}(k)$ is the distance from the cluster head k to the BS. The distance can be treated as the average distance from the BS of the cluster. $J(k)$ is the preferred number of cooperative nodes for the distance from cluster head k to the BS. The value of $J(k)$ can be found according to the conclusion in Chapter 3. The second weighting factor C_2 is defined as

$$C_2(k) = \frac{KD(k) - min(KD)}{max(KD) - min(KD)} \tag{4.4}$$

From the definition of C_2, it is clear that the value of $C_2(k)$ is proportional to $KD(k)$. Then the BS sends these two weighting factors C_1 and C_2 to all the sensor nodes. Each sensor node will calculate the weighted distances to all the cluster heads based on the following formula.

$$d_{ch2}(i,k) = (m_1C_1(k) + m_2C_2(k) + m_3) \times d_{ch}(i,k) \tag{4.5}$$

where $d_{ch2}(i,k)$ is the weighted distance between the sensor node i and cluster head k, m_1, m_2 and m_3 are constant coefficients between [0,1] with the constraint that $m_1+m_2+m_3 = 1$. If $m_1 = m_2 = 0$, it is the same as the distance in the first round. These constant coefficients should be carefully chosen to give a good system performance. If at the first stage of cluster formation, the density of sensor nodes is high in vicinity of some cluster heads but low in the others, the cluster head will spent more energy in receiving and aggregating data in its cluster. This defect is remedied in EBPACP. Weighting factor C_1 is proportional to the number of sensor nodes in one cluster. The more members cluster head k has, the longer weighted distance the sensor nodes to it, and therefore, less sensor nodes will join it. The other weighting factor C_2 takes the long-haul transmit energy into consideration. Since our goal is to balance the energy by assigning different size to clusters according to the energy consumed to communicate with the BS. Cluster heads consume more energy to communicate with the BS are assigned smaller size. Energy saved from inside-cluster data processing compensates for energy to communicate with the BS. m_1, m_2 and m_3 are constant coefficients which reflect the weight of each factor. Generally m_3 counts for the geographical distance which is an important factor to determine the distance. Hence m_3 cannot be set to 0. m_1C_1 and m_2C_2 serve as a remedy that help a better cluster formation. m_1C_1 remedies the defect of uneven sensor deployment problem that is harmful to WSNs and m_2C_2 leads to unequal cluster size to balance energy.

In the second stage of cluster formation, the distances from sensor nodes to cluster heads are lengthened or shortened according to the energy balance criteria. It should be noticed that this energy balance is not absolute energy balance since the WSNs should be treated as a whole instead of single sensor node performance. In [34] it is pointed out that absolute fairness among sensor nodes are only achieved when some nodes are inefficiently used. The preferred number of cooperative nodes is found based on the criterion defined chapter 3 with the energy efficiency consideration. Moreover, the weighting factors and preferred number of cooperative nodes vary with the system parameter. When the deployment of sensor nodes is not randomly but carefully planned, the first weighting factor will not contribute much so that m_1 could be assigned a small value or even set to 0. If the BS is located very far compared with the coverage area of the WSN or no multi-hop is used, the energy difference between the distant sensor nodes and close nodes are not evident and m_2 could be assigned a smaller weight so that it will not affect much on the cluster formation. The preferred number of cooperative nodes is also subject to change with the system parameters. This adaptable scheme is easy to realize with some simple calculations and small control messages.

With the weighted distance, each sensor node chooses their closest cluster head and replaces the one chosen at the first round. Then each sensor node sends a joining message to its cluster head with its node_ID, cluster head_ID, location, E_{BS}, and E_{re}. The cluster heads receive joining messages from their members and record this information. After each cluster head receives all the joining information from its members, it will create a TDMA schedule for its members to communicate with it and sends this information back to all its members. The cluster formation is finished at this time. This stage is illustrated in the flow chart in Figure 4.3.

4.2.4 Fourth Stage: Cooperative Relationship Formation

In EBPACP, the cluster heads form a cooperative relationship to communicate with the BS together. Since this cooperative relationship is among clusters and each cluster head may have a different number of preferred cooperative nodes, the optimal cooperative relationship may either not exist or too complicated to realize. From another perspective, finding cooperative partners is in fact to group the cluster heads to cooperate, which forms a higher hierarchical level of clusters. Thus the problem of cooperative relationship formation can be treated as how to group the cluster heads to minimize the total energy consumption with a BER guarantee. We name the formation of cooperative relationship among cluster heads as region formation. Cluster heads grouped into one region transmit to the BS cooperatively.

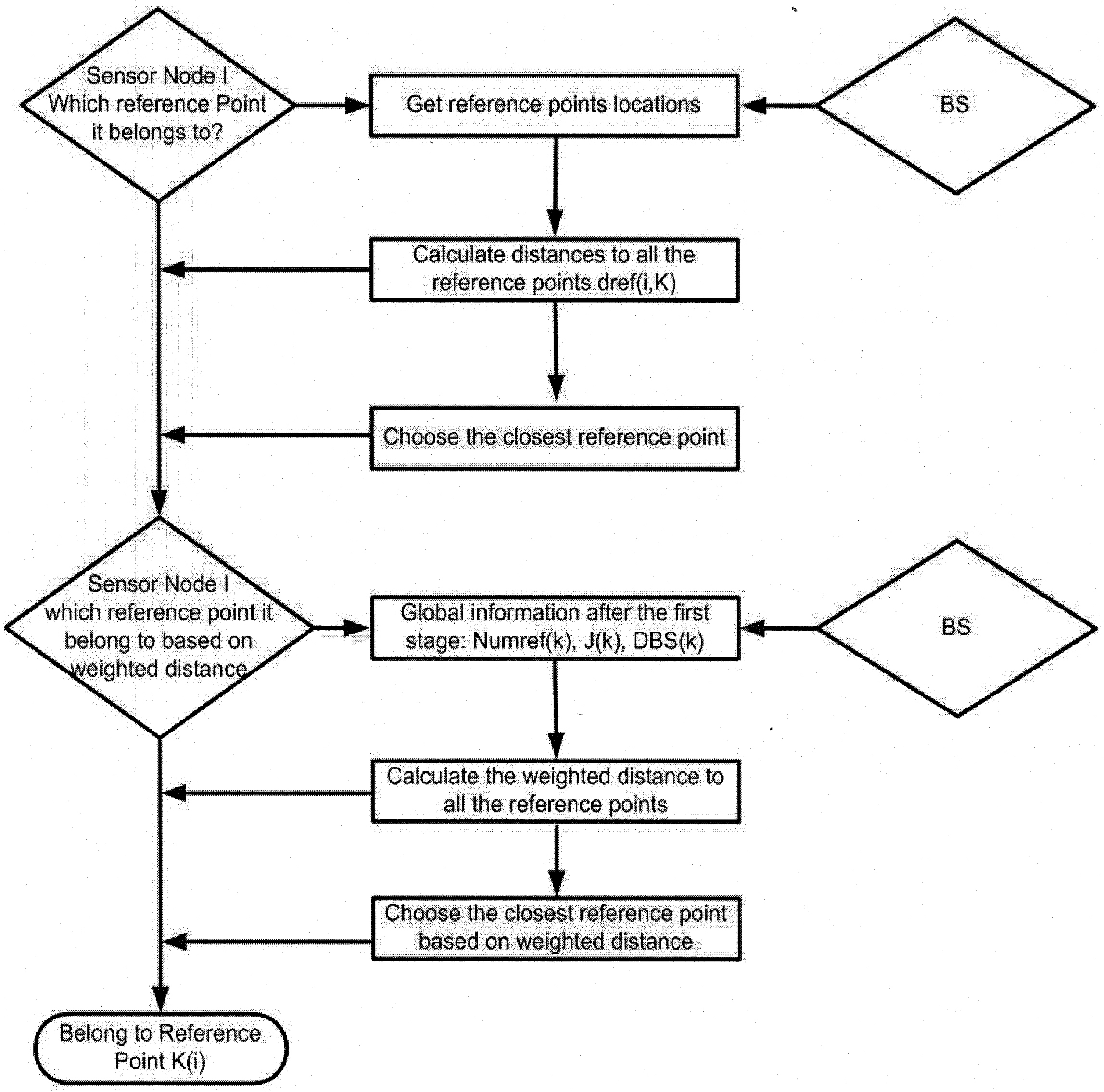

Figure 4.3: Flow chart of cluster formation

For the ideal region formation, cluster heads grouped into one region are expected to be close to each other and share the same preferred number of cooperative nodes. This may not be feasible since the preferred number of cooperative nodes varies for different nodes. Due to the fact that the total number of cluster heads is fixed, it may not be able to form regions with the number of cluster heads which is also the number of preferred cooperative nodes for all the cluster heads in one region. Since an optimal region formation is infeasible, we turn to suboptimal region formation which is easier but also maintain a good performance. The number of preferred cooperative nodes is determined by the distance to the BS and the ratio of circuit power over transmit power as shown in Table 3.6. For the sensor nodes in one WSN, we can treat the ratio of circuit power over transmit power the same for all the sensor nodes since they share the same system parameters. Therefore, the only factor that determines the preferred number of cooperative nodes is the distance to the BS. For cluster heads that close to each other, their preferred numbers of cooperative nodes either equal to each other or vary a little bit as we observe from Table 3.6. Therefore, the BS will group the cluster heads close to each other into one region with the condition that the number of cluster heads in the region is close to the average preferred number of cooperative nodes. The formation of cooperative relationship is in Figure 4.4.

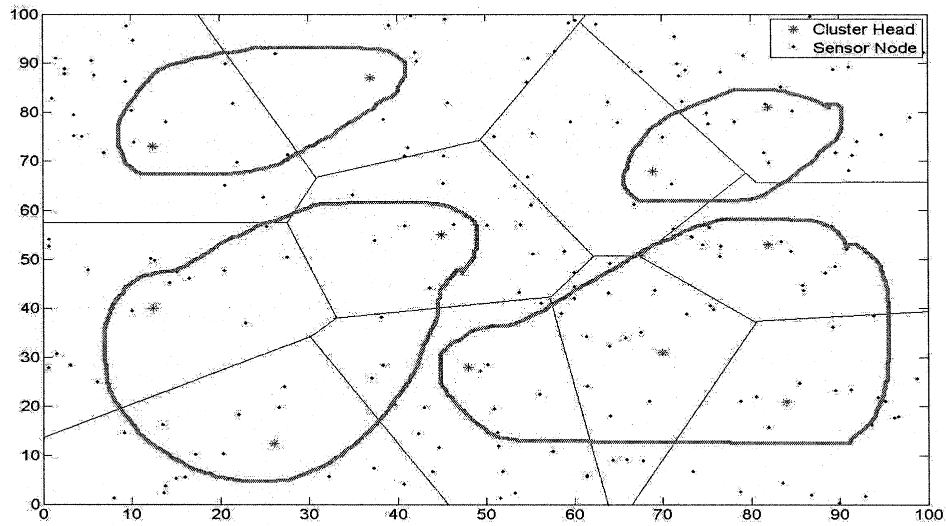

Figure 4.4: Cluster cooperative relationship formation

4.3 Data Transmission Stage

At the data transmission stage, sensor nodes send data to the cluster heads where data aggregation is taken place. Then the cluster heads share the aggregated information with their cooperative partners and create STBC codes for cooperative transmission. The cluster heads that are responsible for long-haul data transmission communicate with the BS in a cooperative manner. Figure 4.5 shows the operation of data transmission.

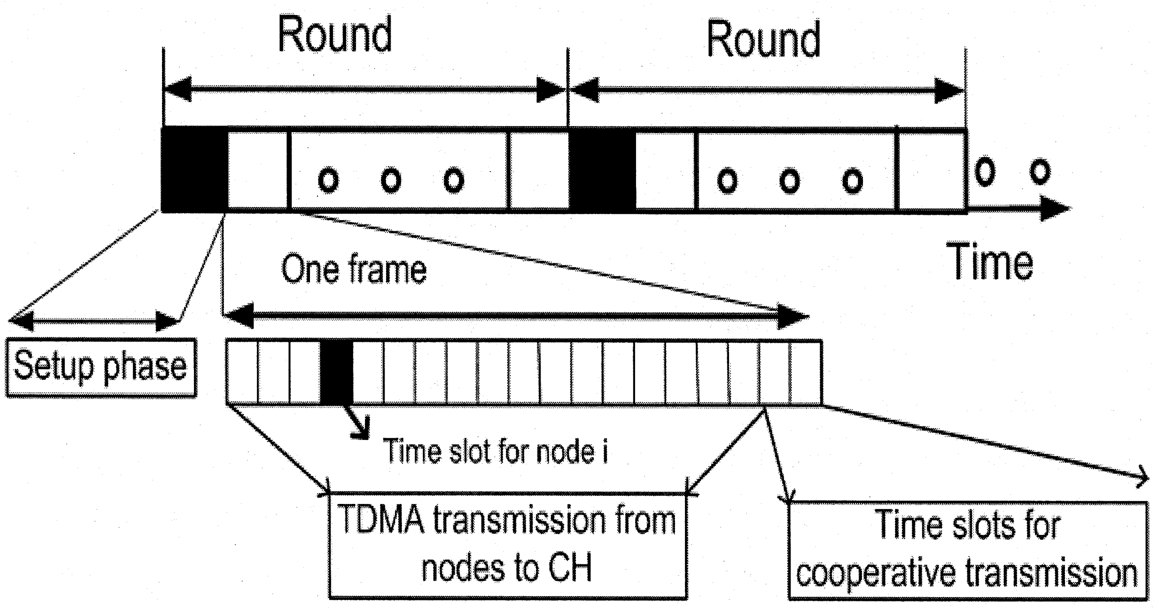

Figure 4.5: Data transmission

4.3.1 Local Data Transmission

At the local data transmission stage, each sensor node wakes up from sleep mode at the beginning of its allocated time slot. It sends data to its cluster head and then turns off its radio components and goes back to the sleep mode again to save energy. After a cluster head collects all the information from its cluster members, it performs data aggregating. The ratio of data aggregation is dependent on application scenarios and correlation of the information among sensor nodes. Then it will broadcast a ready message to inform its partner cluster heads that it is ready to go on to cooperative transmission. This step is shown in the flow chart in Figure 4.6.

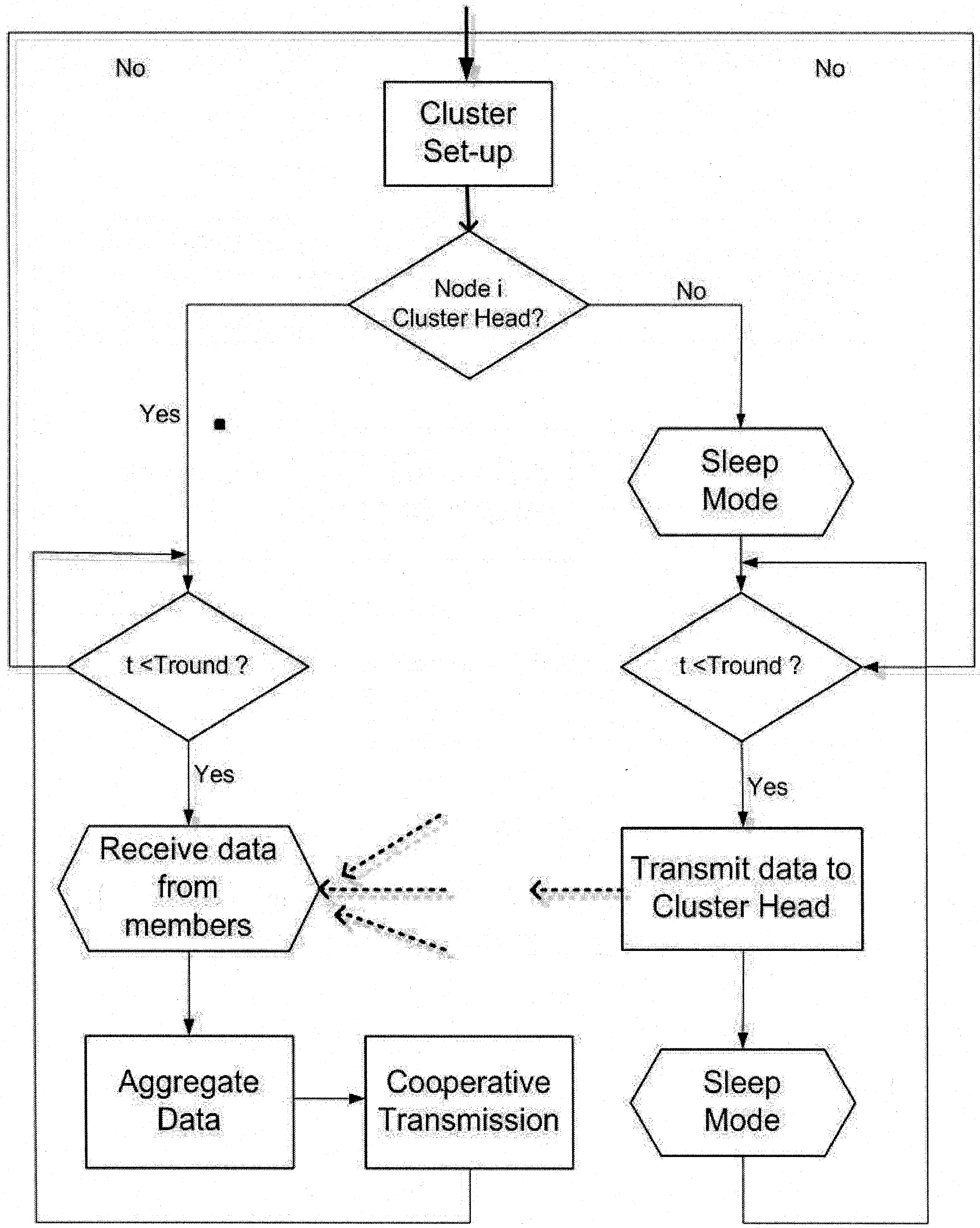

Figure 4.6: Flow chart of data transmission

4.3.2 Cooperative Data Transmission

During cooperative data transmission stage the cluster heads send their data to the BS cooperatively. Generally there are three cases in the cooperation stage.

- Case 1: The number of region members is smaller than the average number of cooperative nodes.
- Case 2: The number of region members equals to the average number of cooperative nodes.
- Case 3: The number of region members is larger than the average number of cooperative nodes.

All these three cases are possible since the cluster heads are distributed evenly across the WSN and when the BS groups the region for cooperation, it considers not only the preferred number of cooperation but also the distances to each cluster heads or the areas covered by the cluster heads. The region division is a tradeoff solution that benefits the overall performance instead of local performance. For these three cases, the cluster heads in one region take different measures to cooperation.

- Case 1: When the number of region members is smaller than the preferred number of cooperative nodes, the cluster heads will choose some of their cluster members to get involved in cooperative transmission. It does not simply choose the sensor nodes with the most energy since the sensor nodes with the most energy may consume relatively large amount of energy to communicate with the BS due to the long distance to the BS or the bad channel condition. Therefore, the criterion for choosing cooperative nodes is given as

  $$\varphi(i) = \frac{E_{re}(i)}{E_{BS}(i)} \tag{4.6}$$

  $E_{re}(i)$ is the remaining energy for node i and $E_{BS}(i)$ is the energy required for node i to communicate with the BS given preferred number of cooperative nodes at the system BER requirement. Sensor node with the highest φ will be chosen as the cooperative nodes. This is easy to realize since once the region is formed, the cluster heads will know the number of cluster heads in its region and how many cooperative nodes needed. Cluster heads will find the nodes with the highest φ value and send a small nominate message to alert the chosen cooperative nodes.

- Case 2: This is the preferred situation so that all these cluster heads in one region will participate in the cooperative transmission.

- Case 3: Since the number of region members exceed the average preferred number of cooperative nodes, it is not necessary for all the cluster heads to participate in. Thus each frame, only those cluster heads with the highest φ values are chosen to participate in the long-haul transmission. The definition of φ is the same as in Equation (4.6).

No matter which case the region falls into, the cooperative nodes will know its role before the beginning of the cooperative data transmission stage. Once the cluster heads receive all the ready messages from its cooperative partners, they start the cooperative transmission. First of all, they broadcast their data at the allocated time slot to share their information with all the other cooperative nodes which is also applied in [6]. After the data are shared by all the cooperative nodes, STBC codes are created for cooperative nodes to communicate with the BS. Whether further data aggregation is needed or not depends on application scenarios and the degree of redundancy among the information. If it is a maximum or minimum scenario or the data are highly correlated though they come from different clusters, further data aggregation is necessary. However, since the data from different clusters are treated as geographically apart, the correlation among the data is not as high as that among data inside one cluster. In this case, no further data aggregation is performed. When the cooperative transmission is finished, it is the end of one frame. Then another frame starts with local data transmission again. When a round is finished, the network will go back to the set up stage to select cluster heads and form new clusters. In this way, the roles of cluster heads rotate and the energy is balanced among the sensor nodes.

Chapter 5

Analysis and Simulation Results

Simulation is used to determine the benefits of the proposed protocol. In this chapter, EBPACP is compared with LEACH protocol [4], MIMO LEACH [7] in terms of system lifetime, energy dissipation and effective packets received at the BS. In this chapter, the simulation set up is first described and then followed by the simulation results.

5.1 Simulation Set up

5.1.1 Energy Model and Parameters

Energy model is essential for the choice of protocols for WSNs. Different assumptions about the radio characteristics such as energy dissipation in transmit and receive modes give priority to different protocols. As we discussed in Chapter 3, the changes in the ratio of transmit power over circuit power will result in changes of whether cooperation or not, multi-hop or direct transmission, and how many sensor nodes cooperatively transmit if cooperation is beneficial. The local and long-haul data propagation channels may be different from each other since in most cases the local data transmission has a better channel condition than long-haul data transmission. EBPACP adjusts the transmission scheme with different channel and energy models. For example, when circuit energy consumption counts for a significant ratio in total energy dissipation, the preferred number of cooperative nodes may become 1 which indicates non-cooperative transmission. When the local or long-haul signal propagation model changes, EBPACP will adjust the optimal number of clusters correspondingly.

In our simulation, we choose the energy model proposed in [6], which is widely used in the research of energy consumption in WSNs. For local data transmission, AWGN channel is assumed with path loss index κ_1. For long-haul data transmission, Rayleigh fading channel is assumed with path loss index κ_2. When the signal propagates under Rayleigh fading channel, the instantaneous SNR is $\frac{h_{ij}P_r}{BN_0}$ where h_{ij} is the instant fading power gain between the two terminals of i and j, and the average SNR is $\frac{H_{ij}P_r}{BN_0}$ where H_{ij} is the expectation of h_{ij}. Here in our simulation, we assume that H_{ij} is the same for all the channels and equals to one. This is reasonable since in WSNs, the BS is usually located far from the network and most of the sensor nodes are in similar environment.

From Table 3.2 we observe that AWGN channel provides a much better environment for signal propagation. However, in real applications, the channel is mostly corrupted by fading along propagation. Therefore, we apply AWGN channel for local data communication but Rayleigh fading for long-haul data transmission.

The energy consumption for transmitting and receiving one bit is given in Equations (3.1)-(3.10). Here we write the energy consumption for transmission one bit in (5.1) and receiving one bit data in (5.2).

$$E_{bt} = \begin{cases} \varepsilon\gamma_{AWGN}d^{\kappa_1} + \frac{P_{ct}}{R_b} & d < d_0 \\ \varepsilon\gamma_{Rayleigh}d^{\kappa_2} + \frac{P_{ct}}{R_b} & d \geq d_0 \end{cases} \tag{5.1}$$

$$E_{br} = \frac{P_{cr}}{R_b} \tag{5.2}$$

where κ_1 and κ_2 are path loss index under AWGN channel and Rayleigh fading channel respectively, γ_{AWGN} is the average SNR requirement for a certain BER under AWGN channel and $\gamma_{Rayleigh}$ for Rayleigh fading channel, d_0 is the distance threshold for local and long-haul data transmission, ε is radio amplifier coefficient. Definitions of d_0 and ε are given as

$$d_0 = \sqrt[\kappa_1-\kappa_2]{\frac{\gamma_{Rayleigh}}{\gamma_{AWGN}}} \tag{5.3}$$

$$\varepsilon = (1+\alpha)\frac{(4\pi)^2}{G_tG_r\lambda^2}N_0M_lN_f \tag{5.4}$$

The radio characteristics and parameter values are summarized in Table 5.1.

Table 5.1: Radio characteristics and parameter values

Description	Parameter	Value
Distance threshold for local and long-haul data transmission	d_0	$\sqrt[\kappa_1-\kappa_2]{\frac{\gamma_{Rayleigh}}{\gamma_{AWGN}}}$
Transmit power coefficient	ε	$(1+\alpha)\frac{(4\pi)^2}{G_tG_r\lambda^2}N_0M_lN_f$
Transmit energy per bit	E_{bt}	$\varepsilon\gamma_{AWGN}d_1^{\kappa}+\frac{P_{ct}}{R_b}$ $\quad d<d_0$ $\varepsilon\gamma_{Rayleigh}d_2^{\kappa}+\frac{P_{ct}}{R_b}$ $\quad d\geq d_0$
Receive energy per bit	E_{br}	$\frac{P_{cr}}{R_b}$
Wave length of carrier signal	λ	$\frac{v_c}{f_c}=\frac{3\times10^8}{f_c}$
Power amplifier coefficient	α	1.47
Carrier signal frequency	f_c	2.5 GHz
Carrier signal wave length	λ	0.12 m
Receiver noise figure	N_f	10 dB
Single sided thermal noise power spectral density	N_0	-174 dBm
Link margin	M_l	10^4
Antenna gains	G_tG_r	5 dBi
Receiver circuit power	P_{cr}	112.6 mW
Transmitter circuit power	P_{ct}	98.2 mW
BER threshold	P_b	10^{-3}
Bit rate	R_b	10 $kbps$
Code rate	R	0.5

5.1.2 Data Aggregation Model

Sensor nodes in one cluster are very likely to share highly correlated data, and therefore it is energy efficient if the cluster heads remove the redundant data and send only useful information to the BS. In LEACH, the authors use beamforming to combine the data from multiple sensors in order to satisfy a given performance criterion. The advantage of beamforming is that the desired signal is enhanced while uncorrelated noise is reduced. We use this beamforming model to remove the redundant information inside clusters in our simulation. The computation energy for aggregating one bit per signal is $5nJ/bit/signal$ and is denoted as E_{agg}.

In EBPACP, there are two stages that data aggregation can be performed. The first one is at the end of local data transmission and the cluster heads have the chance to perform data aggregation. The second one is that when the cooperative nodes share their information and prepare to communicate with the BS, data aggregation can be carried out as well. In our simulation, we assume the message from one cluster can be aggregated into one packet. But for the second stage, we do not perform any further data aggregation since for different clusters, they are geographically apart from each other and the correlation among the data is relatively low. However, this is dependent on the application scenarios. For example, in a maximum- or minimum- search application further data aggregation is also possible and advisable at the cooperative data transmission stage.

5.1.3 Energy Analysis in EBPACP

In this section, we will give energy consumption in one frame for all the sensor nodes. In one frame, the non cluster head sensor nodes dissipate energy in sending data to their cluster heads and cluster heads consume energy in receiving and aggregating data, then the cooperative nodes share the information and send them to the BS using STBC codes. Here the cooperative nodes are the cluster heads in one region or sometimes non cluster head sensor nodes get involved if the cooperative relationship formation falls into Case 1 as we mentioned in Chapter 4. Thus we sort the energy consumption into three categories:

- Non cluster head sensor nodes.

- Cluster heads.

- Cooperative nodes.

Energy consumption for non cluster head nodes

For the non cluster head nodes, they wake up at their allocated time slot and send the sensed data to the BS. Since this is inside cluster data transmission, we assume AWGN channel with a path loss index of κ_1 given the signal propagation channel is relatively good. No cooperation is used in this stage. Given each message has l bits, the energy consumption for each sensor node i is:

$$E_{sn}(i) = l\varepsilon\gamma_{AWGN}d_{ch}^{\kappa_1} + l\frac{P_{ct}}{R_b} \tag{5.5}$$

Where d_{ch} is the distance from sensor nodes to the cluster head and the other parameters are the same as we defined before.

Energy consumption for cluster heads

Although the cluster heads are also responsible for data transmission to the BS, at this step we only consider the energy they spent on data collection and aggregation. For a cluster with T members, the energy consumption for the cluster head in data collection and aggregation is

$$E = Tl\frac{P_{cr}}{R_b} + TlE_{agg} \tag{5.6}$$

where E_{agg} is energy consumption per bit per message in data aggregation. From Equation (5.6) we observe that if the circuit energy consumption, or namely $\frac{P_{cr}}{R_b}$, is comparable to the transmit energy, cluster heads will dissipate a lot more energy in receiving data than the non cluster head nodes. At the end of local data transmission, cluster heads that are ready for cooperative transmission will broadcast a small ready message to their cooperative partners. This ready message is very small compared with the regular message sent between sensor nodes and cluster heads. In order to make sure all the partners hear this message, cluster heads broadcast it with relatively high power which corresponds to a long broadcast distance D under Rayleigh fading channel. Given the ready message is l_r bits long and the cluster heads broadcast it p times, the energy consumption is

$$E = p \times l_r(\varepsilon \gamma_{Rayleigh} D^{\kappa_2} + \frac{P_{ct}}{R_b}) \tag{5.7}$$

Combining (5.6) and (5.7) the energy consumption for each cluster head can be written as

$$E_{CH} = Tl\frac{P_{cr}}{R_b} + TlE_{agg} + p \times l_r(\varepsilon \gamma_{Rayleigh} D^{\kappa_2} + \frac{P_{ct}}{R_b}) \tag{5.8}$$

Energy consumption for cooperative nodes

In EBPACP, the number of cooperative nodes is adaptable but remains the same for one region. In cooperative transmission, firstly the cooperative nodes will share their data. Each node broadcasts its data in the allocated time slot and listens to others during the rest time slots. If J cooperative nodes are preferred, the cooperative nodes will calculate the threshold of the SNR at the receiver for a targeted BER. Let D_{max} denote the maximum distance between cooperative nodes, the energy consumption for each cooperative node is

$$E_{coop} = l\left(\varepsilon \gamma_{Rayleigh} D_{max}^{\kappa_2} + \frac{P_{ct}}{R_b}\right) + (J-1)l\frac{P_{cr}}{R_b} + l\left(\frac{\varepsilon \gamma(J) d_{BS}^{\kappa_2}}{R} + \frac{P_{ct}}{R_b R}\right) \tag{5.9}$$

where $\gamma_{Rayleigh}$ is the SNR threshold under Rayleigh fading channel without any cooperation, $\gamma(J)$ is the SNR threshold under Rayleigh fading channel for J cooperative nodes, R is the code rate.

5.1.4 Optimal Number of Clusters

Grouping the sensor nodes into clusters is proven to be an energy efficient way in the design of WSNs. The fundamental work of cluster-based WSNs is done by W. B. Heinzelman et al. in [4], which is based on non-cooperative transmission. In [4] the authors gave a method to calculate optimal number of clusters based on the energy efficiency principle, which is mainly dependent on the network size like coverage area and number of sensor nodes, the ratio of energy consumed in long-haul data transmission to the BS and inside cluster data transmission. Since cooperation has changed the energy consumption as well as the roles of the sensor nodes, the energy consumption is more complicated and the optimal number of clusters has also changed in cooperative WSNs. In the following, we set up an optimization model to find out how to determine the optimal number of clusters. For a region of $M\ m \times M\ m$ with N sensor nodes randomly distributed, we assume the number of clusters is K. Since in EBPACP the number of cooperation is not the same for all the regions, we use the average cooperative nodes, denoted as J to calculate the energy consumption. The number of regions can be estimated as $\frac{K}{J}$. Combining (5.5) to (5.9), the total energy consumption to transmit a message of l bits to the BS in WSN can be written as

$$E_{total} = \sum_{i=1}^{N} E_{sn}(i) + \sum_{k=1}^{K} E_{CH}(k) + \sum_{1}^{K/J} \sum_{1}^{J} E_{coop} \tag{5.10}$$

Based on (5.10), the optimal number of clusters K is the one that minimize the total energy consumption in a WSN. It can be formulate as

$$K_{opt} = min_K\ E_{total}(K) \tag{5.11}$$

5.2 Simulation Results

In the simulation, 500 sensor nodes are randomly deployed in a region of $100\ m \times 100\ m$. The BS is located at [50, 100] as shown in Figure 5.1. The system parameters and their meanings are listed as in Table 5.1. Each of the sensor node begins with 50 J initial energy and has a packet of 2000 bits to transmit at each frame. When nodes run of their energy they can no longer transmit or receive message. We assume when 80% of the sensor nodes die, the WSN is considered out of service or dead. We assume the transmission is information lossless at the targeted BER requirement, the effective packets received at the BS is the number of packets transmitted by the source nodes. In our simulation, only data inside one cluster are aggregated and no more aggregation is carried out for cooperative data. However, in some application scenarios, there is still room for data aggregation in the cooperative transmission stage. In those cases, EBPACP will promise even more energy conservation since cooperation takes place among clusters instead of sensor nodes inside one cluster and data redundancy among clusters will be further removed.

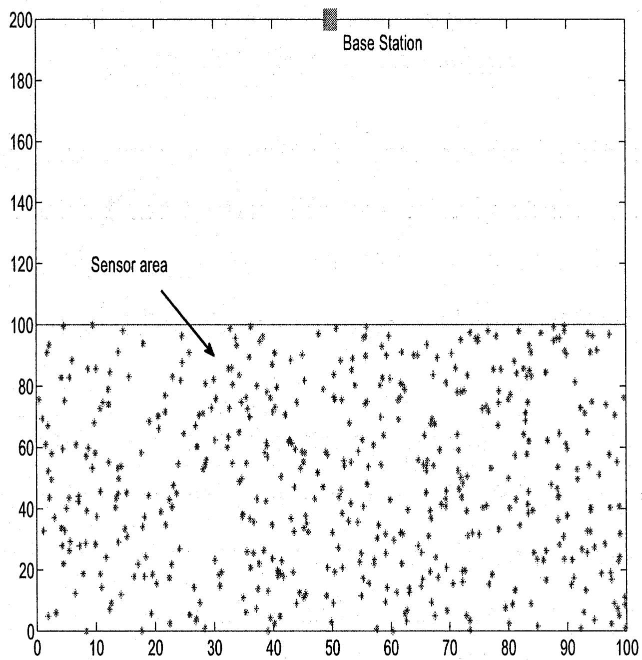

Figure 5.1: Simulation scenario

Figure 5.2 shows the number of alive nodes over rounds. It demonstrates that MIMO LEACH and EBPACP prolong the system lifetime greatly compared with LEACH, which indicates that cooperative transmission in WSNs is beneficial in terms of system lifetime. EBPACP prolongs the system lifetime even longer, about 22.5% improvement compared with MIMO LEACH.

However, the system lifetime is not the only yardstick to measure the performance of WSN protocols. The effective packets that arrive at the BS count a lot in the choices of different schemes. Figures 5.3 shows the number of effective packets received by the BS and Figure 5.4 shows the number of alive nodes versus effective packets received by the BS. Both of the figures demonstrate the advantages of EBPACP over LEACH and MIMO LEACH. Since the system lifetime are greatly increased by EBPACP, more time is allowed for

EBPACP to transmit data to the BS, and therefore the number of effective packets received by the BS increased. As shown in Figures 5.3 and 5.4, EBPACP has the best performance out of the three.

Figures 5.5 and 5.6 show the remaining energy over the rounds and the effective packets received at the BS. It is more energy efficient if cooperation is applied as MIMO LEACH and EBPACP all consume less energy for a certain amount of packets transmitted to the BS than LEACH. For a certain amount of packets arrived at the BS, LEACH consumes the most energy while EBPACP uses the least energy.

Figure 5.7 gives a comparison of energy consumed by the sensor nodes close to or far from the BS respectively. We keep a track of the energy consumption of 10 closest sensor nodes and 10 most distant sensor nodes during each round. The histogram shows the difference between close nodes and distant nodes in WSN. Since in EBPACP, energy balance is considered in the design, the energy differences are greatly reduced. Both MIMO LEACH and EBPACP reduce the energy differences compared with LEACH, which indicates that cooperation contributes to the energy consumption. Because when cooperation is applied, the energy consumed by close and distant sensor nodes is greatly reduced. Consequently the differences in energy between close and distant sensor nodes are reduced. However, the energy imbalance problem still remains even cooperation is used. The sensor nodes far from the BS still dissipate more energy to communicate with the BS than close nodes, and this difference will affect the lifetime of WSNs. As shown in Figure 5.7 that distant sensor nodes consume much more energy than close sensor nodes in MIMO LEACH. In EBPACP the differences are dwindled since energy balance is considered. Those cluster heads consuming more energy to communicate with the BS have smaller cluster size. As a result, the energy saved from inside-cluster data receiving and aggregating compensates for long-haul transmission energy consumption. However, the energy balance in EBPACP is not absolute balance among sensor nodes since WSNs should be designed more focus on the whole system performance instead of single node performance. It is not advisable to sacrifice whole system efficiency to achieve absolute fairness among sensor nodes. Although the imbalance problem still remains, it is improved a lot compared with protocols without energy balance consideration.

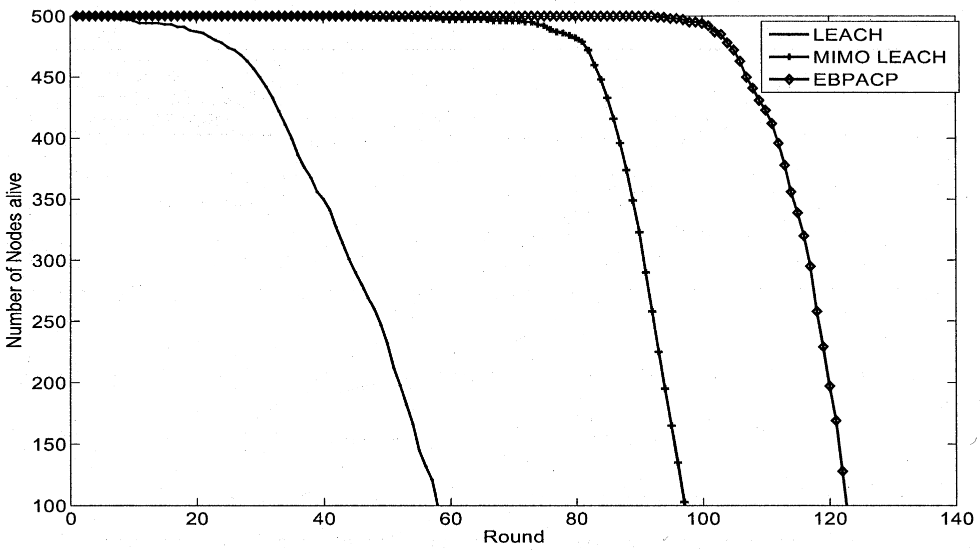

Figure 5.2: Number of alive nodes over rounds

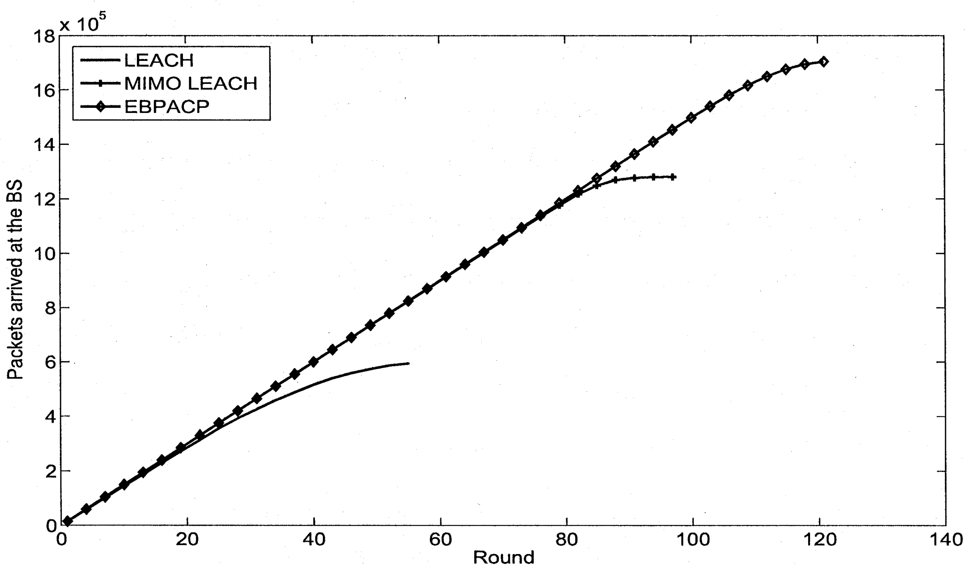

Figure 5.3: Packets arrived at the BS

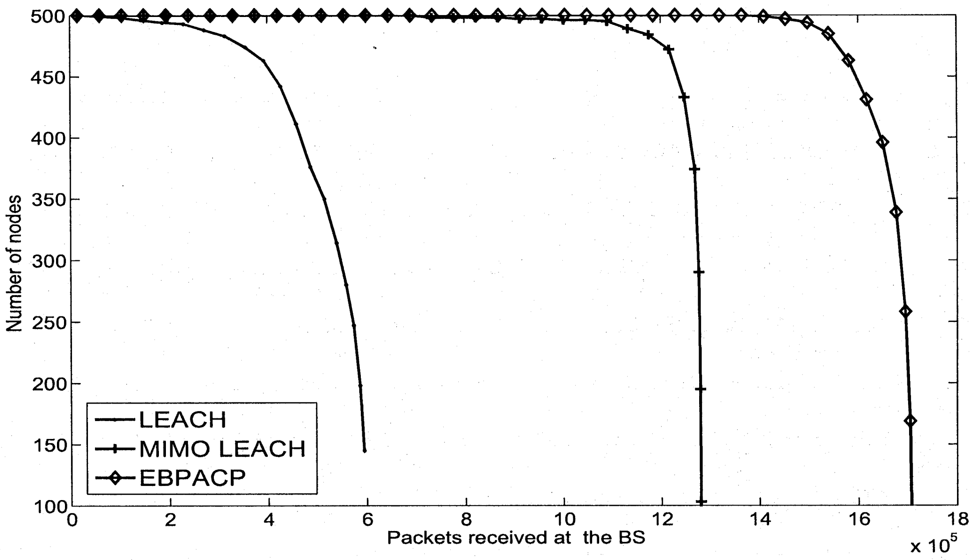

Figure 5.4: Number of alive nodes vs packets arrived at the BS

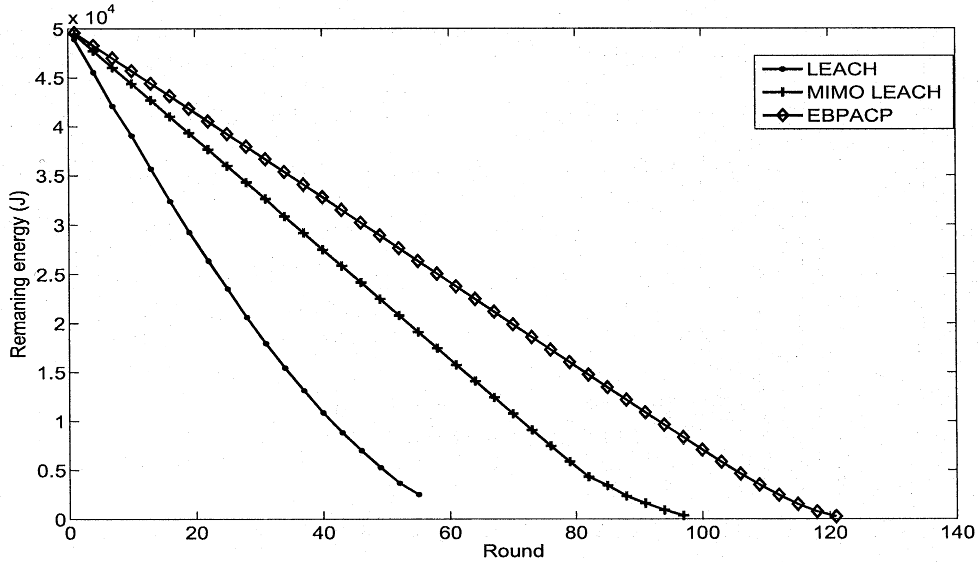

Figure 5.5: Remaining energy over rounds

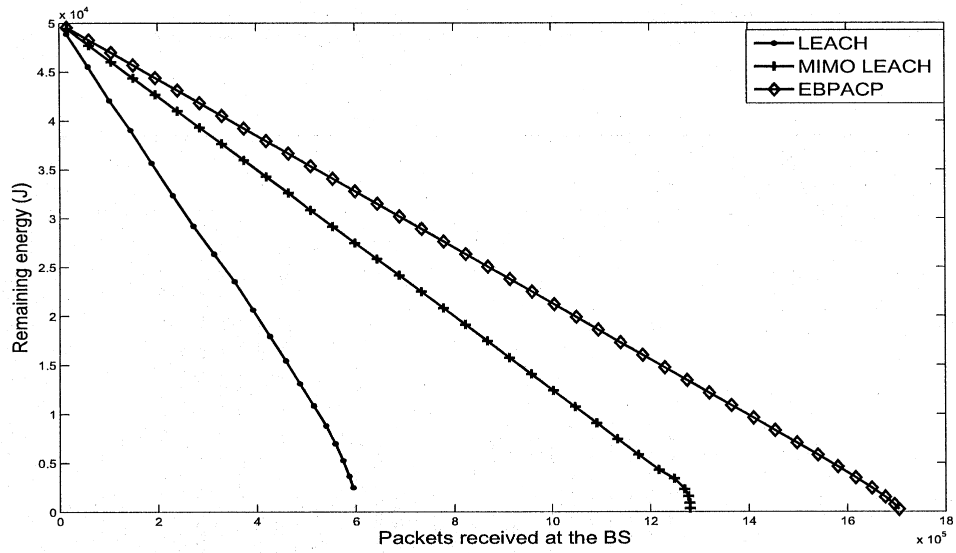

Figure 5.6: Remaining energy vs packets arrived at the BS

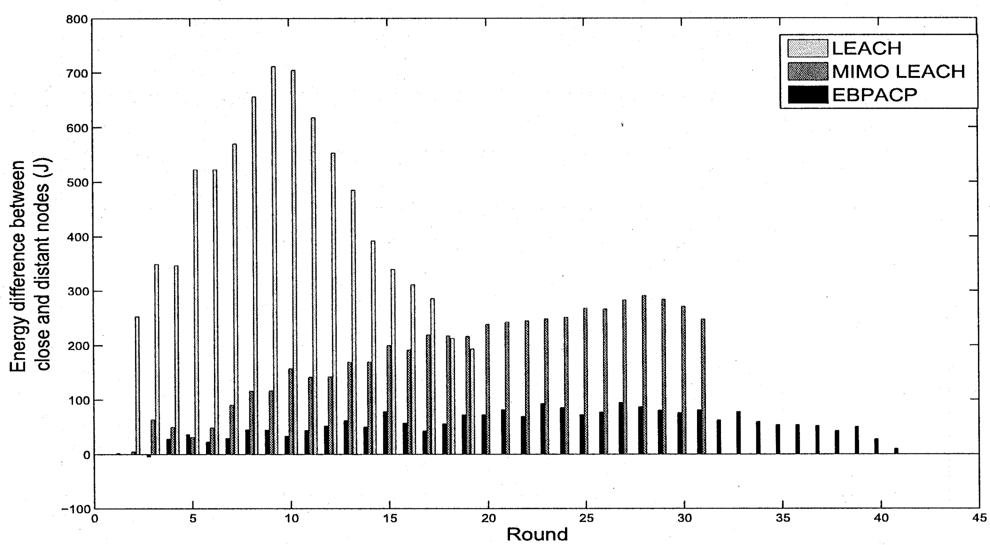

Figure 5.7: Energy difference between close and distant nodes

Chapter 6

Conclusions

There is a wide range of research topics in WSNs to improve the system performance. In our research, we focused on a protocol design of cooperative transmission in cluster-based WSNs with energy balance consideration. It is referred as Energy-Balanced Parameter-Adaptable Cooperative Protocol (EBPACP). Cluster structure is adopted to remove redundant data from neighbor sensor nodes. Cooperative transmission has been proved to be a promising technique in wireless communication to combat fading effects and save energy. Therefore, it holds high potential to improve the performance of WSNs. Although cooperative transmission and cluster structure are well developed respectively, how to combine these two to work efficiently in WSNs requires much more research attention. Moreover, energy balance problem is investigated a lot in non-cooperative WSNs but little research has been done in cooperative WSNs. Due to the feature of highly application dependent, the choice of protocols is closely related to application scenarios.

In our work, we carried out some simulation to analyze the impacts of each parameter. Each parameter affects the energy consumption of sensor nodes in either transmit or circuit power consumption. Due to this fact, we defined two coefficients for transmit and circuit power consumption respectively. The ratio of these two coefficients determines the threshold that cooperative transmission outperforms non-cooperative transmission and the preferred number of cooperative nodes for a specific situation if cooperation is preferable. The selection of transmission scheme only has to consider this ratio instead of each of the system parameters. With this knowledge, a parameter-adaptable protocol is possible. The proposed EBPACP is based on this information to choose how many cooperative nodes to transmit signals to the BS. If the preferred number of cooperative nodes equals to one, this means non-cooperative transmission is more energy efficient.

One of the distinguishabilities of our protocol is that cooperation is carried out mainly among clusters instead of sensor nodes inside one cluster. This leaves room for further data aggregation if possible, though it is not adopted in our simulation. The preferred number of cooperative nodes is subject to change for different regions in a WSN. The number of cooperative nodes is based on the principle of energy efficiency. The formation of clusters and the buildup of cooperative relationship are also given in EBPACP. Since cooperation has changed the ratio of energy dissipated in long-haul data transmission and local data transmission, the calculation of optimal number of clusters has also changed from traditional LEACH and is given in this thesis.

Energy balance is considered during the cluster formation stage. We use the help of weighted distance to form clusters instead of only considering geographical distances. We defined some weighting factors based on those elements that affect energy balance to adjust the weighted distance from sensor nodes to cluster heads. The cluster heads which require higher power to communicate with the BS have larger weighting factors. Thus the weighted distances from sensor nodes to these cluster heads are longer and less sensor nodes will join them. The energy saved from inside cluster consumption will compensate for the energy dissipated in the communication with the BS. Simulation results show that EBPACP efficiently prolongs the system lifetime compared with traditional LEACH (no cooperation) and MIMO LEACH (with cooperation) in terms of energy efficiency. Moreover, since EBPACP takes energy balance into consideration, it reduces the difference of energy consumption between close sensor nodes and distant sensor nodes. It should be noted that EBPACP contributes to energy balance but it is not absolute balance among all sensor nodes. This is because that WSNs should focus to work as a whole instead of single sensor node performance.

Our work is done based on direct transmission and no multi-hops are used to communicate with the BS. However, EBPACP can be extended to multi-hop cluster-based WSNs as well. The key to balance energy is to adjust the cluster size and make a balance between energy consumption inside the cluster and outside of the cluster. In a single-hop system, the main difference in energy consumption is resulted from distance differences to the BS. The corresponding weighting factor is adjusted by the distance to the BS. In a multi-hop system, the hot-spot nodes are no longer distant sensor nodes but those nodes close to the BS. Though the distance differences are not evident, the energy imbalance problem is resulted from unequal transmission load. Sensor nodes close to the BS not only transmit their own data but also relay those data of distant sensor nodes. Therefore, sensor nodes close to the BS bear a heavier burden to transmit more data to the BS and should be allocated smaller cluster size than distant nodes. It seems that for single-hop systems and multi-hop systems the schemes are opposite: in single-hop systems distant sensor nodes are allocated smaller cluster size while in multi-hop systems close sensor nodes form smaller clusters. However, the principle for energy balance remains unchanged. Sensor nodes require higher energy in outside-cluster communication are allocated smaller cluster size. The difference is that for sing-hop and multi-hop systems sensor nodes have heavier burden of outside-cluster communication are different.

In the future work, EBPACP will be extended to multi-hop systems where routing is another research issue. Also, latency is also an important research issue related to the performance of WSNs. In some applications latency is even more important than energy conservation such as invasion detection. We will analyze the latency performance of EBPACP in the future.

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