Design Study of Energy-Efficient Routing Protocol for Wireless Sensor Networks

by

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Abstract

Recent advances in wireless sensor networks have led to an emergence of many routing protocols. Limited battery capacity of sensor nodes makes energy efficiency a major and challenge problem in wireless sensor networks. Thus, the routing protocols for wireless sensor networks must be energy efficient in order to maximise the network lifetime.

In this thesis, we developed a centralised clustering, energy-efficient routing protocol for wireless sensor networks. Our protocol consists of a cluster head selection algorithm, a cluster formation scheme and a routing algorithm for the data transmission between cluster heads and the base station. The cluster head selection algorithm is performed by the base station using global information of the network. This algorithm aiming at choosing cluster heads that ensure both the intra-cluster data transmission and inter-cluster data transmission are energy-efficient. The cluster formation scheme is accomplished by exchanging messages between non-cluster-head nodes and the cluster head to ensure a balanced energy load among cluster heads. The routing algorithm is based on the optimal transmission range for the data transmission between cluster heads and the base station using multi-hop.

The performance of our routing protocol is evaluated by comparing with three existing routing protocols on a simulation platform. The simulation results show that our protocol can achieve better performance in terms of energy efficiency and network lifetime. Because of the centralised algorithm and multi-hop routing, there is a small communication overhead and transmission delay when using our protocol. Since our protocol can save energy and prolong network lifetime, it is well suited for applications where energy and network lifetime are the primary considerations and small overhead and time delay can be tolerated.

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Statement of Originality

This work contains no material that has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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List of Symbols

E_{elec}	per bit energy dissipation for running the transceiver circuitry	25
ϵ_{fs}	amplifier parameter for free space propagation model	25
ϵ_{tg}	amplifier parameter for two-ray ground propagation model	25
d_0	cross-over distance	25
N	number of nodes in the network	28
$N(v)$	number of neighbours of node v	28
$dist(v, v')$	distance between node v and node v'	28
R_c	intra-cluster transmission range	28
Δv	degree-difference of node v	28
δ	ideal number of nodes for a cluster to accommodate	28
d_v	sum of square distance between node v and its neighbours	28
$D(v, BS)$	distance between node v and the base station (BS)	28
E_v	residual energy of node v	28
W_v	combined weight of node v	28
w_1, w_2, and w_3	weighting factors	28
E_{ini}	initial energy of node	28
A	area of network field	33
$\rho(x, y)$	node distribution in the network	33

Chapter 1

Introduction

1.1 Aims of Research

The wireless sensor networks have been applied in a wide range of applications and the limited capacity of sensor nodes has brought many design challenges. One important challenge is that the resources, such as energy and communication bandwidth, are more limited than those in a traditional wireless network. These restrictions require innovative design techniques and protocols to use available resources efficiently. In this thesis, we address the design of routing protocol for wireless sensor networks. Because of the constraints of wireless sensor networks, many issues, especially the energy, should be considered when designing the protocol. Numerous routing protocols have been proposed for wireless sensor networks. Although many of them perform efficiently in some aspects, such as energy saving, there are still some problems which exist in these protocols.

The aims of this research study are:

1. To design an efficient routing protocol for wireless sensor networks.

2. To justify the validity of the designed protocol on a simulation platform.

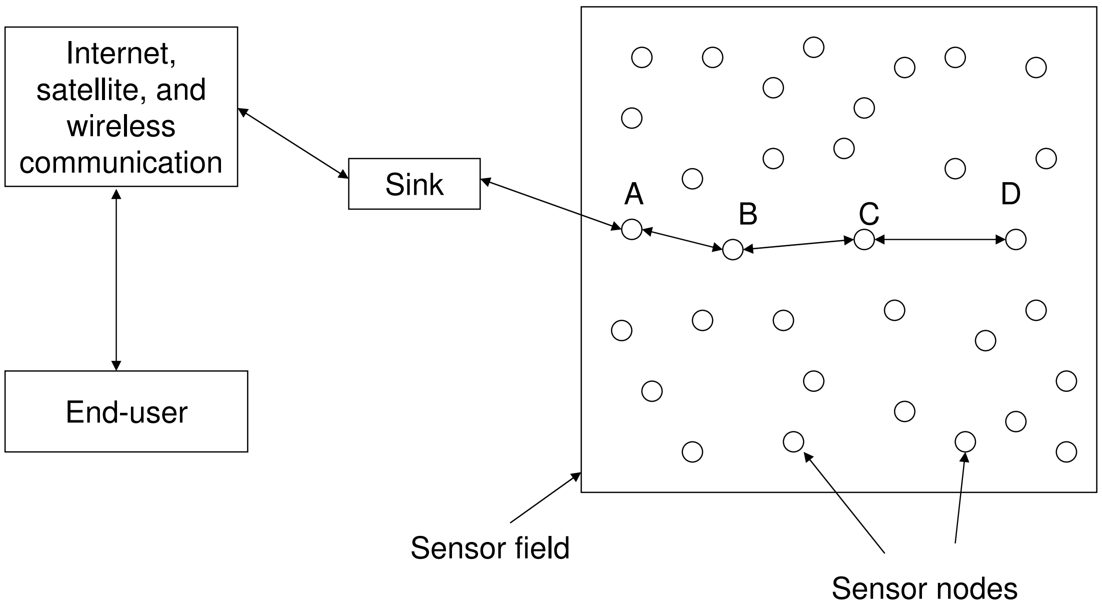

Figure 1.1. System structure of wireless sensor network

1.2 Introduction to Wireless Sensor Networks

Advances in micro-electromechanical systems, processors, radio and memory technologies have enabled the rapid development of wireless sensor networks [2, 3, 4, 5]. Figure 1.1 presents the structure of a typical wireless sensor network. Numerous sensor nodes are distributed in an area of interest with a sink (base station) located out of the network area. Each sensor node obtains a certain "view" of the environment. Combining or aggregating the views of the individual nodes allows end-users to accurately and reliably monitor an environment. To enable remote monitoring of an environment, the nodes must send the high-level description of events to the sink, through which end-users can access the information via internet, satellite, or wireless communication.

Wireless sensor networks represent a new paradigm for extracting data from the environment. Different from the conventional wired sensor networks, where the positions of sensors are fixed, wireless sensor networks allow sensors to be arbitrarily deployed in the monitoring area [6, 7, 8]. Furthermore, sensors in wireless sensor networks communicate with the base station via a wireless model instead of directly being wired to an end-user in wired sensor networks. The wireless communication between sensor nodes eliminate the need for a fixed infrastructure in wireless sensor networks. Therefore, wireless sensor networks are more flexible for obtaining data from the environment. The sensor nodes in conventional wired sensor networks are expensive and require large amounts of energy for operation. Furthermore, the deployment of these nodes is costly. Therefore, it will be economical if these expensive nodes could be replaced with low-cost nodes that can be easily deployed. Since large numbers of nodes in wireless sensor networks can ensure that there is enough redundancy in data acquisition, not all nodes need to function. Thus, wireless sensor networks are fault-tolerant.

Because of the advantages of wireless sensor networks, they have been employed in a wide range of applications, such as environment monitoring, biomedical purpose, and machine failure diagnosis [9, 10, 11, 12]. However, the physical constraints of sensor nodes bring challenging issues in designing wireless sensor networks. In the following, we summarise some constraints that may affect the design of wireless sensor networks.

- **Limited energy supply**. The energy of a typical sensor node that is equipped with two AA batteries as the power supply is very limited [13]. Since most operations of a sensor node, such as data processing and data transmission, are energy-consuming, it is easy to drain the energy of the node during the network operation. This problem is aggravated by the fact that nodes in some applications of wireless sensor networks are left unattended. For example, in a field surveillance application, sensor nodes are distributed in an inaccessible and dangerous territory. Recharging or replacing the batteries of nodes is impossible. Furthermore, to replace all the batteries of nodes in a large area can be costly and unrealistic. Therefore, limited energy of a node is the most crucial challenge for the design of wireless sensor networks

- **Limited transmission range**. The transmission range of a sensor node is limited due to the constraint of antenna capability and node energy [14, 15]. Although some nodes (such as Crossbow mica nodes [16]) are able to vary their power level so as to adjust the transmission range in specific applications, the maximum reachable area of a sensor node is relatively small compared with the traditional wireless network [8, 17]. Therefore, for many applications, nodes have to be deployed in large numbers in order to guarantee good coverage of the network. Furthermore, the limited transmission range implies there is a requirement of high node density for the sake of maintaining reliable connection between nodes.

- **Small storage size**. The storage size of a sensor node is very small compared with those of traditional networks (for example, a Crossbow mica2 sensor node only has 4 KB RAM) [16]. This constraint of sensor node makes wireless sensor networks unsuitable to be employed in applications that require big data storage capacity. Furthermore, small storage will lead to limited capacity for data processing and data communication.

1.3 Challenges of Routing Protocol for Wireless Sensor Networks

Wireless sensor networks may contain hundreds or thousands of nodes that are deployed in a large area. These nodes are required to be able to communicate with each other even in the absence of an established network infrastructure. Furthermore, although nodes in a wireless sensor network are immobile, the network topology is continuously changing due to node failure and fluctuating channel conditions. Therefore, the routing protocols for wireless sensor networks must be able to efficiently manage network topology. In addition, wireless sensor networks are expected to have the capacity to maintain the performance without considering the size of the network. That means the performance of the network will not be affected even when the number of nodes is large. Thus, scalability is a design challenge of routing protocol for wireless sensor networks.

The energy supply of a node is limited. In the scenarios where the sensor nodes operate in remote or dangerous territory, it may be impossible to retrieve the nodes in order to recharge batteries. Therefore, the network is expected to have a certain lifetime during which nodes have sufficient energy to gather, process, and transmit data. This means that the routing protocols for wireless sensor networks must be designed to be energy-efficient. In addition to reducing energy dissipation, protocols should be able to balance the energy dissipation of nodes in order to maximise the system lifetime.

Other challenges, such as data quality and time latency, also exist in the design of routing protocols for wireless sensor networks. Tradeoffs can be made among these challenges according to the specific requirements of application.

1.4 Contributions of This Thesis

The main contribution of this thesis is that we developed a centralised clustering, energy-efficient routing protocol for wireless sensor networks. The clustering-based structure is used in our protocol to efficiently organise numerous nodes and utilise limited resource of system (such as energy). The centralised cluster head selection algorithm of our routing protocol is performed by the base station in order to choose better cluster heads using the global information of the network. These selected cluster heads ensure that both the intra-cluster data transmission and data transmission from cluster heads to the base station are energy-efficient. Furthermore, the energy dissipation of selected cluster heads can be balanced when using the cluster head selection algorithm of our protocol.

The cluster formation in our protocol is able to balance the load of clusters. Thus, the cluster heads will not drain their energy quickly due to over-burdened load. The multi-hop routing algorithm used in our protocol can reduce the energy consumption for the data transmission from cluster heads to the base station. Benefiting from both the energy-efficient data transmission and balanced energy dissipation of nodes, the network lifetime can be prolonged when using our routing protocol. Since the residual energy of node is considered when choosing cluster heads and intermediate nodes, our protocol can efficiently utilise high-energy nodes in the network.

The performance of our protocol is evaluated by comparing with three other existing routing protocols on a simulation platform. The simulation results show that our protocol performed better than three other routing protocols in terms of energy efficiency, energy distribution, and network lifetime. These simulations evaluate different aspects of the routing protocols. In addition, the advantages and disadvantages of different protocols are illustrated based on the simulation results.

Through the performance evaluation, we can conclude that the centralised algorithm performed by the base station for cluster head selection can enhance the performance of routing protocol in terms of energy efficiency and energy distribution. In addition, it can be seen from the simulation results that the multi-hop routing is more energy-efficient than direct transmission for long-distance data transmission. Some simulation results presented in this thesis can be taken as a guideline for the design of routing protocol for wireless sensor networks.

Although our protocol is specific for the applications of wireless sensor networks, some algorithms, such as the centralised cluster head selection algorithm, can be adopted in the protocols for other wireless networks. In addition, the multi-hop routing algorithm in our protocol can be applied to other wireless network routing (like ad hoc network routing).

The following published papers presented part of the work reported in this thesis

- **Position-based, Energy-efficient, Centralised Clustering Protocol for Wireless Sensor Networks**. Proceedings 4th IEEE Conference on Industrial Electronics and Applications, 25-27 May 2009, Xi'an, China
- **Weight-based Clustering Protocol for Wireless Sensor Networks**. Proceedings second IEEE International Symposium on IT in Medicine and Education, 14-16 August 2009, Ji'nan, China

1.5 Thesis Structure

This thesis begins with the introduction in Chapter 1. A detailed description of background, including routing protocol for ad hoc networks and routing protocol for wireless sensor networks, is presented in Chapter 2. Chapter 3 describes the network and energy model along with the problems for our routing protocol. Details of our routing protocol, including the cluster head selection algorithm, cluster formation, and multi-hop inter-cluster routing, are also presented in Chapter 3. We evaluate the performance of our routing protocol by comparing with other routing protocols using a network simulator in Chapter 4. This thesis concludes with a discussion of future directions in Chapter 5.

Chapter 2

Background

2.1 Network Layer Routing Protocol

Routing protocol is a network layer protocol according to the ISO model [18, 19]. Each layer in ISO model performs a well defined function with a specific protocol. When data information transmits between two network hosts, there is a need for protocols to define the way of sending and receiving and the rate of transmitting. In network concepts, routing is the process of selecting paths in a network along which to send network traffic. A communication protocol is a set of formal rules describing how to transmit across a network. A routing protocol is a protocol that specifies how routers communicate with each other, disseminating information that enables them to select multihop routes between any two nodes on a communication network [20, 21].

2.1.1 Approaches for Routing Protocols

Many routing protocols along with efficient routing approaches have been developed for wireless networks. Approaches, such as multi-hop routing and clustering, can enhance the performance of protocols in terms of energy efficiency and network organisation.

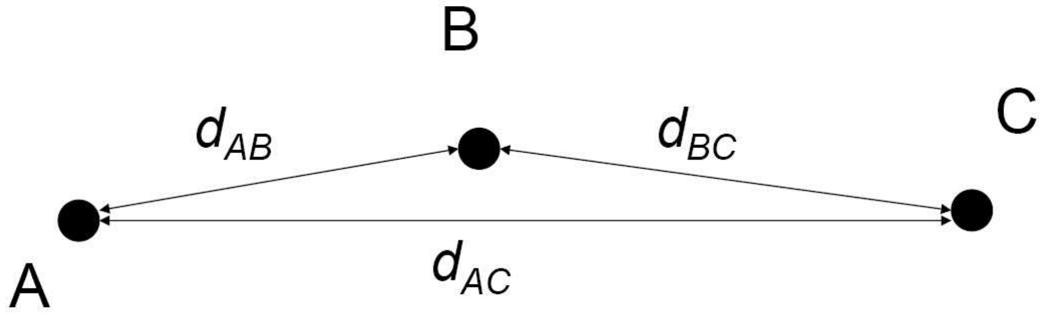

Figure 2.1. Minimum transmission energy (MTE) routing

Multi-Hop Routing

In a wireless network, the distance between a transmitting node and a receiving node may be long. Thus, choosing multi-hop routing to minimise the energy dissipation of long-distance data transmission is sensible. In the multi-hop routing, one or more intermediate nodes are used as sequential hops if and only if the total energy dissipation can be reduced [9, 22, 17].

Minimum transmission energy (MTE) routing is an energy-aware multi-hop routing approach for wireless networks [3, 23, 24]. In MTE, intermediate nodes are chosen to relay data packets from the source node to a given destination so as to minimise the total transmission energy. Assuming a d^2 (d is the distance between the transmitting node and the receiving node) power loss implemented to estimate the energy dissipation during the transmission, for the configuration shown in Figure 2.1, node A will choose node B as the intermediate node to relay the data packet to node C if and only if:

$$d_{AB}^2 + d_{BC}^2 < d_{AC}^2, \tag{2.1}$$

where d_{AB} is the distance between node A and node B, d_{BC} is the distance between node B and node C, and d_{AC} is the distance between node A and node C.

This multi-hop routing can be implemented in wireless sensor networks where all the nodes must send their data to the base station. Each node runs a start-up routine to determine its next-hop neighbour using a particular routing protocol. Data is passed to each node's next-hop neighbour until the data reaches the base station. If some nodes run out of energy (die), the routes need to be recomputed to ensure the connectivity with the base station. Since the distances between nodes and the base station may be long in a typical wireless sensor network, significant energy reduction of data transmission can be achieved by using multi-hop routing.

Clustering

Clustering is an efficient approach that has been implemented in many communication protocols for wireless networks [25, 26, 27, 28, 29]. In a clustering-based network, nodes are divided into several clusters. Each cluster consists of one cluster head and numbers of member nodes. In this case, member nodes send their data to the cluster head which forwards the data to the desired recipient. Furthermore, the cluster head may perform data processing, such as data aggregation, before forwarding the data. Clustering enables bandwidth reuse and can thus increase system capacity. In addition, the hierarchical structure obtained when using clustering can help efficiently manage topology of the network with large numbers of nodes.

Lin *et al.*[30] developed a fully distributed cluster formation and communication algorithm where there are no fixed cluster-head nodes in the cluster. This algorithm has the advantage of avoiding “hot-spots”, or bottlenecks in the network. Their distributed cluster formation uses a lowest-node-ID algorithm, whereby the cluster-head position is assigned to the node with the lowest of its ID and all its neighbours IDs. A cluster maintenance algorithm is created to ensure connectivity of all nodes in the presence of node mobility, and a combination TDMA/CDMA scheme is used to ensure minimum inter- and intra-cluster interference.

In a clustering-based protocol for wireless sensor networks, nodes are organised into clusters. Nodes transmit their data to the cluster heads during each frame of data transfer, and the cluster heads forward the data to the base station. Since data from nodes located close to each other are highly correlated, the cluster head aggregates the signals to reduce the actual amount of data that must be transmitted to the base station. Therefore, the energy needed for data transmission can be reduced. Since the cluster heads must transmit the data to the base station via the shared wireless channel, if the cluster heads could not aggregate the data, there would be no advantage to use this approach over an approach where each node sent its data directly to the base station.

2.1.2 Routing Protocols for Ad Hoc Networks

An ad hoc network is the cooperative engagement of a collection of mobile nodes without the required intervention of any centralised access point [19]. In such a network, each mobile node operates not only as a host but also as a router, forwarding packets for other mobile nodes in the network that may not be within direct wireless transmission range of each other. Each node participates in an ad hoc routing protocol that allows it to discover multi-hop paths through the network to any other nodes. The routing protocols for ad hoc networks are different from those of wireless sensor networks or conventional wireless networks due to the mobility of nodes. Many efficient routing protocols, such as destination-sequenced distance vector (DSDV) and ad hoc on-demand distance vector (AODV), have been developed for ad hoc networks.

Destination-Sequenced Distance Vector (DSDV) Protocol

Destination-sequenced distance vector (DSDV) protocol is a hop-by-hop distance vector routing protocol requiring each node to periodically broadcast routing updates [19, 31]. Each DSDV node maintains a routing table listing the "next-hop" for each reachable destination. To maintain the consistency of the routing table in a dynamically varying topology in ad hoc networks, each node periodically transmits updates when significant new information is available.

The key advantage of DSDV over traditional distance vector protocols is that it guarantees loop-freedom [31]. DSDV tags each route with a sequence number and considers a route R more favorable than R' if R has a greater sequence number, or if the two routes have equal sequence numbers but R has a lower metric. Each node in the network advertises a monotonically increasing sequence number for itself. When a node B decides that its route to a destination D has broken, it advertises the route to D with an infinite metric and a sequence number one greater than its sequence number for the route that has broken. This causes any node A routing packets through B to incorporate the infinite-metric route into its routing table until node A hears a route to D with a higher sequence number.

Ad Hoc On-Demand Distance-Vector (AODV) Protocol

The ad hoc on-demand distance-vector (AODV) routing protocol provides quick and efficient route establishment between nodes desiring communication based on the on-demand mechanism of route discovery and route maintenance [19]. When a node S needs a route to the destination D, it broadcasts a ROUTE REQUEST message to its neighbours, including the last known sequence number for that destination. The ROUTE REQUEST is flooded in a controlled manner through the network until it reaches a node that has a route to the destination. Each node that forwards the ROUTE REQUEST creates a reverse route for itself back to source node S.

When the ROUTE REQUEST reaches a node with a route to destination D, that node generates a ROUTE REPLY that contains the number of hops necessary to reach destination D and the most recently known sequence number for destination D and forwards back to source node S. Each node that participates in forwarding this REPLY creates a forward route to destination D. The state created in each node along the path from S to D is the hop-to-hop state. That is each node remembers only the next hop and not the entire route.

AODV normally requires each node to periodically transmit a HELLO message in order to maintain routes. Failure to receive three consecutive HELLO messages from neighbour is taken as an indication that the link to the neighbour in question is down. When a link goes down, any upstream node that has recently forwarded packets to a destination using that link is notified via an UNSOLICITED ROUTE REPLY containing an infinite metric for that destination. Upon receipt of such a ROUTE REPLY, a node must acquire a new route to the destination.

2.1.3 Routing Protocols for Wireless Sensor Networks

The characteristics of a wireless sensor network that distinguishes it from those of traditional network and wireless ad hoc networks have posed many challenges on the design of routing protocols for wireless sensor networks. First of all, almost all the applications of wireless sensor networks require flow of sensed data from multiple sources (sensor nodes) to a particular sink (the base station) [32, 33, 34]. This many-to-one transmission model is different from the one-to-one or any-to-any models implemented in conventional wireless networks and wireless ad hoc networks. Secondly, since many sensor nodes may generate the same value within the vicinity of the phenomenon, significant redundancy exists in the data traffic from sensor nodes to the base station [4]. Therefore, the data aggregation technique is strongly desired to be exploited in routing protocols for wireless sensor networks. Thirdly, constrain of sensor nodes in terms of transmission power, on-board energy, processing capacity and storage are rigorous. Especially, the energy supply of a sensor node is limited to two AA batteries. Moreover, it is unrealistic or even impossible to recharge or replace batteries for numerous sensor nodes that are distributed in an inaccessible region in many applications of wireless sensor networks. Therefore, energy efficiency is a necessary consideration for the design of routing protocol for wireless sensor networks.

Because of these different characteristics, routing protocols for traditional networks and ad hoc networks are no long suitable for wireless sensor networks. To solve the problem of routing data, many routing protocols have been proposed for wireless sensor networks. The underlying structure can play a significant role in the operation of the routing protocol for wireless sensor networks. According to the structure, these protocols can be classified into three main categories: flat-based routing protocol, hierarchical-based routing protocol, and location-based routing protocol.

Flat-based Routing Protocol

In flat networks, each node typically plays the same role, and sensor nodes collaborate to perform the sensing task. In many applications of wireless sensor networks, large number of nodes are deployed. Thus, it is not feasible to assign a global identifier to each node in the network. The lack of global identification (such as address) along with random deployment of sensor nodes makes it difficult to select a set of specific nodes to be queried. This consideration has led to data-centric routing, where the sink (base station) sends queries to certain regions and waits for data from the sensors located in the selected regions. Sensor protocols for information via negotiation (SPIN) proposed in [35] and directed diffusion (DD) proposed in [36] are two typical data-centric routing protocols, where data negotiation between nodes is considered in order to eliminate redundant data and save energy.

- **Sensor protocols for information via negotiation (SPIN).** Heinzelman et al. in [35] proposed an adaptive, data-centric protocol called sensor protocols for information via negotiation (SPIN). The key feature of SPIN is to exchange meta-data, which are the high-level data descriptors, among nodes via a data advertisement mechanism before data transmission. Upon receiving new data from other nodes, nodes advertise meta-data to their neighbours. If a neighbour is interested in the data, it will retrieve the data by sending a request message.

  SPIN is a 3-stage protocol as sensor nodes use three types of messages, ADV, REQ, and DATA, for communication. The ADV message is used by the nodes to advertise a particular meta-data, the REQ message is used to request the specific data, and the DATA message is the message that carries actual data. The protocol starts when a node obtains new data which can be shared by others. This node broadcasts an ADV message containing meta-data to its neighbours. If a neighbour is interested in the data, it sends a REQ message back to the node and a DATA message is sent to this neighbour node. The neighbour node receive the DATA message then repeats this process with its neighbours. Thus, the entire sensor area will receive a copy of the data.

  Some problems exist in conventional flat-based routing protocols, such as redundant information and overlapping of sensing areas, can be solved in SPIN by meta-data negotiating. One advantage of SPIN is that topological changes are localised since each node only needs to know its single-hop neighbours. However, the data advertisement mechanism of SPIN cannot guarantee the delivery of data. For example, in the intrusion detection application, if a node that is interested in the data is located far away from the source node and the nodes between the destination node and the source node are not interested in that data, the data will not be delivered to the destination node.

- **Directed diffusion (DD).** Directed diffusion (DD) protocol proposed in [36] is a data-centric and application-aware routing protocol that aims at diffusing data through sensor nodes by using a naming scheme for the data. Directed diffusion suggests the use of attribute-value pairs for the data and queries the sensors in an on-demand basis by using those pairs. In order to create a query, an interest is defined using a list of attribute-value pairs such as names of objects and interval. The interest is broadcasted by a sink through its neighbours. After receiving the interest broadcasted from the sink, each node does caching for later use. The interests in the caches are used to compare the received data with the values in the interests. The interest also contains several gradient fields. A gradient is a reply link to a neighbour from which the interest was received. It is characterised by the data rate, duration and expiration time derived from the received interest's field. Hence, the paths between source nodes and the sink can be established by using interest and gradients. The sink resends the original interest message through the selected path with a smaller time interval and the source node on that path will send data more frequently.

The main idea of directed diffusion is to combine the data coming from different source nodes by performing in-network data aggregation. Directed diffusion differs from SPIN in terms of the on demand data querying mechanism. In directed diffusion, the sink queries the sensor nodes only if specific data is available. Whereas in SPIN, sensor nodes advertise the availability of data allowing interested nodes to query that data. Directed diffusion has many advantages. Since it is data centric, there is no need for a node addressing mechanism for the communications between nodes. Each node can do data aggregation and caching, which is a big advantage in terms of energy efficiency. Furthermore, directed diffusion is highly energy-efficient since it is on demand and there is no need for maintaining global network topology.

However, directed diffusion cannot be applied to applications that require continuous data delivery due to the query-driven data delivery model. Therefore, directed diffusion is not a good choice as a routing protocol for the applications such as environmental monitoring.

Hierarchical-based Routing Protocol

In order to cope with a large number of sensor nodes in wireless sensor networks, network clustering is implemented in many routing protocols [37, 38, 39, 40]. In a hierarchical or clustering architecture, higher energy nodes can be used to process and send the information while low energy nodes can be used to perform the sensing task. Furthermore, taking advantage of the clustering mechanism, significant energy can be saved by performing data aggregation that decreases the actual size of data sent to the base station. Therefore, hierarchical architecture as utilised in routing protocols can contribute to overall system scalability, lifetime, and energy efficiency. Low energy adaptive clustering hierarchy (LEACH) protocol proposed in [2] and its improved protocols, such as LEACH-C, are typical hierarchical-based routing protocols for wireless sensor networks.

- **LEACH**. Low energy adaptive clustering hierarchy (LEACH) protocol proposed in [2] is a clustering-based protocol for wireless sensor networks. LEACH employs the technique of randomly rotating the role of cluster head among all the nodes in the network. The operation of LEACH is broken into rounds. Each round begins with a set-up phase when the clusters are organised. The steady-state phase is followed when data transfers to the base station occur.

  During the set-up phase, the nodes organise themselves into clusters where one node serves as cluster head. The decision for a node to become a cluster head is made locally with a certain probability. The probability for each node i to be a cluster head is defined as:

  $$P_i = \frac{k}{N - k(rmod\frac{N}{k})} \tag{2.2}$$

  where k is the optimal number of clusters, N is the total number of nodes in the network, mod is modular arithmetic, $mod(\frac{N}{k})$ is the remainder when N is divided by k. The variable r is the number of rounds that have passed. This probability is not applicable to the nodes that have not been cluster heads in the most recent $(rmod\frac{N}{k})$ rounds. Only nodes that have not been cluster-heads recently may become cluster-heads at round $r + 1$. This cluster head selection scheme can rotate the role of cluster heads among nodes and thereby distribute energy load throughout the network.

  After the set of cluster heads has been identified, other ordinary nodes are invited to join the clusters. Each ordinary node determines to which cluster it belongs by choosing the cluster head that requires the minimum communication energy. That means, the ordinary node will choose the cluster head with the minimum separation distance from itself to be its cluster head. During the set-up phase, cluster heads also assign a TDMA time slot for each registered member for intra-cluster data transmission during the steady-state phase.

  During the steady-state phase of LEACH, member nodes send data to their associated cluster heads when their time slot is up. Cluster heads collect data from nodes within clusters and implement data aggregation to reduce redundancy and size of data before forwarding it to the base station.

LEACH presents many advantages for data gathering applications of wireless sensor networks. The hierarchical network structure and data aggregation implemented in LEACH can save significant energy for data transmission by reducing actual data sent to the base station. In addition, rotating the role of cluster head among nodes can balance the energy load across the network. However, the distributed cluster selection scheme in LEACH cannot guarantee the placement or number of cluster heads within the network. Furthermore, since the base station may be located far away from the network area, the direct data transmission from cluster heads to the base station is energy-consuming.

- **LEACH-C**. LEACH-C proposed in [41] is a centralised version of LEACH. Unlike LEACH, where nodes self-organise themselves into clusters, LEACH-C uses the base station as a coordinator for cluster head selection and cluster formation. The operation of LEACH-C is the same as that of LEACH that divided into rounds and each round consists of a set-up phase and a steady-state phase. During the set-up phase of LEACH-C, every node in the network sends its location information and energy level to the base station. Using this information, the base station selects a set of optimal cluster heads and configures the network into clusters. The cluster grouping is chosen to minimise the energy required for ordinary nodes to transmit data to their associated cluster heads.

  Although the steady-state phase of LEACH-C is identical to that of LEACH, results presented in [41] indicate that a significant improvement over LEACH was achieved by LEACH-C. This is because the base station utilises global information of the network, thus better clusters that require less energy for data transmission can be produced. Additionally, the number of cluster heads in each round of LEACH-C gives an expected optimal value. Because the base station carries out energy intensive tasks, such as cluster head selection, a great reduction in energy dissipation can be achieved for sensor nodes.

- **Novel self-organising hybrid network protocol**. A potential problem in both LEACH and LEACH-C protocols is that all cluster heads send the aggregated data to the base station directly. As sensor nodes are generally distributed in a large area, the distances to the base station are different from node to node. Some nodes may reside far away from the base station, while others can be distributed near to the base station. The different location of nodes can lead to a significant difference between the transmission energy dissipation that the nodes use to transmit data to the base station. Thus, the nodes located far from the base station will deplete their energy more quickly than those reside near to the base station. When some nodes die after certain rounds, the performance of the whole network may decline. In addition, as energy dissipation of data transmission is related to the distance between the source node and the destination node, the long distance between nodes and the base station will incur significant energy dissipation for data transmission.

Zhao and Erdogan in [3] proposed a protocol (novel self-organising hybrid network protocol) that integrates LEACH with a multi-hop routing algorithm called MTE (minimum transmission energy) for data transmission between cluster heads and the base station. When a cluster head has data sent to the base station, it will choose other cluster heads as the intermediate nodes using the MTE algorithm in order to minimise the transmission energy. However, the protocol proposed in [3] only considers the cluster heads in the current round as the potential intermediate nodes. The limited number of cluster heads in one round cannot guarantee the chosen route along which cluster heads send data to the base station is optimal. Furthermore, a "hot-spot" problem may raise when using this multi-hop routing for inter-cluster communication. Because the nodes in the network are stationary, some nodes that are close to the base station will deplete their energy quickly due to their frequent usage as intermediate nodes.

Location-based Routing Protocol

In location-based routing protocols for wireless sensor networks, location information of sensor nodes is required. In this kind of routing protocol, sensor nodes are addressed by means of location. The distance between two neighbouring nodes can be estimated on the basis of incoming signal strength. Relative coordinates of nodes can be obtained by exchanging information between neighbours [42]. Alternatively, the location of nodes may be available directly by communicating with a satellite, using GPS (global positioning system), if nodes are equipped with a small low-power GPS receiver [43, 44]. In some location-based routing protocols, location information can be utilised in routing data in an energy efficient way. For instance, if the region to be sensed is known, using the location of sensors, the query can be diffused only to that particular region. Thus, significant energy can be saved by reducing the number of transmission. Geographic adaptive fidelity (GAF) and Geographic and energy aware routing (GEAR) are two energy-aware location-based routing protocols.

- **Geographic adaptive fidelity (GAF)**. Geographic adaptive fidelity (GAF) proposed in [43] is an energy-aware location-based routing algorithm designed primarily for mobile ad hoc networks, but may be applicable to sensor networks as well. GAF conserves energy by turning off unnecessary nodes in the network without affecting the level of routing fidelity. In GAF, the network area is divided into fixed zones and forms a virtual grid. Inside each zone, nodes collaborate with each other to play different roles. Each node uses its GPS-indicated location to associate itself with a point in the virtual grid. Nodes associated with the same point on the grid are considered equivalent in terms of the cost of packet routing. Such equivalence is exploited for keeping nodes located in a particular grid area in the sleeping state in order to save energy. Thus, GAF can substantially increase the network lifetime as the number of nodes increases.

  There are three states, *discovery*, *active*, and *sleep*, defined in GAF. The state *discovery* is used for determining the neighbours in the grid, *active* reflects participation in routing, and *sleep* is used when the radio is turned off. In order to handle the mobility, each node in the grid estimates its sleep time and sends this to its neighbours. The sleeping neighbours adjust their sleeping time accordingly in order to keep routing fidelity. Before the sleep time of the active node expires, sleeping nodes wake up and then one of them becomes active.

  The simulation results presented in [45] show that GAF performs at least as well as a normal ad hoc routing protocol in terms of latency, packet loss, and network lifetime. Although GAF is a location-based protocol, it may also be considered as a hierarchical protocol, where the clusters are based on their geographic location. For each particular grid area, a representative node acts as the leader to transmit data to other nodes. The leader node however, does not do any aggregation or fusion as in the case of other hierarchical protocols.

- **Geographic and energy aware routing (GEAR)**. Yu et al. proposed geographic and energy aware routing (GEAR) protocol in [46]. GEAR uses energy-aware and geographically-informed neighbour selection heuristics to route a packet towards the destination region. The key idea of GEAR is to restrict the number of interests in directed diffusion by only considering a certain region rather than sending the interests to the whole network. Thus, GEAR can save more energy than directed diffusion.

  Each node in GEAR is aware of an estimated cost and a learned cost of reaching the destination through its neighbours. The estimated cost is a combination of residual energy and distance to the destination. The learned cost is a refinement of the estimated cost that accounts for routing around holes in the network. A hole occurs when a node does not have any closer neighbour to the target region than itself. If there are no holes, the estimated cost is equal to the learned cost.

  There are two phases in the algorithm: forwarding packets towards the target region and forwarding packets within the region. During the first phase, upon receiving a packet, a node checks whether there is one neighbour, which is closer to the target region than itself. If there is more than one, the nearest neighbour to the target region is selected as the next hop. If all the neighbours are further than the node itself to the target region, one of the neighbours is chosen to forward the packet based on the learning cost function. During the second phase, the packet that has reached the region can be diffused in that region by either recursive geographic forwarding or restricted flooding. Restricted flooding is better when the sensor nodes are not densely deployed. In a high-density network, recursive geographic flooding is more energy efficient than restricted flooding.

2.2 Media Access Control (MAC) Protocol

Media Access Control (MAC) protocol is the data communication protocol implemented in data-link layer that specified in seven-layer OSI model [18, 19, 47, 48, 49]. MAC protocol defines the ways for multiple users to share the channel resource. In this section, we introduced two basic MAC protocols: TDMA and CSMA.

2.2.1 Time-Division Multiple Access (TDMA)

TDMA is a type of time-division multiplexing with the special point that there are multiple transmitters instead of one transmitter connected to one receiver [50, 51]. TDMA allows numbers of nodes to share the same frequency channel by allocating different time slots to nodes within the frame in which nodes transmit data. Every node transmits data in its own time slot, during which other nodes are not allowed to access the channel. Therefore, there are no data collisions and the throughput equals to the amount of data transmitted by each node.

Compared with a protocol where the transmission is continuous, the energy dissipation is reduced while using TDMA for large data transmission. This is because the transmission hardware (e.g., the signal amplifier in sensor nodes) can be turned off when the node is not transmitting. However, TDMA protocol requires that some nodes must have the information of all transmitting nodes in order to create the schedule. The change of schedule due to the variation of transmitting nodes will add significant overhead to the protocol. Furthermore, the requirement of time-synchronisation and guaranteed time slot for different nodes increase extra overhead to the TDMA system. TDMA is standardised in IEEE 802.15.3 which is a MAC and PHY standard for high-rate (11 to 55 Mbit/s) WPANs [52].

2.2.2 Carrier-Sense Multiple Access (CSMA)

CSMA is a probabilistic media access control (MAC) protocol where nodes share the channel resource using random-access method [53, 48]. In contract with fixed-assignment multiple access approach, the resources are not assigned to individual nodes in CSMA. When Using CSMA protocol, if a node has data to send, it listens to the channel to determine whether any other node is currently transmitting. There are three different types of CSMA protocol that are followed if the channel is busy or idle: 1-persistent CSMA, p-persistent CSMA and non-persistent CSMA. In 1-persistent CSMA, when one node is ready to transmit data, it checks whether the channel is busy. If the channel is busy, it will continually sense the channel until it is idle, then transmits its data. In case of data collisions, the node waits for a random period of time and attempts to transmit again. The p-persistent CSMA protocl is the generalisation of 1-persistent CSMA. In p-persistent CSMA, the node keeps sensing the channel until it is free, and then transmits its data during the first free slot with probability p. If the transmission did not happen (the probability of this event is $(1 - p)$, the node waits until the next idle slot and transmits again with the same probability p. This process repeats until the node sends its packet or some other nodes start transmitting. In the latter case, the node must wait a random period of time until the channel is idle and begin the process again. In non-persistent CSMA, the node checks the channel when it is ready to send data. If the channel is busy, the node waits a random amount of time and checks again. Repeats the process until the channel is free, and then transmits its data.

Although using this carrier-sense technique can reduce the data collisions, it can not guarantee that collisions will not occur. In the case that two nodes sense the channel at the same time and both decide the channel is free. Then, both nodes transmit data at the same time and thus causing a collision of data message. Protocols, such as carrier sense multiple access with collision detection (CSMA/CD) and carrier sense multiple access with collision avoidance (CSMA/CA), are the efficient solutions to the data collision problem [18]. These carrier-sense multi access protocols, including CMSA, CSMA/CD, and CSMA/CA, have been standardised in IEEE 802.15.3 [54].

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Chapter 3

Centralised Clustering, Energy-Efficient Routing Protocol

This chapter presents a new energy-efficient routing protocol. It consists of a cluster head selection algorithm, a cluster formation method, and an inter-cluster routing algorithm.

3.1 System Model

We describe the system model, including network model and energy model, used in the derivation of the protocol.

3.1.1 Network Model

In developing the protocol, the network model provides the operating environment that consists of N nodes and one base station. Nodes are randomly deployed in an $L \times L$ area with the base station located outside the node area. The sensor nodes periodically sense the environment and send the sensed data to the base station. Whereas the base station is responsible for receiving data from nodes and presenting the end-user a description of the environment the nodes are sensing. The network model has the following properties:

- All nodes have the similar capabilities of sensing, processing, and communication;
- The nodes are energy constrained;

- The initial energy of nodes can be different;
- The nodes are equipped with power control capabilities to vary their transmission power. This means nodes can change their transmitting range based on the requirement;
- All nodes are immobile;
- The base station is fixed and has no energy constraint.

We assume that nodes are location-aware (equipped with the GPS-capable antenna). Additionally, despite the energy constrain, all the nodes have enough energy to directly communicate with any other nodes including the base station. Also each node has enough processing power to support the different protocols and signal processing tasks. Same as those in most wireless sensor networks applications, nodes are left unattended after deployment. Therefore, battery recharge is not possible.

3.1.2 Energy Model

We employ the first order radio module proposed in [8] as the radio energy module to measure the energy dissipation. This radio module consists of three main modules: the transmitter, the power amplifier, and the receiver. The transmitter dissipates energy to run the transmitter circuitry and the power amplifier for transmitting data, and the receiver dissipates energy to run the receiver circuitry for receiving data [8].

There are two propagation models: free space propagation model and two-ray ground propagation model [55, 8, 56]. The free space propagation model means there is direct, line-of sight path between the transmitter and the receiver. The two-ray ground propagation model means the propagation between the transmitter and the receiver is not direct and the electromagnetic wave will bounce off the ground and arrive at the receiver from different paths at different times. In the free space propagation model, the propagation loss of transmitting power is modelled as inversely proportional to d^2, where d is the distance between the transmitter and the receiver. In the two-ray ground propagation model, the propagation loss of transmitting power is modelled as inversely proportional to d^4.

The power amplifier can be used to amplify the transmitting power to compensate propagation loss during the transmission. Thus, the energy dissipation for transmitting an l bit message from the transmitter to the receiver at the distance d is defined as:

$$E_{Tx}(l,d) = \begin{cases} lE_{elec} + l\epsilon_{fs}d^2, & d < d_0; \\ lE_{elec} + l\epsilon_{tg}d^4, & d \geq d_0, \end{cases} \tag{3.1}$$

where E_{Tx} is the energy dissipated in the transmitter of the source node and E_{elec} is the per bit energy dissipation for running the transceiver circuitry. The amplifier parameter for the free space propagation model is ϵ_{fs}. The amplifier parameter for the two-ray ground propagation model is ϵ_{tg}. The cross-over distance, d_0, can be obtained from:

$$d_0 = \sqrt{\frac{\epsilon_{fs}}{\epsilon_{tg}}}. \tag{3.2}$$

If the distance between the transmitter and the receiver is larger than the cross-over distance, the two-ray ground model is employed. Otherwise, the free space model is employed to measure the energy dissipation. Energy required for receiving an l bits message is:

$$E_{Rx}(l) = lE_{elec}. \tag{3.3}$$

We use the same parameters as in [8]: $E_{elec} =$ 50nJ/bit; $d_0 = 87$m; $\epsilon_{fs} =$ 10pJ/bit/m^2; $\epsilon_{tg} =$ 0.0013pJ/bit/m^4.

3.2 Problem Statement

The number of nodes deployed in the network area is large. Thus, the overall data flow in the network is considerable and large data flow will incur significant energy dissipation for nodes. In addition, the densely deployed nodes incur highly correlated data. Since the nodes are energy constrained, the routing protocol is required to be energy-efficient. In addition, because the energy consumption is different from node to node due to various functions and positions in the network, the protocol should be able to balance the energy dissipation of nodes. The distances from nodes to the base station are usually long in a wireless sensor network. Long distant data transmission will incur considerable energy dissipation. Thus, the routing protocol should be able to minimise the energy consumption of data transmission from nodes to the base station. Therefore, the problems that need to be addressed in the design of routing protocol for wireless sensor networks can be summarised as:

- How to efficiently organise numerous nodes in the network in order to reduce the energy dissipation of nodes
- How to balance the energy consumption of nodes
- How to minimise the energy dissipation of data transmission from sensor nodes to the base station

3.3 Proposed Solution to the Energy-Efficient Problem

The central theme of the problems above is energy-efficiency in a large wireless sensor network where the data is highly correlated and the end-user only needs a high-level function of the data that described the events occurring in the environment. The clustering approach is a sensible solution for a large network. It can efficiently organise numerous nodes, aggregate data, and reduce energy dissipation of nodes [10].

The protocols that use centralised clustering, where the base station utilise the global information of the network for cluster head selection and cluster formation, can produce better clusters that require less energy for data transmission [11]. The cluster heads forward aggregated data to the base station and the distance between the cluster heads and the base station is long. Using an efficient multi-hop routing can minimise the energy dissipation of data transmission from cluster heads to the base station [17].

The good performance of these efficient methods lead us to develop a centralised clustering, energy-efficient (CCEE) routing protocol for wireless sensor networks. This clustering-based protocol consists of

- a centralised cluster head selection algorithm,
- a cluster formation scheme that aims at balancing energy load among cluster heads, and

- an energy-efficient multi-hop routing algorithm for data transmission from cluster heads to the base station.

3.4 Details of the Proposed Protocol

3.4.1 Cluster Head Selection Algorithm

In the clustering-based protocol, the nodes are organised into local clusters. Each cluster consists of one cluster head and number of member nodes (the non-cluster-head nodes belong to the same cluster). All non-cluster-head nodes must transmit their data to the cluster head, while the cluster head must receive data from all the cluster members, perform aggregation on the data, and transmit processed data to the remote base station. Therefore, being a cluster head is much more energy-intensive than being a non-cluster-head node. In the scenario where all nodes are energy-limited, it is important to choose appropriate cluster heads for the protocol.

Weight-based Cluster Head Selection

In the proposed protocol, a centralised weight-based cluster head selection algorithm is proposed. This algorithm aims at choosing cluster heads that ensure both the intra-cluster data transmission and inter-cluster data transmission are energy-efficient. In addition, the energy balance is considered when designing this algorithm. This algorithm is performed by the base station which has no energy constraint.

Cluster heads are the local centres in their own clusters. They perform many energy-consuming tasks such as collecting data from member nodes and forwarding processed data to the base station. Thus, the number of neighbouring nodes, the distances between cluster head and member nodes, and the distances between cluster heads and the base station are all crucial issues when choosing cluster heads. In addition, in order to choose nodes with more energy to be the cluster heads, residual energy of nodes is considered for cluster head selection in the protocol.

We define the set of nodes in the network as $V = \{v_1, v_2, ...v_N\}$, where N is the number of nodes in the network. The cluster head selection algorithm is performed as followings:

Step 1. Find the neighbours of each node v (i.e., nodes within the transmission range of node v) as:

$$N(v) = \sum_{v' \in V, v' \neq v} \{dist(v, v') \leq R_c\}, \tag{3.4}$$

where $N(v)$ is the number of neighbours of node v, $dist(v, v')$ is the distance between node v and node v', and R_c is the intra-cluster transmission range.

Step 2. Compute the degree-difference for every node v:

$$\Delta v = |N(v) - \delta|, \tag{3.5}$$

where Δv is the degree-difference of node v and δ is the ideal number of nodes in a cluster.

Step 3. Calculate the sum of square distance between node v and its neighbours as

$$d_v = \sum_{v' \in N(v)} \{dist(v, v')^2\}, \tag{3.6}$$

where d_v is the sum of square distance between node v and its neighbours.

Step 4. Compute the D_v for each node v

$$D_v = D(v, BS), \tag{3.7}$$

where $D(v, BS)$ is the distance between node v and the base station (BS).

Step 5. Estimate the residual energy of every node v, E_v.

Step 6. Calculate the combined weight of each node v from:

$$W_v = (w_1 \Delta v + w_2 d_v + w_3 D_v) \frac{E_{ini}}{E_v}, \tag{3.8}$$

where W_v is the combined weight of node v, w_1, w_2, and w_3 are the weighting parameters that determined by the system property and protocol requirements, and E_{ini} is the initial energy of node v.

Step 7. Select the node with the smallest W_v as the cluster head. All the neighbours of the selected cluster head are no longer allowed to participate in the remaining part of selection procedure.

Step 8. Repeat steps 2-7 for the remaining nodes until all the nodes have been selected as a cluster head or assigned to a cluster.

Analysis of Cluster Head Weighting Function

Consider Equation 3.8. The first variable, Δv, contributes to producing better clusters in terms of balanced load in the weighting function. Because only when the value of $N(v)$ is close to or even equal to δ can result in a small Δv. Small value of Δv means the size of cluster (mainly depend on the number of member nodes) is close to the ideal size of cluster and similar to each other. Similar cluster size implicates balanced load of cluster heads in the network.

The motivation of d_v is mainly related to the energy consumption of intra-cluster communication. The energy dissipation is inversely proportional to certain exponent of the distance between two separate nodes. Presumably the distance between the non-cluster-head node and its cluster head is less than the cross-over distance, so the energy dissipation follows the free space model (e.g., d^2 power loss). This cluster head selection algorithm tries to choose the nodes with smaller d_v as cluster heads in order to reduce the energy dissipation of communication between member nodes and the cluster head.

The third variable D_v is used to estimate the inter-cluster communication cost. The energy consumed by inter-cluster data transmitting is considerable for cluster heads. Bigger D_v implies heavier energy budget of the cluster head for data transmission. The results in later section indicates that the energy dissipation of a cluster head for transmitting data to the base station using multi-hop routing is linear to the distance between the cluster head and the base station. Therefore, D_v is used to estimate the weight of node and nodes with smaller $D(v, BS)$ are more likely to become the cluster heads.

The component $\frac{E_{ini}}{E_v}$ is related to the energy issue of node for cluster head selection. The weighting equation implicates that nodes with more residual energy are better candidatures to become cluster heads. Although the positions of nodes are fixed, the energy dissipation differs from nodes to nodes in each round. Therefore, if $\frac{E_{ini}}{E_v}$ is integrated in the weighting function, nodes will become cluster heads in turn. Since a cluster head usually consumes more energy than a non-cluster-head node, the rotation of the role of cluster head among nodes can efficiently balance the energy load across the whole network.

Determine the Parameters

Since the variables of Equation 3.8, Δv, d_v, and D_v, have different range of values, we try to set the appropriate parameters (w_1, w_2, and w_3) to balance the value of these three terms in the weighting function. This ensures that all the variables in the weighting equation make equivalent contributions to the node weight. We try to determine these parameters based on a specific network model example of the CCEE protocol, where 100 nodes are distributed in a 200m×200m area with the base station located at (275m,100m).

Before calculating the value range of Δv, we will investigate the optimal cluster number of the CCEE protocol that can minimise the energy dissipation in the system. We analytically determine the optimal number of clusters using the energy model described in Section 3.1.2.

Assume that there are N sensor nodes uniformly distributed in an $L \times L$ region in the CCEE protocol. If there are n clusters, on average there are $\frac{N}{n}$ nodes per cluster (Considering the overlap between clusters, we take $\lceil \frac{N}{n} \rceil$ as the number of nodes per cluster when $\frac{N}{n}$ is not an integer.). Each cluster consists on average of one cluster head and $\frac{N}{n} - 1$ member nodes. Each cluster head dissipates energy by receiving data from member nodes, performing aggregation on collected data and forwarding the processed data to the base station. Therefore, the energy dissipation of the cluster head E_{CH} is:

$$E_{CH} = lE_{elec}(\frac{N}{n} - 1) + lE_{DA}\frac{N}{n} + E_{inter}, \tag{3.9}$$

where l is the number of bits in each data message, E_{elec} is the parameter defined in the energy model, and E_{DA} is the energy for data aggregation. The energy dissipation of data transmission from the cluster head to the base station is denoted as E_{inter}.

The member nodes in clusters only have to send their data to the cluster head. Presumably the distances between cluster heads and the member nodes in the same cluster is less than the cross-over distance, so the energy dissipation follows the free space model. Thus, the energy consumed by one member node E_{mem} is:

$$E_{mem} = lE_{elec} + l\epsilon_{fs}d_{toCH}^2, \tag{3.10}$$

where l is the number of bits in each data message, E_{elec} and ϵ_{fs} are the parameters defined in energy model, and d_{toCH} is the distance from the member node to the cluster head. The average area of the cluster is approximately $\frac{L^2}{n}$. In general, this is an arbitrary-shaped area with local number density $\rho(x, y)$. If the density of nodes in a cluster is uniform throughout the cluster area, then $\rho(x, y) = \frac{1}{\frac{L^2}{n}} = \frac{n}{L^2}$. The expected squared distance from nodes to the cluster head (assumed to be at the center of the cluster) is given by:

$$E[d_{toCH}^2] = \int\int (x^2 + y^2)\rho(x, y)dxdy \tag{3.11}$$

If we assume that the area is a circle with radius $R = \frac{L}{\sqrt{\pi n}}$, Equation 3.11 simplifies to:

$$\begin{aligned} E[d_{toCH}^2] &= \frac{n}{L^2}\int_{\theta=0}^{2\pi}\int_{r=0}^{\frac{L}{\sqrt{\pi n}}} r^3 dr d\theta \\ &= \frac{L^2}{2\pi n}. \end{aligned} \tag{3.12}$$

Therefore, in this case,

$$E_{mem} = lE_{elec} + l\epsilon_{fs}\frac{L^2}{2\pi n} \tag{3.13}$$

Now the average energy dissipated in a cluster is:

$$E_{cluster} = E_{CH} + (\frac{N}{n} - 1)E_{mem} \tag{3.14}$$

Total energy is:

$$\begin{aligned} E_{total} &= nE_{cluster} \\ &= l(2NE_{elec} + NE_{DA} - 2nE_{elec} + \frac{nE_{inter}}{l} + \frac{NL^2\epsilon_{fs}}{2\pi n} - \frac{L^2\epsilon_{fs}}{2\pi}) \end{aligned} \tag{3.15}$$

We can find the optimal number of clusters by setting the derivative of E_{total} with respect to n to zero:

$$\begin{aligned} \frac{dE_{total}}{dn} &= 0 \\ n_{opt} &= \sqrt{\frac{NL^2\epsilon_{fs}}{2\pi(\frac{E_{inter}}{l} - 2E_{elec})}} \end{aligned} \tag{3.16}$$

The analysis in a later section indicates that $E_{inter} = 2.14lD$ can approximately estimate the energy consumed for the inter-cluster communication in the CCEE protocol, where D is the distance from the cluster head to the base station. For the example network model of the CCEE protocol, $N = 100$, $L = 200$m, ϵ_{fs}=0.01nJ/bit/m^2, and 75m$\leq D \leq$292m, so we expect the optimal number of clusters for our protocol to be: $4 \leq n \leq 10$.

To verify the analytical result of the optimal number of clusters in the CCEE protocol, we ran our protocol on a simulation platform (introduced in later section) for 100 rounds

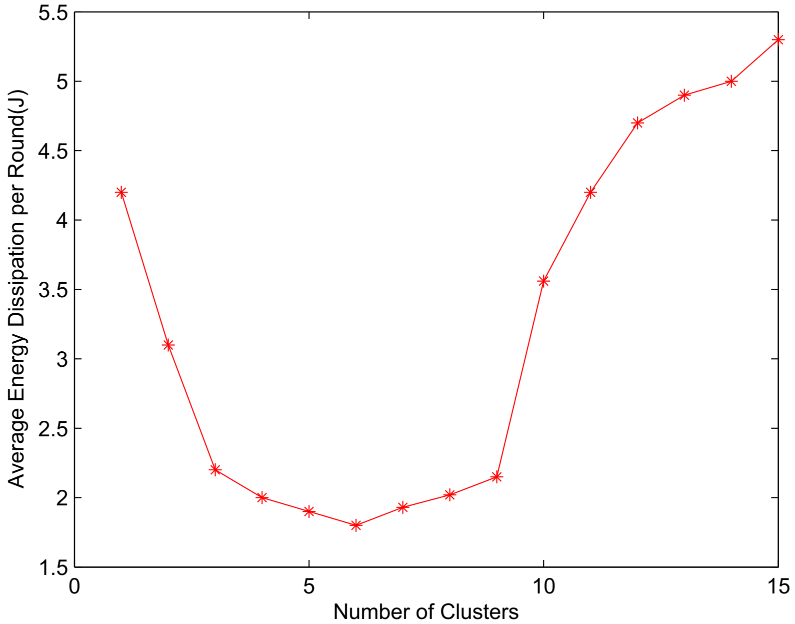

Figure 3.1. Average energy dissipation per around in the CCEE protocol as the number of clusters varying between 1 and 15. This graph shows that the CCEE protocol is most energy-efficient when there are between 4 and 7 clusters in the 100-node network.

with the number of cluster varied from 1 to 15. These simulations are based on the network model and scenarios defined for the CCEE protocol. Figure 3.1 shows the average energy dissipated per round as a function of the number of clusters. This graph shows that the optimal number of clusters is, as predicted by the analysis, around 4 to 7 for the CCEE protocol. When the number of clusters is small, such as 1, the distances between member nodes and cluster heads becomes too large and the energy dissipation of intra-cluster communication is significant. When there are too many clusters (more than 10), there is not as much local data aggregation being performed. Thus, we set the optimal number of clusters, n, to 6 for the CCEE protocol.

Assuming the sensor nodes are uniformly distributed in the network, the ideal number of nodes in a cluster is given by:

$$\delta = \frac{N}{n}, \tag{3.17}$$

where N is the number of nodes in the network. We set $\delta = \lceil \frac{N}{n} \rceil$ when $\frac{N}{n}$ is not an integer. For the network of our protocol, $N = 100$, thus $\delta = 17$.

The intra-cluster transmission range can be estimated based on the number of clusters. The area occupied by each cluster is approximately $\frac{A}{n}$, where A is the area of network field and n is the number of clusters. If we assume the area of a cluster is a circle with radius $R = R_c$, where R_c the intra-cluster transmission range of a cluster head, then the average area per cluster head is:

$$\pi R_c^2 = \frac{A}{n}. \tag{3.18}$$

For the network model of the example CCEE protocol, $A = 200\text{m}\times\ 200\text{m} = 40000\text{m}^2$ and $n = 6$, so we can obtain $R_c \approx 46\text{m}$. Since the overlap of the coverage area of clusters in the network is non-trivial, we arbitrarily set R_c=60m as the intra-cluster transmission range for our protocol to ensure a good coverage for the whole network.

Based on the network structure of our protocol, the number of neighbours of node v, $N(v)$, is a minimum when the node is located at the corner of network and the minimum value of $N(v)$ is average area per cluster head times average number of nodes per unit area:

$$N(v)_{min} = \frac{\frac{\pi R_c^2}{4}}{A} N \approx 7. \tag{3.19}$$

The maximum $N(v)$ can be obtained when the node is located near the network center,

$$N(v)_{max} = \frac{\pi R_c^2}{A} N \approx 28. \tag{3.20}$$

Thus, we obtain $N(v) \in [7, 28]$ and $\Delta v = |N(v) - \delta| \in [0, 11]$, where δ=17.

The sum of square distance between node v and its neighbours, d_v, is minimised when node v is located at the corner of the network area. The expected value of $d(v, v')^2$ is then given by:

$$\begin{aligned} E[d(v,v')^2]_{min} &= \int\int (x^2 + y^2)\rho(x,y)dxdy \\ &= \int\int r^2 \rho(r,\theta) r dr d\theta, \end{aligned} \tag{3.21}$$

where $\rho(x, y)$ is the node distribution in the network. If the density of nodes is uniform throughout the cluster area, then $\rho(x, y) = \frac{1}{\frac{\pi R_c^2}{4}}$. Thus, Equation 3.21 can be simplified to:

$$E[d(v,v')^2]_{min} = \int_{\theta=0}^{\frac{\pi}{4}} \int_{r=0}^{R_c} \frac{4}{\pi R_c^2} r^3 dr d\theta$$

$$= \frac{R_c^2}{4} \tag{3.22}$$

Since $R_c = 60$m, we can obtain $E[d(v,v')^2]_{min} = 900\text{m}^2$. Thus, the minimum value of d_v is:

$$[d_v]_{min} = [N(v)]_{min} E[d(v,v')^2]_{min} = 6300\text{m}^2. \tag{3.23}$$

The maximum value of d_v occurs when node v is located near the center of the network where node v has the largest number of neighbour nodes. The expected value of $d(v,v')^2$ is:

$$\begin{aligned} E[d(v,v')^2]_{max} &= \int\int (x^2+y^2)\rho(x,y)dxdy \\ &= \int\int r^2 \rho(r,\theta) r dr d\theta. \end{aligned} \tag{3.24}$$

In this case, $\rho = \frac{1}{\pi R_c^2}$, thus

$$\begin{aligned} E[d(v,v')^2]_{max} &= \int_{\theta=0}^{2\pi}\int_{r=0}^{R_c} \frac{1}{\pi R_c^2} r^3 dr d\theta \\ &= \frac{R_c^2}{2}. \end{aligned} \tag{3.25}$$

For our protocol, $R_c = 60$m, so we obtain $E[d(v,v')^2]_{max} = 1800\text{m}^2$. The maximum value of d_v is given as:

$$[d_v]_{max} = [N(v)]_{max} E[d(v,v')^2]_{max} = 50400\text{m}^2. \tag{3.26}$$

Thus, the range of d_v value is: $d_v \in [6300, 50400]$ in m^2.

Nodes are distributed in a 200m×200m area with the base station located at (275m,100m) in the network model of our protocol(see Figure 3.6). We can obtain the value range of $D(v, BS)$ by using Euclidean geometry as: $D(v, BS) \in [75, 292]$ in m.

We define in our protocol that if the residual energy of a node is less than 5% of its initial energy, this node is no longer allowed to participate in the election procedure for cluster head. Therefore, we can obtain $\frac{E_{ini}}{E_v} \in [1, 20]$.

Based on the value ranges of Δv, d_v, and D_v, we determine the parameters of the weighting equation as: $w_1 = 0.95$, $w_2 = 1.0 \times 10^{-4}$, and $w_3 = 0.05$. Thus, Equation 3.8 can be simplified to:

$$W_v = (0.95\Delta v + 1.0 \times 10^{-4} d_v + 0.05 D_v)\frac{E_{ini}}{E_v}. \tag{3.27}$$

Note that, these parameters may be adjusted according to the system properties and protocol objectives. For example, if protocols address the energy dissipation of inter-cluster communication, the value of w_3 can be increased. Therefore, although the parameters are determined based on the network model and scenarios defined for our protocol, the cluster head selection algorithm is applicable to other situations because of the adjustability of the parameters.

The cluster head selection algorithm of a routing protocol can be performed in a centralised manner by the base station or accomplished by the sensor nodes themselves. In order to produce better clusters using global information of the network, we choose the centralised approach accomplished by the base station. This centralised algorithm can save the energy dissipation of maintaining the information of all nodes in the network at the nodes. To perform this centralised cluster head selection algorithm, the base station will receive the information messages, including location and current energy level, from nodes at the beginning of each round. Using the information of nodes in the weighting function, the base station chooses a set of cluster heads and organises the network into clusters.

Since the distance between nodes and the base station is considered, the selected cluster heads will consume less energy for forwarding data to the base station. In addition, using the information of neighbouring nodes in the algorithm, we ensure that the intra-cluster energy consumption is minimised. The base station will rechoose the cluster heads according the current information of nodes at the beginning of each round. Since the energy issue of the nodes, which varies during the course of network operation, is considered in the head selection algorithm, the role of cluster head can be rotated among nodes. The rotation of cluster heads can distribute the energy load across the network. The constraint of this centralised algorithm is that nodes must have the capacity of obtaining their own information, such as location. In addition, there is communication overhead when nodes send information to the base station.

3.4.2 Cluster Formation

The cluster formation of the CCEE protocol aims at balancing the energy load of cluster heads. Once the nodes have been selected as cluster heads, they will invite other non-cluster-head nodes (we refer to them as ordinary nodes) in the network to join the clusters.

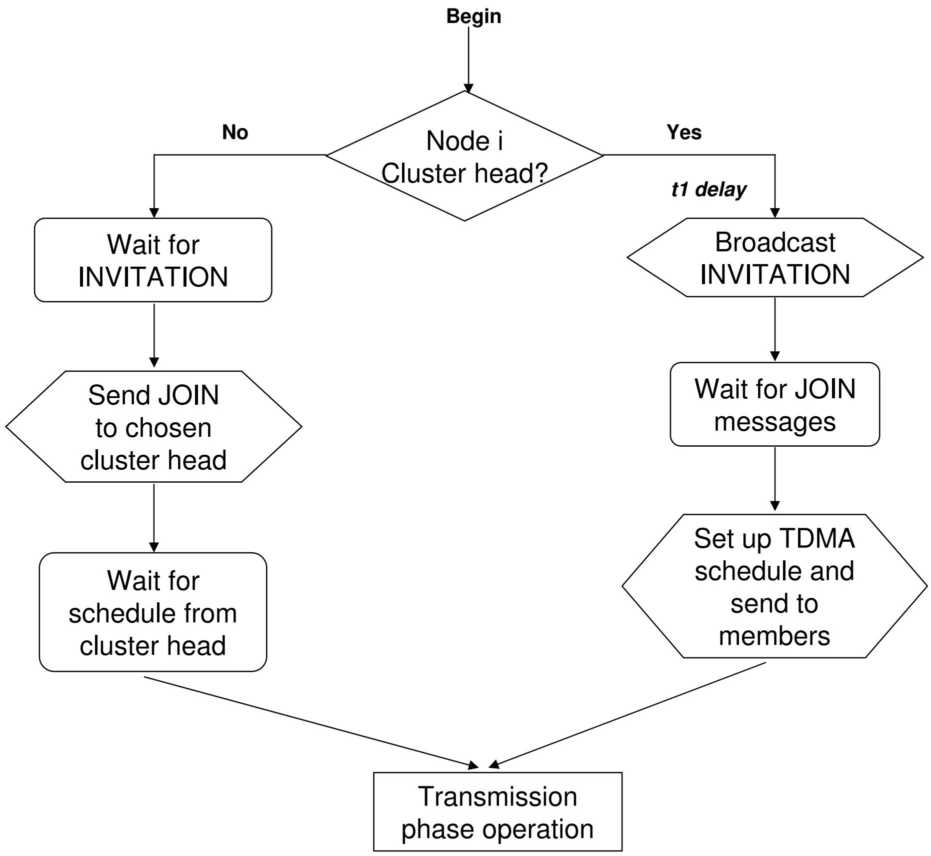

Figure 3.2. Flow-graph of cluster formation for CCEE

To do this, each cluster head broadcasts an invitation message using a non-persistent carrier-sense multiple access(CSMA) MAC protocol (see Figure 3.2). The cluster head selection algorithm used in our protocol ensures that the selected cluster heads can cover all the nodes in the network with limited transmission range. Thus, in order to reduce the transmission energy for cluster heads, the invitation messages from cluster heads do not have to reach all of the nodes in the network.

In order to reduce the interference of transmission, all cluster heads load a random time delay t_1, after which they broadcast the invitation messages. The random time delay t_1 should be set appropriately to ensure there is enough interval time between broadcasting an invitation by two random cluster heads without incurring considerable time delay of the system.

Since some ordinary nodes may reside in multiple neighbourhoods of cluster heads, they will receive more than one invitation messages (if a cluster head receives invitation messages from other cluster heads, it will just discard the messages). In order to balance the energy load of cluster heads, we set node degree of a cluster head as the criterion for ordinary nodes to choose a cluster. The node degree of a cluster head, say head a, is defined as:

$$d(a) = \sum_{i=1}^{M} d_i^2, \tag{3.28}$$

where $d(a)$ is the node degree of head a, M is the number of neighbour nodes of the cluster head, and d_i is the distance between the neighbour node i and the cluster head. This node degree information will be contained in the invitation message broadcasted from the cluster head.

The energy dissipation largely depends on the distance between two separated nodes and the data transmission within the cluster follows the free space energy model. Therefore, the node degree is an estimation of the intra-cluster communication cost of a cluster head. Larger node degree means more energy dissipation of the cluster head for the intra-cluster communication. In order to balance the energy dissipation among cluster heads, ordinary nodes will select the cluster head with minimum node degree as their cluster head in the current round.

After every node has decided to which cluster it belongs, it must inform the cluster head that it will be a member of that cluster. Each node transmits a join message back to the chosen cluster head using a CSMA MAC protocol. The cluster heads act as local control centres to coordinate the data transmission in their clusters. Based on the information of joined nodes, the cluster head sets up a time division medium access (TDMA) schedule and sends this schedule to the joined nodes. After the TDMA schedule is known by all nodes in the cluster, the set-up phase is complete and the transmission phase can begin.

3.4.3 Inter-cluster Routing Algorithm

Generally, there are two models, direct transmission and multi-hop transmission, used for the data transmission between two separated nodes. Many researches (e.g., [17, 44]) have proved that using multi-hop transmission is more energy-efficient than using direct transmission because of the characteristics of a wireless channel. Since the CCEE protocol is required to minimise the energy dissipation of nodes, a multi-hop routing algorithm is developed for the data transmission from cluster heads to the base station. This multi-hop routing algorithm integrates an optimal inter-cluster transmission range, based on which cluster heads choose intermediate nodes to relay data packets to the base station.

Determine Optimal Inter-cluster Transmission Range

In a wireless sensor network, the transmission range of multi-hop routing may vary to meet the requirements of the protocol. For the multi-hop routing algorithm in the CCEE protocol, we try to determine the optimal transmission range in order to minimise the total energy consumption of data transmission.

According to the energy model described in Section 3.1.2, the energy needed for a source node transmitting an l bit message to a destination node at distance d is:

$$E_{Tx}(l,d) = lE_{elec} + l\epsilon_{amp}d^k, \tag{3.29}$$

where E_{elec} is the per bit energy dissipation for running the transceiver circuitry, ϵ_{amp} is the amplifier parameter, k is the energy loss exponent which depends on the distance between the transmitter and the receiver. If $d < 87$m, the free space propagation model is used and $k = 2$. Otherwise, the two-ray ground propagation model is used and $k = 4$. Energy required for receiving an l bit message is:

$$E_{Rx}(l) = lE_{elec}. \tag{3.30}$$

Thus, the total energy dissipation of a one-hop transmission equals to the transmission energy consumed at the sending node plus the energy for receiving the message at the receiving node. So, with $d = R$

$$E_{1-hop} = E_{Tx} + E_{Rx} = 2lE_{elec} + l\epsilon_{amp}R^k, \tag{3.31}$$

where E_{1-hop} is the total energy dissipation for the one-hop transmission, E_{Tx} is the energy consumed by the transmitter, E_{Rx} is the energy dissipation of the receiver, and R is the inter-cluster transmission range. Therefore, for K hops there are $K-1$ relays between a cluster head node and the base station at a separated distance D, the total energy dissipation for transmitting a one bit packet from this cluster head to the base station is given by:

$$E_{total} = \sum_{i=1}^{K-1} E_{i-hop}, \tag{3.32}$$

where K is the number of hops for the data transmission from the cluster head to the base station and E_{i-hop} is the energy consumed for the ith hop data transmission.

Based on the results in [13], in order to minimise the total energy consumption of data transmission, the transmission range of each hop must equal to an optimal transmission range, R_{opt}, which can be obtained from:

$$R_{opt} = (\frac{2E_{elec}}{\epsilon_{amp}})^{\frac{1}{k}}, \tag{3.33}$$

where E_{elec}, ϵ_{amp}, and k are parameters defined in the energy model. The expected minimum total energy dissipation of data transmission is:

$$E_{total-min} = (2E_{elec} + \epsilon_{amp} R_{opt}^{k})(\frac{D}{R_{opt}}), \tag{3.34}$$

where D is the distance between the cluster head and the base station.

There are two propagation models, the free space model and the two-ray-ground model, used for the data transmission in our protocol. Both models have their own energy models with associated parameters. We try to determine which model is used for the inter-cluster data transmission by substituting the parameters of both models in Equation 3.33. Firstly, we assume that the free space model is used. Substituting parameters of the free space energy model, E_{elec} = 50nJ/bit, $k = 2$, and ϵ_{fs} = 0.01nJ/bit/m^2, in Equation 3.33, we can obtain R_{opt} = 100m. This obviously contradicts with the condition, $d_0 <$ 87m, under which the free space model can be used. Next, we assume that the two-ray ground model is used. Substituting the parameters of the two-ray-ground model, E_{elec} = 50nJ/bit, $k = 4$, and $\epsilon_{tg} = 1.3 \times 10^{-6}$nJ/bit/m^4, in Equation 3.33, we obtain R_{opt} = 94m. This result meets the requirement of the two-ray-ground model, which is $d_0 \geq$ 87m. Therefore, we deduce that the two-ray-ground propagation model is to be utilised for the inter-cluster communication in our protocol and R_{opt} = 94m. Since the base station is located far away from the network area in a wireless sensor network, it is reasonable to use the two-ray ground propagation model for inter-cluster data transmission.

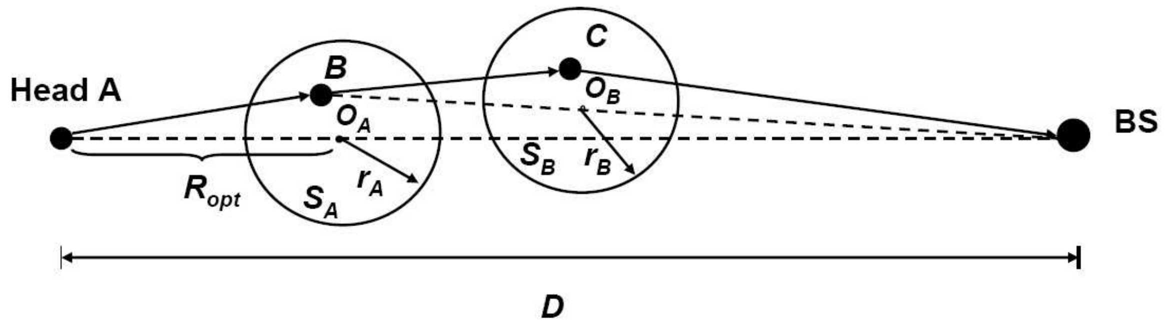

Figure 3.3. Data forwarding procedure of the CCEE protocol

Therefore, Equation 3.34 can be simplified to:

$$E_{total-min} = (2E_{elec} + \epsilon_{tg} R_{opt}^4)(\frac{D}{R_{opt}}). \tag{3.35}$$

Substituting $E_{elec} = 50$nJ/bit, $\epsilon_{tg} = 1.3 \times 10^{-6}$nJ/bit/m^4 and $R_{opt} = 94$m in Equation 3.35, we can obtain the minimum energy dissipation of sending one bit message the cluster head to the base station: $E_{total-min} = 2.14D$(nJ/bit).

Selection of Intermediate Nodes Based on R_{opt}

If the distance between a cluster head and the base station is smaller than the optimal inter-cluster transmission range, it will send data to the base station directly. Otherwise, this cluster head will use the multi-hop route to transmit data to the base station and one or more intermediate nodes will be chosen to perform the relaying task during the data transmission. When a cluster head, say Head A, has data to send to the base station, the optimal position of the first intermediate node for Head A is O_A as shown in Figure 3.3, where the distance between O_A and Head A is R_{opt}. However, it cannot be guaranteed that there are nodes exactly located at O_A. An alternative approach is to choose the node that is closest to O_A as the intermediate node.

The intermediate node selection procedure is triggered by Head A using small control messages as follow:

Step 1. When Head A has data ready to send to the base station, it will send a request message to the nodes near O_A. Let (x_a, y_a) and (x_{BS}, y_{BS}) be the coordinators of Head A and the base station, respectively. The coordinates of O_A is denoted by (x_o, y_o), then, assuming approximately straight line transmission from Head A to BS,

$$\begin{cases} x_o = x_a + \frac{R_{opt}}{D}(x_{BS} - x_a) \\ y_o = y_a + \frac{R_{opt}}{D}(y_{BS} - y_a) \end{cases} \tag{3.36}$$

where R_{opt} is the optimal inter-cluster transmission range and D is the distance between Head A and the base station.

In order to reduce the message complexity, not all the nodes that located near to O_A participate in the contention for the relaying task. As shown in Figure 3.3, a search region for Head A, denoted by S_A, is defined as the circle area centered at O_A with radius r_A, where $r_A \leq\mid AO_A \mid$. Only the nodes in S_A need to perform the contention for the role of intermediate node. The optimal r_A can be estimated according to the nodes distributing density in the network. The request message from Head A contains three quantities: r_A, (x_a, y_a), and (x_o, y_o).

Step 2. Based on the quantitative information in the request message received from Head A, the nodes near O_A will judge whether they fall in S_A. If a node, say Node B, resides in S_A, it will send a reply message that includes its own coordinates and residual energy, (x_b,y_b) and E_{resB}, to Head A. Otherwise, it simply discards the request message.

Step 3. When Head A receives the reply message from Node B, it will update its next-hop node n_A as follows: If n_A is empty, Node B directly becomes the next-hop node of Head A. Otherwise, Head A computes the relay factor of Node B, $f(B)$, which is defined as:

$$f(B) = \frac{E_{iniB}}{E_{resB}}((x_o - x_b)^2 + (y_o - y_b)^2), \tag{3.37}$$

where E_{iniB} is the initial energy of Node B and E_{resB} is the residual energy of Node B. Then, $f(B)$ is compared with the relay factor value of node n_A, $f(n_A)$. If $f(B) < f(n_A)$, Head A will reset Node B as its next-hop node. Otherwise, Head A remains the previous next-hop node n_A. This calculation and comparison will repeat once Head A receives a reply message. Once the next-hop node is determined, Head A will send the data packet to this node immediately

Step 4. If Node B has been selected as the intermediate node and received a packet from Head A, it will determine its next-hop node according to the procedures described in steps 1-3.

Step 5. Steps 1-4 will be iterated until the data packet arrives at the base station

The computation and comparison procedure for intermediate node selection incurs considerable communication overhead and energy dissipation at Head A. One approach to alleviate this problem is to reduce the size of the relay search region in order to minimise the number of candidate nodes for the selection. However, the optimal size of search region can only be roughly estimated since Head A does not have the information of other nodes located out of its cluster. Another method is to set a delay time for each node that falls in the search area. For any node v in the search region that receives the request message from Head A, instead of generating and sending the reply message immediately, it sends the reply message after delay t_{delay} which can be obtained from

$$t_{delay} = \lambda f(v), \tag{3.38}$$

where λ is a constant which can be determined empirically and $f(v)$ is the relay factor of node v.

Obviously, t_{delay} is proportional to the relay factor of the node, which can ensure that the node with the smallest value of relay factor will send the reply message first. On the other hand, if some nodes with longer delay time overhear reply messages from other nodes, they are not allowed to send a reply message to Head A. In the best situation, Head A will only receive one reply message from all the candidate nodes in the relay search region. Therefore, choosing an appropriate λ, the communication overhead and computation energy dissipation of Head A can be reduced significantly.

This multi-hop routing algorithm that integrates the optimal inter-cluster transmission range is expected to reduce the energy dissipation of data transmission. In addition, since the residual energy of nodes varies during the network operation, integrating the residual energy when choosing the relaying nodes makes the rotation of intermediate nodes possible. Thus, the energy load can be distributed and the “hot-spot” problem (some nodes may be used as intermediate nodes too frequently that will deplete their energy much earlier than other nodes) can be avoided. Because the distances between nodes and the base station differ from node to node, the number of hops (or whether using single hop or multi-hop) is depended on the specific distance between the sending cluster head and the base station. Since this routing algorithm uses the multi-hop way for data transmission, there is a small time delay when using this algorithm.

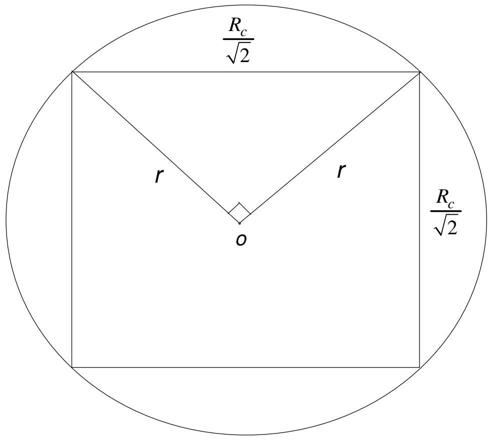

Figure 3.4. Conditions on transmission range for network connectivity

Connectivity of the Network

For the multi-hop data transmission in a wireless sensor network, the transmission range may vary to ensure a certain degree of connectivity in the network. For example, the author in [57] proved that if n nodes are uniformly and independently dispersed at random in an area which is divided into N square cells of size $\frac{R_c}{\sqrt{2}} \times \frac{R_c}{\sqrt{2}}$, there is at least one node in each cell.

For the case in our routing protocol, R_c is the intra-cluster transmission range. In order to ensure the connectivity of inter-cluster data transmission, there is at least one node that resides in the search area of the transmitting cluster head. As shown in Figure 3.4, to inscribe the cell of size $\frac{R_c}{\sqrt{2}} \times \frac{R_c}{\sqrt{2}}$ in the search area S_A, the minimum value of the radius of S_A is $\frac{R_c}{2}$. In other words, if r satisfies the requirement, $r \geq \frac{R_c}{2}$, there is at least one node in the search area of the transmitting cluster head and the connectivity of the inter-cluster transmission is guaranteed. Since the cluster head can reach every node within its cluster in our protocol, the connectivity of the intra-cluster transmission is ensured. Therefore, the connectivity of the whole network can be guaranteed.

Energy Dissipation Analysis

In order to assess the advantage of our multi-hop routing algorithm in terms of energy efficiency, we compare the expected energy dissipation of inter-cluster data transmission when using our algorithm with the energy consumed by direct transmitting. For this

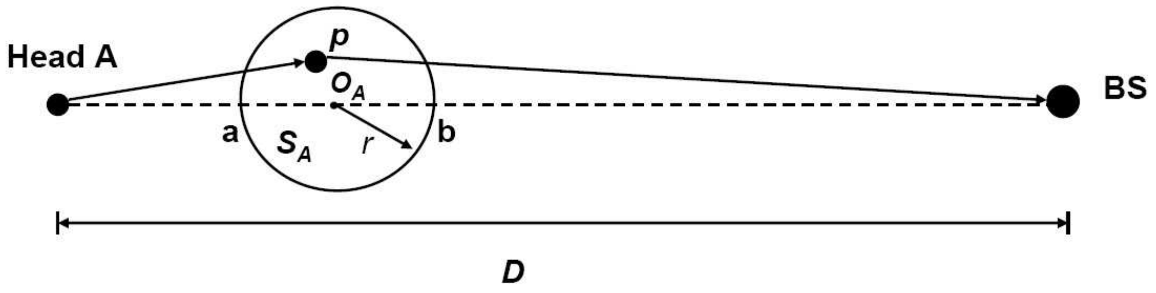

Figure 3.5. Two-hop routing for Head A

comparison analysis, we assume that a cluster head, say Head A, uses a two-hop routing to transmit data to the base station. As shown in Figure 3.5, Head A sends data to an intermediate node, say Node P, and Node P forwards the received data to the base station. Intuitively, if the two-hop routing is more energy-efficient than the direct transmission, total energy dissipation for transmitting data will be further reduced if there are more hops between Node P and the base station. Therefore, two-hop routing between Head A and the base station can be regarded as the worst situation for multi-hop routing in terms of energy efficiency. In order to prove that our routing algorithm is more energy-efficient than the direct transmission, we compare the possible largest energy dissipation when using our algorithm with the energy consumed by direct transmitting.

According to the energy dissipation model, if Head A directly sends an l bits data message to the base station, the energy consumed by Head A is:

$$E_{dir} = lE_{elec} + l\epsilon_{tg}D^4, \tag{3.39}$$

where E_{dir} is the energy dissipation of Head A using direct transmission, E_{elec} and ϵ_{tg} are the parameters defined in the energy model, and D is the distance between Head A and the base station. It has been determined that the two-ray ground energy propagation model is used for inter-cluster data transmission. The energy consumed by the base station for receiving the data is not included in the energy dissipation of nodes, thus the total energy dissipation of the direct transmission equals the energy consumed by Head A.

When Head A uses our multi-hop routing algorithm and chooses Node P as the intermediate node to relay data to the base station, the total energy dissipation of transmitting an l bits message to the base station is:

$$E_{mh} = E_A + E_P, \tag{3.40}$$

where E_{mh} is the total energy dissipation when Head A using the multi-hop routing, E_A is the energy dissipation of Head A, and E_P is the energy consumed by Node P. The energy dissipated by Head A only includes the energy for transmitting the data message to Node P:

$$E_A = lE_{elec} + l\epsilon_{tg} d_1^4, \tag{3.41}$$

where d_1 is the distance between Head A and Node P, E_{elec} and ϵ_{tg} are the parameters defined in energy model. In contrast, for a single hop, the energy consumed by Node P consists of the energy for receiving the data message from Head A and the energy for forwarding the data message to the base station:

$$E_P = lE_{elec} + lE_{elec} + l\epsilon_{tg} d_2^4 = 2lE_{elec} + l\epsilon_{tg} d_2^4, \tag{3.42}$$

where d_2 is the distance from Node P to the base station. Substituting Equation 3.41 and Equation 3.42 into Equation 3.40, then

$$E_{mh} = 3lE_{elec} + l\epsilon_{tg}(d_1^4 + d_2^4). \tag{3.43}$$

As depicted in Figure 3.5, d_1 is minimised when Node P locates at point a, and maxmised when Node P locates at point b. Thus, we obtain $R_{opt} - r \leq d_1 \leq R_{opt} - r$. The intra-cluster transmission range for the network model of our protocol is 60m. Thus, we set $r = \frac{R_c}{2} = 30$m to ensure the network connectivity. Since $R_{opt} = 94$m, we can obtain 64m $\leq d_1 \leq$ 124m. When nodes are densely deployed, S_A is small, and $D - d_1$ is a good approximation of d_2. Therefore, Equation 3.43 can be expressed as:

$$E_{mh} = 3lE_{elec} + l\epsilon_{tg}(d_1^4 + (D - d_1)^4), 64 \leq d_1 \leq 124, \tag{3.44}$$

where D is the distance between Head A and the base station.

Since the position of Head A is undetermined, the distance from Head A and the base station, D, cannot be decided. However, we can analyse the energy issue when Head A is located at representative positions in the network to estimate the energy efficiency of our multi-hop routing algorithm. We investigate two possible representative positions of Head A as shown in Figure 3.6.

In case 1 shown in Figure 3.6, Head A is located at the left top corner of the network area, where is farthest from the base station. According to the network model of our

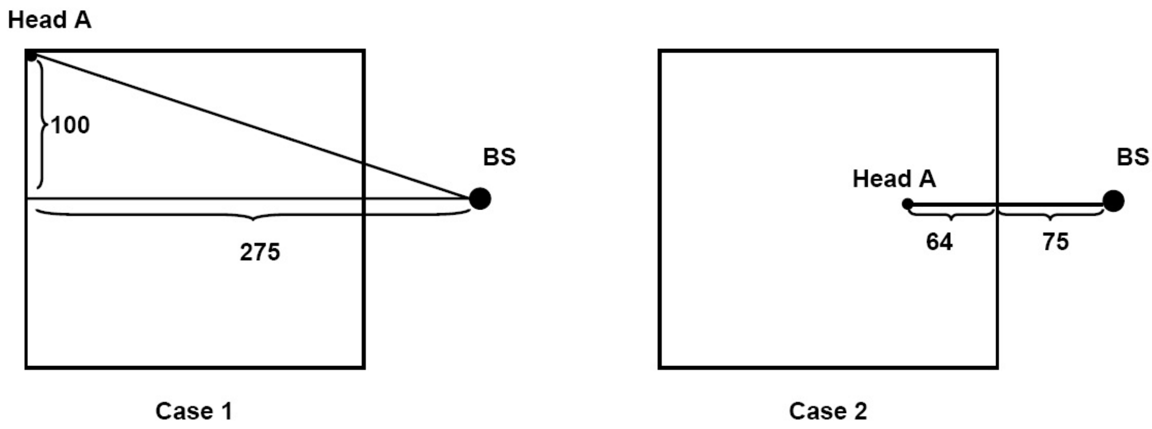

Figure 3.6. Positions of Head A

protocol, we can obtain $D = 292$m using Euclidean geometry. Before computing the maximum value of E_{mh}, we try to obtain the maximum value of the function: $y = x^4 + (292 - x)^4, 64 \leq x \leq 124$. Using matlab, we can obtain a plot of this function as shown in Figure 3.7.

It can be easily concluded from Figure 3.7 that y is a maximum when $x = 64$. As such, E_{mh} will be maximised when $d_1 = 64$m for Equation 3.44. Substituting $E_{elec} = 50$nJ/bit, $\epsilon_{tg} = 1.3 \times 10^{-6}$nJ/bit/m^4, and $d_1 = 64$m in Equation 3.44, we can obtain the maximum value of E_{mh}, denoted by E_{mh-max}, as:

$$E_{mh-max} = 3685l(\text{nJ}). \tag{3.45}$$

Thus, in this case, the maximum energy dissipation of transmitting an l bit message to the base station for Head A using our multi-hop routing is $3685l$(nJ).

The energy consumed by direct transmission can be obtained by substituting $d = D = 292$m, $E_{elec} =$ 50nJ/bit and $\epsilon_{tg} = 1.3 \times 10^{-6}$nJ/bit/m^4 in Equation 3.39 as:

$$E_{dir} = 9501l(\text{nJ}). \tag{3.46}$$

Obviously, $E_{dir} > E_{mh-max}$, which implicates that our multi-hop routing is more energy-efficient than direct transmission for the inter-cluster transmission in this case.

For case 2 in Figure 3.6, Head A is located at the closest possible position, where Head A can use multi-hop routing, to the base station (since $d_1 \geq 64$m). Assuming

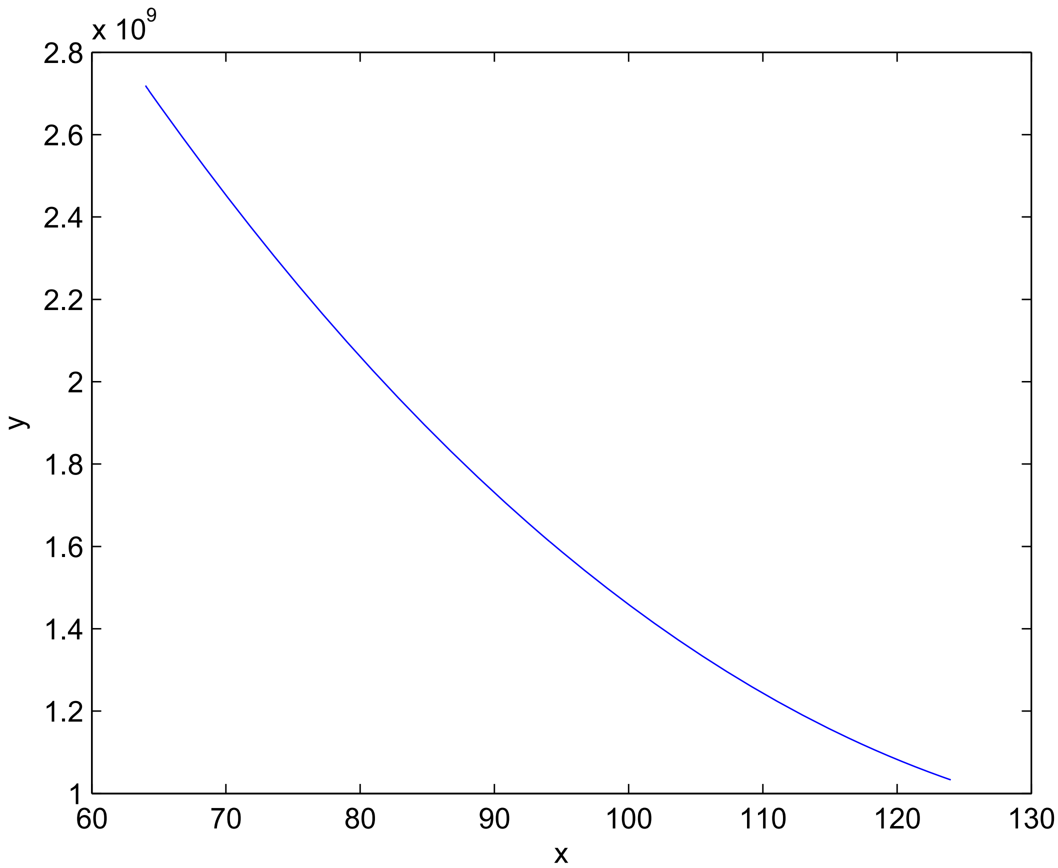

Figure 3.7. Function: $y = x^4 + (292 - x)^4, 64 \leq x \leq 124$

the intermediate node of Head A, Node P, is located at the edge of network area, that is $d_1 = 64$m and $d_2 = 75$m. Substitute $E_{elec} = 50$nJ/bit, $\epsilon_{tg} = 1.3 \times 10^{-6}$nJ/bit/m^4, $d_1 = 64$m and $d_2 = 75$m in Equation 3.43, we can obtain

$$E_{mh} = 213l(\text{nJ}). \tag{3.47}$$

For this case, the energy dissipation of direct transmission can be obtained by substituting $d = 139$m in Equation 3.39 as:

$$E_{dir} = 535l(\text{nJ}). \tag{3.48}$$

Thus, $E_{dir} > E_{mh}$, which means less energy is needed for data transmitting from Head A to the base station when using our multi-hop routing.

When Head A located at other positions in the network, the energy efficiency can be analysed in a similar way. Therefore, we can conclude that the multi-hop routing algorithm implemented in our protocol is more energy-efficient than the direct transmission.

3.4.4 Operation of the Protocol

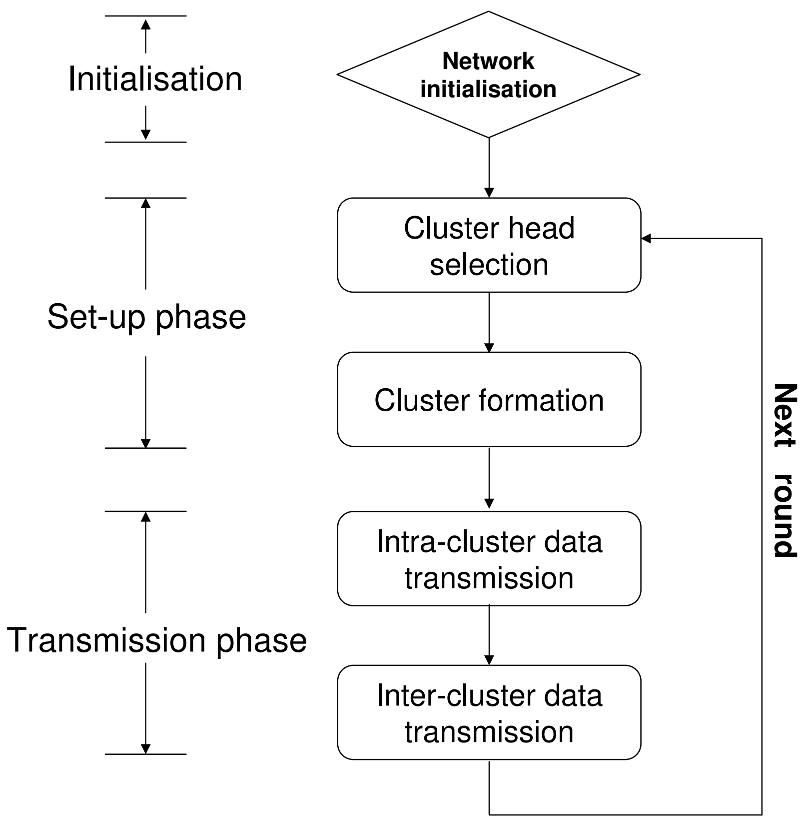

Figure 3.8. Network operation of the CCEE protocol

The operation of CCEE protocol is divided into rounds. As shown in Figure 3.8, each round begins with a set-up phase, when the clusters are organised, and followed by a transmission phase, when data transfers to the base station occur. The procedure of the protocol operation is as follows:

1. Network initialisation.
2. Cluster heads are selected by the base station for the current round.

3. Clusters are formatted by organising non-cluster-head nodes into clusters.

4. Cluster member nodes directly transmit data to their associated cluster heads.

5. Cluster heads forward processed data to the base station.

6. After the base station receives data from all the cluster heads, the next round begins.

The steps shown in Figure 3.8 enable the protocol to efficiently route data from sensor nodes to the base station. In order to minimise the set-up overload, the set-up phase should be short compared with the transmission phase.

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Chapter 4

Performance Evaluation by Simulation

Simulation is a flexible tool for evaluating the performance of protocols under different environment and conditions. In this Chapter, the centralised clustering, energy-efficient routing protocol presented in Chapter 3 is evaluated on a simulation platform. The performance of the protocol is compared with those of three existing protocols in terms of energy efficiency, energy distribution, and network lifetime.

4.1 Simulation Set-up

We run the protocol simulations using OMNeT++. OMNeT++ is a public source, component-based, modular and open-architecture simulation environment [1]. It is supported by strong GUI and an embeddable simulation kernel. Its primary application area is the simulation of communication networks. Because of its generic and flexible architecture, it has been successfully used in other areas [1]. The main features of OMNeT++ are:

- Programming languages used are C++ and Tcl/Tk.
- Support hierarchically nested modules with no limit on the depth.

NOTE:
This figure is included on page 52 of the print copy of the thesis held in the University of Adelaide Library.

Figure 4.1. Core component of simulation in OMNeT++ (redrawn from [1])

- Modules can modify their behaviours based on model parameters. These parameters are also used as shared variables between modules.
- Modules at the lowest level of the module hierarchy are to be provided by users, and they include the algorithms in the module.
- Provides user interfaces for different purposes: debugging, demonstration and batch execution. Also provides data vectors and scalars in the output file.

The simulation kernel of the OMNeT++ mainly consists of three files which carry out different functionalities [1]. Figure 4.1 gives an overview of the process of building and running simulation programs. The simple modules displayed in this figure are the core component of simulation. The algorithms need to be written in the simple modules. One advantage of OMNeT++ is its flexibility which enables us to compose different codes for nodes that can perform different functionalities. Since the location information of nodes

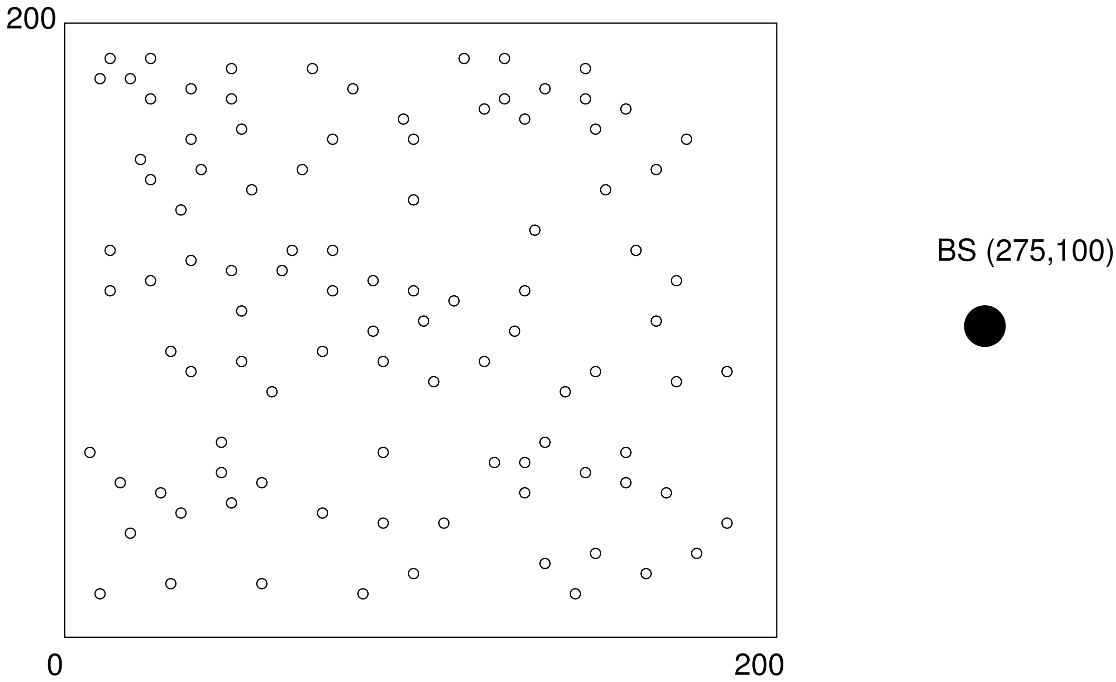

Figure 4.2. Network structure of the CCEE protocol

is needed in our protocol, being able to locate the modules (nodes) at any place is another reason why we choose OMNeT++ as our simulator.

The simulation model built in OMNeT++ for evaluating the performance of our routing protocol consists of two sub-models: a sensor node model and a base station model. In the network model of our protocol, 100 nodes are distributed across an area of 200m×200m with the base station located at position (275m,100m). As shown in Figure 4.2, the base station is located out of the network field and 75m away from the closest node.

The data packet size and the size of a signal packet adopted in simulations are 2000 bits and 64 bits, respectively. That means each node periodically transmits a 2000 bits data packet to the base station and the advertising message broadcast from a cluster head is 64 bits. These parameters are the same as the those proposed in [2, 58]. The calculation of energy consumption for data transmission is based on the energy model

Table 4.1. Parameters of simulation

Parameter	Value
Number of nodes N	100
Network size	200m $\times$ 200m
Base station location	(275m,100m)
Data packet size	2000 bits
Signal packet size	64 bits
Radio electronics energy E_{elec}	50 nJ/bit
Cross-over distance d_0	87 m
Amplifier parameter of free space model ϵ_{fs}	10 pJ/bit/m^2
Amplifier parameter of two-ray ground model ϵ_{tg}	0.0013 pJ/bit/m^4
Data aggregation energy E_{DA}	5 nJ/bit/signal

presented in Section 3.1.2. The parameters utilised in the simulations are summarised in Table 4.1.

4.2 Energy Consumption Calculation

There are three modules contributing to the energy consumption of a sensor node: a micro controller module, a sensor module, and a radio module [58]. The micro controller module is responsible for controlling all activities of a node and executing communication protocols. The sensor module includes sensors attached to the node and the radio module is responsible for wireless communications.

We have investigated the energy calculation for the radio module (data transmitting and data receiving) based on the energy model described in Section 3.1.2. Besides the energy consumption of the radio module, we consider the energy consumed by the sensor board and micro controller board in order to realistically evaluate the performance of the CCEE protocol in the simulations.

The sensor board and the micro controller board work in two modes: full operation and sleep. In the sleep mode, the energy dissipation is almost zero [59, 60]. The full operation mode consumes energy as shown in Table 4.2 (redraw from [60]). In which, mA means milli-ampere, μA is micro-ampere.

Table 4.2. Current of boards in sensor node MICA2DOT (MPR 500)

Currents		Example Duty Cycle
Processor		
Current (full operation)	8mA	1
Current sleep	8μA	99
Radio		
Current in receive	8mA	0.75
Current transmit	12mA	0.25
Current sleep	2μA	99
Logger Memory		
Write	15mA	0
Read	4mA	0
Sleep	2μA	100
Sensor Board		
Current (full operation)	5mA	1
Current sleep	5μA	99

From Table 4.2, we deduce that the current of the micro controller board in full operation is equal to that of the radio board in the receiving mode. In addition, the current of the sensor board in full operation is around 2/3 of the current of the radio board in receiving mode. Based on the energy model described in Section 3.1.2 and the parameters set in Section 4.1, we can calculate the energy consumption in our simulations as follows:

- The energy consumption for receiving a data message is:

$$\begin{aligned} E_{Rx\_data} &= lE_{elec} \\ &= 2000\text{bits} \times 50\text{nJ/bit} = 100\mu\text{J}. \end{aligned} \tag{4.1}$$

- The energy consumption for receiving a signal message is:

$$\begin{aligned} E_{Rx\_signal} &= lE_{elec} \\ &= 64\text{bits} \times 50\text{nJ/bit} \approx 3.2\mu\text{J}. \end{aligned} \tag{4.2}$$

- The energy consumption for transmitting a data message to a distance d, $d < 87$m is:

$$E_{Tx}(l,d) = lE_{elec} + l\epsilon_{fs}d^2$$

$$\begin{aligned} &= 2000\text{bits} \times 50\text{nJ/bit} + 2000\text{bits} \times 10\text{pJ/bit/m}^2 \times d^2 \\ &= (100 + 0.02d^2)\mu\text{J}. \end{aligned} \tag{4.3}$$

- The energy consumption for transmitting a data message to a distance d, $d \geq 87$m is:

$$\begin{aligned} E_{Tx}(l,d) &= lE_{elec} + l\epsilon_{fs}d^4 \\ &= 2000\text{bits} \times 50\text{nJ/bit} + 2000\text{bits} \times 0.0013\text{pJ/bit/m}^4 \times d^4 \\ &= (100 + 2.6 \times 10^{-6}d^4)\mu\text{J}. \end{aligned} \tag{4.4}$$

- The energy consumption for transmitting a signal message to a distance d, $d < 87$m is:

$$\begin{aligned} E_{Tx}(l,d) &= lE_{elec} + l\epsilon_{fs}d^2 \\ &= 64\text{bits} \times 50\text{nJ/bit} + 64\text{bits} \times 10\text{pJ/bit/m}^2 \times d^2 \\ &= (3.2 + 6.4 \times 10^{-4}d^2)\mu\text{J}. \end{aligned} \tag{4.5}$$

- The energy consumption for transmitting a signal message to a distance d, $d \geq 87$m is:

$$\begin{aligned} E_{Tx}(l,d) &= lE_{elec} + l\epsilon_{fs}d^2 \\ &= 64\text{bits} \times 50\text{nJ/bit} + 64\text{bits} \times 0.0013\text{pJ/bit/m}^4 \times d^4 \\ &= (3.2 + 8.3 \times 10^{-8}d^4)\mu\text{J}. \end{aligned} \tag{4.6}$$

- The energy consumption for sensing a data message of l bits is:

$$E_{sensing} = E_{Rx\_data} \times 2/3 = 66.7\mu\text{J}. \tag{4.7}$$

- The energy consumption for creating a data message of l bits in the micro controller board is:

$$E_{creating\_data} = 2000\text{bits} \times 50\text{nJ/bit} = 100\mu\text{J}. \tag{4.8}$$

- The energy consumption for creating a signal message in the micro controller board is:

$$E_{creating\_signal} = 64\text{bits} \times 50\text{nJ/bit} \approx 3.2\mu\text{J}. \tag{4.9}$$

Derived from the above calculations, Table 4.3 summarises the operations and their respective consumed energy.

Table 4.3. Energy summary table

Receive/Create a data message	100μJ
Receive/Create a signal message	3.2μJ
Send a data message ($d < 87$m)	(100+0.02d^2) μJ
Send a data message ($d \geq 87$m)	(100+2.6$\times 10^{-6} d^4$) μJ
Send a signal message ($d < 87$m)	(3.2+6.4$\times 10^{-4} d^2$) μJ
Send a signal message ($d \geq 87$m)	(3.2+8.3$\times 10^{-8} d^4$) μJ
Sensor board(full operation)	66.7 μJ

4.3 Performance Evaluation

For the simulations described in this section, we implemented the LEACH protocol [2], the LEACH-C protocol [41], the LEACH-MTE protocol [3], and the CCEE protocol. We will briefly summarise these protocols.

In the LEACH protocol, nodes organise themselves into clusters using a distributed algorithm. The decision to become a cluster head is made locally within each node with a certain probability. Once the clusters are formed, the cluster heads create TDMA schedules. The member nodes transmit data to associated cluster heads during their assigned time slots, and the cluster heads aggregate all the data into a representative packet to send to the base station. The LEACH protocol has the advantage of being distributed, and self-configuring for cluster formation. In addition, the LEACH protocol can rotate the role of cluster head among nodes in order to balance the energy load throughout the whole network. Although the steady-state in the LEACH protocol is low-energy, the direct data transmission from cluster heads to the base station is energy-consuming. Furthermore, the LEACH protocol cannot guarantee the number or placement of cluster heads within the network.

The LEACH-C protocol is a centralised version of the LEACH protocol. Unlike the LEACH protocol, where nodes self-configure themselves into clusters, the LEACH-C protocol uses the base station for cluster formation. During the setup phase of the LEACH-C protocol, every node in the network sends its location information and energy level to the base station. Using this information, the base station chooses the predetermined percentage of cluster heads and configures the network into clusters. As the base station utilises global information of the network, better clusters that require less energy for data transmission can be produced. In addition, since the base station carries out energy intensive tasks, such as cluster formation, a reduction in energy dissipation can be achieved for sensor nodes.

The LEACH-MTE protocol (self-organizing hybrid network protocol proposed in [3]) improves the LEACH protocol by implementing MTE (minimum transmission energy) routing algorithm for the inter-cluster communication. When a cluster head has data to send to the base station, it uses MTE to choose one or more other cluster heads as the intermediate nodes to perform the relaying task. The procedure of selecting intermediate nodes is iterated until the data packet arrives at the base station. The energy dissipation of inter-cluster data transmission can be reduced by using this multi-hop routing in the LEACH-MTE protocol. The operations of set-up phase as well as the data aggregation on cluster heads in the LEACH-MTE protocol are identical to those in the LEACH protocol.

The CCEE protocol uses a centralised cluster head selection algorithm to choose cluster heads. This algorithm is performed by the base station using global information of the network. The cluster formation in the CCEE protocol aims at balancing energy load of cluster heads. A multi-hop routing algorithm is implemented in the CCEE protocol for the data transmission from cluster heads to the base station in order to reduce the energy consumption. The advantage of the CCEE protocol is that it can prolong the network lifetime by reducing energy dissipation of data transmission and distributing energy load among nodes. However, centralised cluster formation and multi-hop routing in the CCEE protocol incur small communication overhead and time delay for the network.

4.3.1 Performance Metrics

We introduce energy efficiency, energy distribution, and network lifetime metrics to evaluate the performance of the CCEE protocol.

- **Energy efficiency**. Energy efficiency is a vital consideration of routing protocols for wireless sensor networks due to the limited energy of nodes. In our simulations, energy efficiency is measured by two metrics: average energy dissipation over number of rounds, and total data received at the base station per given amount of energy. The network operation of the CCEE protocol, the LEACH protocol, the LEACH-C protocol, and the LEACH-MTE protocol are all divided into rounds. One round is defined as the time duration from the beginning of the set-up phase to the end of the transmitting phase when all the data from nodes are received at the base station. Thus, the average energy dissipation over rounds can evaluate the performance of these protocols in terms of energy efficiency. Whereas the total data received at the base station per given amount of energy can measure the energy efficiency of protocols for transmitting data. More data received at the base station means more energy efficiency in data delivering.

- **Energy distribution**. In addition to energy efficiency, energy distribution is another important issue of routing protocol in order to prolong the network lifetime. We used two metrics, variance of cluster member and variance of energy dissipation of cluster heads, to evaluate the performance of protocols in terms of energy distribution. The variance of cluster member is defined as:

$$\sigma_{load}^2 = \frac{\sum_i^n (M_i - \overline{M})^2}{n}, \tag{4.10}$$

where n is the number of clusters in each round, M_i is the number of cluster members in cluster i, and $\overline{M}$ is the average number of cluster members. Note that small σ_{load}^2 implies that the variance of number of member nodes is small from cluster to cluster. The load of a cluster head mainly depends on the number of member nodes in the cluster. Thus, similar member nodes in each cluster means the load is well distributed among cluster heads.

Likewise, the variance of energy dissipation of cluster heads is given as:

$$\sigma_{energy}^2 = \frac{\sum_i^m (E_i - \overline{E})^2}{m}, \tag{4.11}$$

where m is the number of cluster heads, E_i is the energy dissipation of cluster head i, and $\overline{E}$ is the average energy dissipation of cluster heads. Small σ_{energy}^2 means the energy dissipation of cluster heads is well balanced. Since being a cluster head is much more energy intensive than being a member node, balanced energy consumption of cluster heads will lead to well distributed energy dissipation throughout the whole network.

- **Network lifetime**. A wireless sensor network is expected to work up to a certain time duration due to the limited energy supply of sensor nodes. Thus, network lifetime is a crucial measurement to evaluate the performance of a protocol. For some wireless sensor network applications, every node is required to work in order to ensure good coverage of the network. Thus, the network lifetime is determined by the lifetime of the shortest-living node. For some other applications, sensor nodes are densely deployed and the network will work until a fixed percent of nodes die. Therefore, both the number of rounds until the first node dies and the number of rounds until half the nodes die are used to evaluate the performance of protocols in terms of network lifetime in our simulations. 'First node dies' means the first node exhausts its energy in the network; 'Half nodes die' means 50% of nodes in the network have exhausted their energy. Since the network operation of the CCEE protocol and other protocols in the simulations are divided into rounds, a greater number of rounds means a longer network lifetime.

4.3.2 Simulation Results

Nodes Begin with Equal Energy

For the first set of simulations, each node begins with only 2J of energy[1] and has unlimited data periodically sent to the base station. We track the amount of energy required to send data to the base station in each round and the total energy dissipation every 5 rounds. In addition, we record the number of clusters, number of member nodes in each cluster, and energy dissipation of each cluster head in each round. Since the nodes have limited energy, they use up their energy during the course of the simulation. Once a node runs out of energy, it is considered dead and can no longer sense, transmit, or receive data. Thus, we record the dead nodes and the associated rounds when the nodes die. These results are recorded in text files generated by the simulator.

For these simulations, energy is consumed whenever a node transmits or receives data as well as it performs data aggregation. In addition, energy for sensing or creating data is also accounted for in the simulations. We do not assume any static energy dissipation, nor do we consider the energy dissipation during the carrier-sense operation. The detailed energy calculations for data transmitting, data receiving, data creating, and data sensing in the simulations is described in Section 4.2. The energy consumption of data aggregation

[1] Assuming nickel cadmium (NiCd) technology, this corresponds to a 15 mg battery [61]

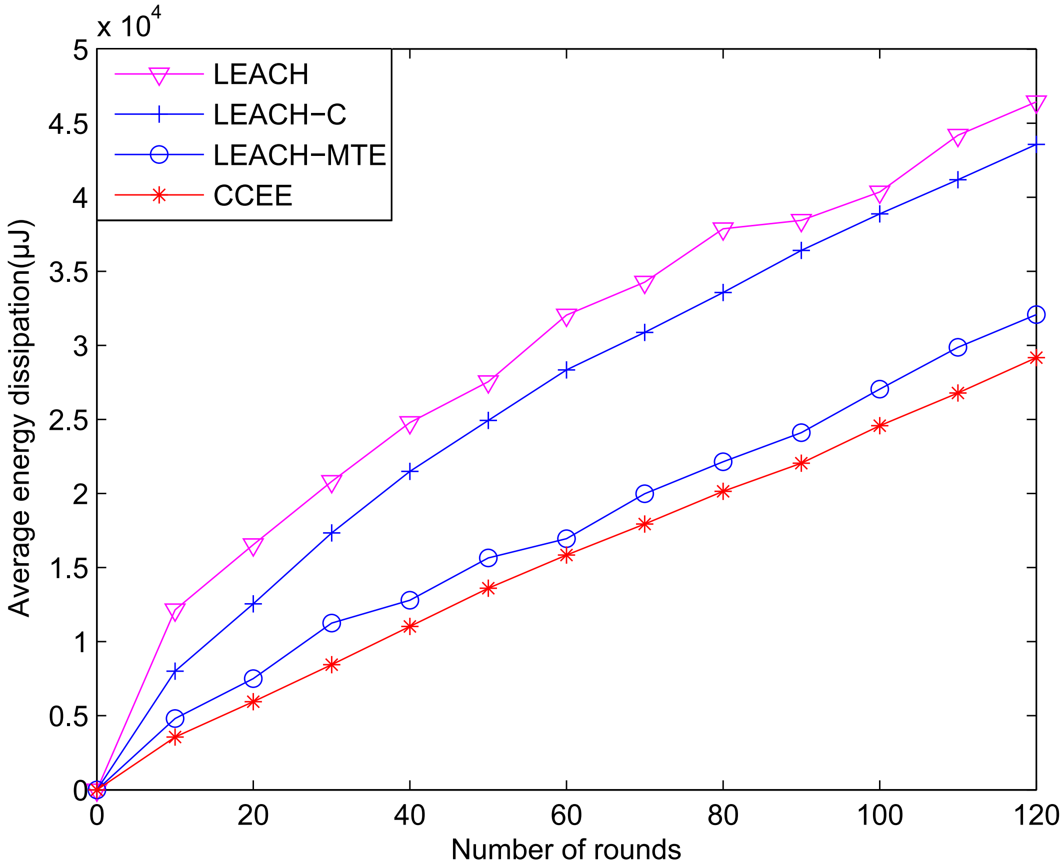

Figure 4.3. Average energy dissipation versus number of rounds

is based on E_{DA} presented in Section 4.1. Since we assume that the base station has no energy constraint, the energy consumed by the base station is not considered.

Figure 4.3 shows the average energy dissipation versus number of rounds when using the CCEE protocol and the three other protocols: the LEACH protocol, the LEACH-C protocol, and the LEACH-MTE protocol. Clearly, the CCEE protocol and the LEACH-MTE protocol reduce energy consumption significantly over the LEACH protocol and the LEACH-C protocol. This is because all the cluster heads in both the LEACH protocol and the LEACH-C protocol transmit data directly to the distant base station, which in turn causes significant energy losses in the cluster head nodes. The CCEE protocol and the LEACH-MTE protocol alleviate this problem by adopting a multi-hop routing for the data transmission from cluster heads to the base station. Furthermore, the CCEE protocol utilises the base station to choose the cluster heads based on the global information of the network. Thus, better clusters that require less energy for data transmission are

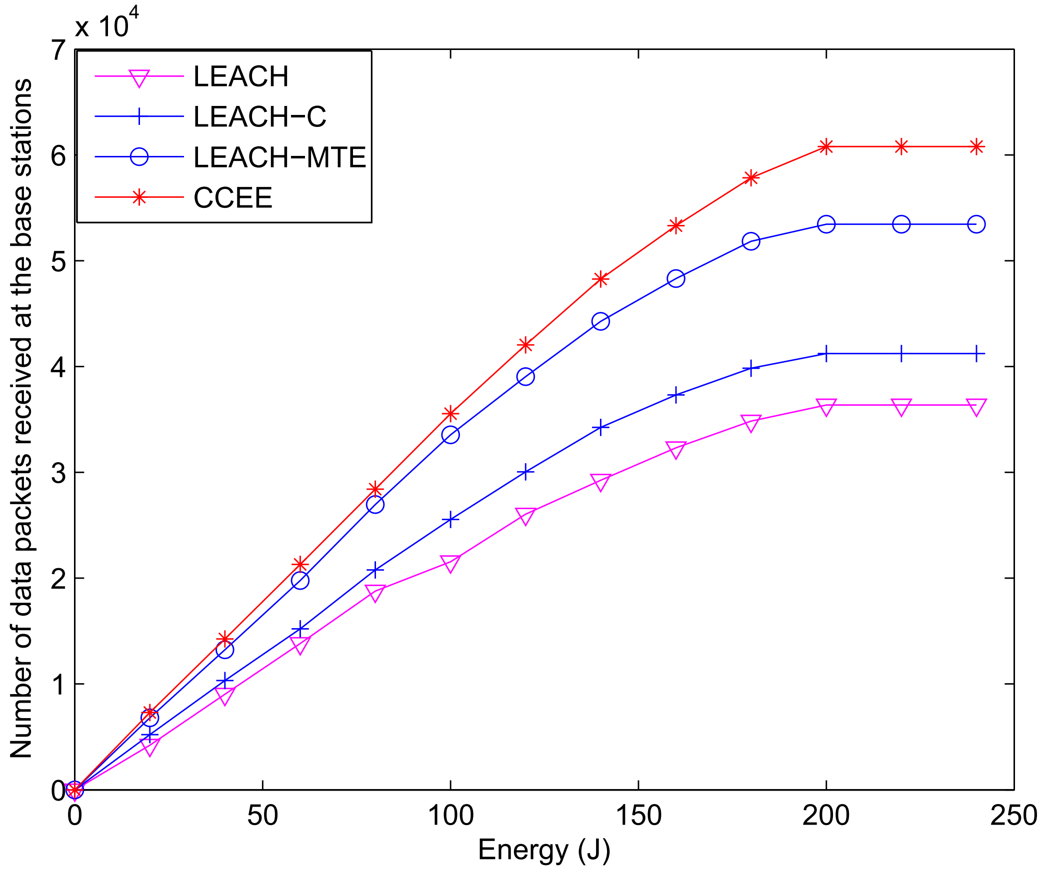

Figure 4.4. Total data packet received at the base station per given amount of energy

produced. About 45% and 60% reduction of average energy dissipation can be obtained by the CCEE protocol over the LEACH-C protocol and the LEACH protocol, respectively. The LEACH-MTE protocol consumed about 10% more energy than the CCEE protocol due to the distributed cluster head selection algorithm which still cannot guarantee the number or placement of cluster heads. The better performance of the LEACH-C protocol over the LEACH protocol indicates the advantage of the centralised clustering algorithm in terms of energy efficiency. In addition, it can be clearly seen from Figure 4.3 that the curves of both the LEACH protocol and the LEACH-MTE protocol fluctuate during the simulation. This is because both the number and position of cluster heads in the LEACH protocol and the LEACH-MTE protocol vary dramatically due to the distributed cluster head selection and the energy dissipation of nodes thus are very different in each round.

The comparison of total data packets received at the base station per given amount of energy between the CCEE protocol and the three other protocols is shown in Figure

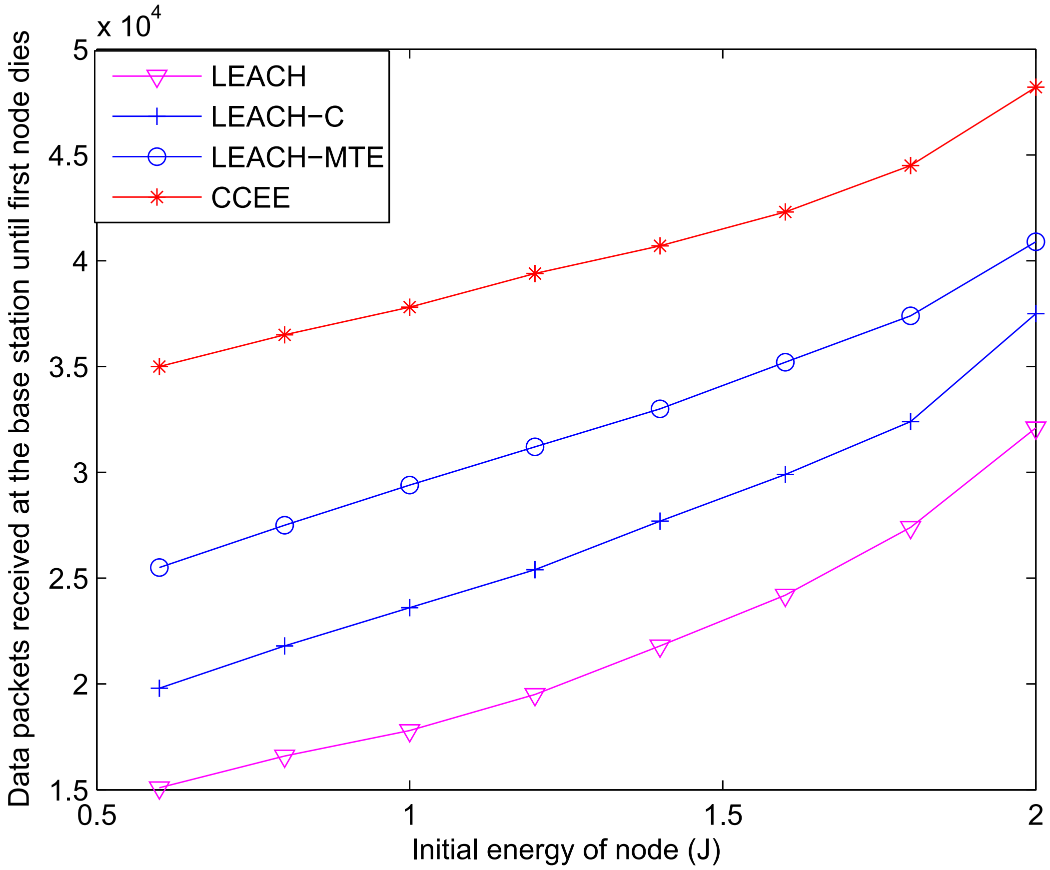

Figure 4.5. Amount of data packets received at the base station until the first node dies versus initial energy

4.4. From this graph, it can be easily observed that the CCEE protocol delivers more data per unit energy than the three other protocols. There are around 50%, 40%, and 10% more data packets delivered by the CCEE protocol over the LEACH protocol, the LEACH-C protocol, and the LEACH-MTE protocol, respectively. Therefore, the CCEE protocol outperforms the three other protocols in terms of energy efficiency for data delivery. Although the multi-hop routing for inter-cluster communication implemented in the CCEE protocol incurs a small time delay, if considering the energy issue, the CCEE protocol can achieve better performance in terms of data delivery.

Benefiting from the energy-efficient data transmission, the CCEE protocol is expected to route more data to the base station until the network terminates. Figure 4.5 and Figure 4.6 show the amount of data packets received at the base station until the first node dies and half the nodes die. It can be seen from Figure 4.5 that there are round 60%, 30%, and

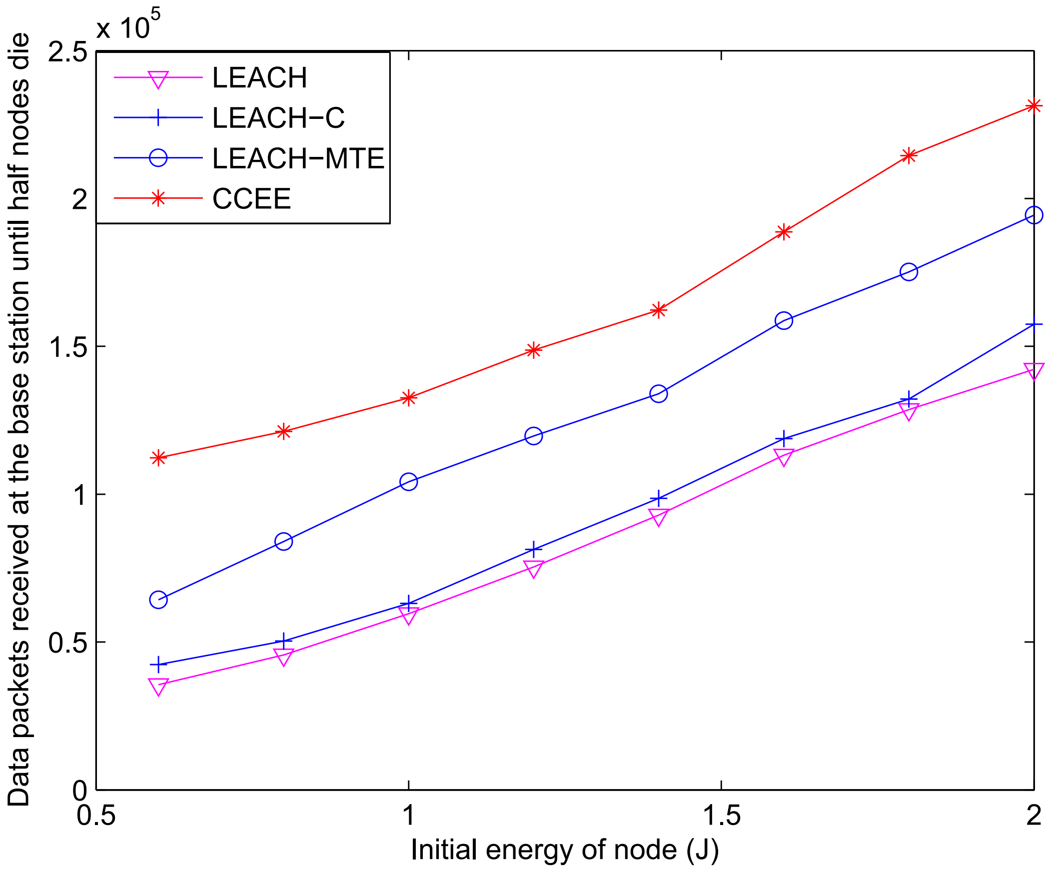

Figure 4.6. Amount of data packets received at the base station until half the nodes die versus initial energy

20% more data packets that are received at the base station until the first node dies by the CCEE protocol than the LEACH protocol, the LEACH-C protocol, and the LEACH-MTE protocol, respectively. In addition, Figure 4.6 shows that the CCEE protocol delivers around 50%, 30%, and 15% more data to the base station than the LEACH protocol, the LEACH-C protocol, and the LEACH-MTE protocol respectively until half the nodes die. These results show the efficiency of the CCEE protocol in terms of data delivery. More data is received at the base station, and more accurate information about the monitoring area can be acquired.

Since the cluster head selection is performed by the base station using global information, the number of clusters in the CCEE protocol is expected be the optimal number, 6. Figure 4.7 shows the number of clusters when using different protocols. It can be seen from the figure that the cluster number of the CCEE protocol is centralised to 6 as

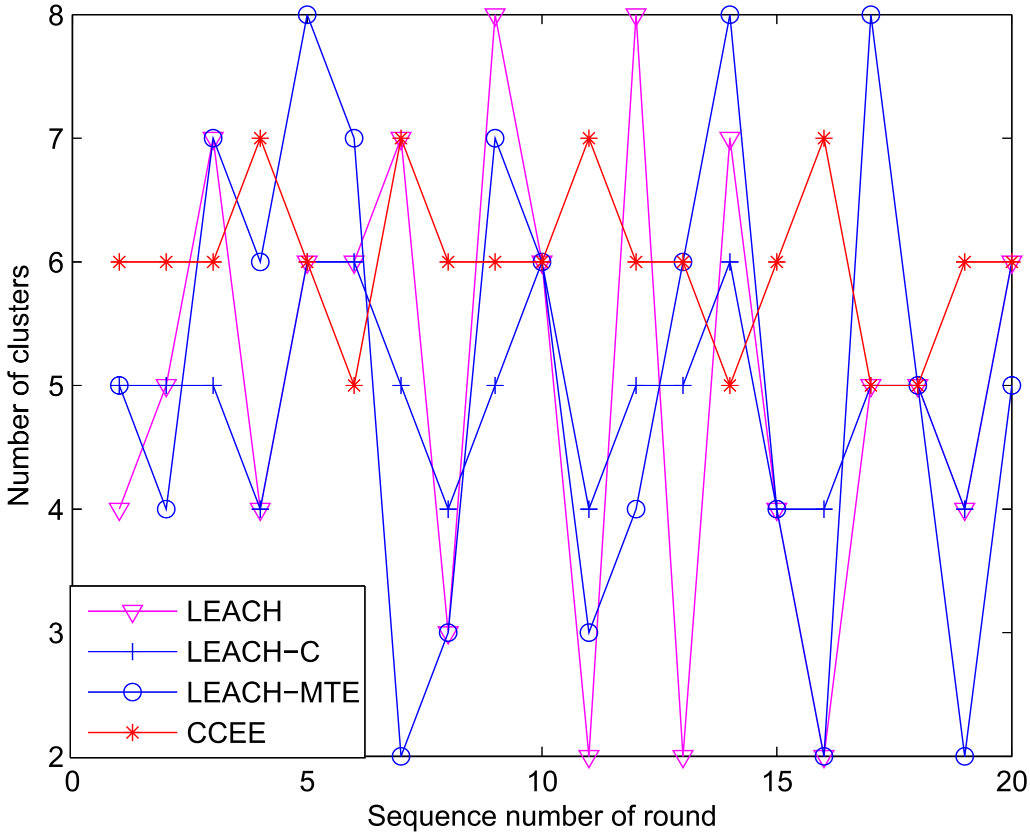

Figure 4.7. Number of clusters in different rounds

expected. Whereas for the LEACH protocol, the cluster number varies from 2 to 8 in different rounds. This is because the distributed cluster head selection algorithm of the LEACH protocol cannot guarantee the number of clusters. Since the LEACH-MTE protocol uses the same cluster head selection algorithm as the LEACH protocol, the number of clusters is variable in different rounds as well. But for the LEACH-C protocol, the centralised algorithm ensures the number of clusters is 5, close to the expected value.

Figure 4.8 depicts the variance of cluster member of the CCEE protocol and the three other protocols. As seen in Figure 4.8, the cluster member variance of both the LEACH protocol and the LEACH-MTE protocol are larger than the CCEE protocol and the LEACH-C protocol on average. This implies that the number of member nodes is largely different from cluster to cluster when using the LEACH protocol and the LEACH-MTE protocol. In addition, the fluctuation of curves of the LEACH protocol and the LEACH-MTE protocol means that the number of cluster member in different rounds

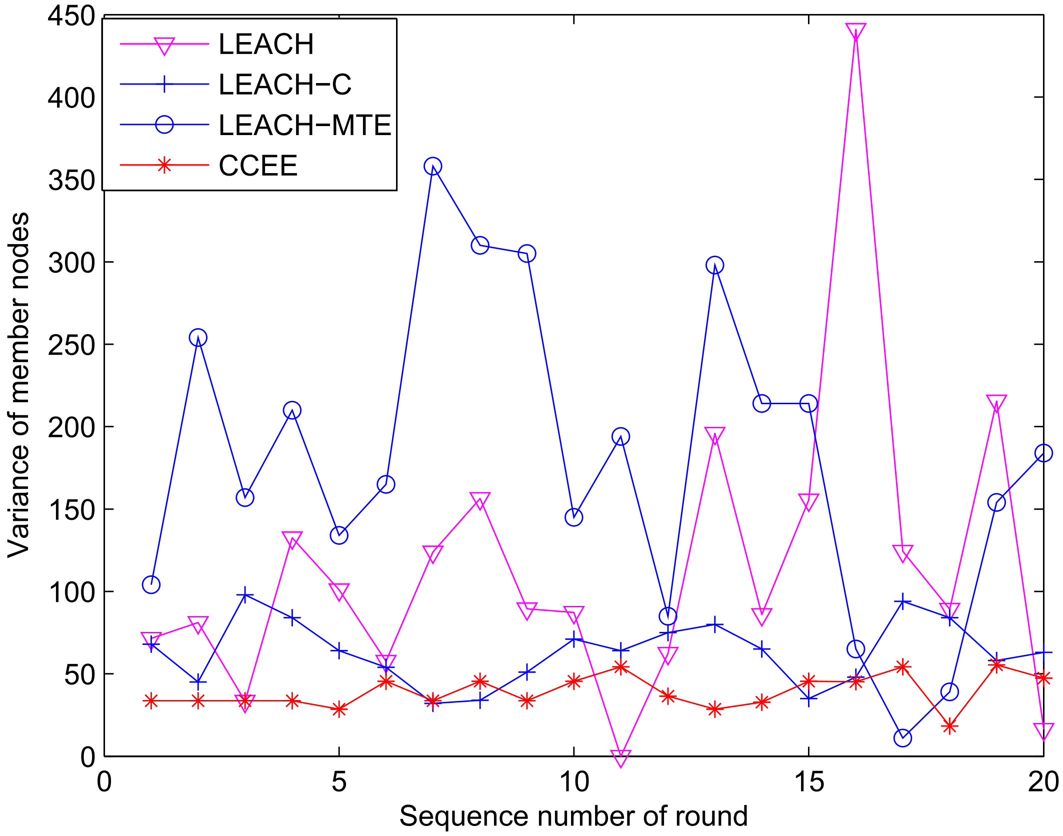

Figure 4.8. Cluster member variance in different rounds

varies dramatically. These results again emphasise the advantage of centralised cluster head selection developed in the CCEE protocol in terms of load balance. Since the nodes may not be uniformly distributed in the network, the number of neighbour nodes of the cluster heads are different. In the LEACH-C protocol, the non-cluster-head nodes only consider the intra-cluster transmission energy when choosing cluster heads and join the clusters with the closest cluster heads to them. Therefore, the variance of cluster member of the LEACH-C protocol is bigger than that of the CCEE protocol.

Better cluster heads that consume less energy for data transmission can be selected in the CCEE protocol by using the centralised cluster head selection algorithm. This can be seen from Figure 4.9 which shows the comparison of average energy dissipation for cluster head in each round between the CCEE protocol and the three other protocols. This graph indicates that the cluster heads of the CCEE protocol consume less energy than the three other protocols. Around 50%, 40%, 20% reduction of average energy

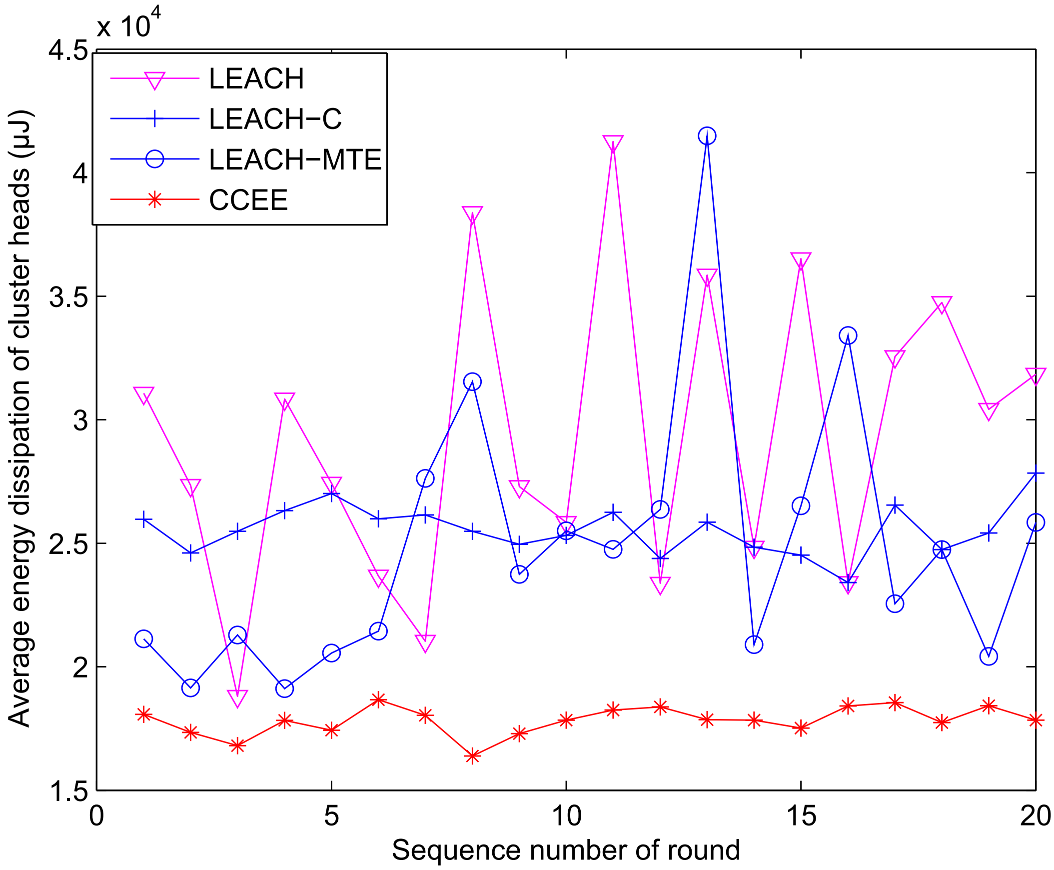

Figure 4.9. Average energy dissipation of cluster heads in different rounds

per cluster head can be achieved by the CCEE protocol over the LEACH protocol, the LEACH-C protocol, and the LEACH-MTE protocol, respectively. Although the cluster head selection algorithm of the LEACH-C protocol tries to minimise the energy dissipation for the intra-cluster communication, it does not consider the distance between the cluster head and the base station. Thus, the cluster heads in the LEACH-C protocol may consume significant energy transmitting data to the base station. Since the centralised cluster head selection algorithm of the CCEE protocol considers energy dissipation for both intra-cluster communication and inter-cluster communication, more energy saving can be achieved for the cluster heads. Furthermore, this algorithm is performed by the base station using global information of the network, the number and placement can be determined and thus the energy dissipation of cluster heads does not vary dramatically from round to round.

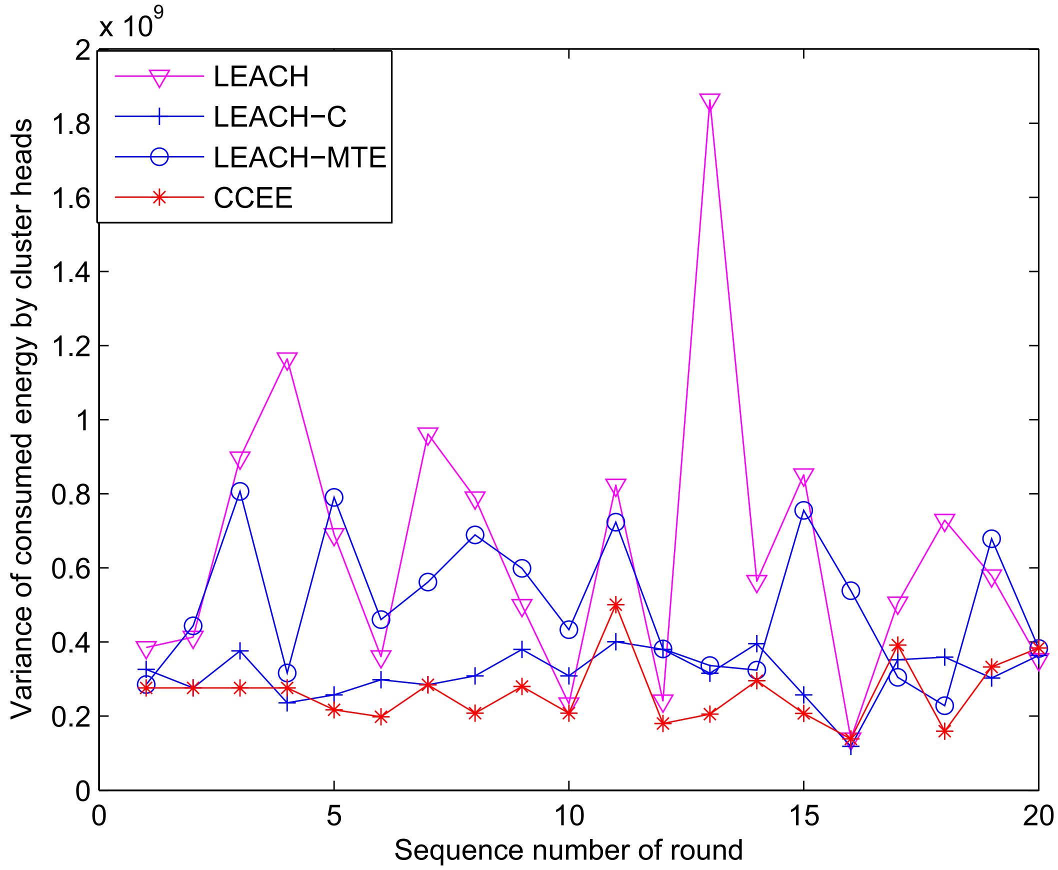

Figure 4.10. Variance of consumed energy by cluster heads in different rounds

The comparison of the variance of consumed energy by cluster heads in different rounds is illustrated in Figure 4.10. The large value of variance means significant difference between the energy dissipation of different cluster heads. The graph indicates that the variance of the CCEE protocol is smaller than those of the three other protocols. That means that the CCEE protocol performs better in distributing energy among cluster heads than other protocols. This is because the cluster head selection algorithm of the CCEE protocol takes the weighting facts of node, including node position, neighbours of node and node energy level, into account in order to balance the energy dissipation of cluster heads. Furthermore, the cluster formation of the CCEE protocol can balance the energy dissipation of cluster heads by considering the node degree of cluster heads when non-cluster-head nodes are choosing clusters. In the CCEE protocol, since the role of cluster head can be rotated among nodes, and the cluster heads consume more energy

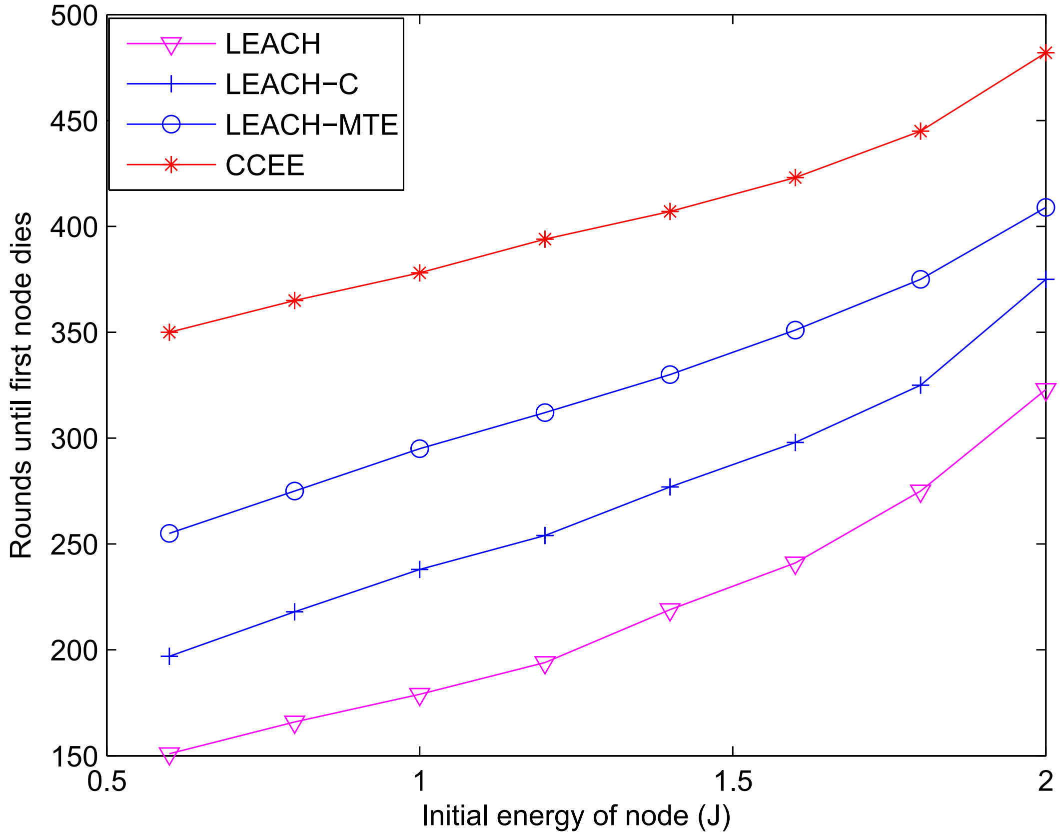

Figure 4.11. Rounds until first node dies versus different initial energy

than non-cluster-head nodes, more balanced energy consumption of cluster heads implies better energy distribution throughout the whole network.

The comparison of network lifetime in terms of "first node dies" and "half nodes die" between the CCEE protocol and the three other protocols are shown in Figure 4.11 and Figure 4.12. We can see from the figures that the CCEE protocol outperforms the three other protocols significantly in terms of network lifetime (for both the "first node dies" and the "half nodes die"). The CCEE protocol achieves about 60% and 30% longer network lifetime over the LEACH protocol and the LEACH-C protocol, respectively. In addition, about a 20% improvement in network lifetime is obtained by the CCEE protocol over the LEACH-MTE protocol. Moreover, since the CCEE protocol takes the energy issue into account when choosing the cluster head and intermediate node, the network lifetime of the CCEE protocol decreases less than the three other protocols when the initial energy of the node is reduced.

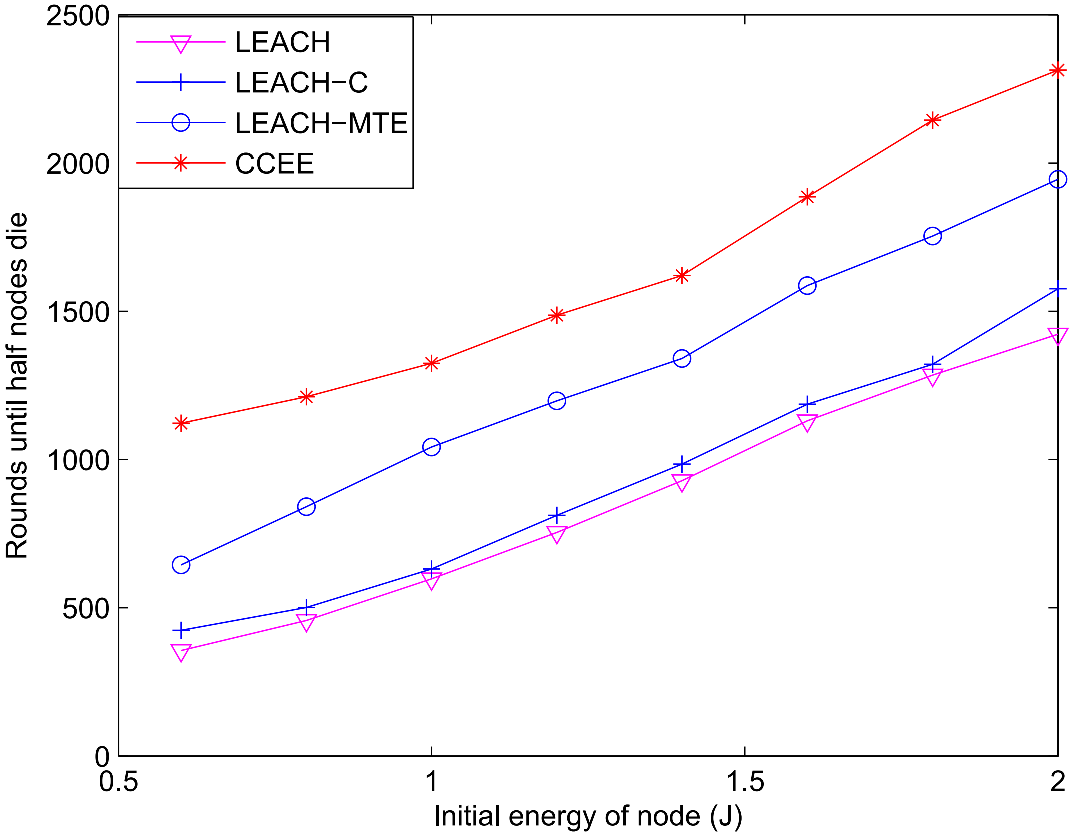

Figure 4.12. Rounds until half nodes die versus different initial energy

Figure 4.13 and Figure 4.14 depict the network lifetime comparison between those four protocols when the base station moves further from the network area. Since the energy dissipation of data transmission is proportional to the distance, longer distance between nodes and the base station means more data transmission energy. On the benefit of multi-hop routing, the CCEE protocol and the LEACH-MTE protocol perform better than the LEACH protocol and the LEACH-C protocol when the base station moves further away from the network area. The results indicate that the lifetime of the LEACH protocol and the LEACH-C protocol severely decreases when the base station moves further away from the network. The CCEE protocol and the LEACH-MTE protocol can alleviate the severe network decrease by adopting a multi-hop routing algorithm for inter-cluster communication. This emphasises the advantage of the multi-hop routing algorithm in terms of energy efficiency.

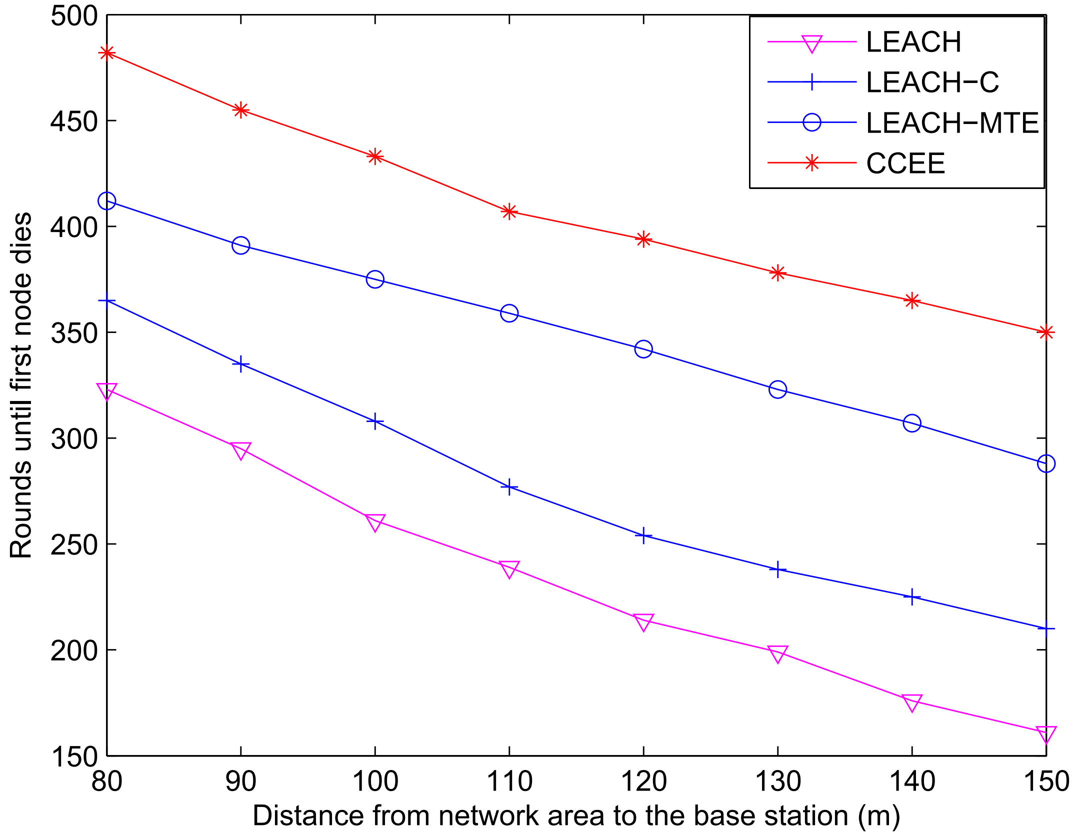

Figure 4.13. First node dies versus different base station locations

Nodes Begin with Unequal Energy

To evaluate the performance of the CCEE protocol that takes energy issues into account in cluster head selection and inter-cluster routing, we assign different initial energies to nodes. Without loss of generality, we assume 10 nodes assigned with 4J initial energy each and 90 other nodes begin with 2J initial energy each, since the analysis is suitable for simulations that have more high-energy nodes.

Figure 4.15 shows the cluster head component over a number of rounds when using the CCEE protocol. The graph indicates that the high-energy nodes have much more chance to become cluster heads than other ordinary nodes. It is around 70% possibility for these nodes taking the role of cluster head. This is because the ratio of the initial energy to the residual energy of a node, E_{ini}/E_{res}, is taken into account when the CCEE protocol selects cluster heads. Nodes with smaller value of E_{ini}/E_{res} are more likely to

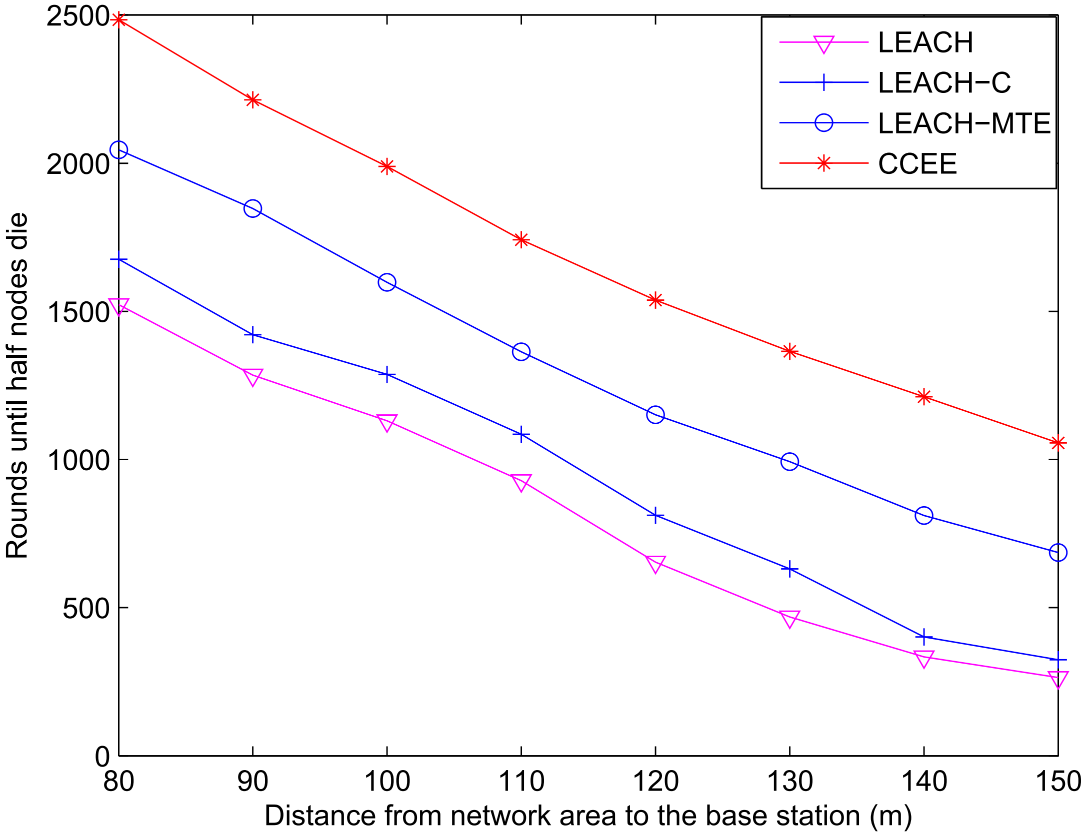

Figure 4.14. Half nodes die versus different base station locations

become the cluster heads. At the beginning of network operation, E_{res} equals to E_{ini} for every node. If the energy dissipation of high-energy nodes is the same as that of other nodes, the ratio value of high-energy nodes will be smaller due to more initial energy. Therefore, the chance for high-energy nodes to become cluster heads is much higher than that of other ordinary nodes.

Figure 4.16 and Figure 4.17 show the comparison of network lifetime between the CCEE protocol and the three other protocols in terms of "first node dies" and "half nodes die" with unequal initial energy. It can be seen from these figures that the CCEE protocol performs much better than the three other protocols in terms of both the "first node dies" and the "half nodes die". This is because the CCEE protocol can take advantage of the high-energy nodes in cluster heads and intermediate nodes selection. If these high-energy nodes take the role of cluster heads or intermediate nodes for the relaying task, the time

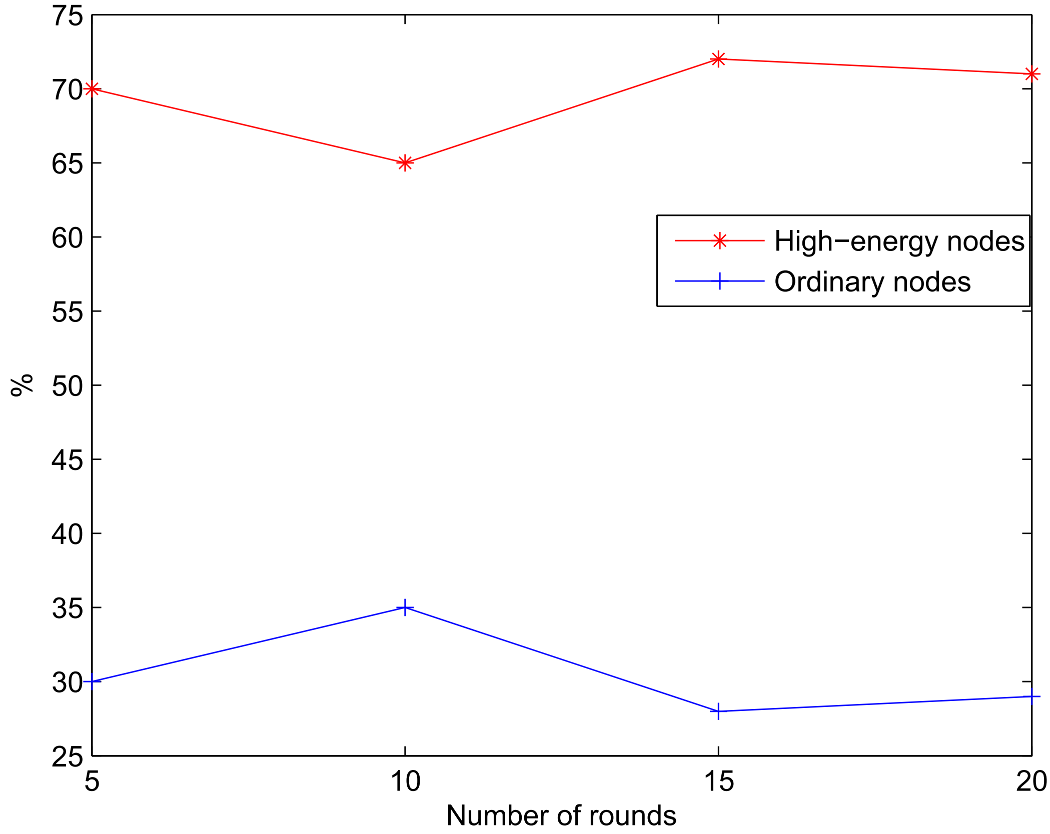

Figure 4.15. Cluster head component versus number of rounds

for them to deplete their energy will be longer than that of normal nodes. Thus, the network lifetime of the CCEE protocol can be further prolonged.

We compare the network lifetime when using equal initial energy with the network lifetime when using unequal initial energy for those four protocols in Figure 4.18 and Figure 4.19. It can be seen from these figures, the network lifetime of the LEACH protocol, the LEACH-C protocol, and the LEACH-MTE protocol does not increase significantly when there are high-energy nodes in the network. This is because these three protocols cannot take advantage of the high-energy nodes. Whereas for the CCEE protocol, since the energy issue is considered when choosing cluster heads and intermediate nodes, both the number of rounds until first node dies and the number of rounds until half the nodes die increases significantly. About 10% improvement is obtained by the CCEE protocol when there are high-energy nodes in the network. There is about 70%, 55%, and 25%

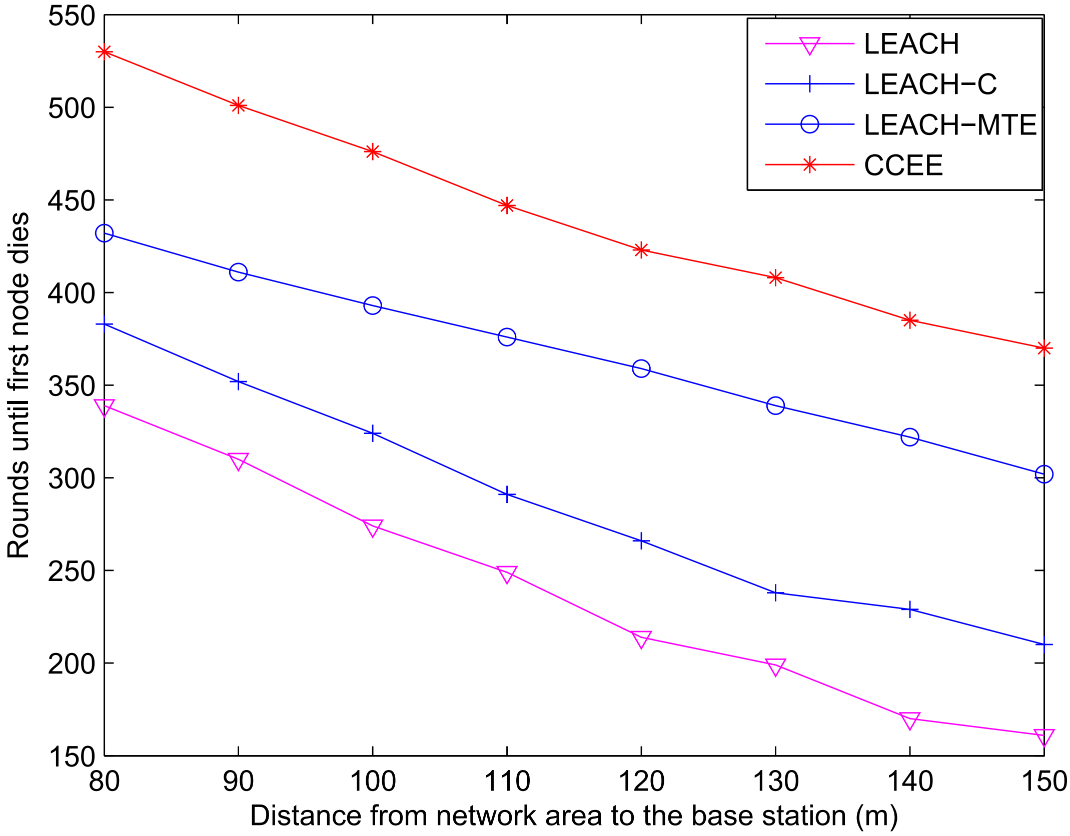

Figure 4.16. Rounds until the first node dies versus different base station locations with unequal initial energy

longer network lifetime that can be achieved by the CCEE protocol over the LEACH protocol, the LEACH-C protocol, and the LEACH-MTE protocol, respectively.

4.3.3 Observation

Section 4.3.2 has shown many advantages of using the CCEE protocol versus the three other clustering-based protocols in terms of energy efficiency, energy distribution, and network lifetime. The centralised cluster head selection algorithm of the CCEE protocol ensures that better cluster heads in terms of energy balance and energy efficiency are chosen to organise nodes into clusters. In addition, taking advantage of this centralised algorithm, the variations of network structure and energy dissipation in each round is

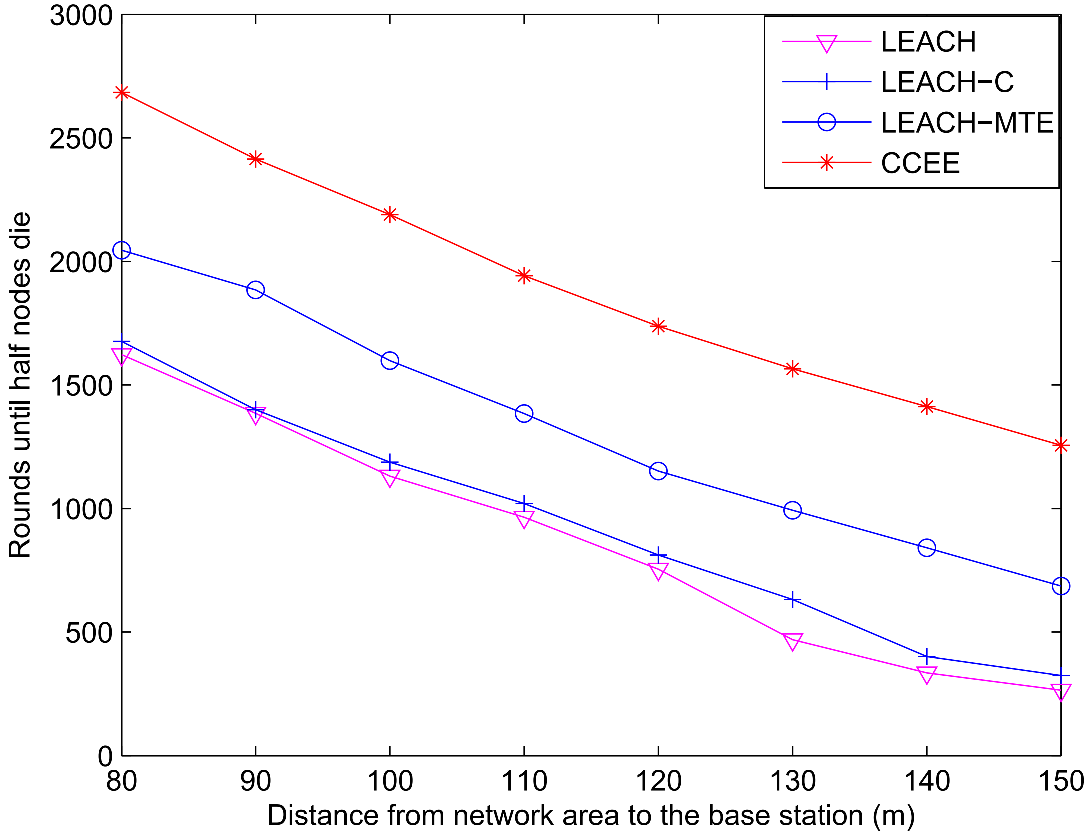

Figure 4.17. Rounds until the Half nodes die versus different base station locations with unequal initial energy

small. The multi-hop routing implemented in the CCEE protocol can reduce the energy consumption of inter-cluster data transmission. On the benefit of both distributed energy load and reduced energy dissipation, the CCEE protocol can achieve longer network lifetime over those of the three other protocols. Therefore, we can conclude that the centralised cluster head selection algorithm and the multi-hop routing can improve the performance of the routing protocol for wireless sensor networks in terms of energy efficiency and network lifetime.

To assess the advantage of the CCEE protocol in utilising high-energy nodes in the network, we investigate the situation when a fraction of nodes in the network is assigned with high energy. The simulation results indicate that the network lifetime can be significantly prolonged when using the CCEE protocol. This is because the CCEE protocol considers the energy issue when choosing the cluster heads and the relaying

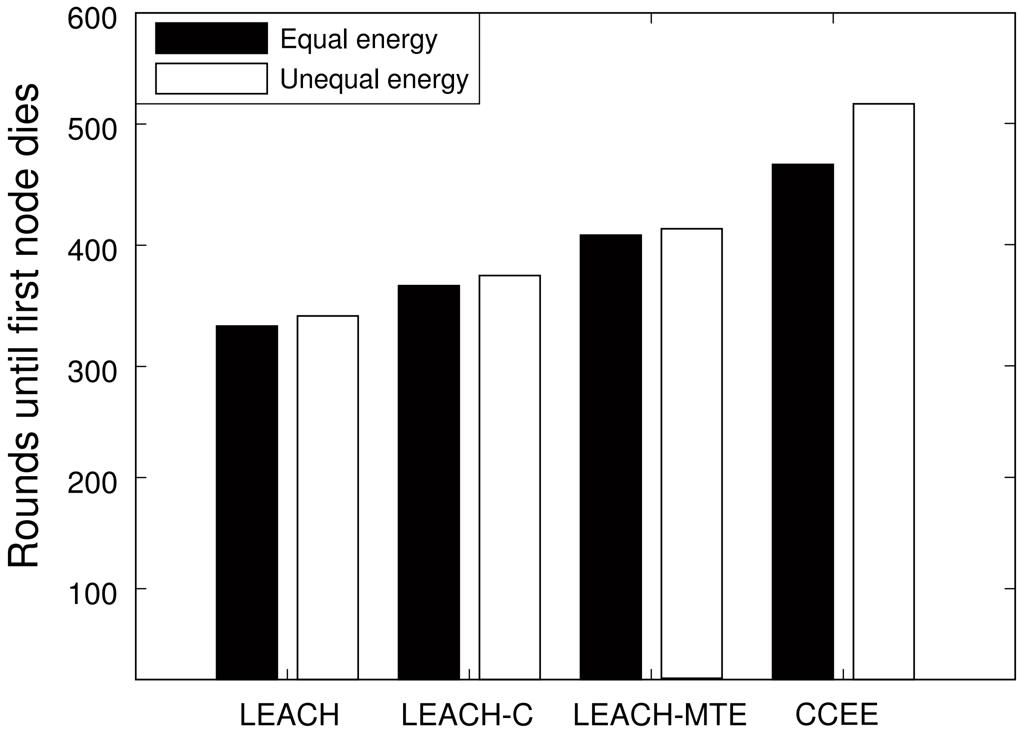

Figure 4.18. Rounds until the first node dies versus unequal initial energy

nodes. In contrast, the performance of the LEACH protocol, the LEACH-C protocol, and the LEACH-MTE protocol in terms of network lifetime are not largely enhanced due to the inefficient usage of high-energy nodes. Therefore, taking energy issue into account is advantageous to the energy-efficient routing protocol for wireless sensor networks.

One disadvantage of the CCEE protocol is that the centralised cluster head selection and the multi-hop routing incur a small communication overhead and time delay. During the set-up phase of the CCEE protocol, extra time should be assigned for nodes sending information to the base station and the base station sending back selected cluster heads information to nodes. In addition, the time of transmission phase of the CCEE protocol will be longer due to the multi-hop routing. Therefore, the CCEE protocol is less time-efficient than the LEACH protocol, the LEACH-C protocol and the LEACH-MTE protocol.

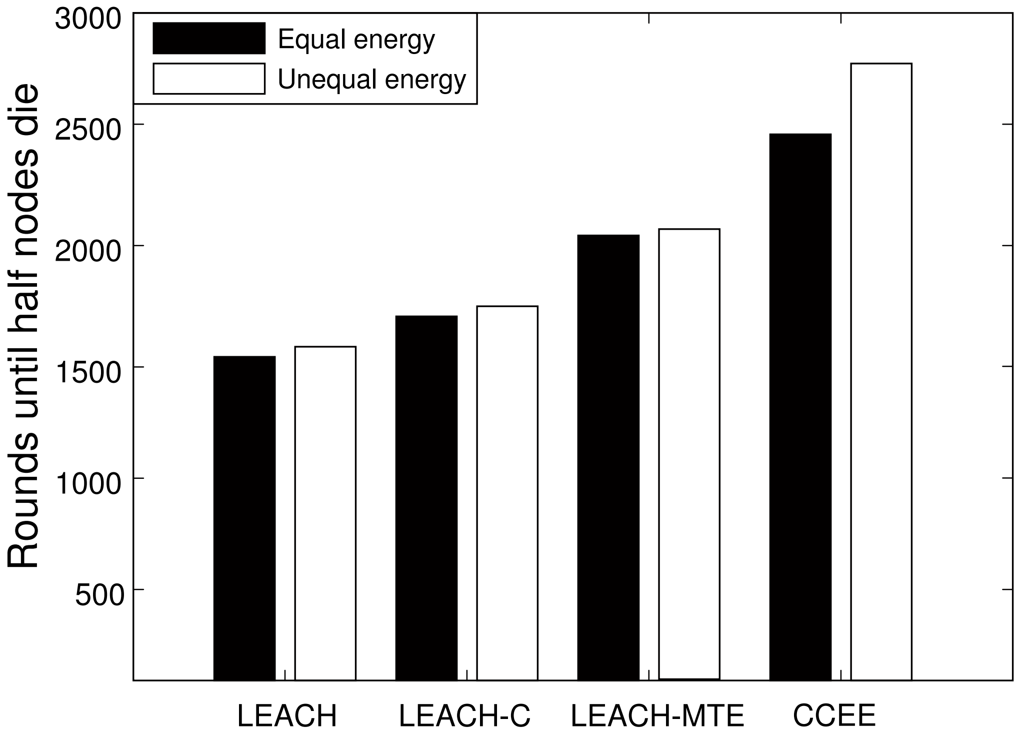

Figure 4.19. Rounds until the Half nodes die versus with unequal initial energy

Figure 4.20 shows the total amount of data packets received at the base station over time when all the nodes are uniformly assigned with 2J initial energy. Since the LEACH-C protocol and the LEACH-MTE protocol are less time-efficient than the LEACH protocol due to the centralised cluster formation and multi-hop routing, we compare the CCEE protocol with the LEACH protocol in terms of time latency. From Figure 4.20, it can be observed that the amount of data packets received at the base station when using the CCEE protocol is about 5% to 10% less than the the LEACH protocol. Since the CCEE protocol can significantly reduce energy dissipation and prolong network lifetime, it is well suited for applications where energy and network lifetime are the primary considerations and small overhead and time delay can be tolerated.

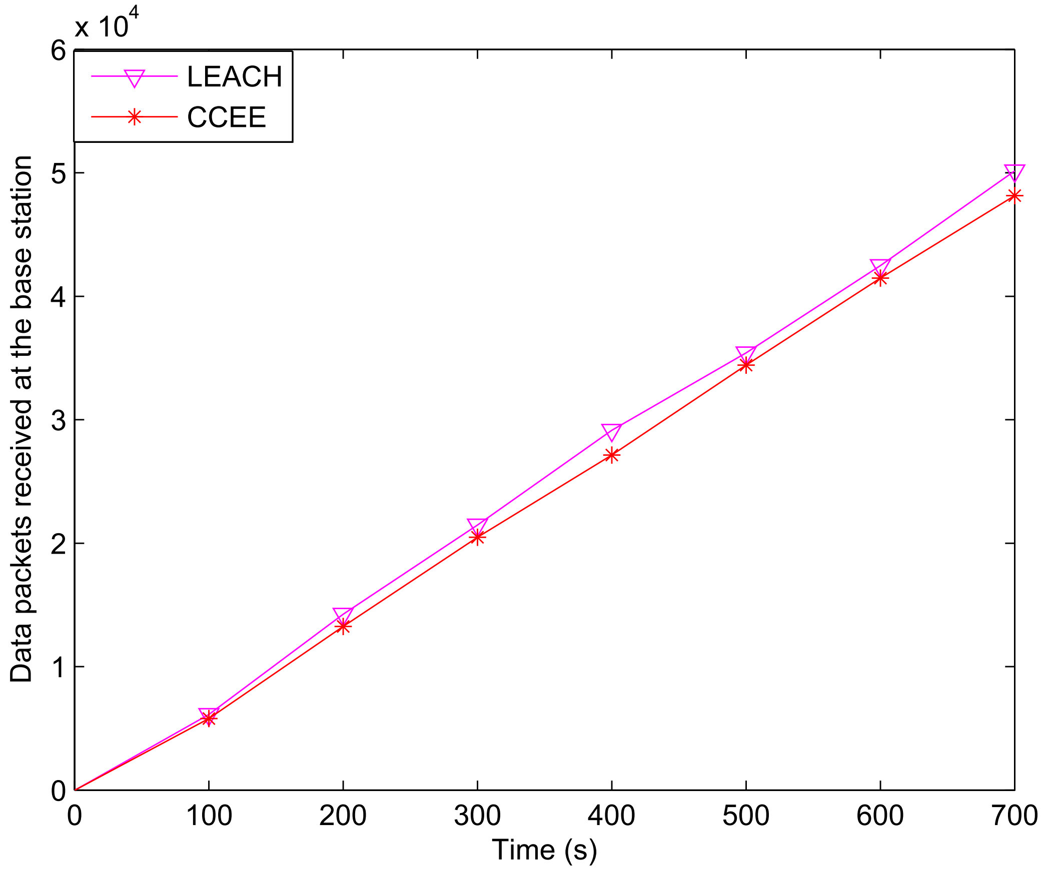

Figure 4.20. Total data packets received at the base station over time

Chapter 5

Conclusions and Future Work

5.1 Conclusions

We developed a centralised clustering, energy-efficient routing protocol that meets the energy challenges in wireless sensor networks. A centralised cluster head selection algorithm which is performed by the base station is utilised in the protocol to choose cluster heads using global information of the network. Using this centralised algorithm, better deterministic cluster heads in terms of energy-efficiency and energy distribution can be selected. The cluster formation scheme in the protocol aims at distributing energy load among cluster heads. This can avoid the situation that some cluster heads may die earlier than others due to the heavy load. In order to reduce the energy consumption for data transmission from cluster heads to the base station, an energy-efficient routing algorithm is developed in the protocol. This algorithm conducts a multi-hop routing based on a optimal transmission range in terms of energy-efficiency. Significant energy dissipation of data transmission can be reduced by using this routing algorithm.

The performance of the developed protocol is evaluated using OMNeT++. Energy efficiency, energy distribution, and network lifetime are defined as the performance metrics to compare the proposed protocol with three existing routing protocols. Simulation results show that the proposed protocol outperformed existing protocols in terms of most of the performance metrics. Furthermore, these results verified the theoretic analysis of our protocol about the centralised cluster head selection algorithm and the multi-hop routing algorithm. It is shown that centralised cluster head selection and multi-hop routing can perform well in the routing protocol for wireless sensor networks.

Because of the centralised control for the cluster head selection, there are small time latency and communication overhead problems when using the proposed protocol as the routing protocol for wireless sensor networks. In addition, using the multi-hop routing for data transmission from cluster heads to the base station needs a bit more time than direct transmission. Since the protocol can save energy and prolong network lifetime, it is well suited for applications where energy and network lifetime are the primary considerations and small overhead and time delay can be tolerated.

5.2 Future Work

The centrailised clustering, energy-efficient routing protocol proposed in this thesis offered good performance in data-gathering applications of wireless sensor networks. The analysis and simulation results show that the protocol outperforms the three other existing protocols. However, some aspects of the protocol still need to be improved.

The data aggregation of the proposed protocol is developed under the scenarios where sensor nodes sense similar data and data-correlation exists. For applications where nodes may sense different data, compressing all the data on cluster head into one fixed-length packet is not suitable any more and significant data information will lost. Therefore, developing an adaptive algorithm for the data aggregation of the protocol needs to be done in the future work.

The communication overhead in the protocol should be reduced for the applications that require quick response and little overhead. The communication overhead of the protocol can be reduced by using the "passive-BS-based approach" proposed in [22]. In this approach, the base station obtains node information about the location and residual energy by extracting this information contained in the data packets received from cluster heads.

Appendix A

A.1 Sensor Node Structure in Simulation

The Sensor Network Research Group at Louisiana State University has defined a generic sensor nodes [62]. Based on this generic design, we have built a simulated sensor node as illustrated in Figure A.1.

- The physical layer module is responsible for making a connection between the node and its neighbors, and forwarding the message from a higher layer to its neighbors, and vice versa.
- The MAC layer module is responsible for performing MAC protocols. It contains incoming queues and outgoing queues. When the queue is full, it deletes some of the oldest messages to make room in the queue for the new message.
- The network layer module defines the network packets and performs the routing protocol.
- The sensing application module represents the application layer. It is responsible for generating messages, including data message and information messages. These messages are sent to the network layer at a specific time. In addition, the application module has the capacity of obtaining the geographic information of the nodes (GPS equipment) used for cluster head selection in our protocol. Note that, each time after sending a message, the module automatically sends a DECREASE_ENERGY message to the energy module (through the coordinator) to let the module decrease its energy by a number of energy units.

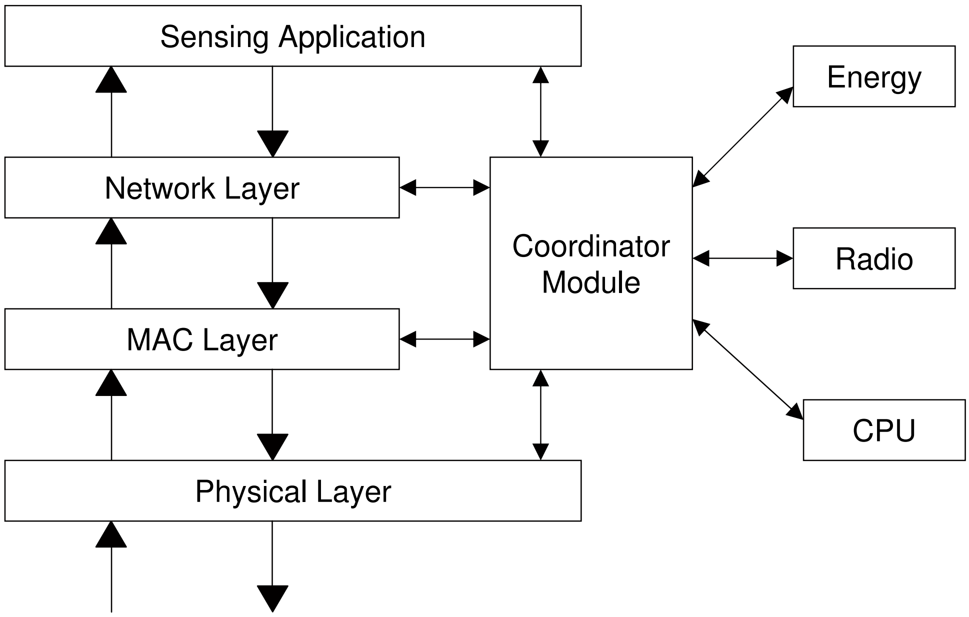

Figure A.1. A simulated sensor node structure

- The coordinator module is an interface to connect all modules together. It categorises an incoming message in order to deliver it to the right module. For example, when receiving a DECREASE_ENERGY message, it will forward the message to the energy module.

- The energy module represents the battery in a sensor node. If the module receives a DECREASE_ENERGY message, it deceases the energy level by a number of energy units.

- The radio module represents the radio board in a sensor node.

- The CPU module is responsible for data processing, such as data aggregation.

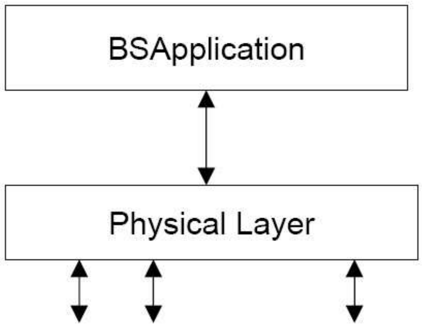

Figure A.2. Base station structure

A.2 Base Station Application

The base station in our simulations consists of two modules: an application module and a physical layer module as illustrated in Figure A.2. The physical layer module of the base station performs the function of receiving and transmitting messages. Whereas the application module performs the cluster head selection algorithm for our protocol and passes the information of selected cluster heads to the physical layer.

The base station has no energy constraints and receives all the data from the nodes. Therefore, the base station node can keep a track of all the data it receives. Determining when the base station receives the data allows us to estimate the latency of different protocols and determining how much data is received during a given time allows us to determine the quality of different protocols.

For our routing protocol, the base station must receive small information packets from each node at the beginning of each round that contain the node's location and current energy level. Once the base station receives all these packets from nodes, it must determine the cluster heads according to the cluster head selection algorithm described in Section 3.4.1. After determining all the cluster heads in this round, the base station broadcasts an information packet that contains the IDs of selected cluster heads to the nodes in the network. When a node receives this packet, it will check whether its own ID is same as one of the IDs in the packet. If it is, this node turns out to be a cluster head. Otherwise, it waits for the invitation messages from neighboring cluster heads to join one of the clusters.

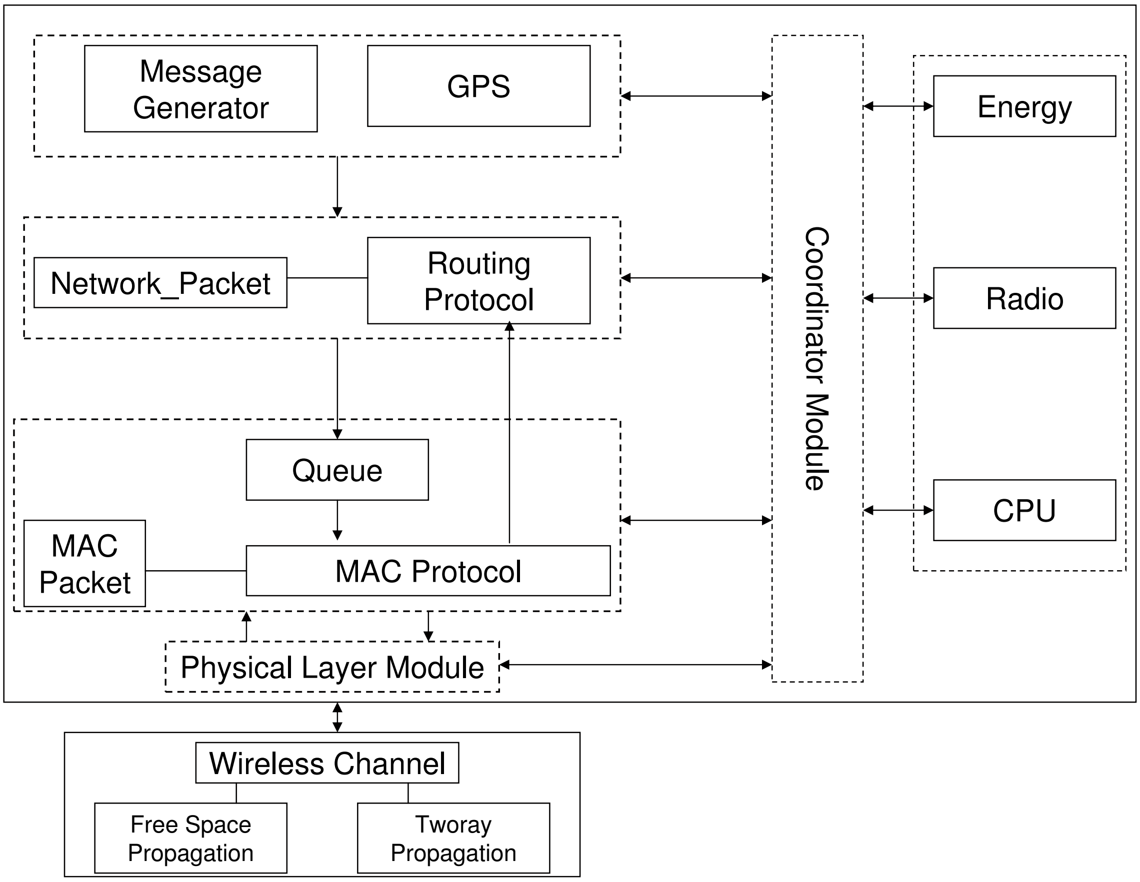

Figure A.3. Implementation in simulations

A.3 Implementation

The implementation of each module of a sensor node along with the routing protocol and MAC protocol is illustrated in Figure A.3. The implementation uses a simple pass through the physical layer, a simple wireless channel module with the application layer generating sensing data and the information message (includes location information) and forwarding it to the network layer.

A.3.1 Routing Protocol

CCEE is implemented as the routing protocol on the network layer. The implementation details of CCEE is exactly as described in Chapter 3. Network packets, such as data packets, advertisement packets, and information packets, are defined in the network layer.

Once a message is received from the application layer or the MAC layer, the CCEE will add a header to the message which depends on the message type. For example, if the received message is a data message from the application layer, the CCEE protocol will add a header, which includes the packet type, its own ID, and the destination address to the message to create a data packet and send it to the MAC layer.

A.3.2 MAC Protocol

A MAC protocol that combines carrier-sense multiple access (CSMA), time-division multiple access (TDMA), and direct-sequence spread spectrum (DS-SS) is created for our simulations. The application determines which MAC protocol is used to send each message based on the constraints of the routing protocol. For example, in CCEE, if the packet is an advertisement, it is transmitted using a CSMA approach. If it is a data message being sent to the cluster head, it is sent using a TDMA slot with the DS-SS code specified by the cluster head. Using such an approach , the MAC protocol is always chosen such that it reduces energy dissipation by allowing nodes to remain in the sleep state for as long as possible (e.g., using TDMA) and minimising collision (e.g., using CSMA to reduce the number of collision).

TDMA is implemented when the application layer has data sent to the network layer during the specified TDMA time-slot. Non-persistent CSMA is used for the experiments. To perform CSMA, the node senses the channel before the transmission. If the channel is currently being used by someone else, the node sets a back-off timer to expire after a random amount of time. The timer is chosen uniformly with a maximum time equal to the transmit time of the packet it is waiting to transmit. This back-off policy for CSMA is efficient because all nodes are transmitting packets with the same length during a given time. Therefore, the maximum amount of time that the channel will be busy is equal to the amount of time it would take to transmit the node's packet. Once the back-off time expires, the node again senses the channel. If it is still busy (presumably someone else captured the channel first), the node again sets a back-off timer. This continues until the node senses a free channel. Once the channel is free, the node passes the packet onto the physical layer. The node must also set a transmit-timer so it knows when it has finished transmitting the packet. This is important because a node cannot transmit two packets at the same time, and a node cannot receive a packet while it is transmitting.

A.3.3 Physical layer

When the physical layer receives a packet from the MAC layer, it sets the transmit power based on an approximation of the distance to the receiver (assuming power control is used in all the protocols described in this thesis), removes the appropriate amount of energy to send the packet, and sends the packet onto the channel. As introduced in Section 3.1.2, there are two propagation models, the free space model and the two ray ground model, for data transmission.

If the node has used up all its energy after transmitting the packet, the node is dead and will be removed from the channel. Nodes that have died do not have any impact on the routing protocols, and any data sent to a node that is dead is thrown away.

When receiving data, the packet enters the node's physical layer from the channel. If the node is in the sleep state, the physical layer discards the packet, since sleeping nodes cannot receive or transmit any packets. Therefore, there is no energy cost to these nodes even when packets are being transmitted in their vicinity. If the node is awake, the packet will be received and passed up to the MAC layer.

A.4 Statistics Collection

We added statistics collection to keep track of the internal state of the network and the individual nodes during the simulation. At periodic intervals, the following data are collected:

1. Amount of energy consumed by each node
2. Amount of data received at the base station
3. Number of nodes still alive

In order to evaluate the cluster head selection of our protocol, we also recorded the number of cluster heads in each round and the number of member nodes in each cluster.

Using these statistics, we can evaluate the effectiveness of different protocols.

Appendix B

Published Papers

Position-based, Energy-efficient, Centralised Clustering Protocol for Wireless Sensor Networks

Lifang Lu and Cheng-Chew Lim
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Lu, L. & Lim, C. (2009) Position-based, energy-efficient, centralised clustering protocol for wireless sensor networks.
Conference Proceedings, 4th IEEE Conference on Industrial Electronics and Applications , Conference Record of the 2009 ICIEA, China, pp. 139-144

Weight-based Clustering Routing Protocol for Wireless Sensor Networks

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Lu, L. & Lim, C. (2009) Weight-based clustering routing protocol for wireless sensor networks. *Symposium Proceedings, 2nd IEEE International Symposium on IT in Medicine and Education, ITIME 2009, China, v. 1, pp. 554-559*

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