A HIERARCHICAL CLUSTERING-BASED ROUTING PROTOCOL APPLIED FOR WIRELESS SENSOR NETWORKS

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Abstract

In this thesis, we propose a two-level hierarchical clustering-based routing protocol for wireless sensor networks (WSNs). WSNs consist of hundreds of thousands of energy-limited sensor nodes that are densely deployed in a large geographical region. Once deployed, the replacement of the energy sources of these sensor nodes is usually not feasible. Hence, energy efficiency is always a key design issue that needs to be enhanced in the WSN to improve the life span of the entire network. Each layer of the Open System Interconnect (OSI) Reference Model should be considered when exploiting the energy constrain in the WSN, the routing protocol proposed in this thesis, which is called the Clustering-Based Expanding-Ring Routing Protocol (CBERRP), lies mainly on the network layer. CBERRP gains the preferred performance over two typical clustering-based routing schemes in terms of network lifetime, power consumption and throughput by adopting the concept of cross-layer design.

CBERRP is centralized-controlled by the base station and utilizes the two-level hierarchical structure of clusters (level-I) and chains (level-II) to route and forward the sensed data from the WSN to the base station. In addition, CBERRP can be fine-tuned to support multiple Data Aggregation Qualities for the WSN applications. The performance of CBERRP is compared to analogous clustering-based schemes such as Low-Energy Adaptive Clustering Hierarchy (LEACH) and LEACH-centralized (LEACH-C). The simulation results show that

CBERRP presents a significant improvement over these two schemes on the performance of overall energy consumption and the network lifetime by around 50% and 100%, respectively.

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List of Abbreviations

ADCs: Analog to Digital Converters

BCDCP: Base-Station Controlled Dynamic Clustering Protocol

BS: Base Station

C4ISRT: Command, Control, Communications, Computing, Intelligence,
Surveillance, Reconnaissance and Targeting

CBERRP: Clustering-Based Expanding-Ring Routing Protocol

CDMA: Code Division Multiple Access

CH: Cluster Head

DAQ: Data Aggregation Quality

DNS: Domain Name System

EAR: Eavesdrop and Register

ID: Identification

LEACH: Low-Energy Adaptive Clustering Hierarchy

LEACH-C: LEACH-Centralized

MAC: Medium Access Control

MANETs: Mobile Ad hoc NETWORKs

MEMS: Micro-Electro-Mechanical Systems

NBC: Nuclear, biological, and Chemical

OSI: the Open System Interconnect Reference Model

PLL: Phase Locked Loop

QoS: Quality of Service

RF: Radio Frequency

RP: Reference Point

SAR: Sequential Assignment Routing

SMACS: Self-organizing MAC for Sensor networks

SPIN: Sensor Protocols for Information via Negotiation

TDMA: Time Division Multiple Access

VCR: Video Cassette Recorder

WSN: Wireless Sensor Networks

Chapter 1

Introduction

Recent Advances in micro-electro-mechanical systems (MEMS) technology, wireless communications, and digital electronics have enabled the development of low-cost, low-power, multifunctional sensor nodes that are small and communicate untethered in short distances. These tiny sensor nodes, which consist of sensing, data processing, and communicating components, leverage the idea of sensor networks based on collaborative effort of a large number of nodes [1].

A wireless sensor network (WSN) is composed of a great number of sensor nodes, which are densely deployed in a large geographical area. The phenomenon of interest is either located in the area or near to it, making the sensor nodes able to carry on the sensing applications for the information of interest. Typically, in order to allow random and easy deployment of WSNs (this is normally due to the fact of the numerous sensor nodes in WSNs), there is little need to engineer or pre-determine positions of the sensor nodes, especially in cases such as deployment in inaccessible terrains or disaster relief operations. Another unique feature of sensor networks is the cooperative effort of sensor nodes. Instead of sending the raw data to the base station (BS), sensor nodes use their processing abilities to locally carry out simple computations and transmit only the required and partially processed data.

In addition, WSNs with the recent advanced technology have represented the differences than traditional sensors or Mobile Ad hoc Networks (MANETs), hence, many protocols and schemes proposed for traditional MANETs are not well suited for the unique features and application requirements of WSNs. To illustrate this point, the differences between WSNs

and MANETs are outlined below [1]:

- 1) The number of sensor nodes in a WSN can be several orders of magnitude higher than that in an ad hoc network.
- 2) Sensor nodes are densely deployed.
- 3) Sensor nodes are prone to failures.
- 4) The topology of a sensor network changes very frequently.
- 5) Sensor nodes are limited in power, computational capacity, and memory.
- 6) Sensor nodes may not have global identifications (IDs) because of the large amount of overhead and large number of sensors.

These differences require new design principles for the protocols and schemes used for WSNs.

Because sensor nodes normally carry limited, generally irreplaceable, power sources, the low power consumption requirement becomes one of the most important constraints on sensor nodes. Therefore, while traditional networks aim to achieve high quality of service (QoS) provisions, WSN protocols must focus primarily on power conservation. They must have inbuilt trade-off mechanisms that give the end user the option of prolonging network lifetime at the cost of lower throughput or higher transmission delay.

Many researchers are currently engaged in developing schemes that fulfill these requirements. In this thesis, we propose a routing protocol for WSNs. The goal of this work is to provide a routing algorithm that will meet some appropriate design objectives (to be discussed in section 1.3) for WSNs, specifically, achieving the power efficiency. The following sections deliver an overview on WSNs from three aspects: Application, Design issues and communication architecture.

1.1 Wireless Sensor Networks Applications

Sensor nodes can be used for continuous sensing, event detection, event ID or location sensing, and local control of actuators. The applications for WSNs can be categorized into military, environment, health, home and other commercial areas.

1.1.1 Military Applications

WSNs can be an integral part of military command, control, communications, computing, intelligence, surveillance, reconnaissance and targeting (C4ISRT) systems. The rapid deployment, self-organization and fault tolerance characteristics of WSNs make them a very promising sensing technique for military C4ISRT.

Monitoring friendly forces, equipment and ammunition: Leaders and commanders can constantly monitor the status of friendly troops, the condition and the availability of the equipment and the ammunition in a battlefield by the use of WSNs. Every troop, vehicle, equipment and critical ammunition can be tagged with small sensors that report their status. These reports are gathered in sink nodes (interchangeable with the BSs in this thesis) and sent to troop leaders. The data can also be forwarded to the upper levels of the command hierarchy while being aggregated with the data from other units at each level.

Battlefield surveillance: Critical terrains, approach routes, paths and straits can be rapidly covered with WSNs and closely watched for the activities of the opposing forces. As the operations evolve and new operational plans are prepared, new WSNs can be deployed anytime for battlefield surveillance.

Reconnaissance of opposing forces and terrain: WSNs can be deployed in critical terrains, and some valuable, detailed, and timely intelligence about the opposing forces and terrain can be gathered within minutes before the opposing forces can intercept them.

Nuclear, biological and chemical (NBC) attack detection and reconnaissance: In chemical and biological warfare, being close to ground zero is important for timely and accurate detection of the agents. Sensor networks deployed in the friendly region and used as a chemical or biological warning system can provide the friendly forces with critical reaction time, which can drastically reduce casualties. We can also use WSNs for detailed reconnaissance after an NBC attack is detected. For instance, a nuclear reconnaissance can be made without exposing a reconnaissance team to nuclear radiation.

1.1.2 Environmental Applications

Some environmental applications of WSNs include tracking the movements of birds, small animals, and insects; monitoring environmental conditions that affect crops and livestock; irrigation; macro instruments for large-scale Earth monitoring and planetary exploration; chemical/biological detection; precision agriculture. Moreover, biological, earth, and environmental monitoring in marine, soil, and atmospheric contexts; forest fire detection; meteorological or geophysical research; flood detection; bio-complexity mapping of the environment; and pollution studies also require emerging networks for successful implementation.

Forest fire detection: Since sensor nodes could be deployed strategically, randomly, and densely in a forest, sensor nodes can relay the exact origin of the fire to the end users before the fire is spread uncontrollable. Millions of sensor nodes can be deployed and integrated by using radio frequencies/optical systems. In addition, they may be equipped with effective power scavenging methods, such as solar cells, because the sensors may be left unattended for months and even years. The wireless sensor nodes will collaborate with each other to perform distributed sensing and overcome

obstacles, such as trees and rocks, which block wireless sensors' line of sight.

Biocomplexity mapping of the environment: Biocomplexity mapping of the environment requires sophisticated approaches to integrate information across temporal and spatial scales. Advances of technology in remote sensing and automated data collection have enabled higher spatial, spectral, and temporal resolution at a geometrically declining cost per unit area. Along with these advances, the sensor nodes also have the ability to connect with the internet, which allows remote users to control, monitor and observe the biocomplexity of the environment. One example of biocomplexity mapping of the environment is done at the James Reserve in Southern California [2].

Flood detection: An example of the flood detection is the ALERT system deployed in the US. Several types of sensors deployed in the ALERT system function as rainfall, water level and weather sensors. These sensors supply information to the centralized database system in a pre-defined way.

Precision Agriculture: Some of the benefits of sensor networks are their ability to monitor pesticides level in the drinking water, the level of soil erosion, temperature, humidity, and the level of air pollution in real time.

1.1.3 Health Applications

Some of the health applications of WSNs include providing interfaces for the disabled; integrated patient monitoring; diagnostics; drug administration in hospitals; monitoring the movements and internal processes of insects or other small animals; telemonitoring of human physiological data; and tracking and monitoring doctors and patients inside a hospital.

Telemonitoring of human physiological data: The physiological data collected by the sensor networks can be stored for a long period, and can be used for medical exploration. The installed sensor networks can also monitor and detect elderly people's behavior, e.g. a fall. These small sensor nodes

allow the subject a greater freedom of movement and allow doctors to identify pre-defined symptoms earlier. In addition, they facilitate a higher quality of life for the subjects compared to treatment centers.

Tracking and monitoring doctors and patients inside a hospital: Each patient has small and lightweight sensor nodes attached to him or her. Each sensor node has a specific task. For example, one sensor node may detect the heart rate while another detects the blood pressure. Doctors may also carry a sensor node, which allows other doctors to locate them within the hospital.

Drug administration in hospitals: If sensor nodes can be attached to medications, the chance of getting and prescribing the wrong medication to patients can be minimized, because patients will have sensor nodes that identify their allergies and required medications.

1.1.4 Home Applications

As technology advances, smart sensor nodes and actuators can be buried in appliances, such as vacuum cleaners, microwave ovens, refrigerators, and VCRs (Video Cassette Recorders). These sensor nodes inside the domestic devices can interact with each other and with the external network via the Internet or Satellite. They allow end users to manage home devices locally and remotely.

Smart environment: The design of smart environment can have two different perspectives, i.e., human-centered and technology-centered. In a human-centered design, a smart environment has to adapt to the needs of the end users in terms of input/output capabilities. For technology-centered designs, new hardware technologies, networking solutions, and middleware services have to be developed. The sensor nodes can be embedded into furniture and appliances, and they can communicate with each other and the room server.

The room server can also communicate with other room servers to learn about the services they offered, e.g., printing, scanning, and faxing. These room servers and sensor nodes can be integrated with existing embedded devices to become self-organizing, self-regulated, and adaptive systems based on control theory models. The computing and sensing in this environment has to be reliable, persistent, and transparent.

1.1.5 Other Commercial Applications

Some of the commercial applications are: monitoring material fatigue; building virtual keyboards; managing inventory; monitoring product quality; constructing smart office spaces; environmental control in office buildings; robot control and guidance in automatic manufacturing ; interactive toys; interactive museums; factory process control and automation; monitoring disaster area; smart structures with sensor nodes embedded inside; machine diagnosis; transportation; factory instrumentation; local control of actuators; detecting and monitoring car thefts; vehicle tracking and detection; and the instrumentation of semiconductor processing chambers, rotating machinery, wind tunnels, and anechoic chambers.

Environmental control in office buildings: Air conditioning and heat in most buildings are centrally controlled. Therefore, the temperature inside a room can vary by few degrees; one side might be warmer than the other because there is only one control in the room and the air flow from the central system is not evenly distributed. A distributed WSN system can be installed to control the airflow and temperature in different parts of the room.

Interactive museums: In the future, children will be able to interact with objects in museums to learn more about them. These objects will be able to respond to their touch and speech. In addition, children can participate in real time cause-and-effect experiments, which can teach them about science and

environment. In addition, WSNs can provide paging and localization inside the museum.

Managing inventory control: Each item in a warehouse may have a sensor node attached. The end users can find out the exact location of the item and total number of items in the same category. If the end users want to insert new inventories, all the users need to do is to attach the appropriate sensor nodes to the inventories. The end users can track and locate where the inventories would be at all times.

Vehicle tracking and detection: There are two approaches to track and detect the vehicle: first, the line of bearing of the vehicle is determined locally within the clusters and then it is forwarded to the BS, and second, the raw data collected by the sensor nodes are forwarded to the BS to determine the location of the vehicle.

It is not difficult to see that the WSN is very application-specific. The different applications will require different setups of the underlying network infrastructure, and therefore, different protocol designs are necessary to comply with the different application needs. In this thesis, monitoring remote environmental conditions is the target application for the WSN studied.

1.2 Design Issues in Wireless Sensor Networks

The WSNs design is involved with many factors, which include fault tolerance, scalability, production costs, operating environment, sensor network topology, hardware constraints, transmission media, and power consumption. These factors are important because they serve as the benchmark for designing a protocol or scheme for WSNs. In addition, these design factors can be used to compare different schemes.

1.2.1 Fault Tolerance

Some sensor nodes may fail or be blocked due to lack of power, as a result of physical damage or environmental interference. The failure of sensor nodes should not affect the overall task of the WSN. This is the reliability to sustain WSN functionalities without any interruption due to sensor node failures.

Note that protocols and schemes may be designed to address the certain level of fault tolerance required by WSNs. If the environment where the sensor nodes are deployed has little interference, then the protocols can be more relaxed. For example, if sensor nodes are being deployed in a house to keep track of humidity and temperature levels, the fault tolerance requirement may be low since this kind of WSNs is not easily damaged or interfered by environmental noise. On the other hand, if sensor nodes are being deployed in a battlefield for surveillance and detection, then the fault tolerance has to be high because the sensed data are critical and sensor nodes can be destroyed by hostile actions. As a result, the fault tolerance level depends on the application of WSNs, and the schemes must be developed with this in mind.

1.2.2 Scalability

The number of sensor nodes deployed for studying a phenomenon may be in the order of hundreds or thousands. Depending on the application, the number may reach an extreme value of millions. Then new schemes must be able to work with this number of sensor nodes. They must also utilize the high-density nature of WSNs. In addition, the number of sensor nodes in a region can be used to indicate the sensor node density that depends on the application for which the sensor nodes are deployed.

1.2.3 Production Costs

Since WSNs consist of a large number of sensor nodes, the cost of a single sensor node is very important to justify the overall cost of the networks. If

the cost of the network is more expensive than deploying traditional sensors, then WSN is not cost-justified. As a result, the cost of each sensor node has to be kept low. The cost of sensor node is a very challenging issue given the amount of functionalities with a price of much less than a dollar.

Figure 0-1 Components of a sensor node

1.2.4 Hardware Constraints

A sensor node consists of four basic components as shown in Figure 1.1: a sensing unit, a processing unit, a transceiver unit and a power unit. They may also have additional application-dependent components such as a location finding system, a power generator and a mobilizer. Sensing units are usually composed of two subunits: sensor and analog to digital converter (ADC). The analog signals produced by the sensors based on the observed phenomenon are converted to digital signals by the ADC unit, and then fed into the processing unit. The processing unit, which is generally associated with a small storage unit, manages the procedures that make the sensor node collaborate with other sensor nodes to carry out the assigned sensing tasks. A transceiver

unit connects the sensor node to the network. One of the most important components of a sensor node is the power unit. A power-scavenging unit such as solar cells may support power units. There are also other subunits, which are application-dependent. For example, most of the WSN routing techniques and sensing tasks require the knowledge of location with high accuracy. Thus, it is common that a sensor node has a location finding system. A mobilizer may sometimes be needed to move sensor nodes when it is required to carry out the assigned tasks.

Since the sensor nodes are often inaccessible, the lifetime of a WSN depends on the lifetime of the power resources of the sensor nodes. Power is also a scarce resource due to the size limitation of the sensor node. The transceiver unit of the sensor node may be a passive or active device as a radio frequency (RF) device. RF communications require modulation, band pass, filtering, demodulation and multiplexing circuitry, which make them more complex and expensive. In addition, the path loss of the transmitted signal between two sensor nodes may be as high as the fourth order exponent of the distance between them because the antennas of the sensor nodes are close to the ground. Nevertheless, RF communication is preferred in most of the ongoing WSN research projects, because the packets conveyed in WSNs are small, data rates are low, and the frequency re-use is high. These characteristics also make it possible to use low duty cycle radio electronics for WSNs. However, designing energy efficient and low duty-cycle radio circuits is still technically challenging.

1.2.5 Wireless Sensor Network Topology

Sheer numbers of inaccessible and unattended sensor nodes, which are prone to frequent failures, make topology maintenance a challenging task. Hundreds to several thousands of nodes are deployed throughout the sensor

field. They are deployed within tens of feet of each other. The node densities may be as high as 20 nodes/ m³ [1]. Deploying high number of nodes densely requires careful handling of topology maintenance. We examine issues related to topology maintenance and change in three phases.

Pre-deployment and deployment phase: Sensor nodes can be either thrown in mass or placed one by one in the sensor field. The design goal for this phase is to reduce the installation cost, eliminate the need for any pre-organization and pre-planning, increase the flexibility of arrangement, and promote self-organization and fault tolerance since the sheer number of sensors and their unattended deployment usually preclude placing them according to a carefully engineered deployment plan.

Post-deployment phase: After deployment, topology changes are due to change in sensor nodes' position, reachability (due to jamming, noise, moving obstacles, etc.), available energy, malfunctioning, and task details. Sensor nodes may be statically deployed. However, device failure is a regular or common event due to energy depletion or destruction. It is also possible to have WSNs with highly mobile nodes. Besides, sensor nodes and the network experience varying task dynamics, and they may be a target for deliberate jamming. Therefore, WSN topologies are prone to frequent changes after deployment.

Re-deployment of additional nodes phase: Additional sensor nodes can be re-deployed at any time to replace the malfunctioning nodes or due to changes in task dynamics. Addition of new sensor nodes poses a need to re-organize the network. Coping with frequent topology changes in a WSN that has myriads of sensor nodes and very stringent power consumption constraints requires some special routing schemes.

1.2.6 Power Consumption

The wireless sensor node, being a micro-electronic device, can only be equipped with a limited power source ($< 0.5\text{Ah}$, 1.2V) [1]. In some application scenarios, replenishment of power resources might be impossible. Sensor node lifetime, therefore, shows a strong dependence on battery lifetime. In a WSN, each sensor node plays the dual role of data originator and data router. The malfunctioning of few sensor nodes can cause significant topological changes and might require re-routing of packets and re-organization of the network. Hence, power conservation and power management take on additional importance. It is for these reasons that researchers are currently focusing on the design of power-aware protocols and schemes for WSNs.

In other mobile or Ad hoc networks, power consumption has been an important design factor, but not the primary consideration, simply because the user can replace power resources. The emphasis is more on QoS provisioning than the power efficiency. In WSNs though, power efficiency is an important performance metric, directly influencing the network lifetime. Application-specific protocols can be designed by appropriately trading off other performance metrics such as delay and throughput with power efficiency.

The main task of a sensor node in a sensor field is to detect events or sense the environment, perform quick local data processing, and then transmit the data. Power consumption can hence be divided into three domains: sensing, communication, and data processing.

Sensing: Sensing power varies with the nature of applications. Sporadic sensing might consume less power than constant event monitoring. The complexity of event detection also plays a crucial role in determining energy expenditure. Higher ambient noise levels might cause significant corruption and increase detection complexity. Typically, this domain of power consumption takes a negligible role in the routing protocols for WSNs.

Communication: Of the three domains, a sensor node expends maximum energy in data communication. This involves both data transmission and reception. Mixers, frequency synthesizers, voltage control oscillators, phase locked loops (PLL) and power amplifiers all consume valuable power in the transceiver circuitry.

Data processing: Energy expenditure in data processing is much less compared to data communication. Hence, local data processing is crucial in minimizing power consumption in a multi-hop WSN. A sensor node must therefore have built-in computational abilities and be capable of interacting with its surroundings. It is to be noted that there may be some additional circuitry for data encoding and decoding. In all these scenarios, the design of WSN schemes and protocols are influenced by the corresponding power expenditures.

Some of these design issues are the challenges this thesis wants to meet. First, the work in this thesis addresses the fault tolerance by using a centralized controller to perform most of control tasks of the routing protocol. Since in the application of monitoring remote environmental conditions the topology failure mainly comes from dead nodes, environmental noise and communication interference, we can achieve the fault tolerance for such a level by re-setting up the network topology by eliminating the failure nodes on a certain interval basis. In doing so, the protocol can also adapt to the topology change of the wireless sensor network due to the re-deployment. The work in this thesis provides a solution for the scalability of the WSN by introducing the two-level cluster hierarchical architecture on the WSN. When the number of sensor nodes is increasing extremely, the number of second level clusters can also increase accordingly. As a result, the control and management to huge numbers of sensor nodes is possible. The work in this thesis focuses mainly on the power consumption in the network layer, skipping the hardware constraints

of the tiny sensor nodes. As to the power consumption, this thesis will only consider the communication part and data aggregation since these two parts have close connection to the routing protocol, which is the subject the network layer issue deals with.

1.3 Wireless Sensor Networks Communication Architecture

The sensor nodes are usually scattered in a sensor field. Each of these scattered sensor nodes has the capabilities to collect data and route data back to the sink and the end users. Data are routed back to the end user by a multi-hop infrastructureless architecture through the sink as shown in Fig 1.2. The sink may communicate with the task manager node via Internet or Satellite.

Figure 0-2 The Communication Architecture of WSN.

The protocol stack [1] used by the sink and all sensor nodes is given in Figure 1.3. This protocol stack combines power and routing awareness, integrates data with networking protocols, communicates power efficiently through the wireless medium, and promotes cooperative efforts of sensor nodes. The protocol stack consists of the application layer, transport layer, network

layer, data link layer, physical layer, power management plane, mobility management plane, and task management plane.

Figure 0-3 The sensor networks protocol stack

Depending on the sensing tasks, different types of application software can be built and used on the application layer. The transport layer helps to maintain the flow of data if WSNs application requires it. The network layer takes care of routing the data supplied by the transport layer. Since the environment is noisy and sensor nodes can be mobile, the MAC protocol must be power-aware and able to minimize collision with neighbors' broadcast. The physical layer addresses the needs of a simple but robust modulation, transmission and receiving techniques. In addition, the power, mobility and task management planes monitor the power, movement, and task distribution among the sensor nodes. These planes help the sensor nodes coordinate the sensing task and lower the overall power consumption.

The power management plane manages how a sensor node uses its power. For example, the sensor node may turn off its receiver after receiving a message from one of its neighbors. This is to avoid getting duplicated

messages. In addition, when the power level of the sensor node is low, the sensor node broadcasts to its neighbors that it is low in power and cannot participate in the routing process. The remaining power might be reserved for sensing. The mobility management plane detects and registers the movement of sensor nodes, so a route back to the user is always maintained, and the sensor nodes can keep track of whom their neighbor sensor nodes are. By knowing who the neighbor sensor nodes are, the sensor nodes can balance their power and task usage. The task management plane balances and schedules the sensing tasks given to a specific region. Not all sensor nodes in that region are required to perform the sensing task at the same time. As a result, some sensor nodes perform the task more than the others depending on their power level. These management planes are needed, so that sensor nodes can work together in a power efficient way, route data in a mobile sensor network, and share resources between sensor nodes. Without them, each sensor node will just work individually. From the whole WSN standpoint, it is more efficient if sensor nodes can collaborate with each other, so the lifetime of WSNs can be prolonged.

In this thesis, it assumes the application is monitoring of remote environment with the dynamic requirements on Data Aggregation Quality (DAQ); each node does not have the ability to move; and also the data link layer and physical layer are ready to support the routing protocol proposed in this thesis. Thus, this thesis simplifies the work on the protocol stack of the WSN by targeting the energy issue in the network layer.

1.4 Organization of the Thesis

The rest of the thesis is organized as follows. In Chapter 2, the current routing protocols proposed in the literature for WSNs are reviewed. In addition,

three clustering-based routing protocols are introduced and their effectiveness on the power conservation is investigated. Chapter 3 introduces the concept of ring and reference point (RP), which are the pertinent components of Clustering-Based Expending-Ring Routing Protocol (CBERRP) that is the proposed routing protocol in this thesis. It is the ring and RP that make CBERRP more efficient on power dissipation than two typical clustering-based routing protocols: LEACH and LEACH-C. Also, the operation of CBERRP is described in Chapter 3. Chapter 4 discusses the simulation results and the comparison between CBERRP and other analogous routing protocols. Finally, the conclusion and future works are stated in Chapter 5.

Chapter 2

Routing Protocols for Wireless Sensor Networks

2.1 Overview

Various applications of WSNs discussed in Chapter 1 have a wide range of network requirements as well as energy constraints for different kinds of wireless sensors. The network requirements must be met in order for the WSN to function properly despite of the variations in the link characteristics, the network topologies, and the node traffic. It is very difficult to ensure the performance of the network and the support of real-time or mission-critical data in the face of these random variations. There have been significant research directed toward energy constraints, application requirements, and network variability at different levels of the network protocol stack. Examples, to name a few, include multiple antennas, coding, power control, and adaptive techniques at the link layer, energy-constrained and delay-constrained routing at the network layer.

Recently, power-aware WSNs design has attracted great research attention across different layers of the communication stack. For example, in [3], several factors affecting the power consumption in terms of characteristics of the radio, including the type of modulation scheme, data rate, transmit power (determined by the transmission distance), and the operational duty cycle are investigated. A medium access control (MAC) protocol designed for WSNs, called S-MAC, is proposed in [4]. S-MAC uses three novel techniques to reduce energy consumption and support self-configuration. First, nodes periodically

sleep to reduce energy consumption in listening to an idle channel. Second, neighboring nodes form virtual clusters to auto-synchronize on sleep schedules. Third, S-MAC applies message passing to reduce contention latency for sensor-network applications that require store-and-forward processing as data move through the network. The characteristics of the power dissipation in MAC layer are also examined in [5] and [6]. Although some potential research introduced in [1] is ongoing, the power-efficient protocols in transport and application layers remain a largely unexplored subject. By contrast, research of power-aware protocols at network layer shows a significant difference due to the close connection between power consumption and the routing scheme when the “power metric” is taken into account to select the best path in WSNs, for example, the Energy Efficient Routing in [7].

In order to have a deep insight on some existing routing protocols, it is better to provide the classifications about the routing protocols proposed for WSNs. There are many ways to classify the routing protocols. According to sensor nodes’ participating style, routing protocols can be classified into three categories, namely, direct communication, flat, and clustering protocols [8]. In direct communication protocols, a sensor node sends data directly to the sink. Under this protocol, if the diameter of the network is large, the power of sensor nodes will be drained very quickly. Furthermore, as the number of sensor nodes increases, the transmission collision becomes a significant factor that defeats the purpose of data transmission. Under flat protocols, all sensor nodes in the network are treated equally. When a sensor node needs to send data, it may find a route consisting of several hops to the sink. Normally, the probability of participating in the data transmission process is higher for the nodes around the sink than those far away from the sink. Compared to the previous two types of protocols, the clustering protocols have some differences. Firstly, it “compresses” the sensed data through data aggregation that will dramatically

decrease the amount of data needed to transmit to the sink, hence substantive power can be saved on data transmission. Meanwhile, grouping a subset of sensor nodes into cluster makes it very scalable to adapt to the growth of WSNs. Secondly, it is easy to incorporate the hierarchy into the cluster, thus facilitates the management and control of a large WSN.

A number of network layer protocols have been proposed to improve the effective lifetime of a network with a limited energy supply. A comprehensive survey of the routing protocols for WSNs can be found in [8]. Some of them are introduced in the following sections.

2.2 Protocols in Flat Class

2.2.1 Gossiping

A derivation of the old technique *flooding* is gossiping [9] in which nodes do not broadcast but send the incoming packets to a randomly selected neighbor. A sensor node randomly selects one of its neighbors to send the data. Once the neighbor node receives the data, it selects randomly another sensor node. Although this approach avoids the implosion problem by just having one copy of a message at any sensor node, it takes long time to propagate the message to all sensor nodes.

2.2.2 Sensor Protocols for Information via Negotiation (SPIN)

A family of adaptive protocols called SPIN [10] is designed to address the deficiencies of classic flooding by negotiation and resource adaptation. The SPIN family of protocols is designed based on two basic ideas: sensor nodes operate more efficiently and conserve energy by sending data that describes the sensor data instead of sending the whole data, e.g., image, and sensor

nodes must monitor the changes in their energy resources.

Figure 2-1 The SPIN protocol

SPIN has three types of messages, i.e., ADV, REQ, and DATA. Before sending a DATA message, the sensor broadcasts an ADV message containing a descriptor, i.e., meta-data, of the DATA as shown in Step 1 of Figure 2.1. If a neighbor is interested in the data, it sends a REQ message for the DATA and DATA is sent to this neighbor sensor node as shown in Steps 2 and 3 of Figure 2.1, respectively. The neighbor sensor node then repeats this process as illustrated in Steps 4, 5, and 6 of Figure 2.1. As a result, the sensor nodes in the entire WSN, which are interested in the data, will get a copy.

Note that SPIN is based on data-centric routing where the sensor nodes broadcast an advertisement for the available data and wait for a request from interested sinks.

2.2.3 Sequential Assignment Routing (SAR)

In [11], a set of algorithms, which performs organization, management and mobility management operations in WSNs, is proposed. Self-organizing

MAC for wireless sensor networks (SMACS) is a distributed protocol that enables a collection of sensor nodes to discover their neighbors and establish transmission/reception schedules without the need for a central management system. The eavesdropping and register (EAR) algorithm is designed to support seamless interconnection of the mobile nodes. The EAR algorithm is based on the invitation messages and on the registration of stationary nodes by the mobile nodes. The SAR algorithm creates multiple trees where the root of each tree is a one-hop neighbor from the sink. Each tree grows outward from the sink while avoiding sensor nodes with very low QoS (i.e., low throughput/high delay) and energy reserves. At the end of this procedure, most sensor nodes belong to multiple trees. This allows a sensor node to choose a tree to relay its information back to the sink. There are two parameters associated with each path, i.e., a tree, back to the sink: Energy resources and Additive QoS metric. The energy resources are estimated by the number of packets that the sensor node can send, if the sensor node has exclusive use of the path. A high additive QoS metric means low QoS.

The SAR algorithm selects the path based on the energy resources and additive QoS metric of each path, and the packet's priority level. As a result, each sensor node selects its path to route the data back to the sink. In addition, two more algorithms called single winner election and multi-winner election handle the necessary signaling and data transfer tasks in local cooperative information processing.

2.2.4 Directed Diffusion

The directed diffusion (data dissemination paradigm) is proposed in [12] where the sink sends out interest, which is a task description, to all sensors as shown in Figure 2.2(a). The task descriptors are named by assigning attribute-value pairs that describe the task. Each sensor node then stores the interest

entry in its cache. The interest entry contains a timestamp field and several gradient fields. As the interest is propagated throughout the WSN, the gradients from the source back to the sink are set up as shown in Figure 2.2(b). When the source has data for the interest, the source sends the data along the interest's gradient path as shown in Figure 2.2(c). The interest and data propagation and aggregation are determined locally. In addition, the sink must refresh and reinforce the interest when it starts to receive data from the source. Note that the directed diffusion is based on data-centric routing where the sink broadcasts the interest.

Figure 2-2 An example of directed diffusion:
(a) propagate interest, (b) set up gradient and (c) send data

It is clear that all these protocols are common in one main drawback which is inherent to Flat class routing protocol: the sensor node near to the sink will be utilized most of time then drain out of power faster than others. This uneven dissipation of power is not good in a situation where the sensor nodes periodically sense the phenomena and send the data back to sink continuously. Thus, typically, the Flat routing protocols are mainly applied for event-trigger or

data-trigger sensor applications.

2.3 Protocols in Clustering Class

Due to the introduction of cluster, clustering protocols gain several advantages. First, it is scalable. Secondly, it could be energy efficient in finding an available route to a destination. Thirdly, it is easy to manage the sensors and routes.

2.3.1 Low-Energy Adaptive Clustering Hierarchy (LEACH)

LEACH [13] is a clustering-based protocol that minimizes energy dissipation in WSNs. The purpose of LEACH is to select some sensor nodes randomly as cluster-heads, and only these cluster-heads communicate with the BS directly. As a result, the high-energy dissipation of communicating with the BS is spread to all sensor nodes in the WSN. The operation of LEACH is divided into two phases, the set-up phase and the steady phase. The duration of the steady phase is longer than that of the set-up phase in order to minimize the overhead.

During the set-up phase, each sensor node independently computes a random number between zero and one. If this random number is less than a predetermined threshold $T(n)$, the n -th sensor node is a cluster-head (CH). $T(n)$ is calculated as

$$T(n) = \begin{cases} \frac{P}{1 - P[r \bmod (1/P)]}, & n \in G; \\ 0, & \text{otherwise;} \end{cases} \quad (2.1)$$

where P is the desired percentage of sensor nodes to become a CH; r , the

current round; and G , the set of nodes that have not being selected as a CH in the last $1/P$ rounds. After the CHs are selected, the CHs advertise to all sensor nodes in the network that they are the new CHs. Once a sensor node in the WSN receives the advertisements, it determines which cluster to join based on the signal strength of the advertisements from all CHs. The sensor node then informs the chosen CH that it will be a member of the cluster the CH holds. Afterwards, the CH assigns the time slots to all the sensor nodes that joined the cluster, and then broadcasts the schedule of timeslots to the whole cluster. Thus, each sensor node in the cluster is able to send gathered data to the CH according to this schedule by using Time Division Multiple Access (TDMA) approach.

During the steady phase, the sensor nodes can begin sensing and transmitting data to the CH. The CH will aggregate the data gathered from the sensor nodes in the cluster, then sends the compressed data to the BS. After a certain period spent on the steady phase, the network goes into the set-up phase again and entering into another round, of selecting the CHs and data transmission.

However, the pure self-configuration feature in LEACH has its merits and drawbacks. On one hand, it achieves the scalability and the ease of deployment, which are required in WSNs; on the other hand, the randomness of the selection of the CHs makes it not optimal in terms of the power efficiency and the cluster formation. To deal with this deficiency, LEACH-Centralized (LEACH-C) is introduced in [13] to enhance the performance of LEACH. LEACH-C takes the BS as the central control point to utilize the whole network resources in a power effective way by retrieving the information of location and power level from all the sensor nodes and coordinating their operations. During the set-up phase of LEACH-C, each sensor node sends information about its current location and energy level to the BS. The BS computes the average node energy,

and whichever node with the energy below this average cannot be CH for the coming up round. All the sensor nodes with higher level of energy than the average will become candidates of the CHs. The BS conducts the clusters by using the simulated annealing algorithm to solve the NP-hard problem of finding k optimal clusters [15]. This algorithm attempts to minimize the amount of energy consumption for the non-CH nodes to transmit the data to the CH by minimizing the total sum of squared distances between all the non-CH nodes and the closest CH.

2.3.2 Power-Efficient GAttering in Sensor Information Systems (PEGASIS)

PEGASIS [14] is a chain based and power efficient protocol. Because each sensor node has global knowledge of the network, the chain can be constructed easily by using a greedy algorithm. To balance the overhead involved in communication between the leader and sink (For example, C2 is the chain leader in Figure 2.3), each sensor node in the chain takes turn to be the leader. Nodes fuse the received data with their own data when data is transmitted in the chain. In PEGASIS, each sensor node communicates only with a close neighbor and takes turn transmitting to the BS, thus reducing the amount of energy spent per round. However, very large transmission delay is traded in PEGASIS for this kind of power conservation. Moreover, due to the rotation of chain leaders, the scenario where data is going back and forth before arriving at the BS cannot be avoided, and therefore, it is not power efficient as a whole. To alleviate this problem, the authors of PEGASIS also proposed two hierarchical PEGASIS variants, namely, a chain-based binary approach and a chain-based three level scheme. Both of them introduce the hierarchy into the PEGASIS. In particular, the later uses the cluster formation based on LEACH [13]. However, the complexity of the global synchronization is not encouraging.

Figure 2-3 Chain construction using the greedy algorithm

2.3.3 Base-station Controlled Dynamic Clustering Protocol (BCDCP)

Base-station Controlled Dynamic Clustering Protocol proposed in [16] is a routing protocol evolved from LEACH. BCDP utilizes the BS to set up the clusters and routing paths. The key idea of BCDP lies in the set-up phase, a cluster split algorithm is applied to make each CH serve an approximately equal number of sensor nodes to avoid CH overload or unbalanced CH workload. It also applies CH-to-CH multi-hop routing to transfer data from the WSN to the BS. In order to do so, a minimum spanning-tree is conducted among the CHs, and then the sensed data is routed back to the BS along with this tree. Obviously, the minimum spanning-tree will over utilize the closer-to-BS CH than other CHs. Besides, it cannot achieve the optimal number of clusters [13], given the network setup of the WSN. Another shortcoming about BCDP is that it cannot prolong the life time of the WSN in a long term because of the uneven power dissipation throughout the whole network.

2.4 Conclusion

WSNs have different characteristics from other networks of today. One of main differences is that WSNs are application-specific, which means that

different WSN applications may require different network layer protocols, sometimes, even though different underlying network infrastructure. With this in mind, this work is focusing on a clustering-based routing protocol applied for WSNs since there are still many open issues that have not been addressed by the current research on the clustering-based routing protocols. With further research like in [17], it is expected that significant improvement on power efficiency, scalability, and transmission synchronization can be achieved.

Chapter 3

Clustering-Based Expanding-Ring Routing Protocol

3.1 Introduction

As shown in Figure 1.3, the architecture of the protocol stack used in the WSN provides a guideline on the combination of power awareness and routing scheme. This combination is exactly the challenge that the routing scheme proposed in this thesis tries to address. Routing protocol lies on the network layer of the protocol stack taking care of routing the data supplied by the upper layer, while power management runs through all the layers.

However, those research efforts mentioned in Chapter 2 have mainly targeted isolated components of the network protocol stack, thereby ignoring important interdependencies among the layers of WSNs. Specifically, current WSN protocol design is largely based on a layered approach. In this model each layer in the protocol stack is designed and operated independently, with interfaces between layers that are static and independent of the individual network constraints and applications. This paradigm has greatly simplified network design and led to the scalable protocols. However, the inflexibility and sub-optimality of this paradigm to the WSN will result in poor overall performance, especially when energy is a constraint or stringent delay constrains. To meet these requirements a cross-layer protocol design that supports adaptiveness and optimization across multiple layers of the protocol stack is needed [18].

Typically, the cross-layer design indicates that information must be

exchanged across all layers in the protocol stack. This information exchange allows the protocols to adapt in a global manner to the application requirements and underlying network conditions. In addition, all protocol layers must be jointly optimized with respect to global system constraints and characteristics such as energy. However, the way to fulfill such a cross-layer design is not well suited for the WSN since the massive overhead associated with control messages will degrade the performance of WSN dramatically due to the limit resources of computation, memory and power on the tiny sensor. An alternative to cross-layer design is to incorporate the factors from different layers of the network model into the proposed protocol in the first place. This method will eliminate the overhead involved in the typical cross-layer design while gaining the benefits of it.

Using this principle, we propose a novel routing scheme in an attempt to fulfill the cross-layer design dedicated for the application-specific WSNs. While this work is inspired by the previous approach LEACH-C, it differs by designing the protocol with the integration of the cross-layer design principle which is proven to be a pertinent method to meet the challenges of power-constrained WSNs [18]. Specifically, the protocol in this thesis integrates the DAQs at the application layer and the clusters at network layer.

The novel clustering-based routing protocol is called Clustering-Based Expanding-Ring Routing Protocol (CBERRP), proposed to improve the effective lifetime of WSNs with a limited energy supply. Salient features of the proposed scheme over previous LEACH-based schemes include:

- 1) CBERRP is a two-level-hierarchy clustering-based routing protocol.
- 2) Unlike in BCDP [16], the number of clusters in CBERRP is able to follow the optimal solution for the number of clusters provided in LEACH [13].

- 3) The node that is closer to the center of a cluster has a higher priority to become the CH of the cluster, making the power consumption within level-I cluster minimum. This is based on the fact (proof provided in Sec 3.4) that for a uniformly distributed sensor cluster, the expected sum of the energy consumption is minimized when the CH locates at the center of the cluster.

The proposed CBERRP runs in the high-energy BS to set up two-level clusters among all the sensor nodes to deliver the sensor data to the BS. After the formation of the level-I clusters (which are as same as the clusters in LEACH or LEACH-C [13]), CBERRP groups the CHs into level-II clusters, called the chain in CBERRP, based on the rings that are concentric circles with the BS as the center. These rings look like a rainbow from the BS's point of view. Within each ring (a color arch in the rainbow), the CHs form a chain, and then one of the CHs in the chain will be determined as the chain leader which is designated to transmit the aggregated data to the BS on behalf of the entire chain. The CH chain, which is a new and super level cluster introduced in CBERRP, is composed of a set of CHs instead of normal sensor nodes. The chain is formed based on the distance from CH to the BS. The formation of the chains is in accordance with the rings that are concentric circles to the BS. Thus compared with PEGASIS [14], CBERRP alleviates "round trip" data path from a closer-to-BS CH to a further-to-BS CH when the chain leader is rotated to the further-to-BS CH.

3.2 System Model

This section describes the system model used in this work, and it includes three aspects: Network Architecture, Radio Model and Address

Architecture.

3.2.1 Network Architecture

One typical application of the WSN is the monitoring of a remote environment, which is also the kind application targeted in this work. Since the data sensed by one sensor node is often highly correlated with that from other nearby sensor nodes, the BS does not require all the (redundant) data; rather, the BS needs a high-level function of the data that describes the events occurring in the monitoring environment [13]. The clustering infrastructure takes advantage of this data aggregation (or data fusion) of the correlated data into a smaller set of message that maintains the effective information for transmission. In this work, we apply similar to those assumptions [13] about the wireless sensor node and the underlying network model with the following properties:

- 1) The studied WSN is homogenous, where all sensor nodes are identical in terms of functionality and structure.
- 2) The BS is located far away from the sensor nodes.
- 3) The sensor nodes are energy constrained with the same initial energy allocation.
- 4) The nodes are equipped with power control capabilities to vary their transmitted power.
- 5) Each node senses the environment at a fixed rate and always has data sent to the BS.
- 6) All sensor nodes are dual-stack in modulation, supporting both TDMA and CDMA.
- 7) The location information of the nodes is known to the BS.
- 8) The transmission of the MAC layer is reliable.
- 9) The wireless communication channels at the remote environment are

clear. Hence, only the path loss is considered in the simulation of this thesis.

It is clear that there are two key elements in the underlying WSN model: the sensor node and the BS. The sensor nodes are scattered in the region of interest, geographically grouped into clusters and capable of operating in two basic modes: the sensor mode and the CH mode. In the sensor mode, a sensor node performs sensing tasks and transmits the sensed data to the CH. In CH mode, a sensor node gathers data from other sensing nodes within its cluster, performs data fusion, and routes the data to the BS directly or through other CH nodes, if needed. The BS acts as a sink for the sensed data and is located far away from the wireless sensor nodes. The BS finally processes the received data and passes to the end user through wired networks or satellite communication. In addition to these data process and transmission, the BS also serves as a central controller to perform the key tasks of CBERRP including level-I cluster formation and level-II cluster formation among all the CHs.

3.2.2 Radio Model

A typical sensor node is made of four major components:

- 1) A data processor unit.
- 2) A micro-sensor.
- 3) A radio communication subsystem that consists of transmitter/receiver electronics, antenna, and an amplifier.
- 4) A power supply unit.

Although energy is dissipated in all of the first three components of a sensor node, this work mainly considers the energy dissipation associated with

the radio component since the core objective of this thesis is to develop an energy-efficient network layer protocol to improve the power conservation occurring in data forwarding of the whole WSN. In addition, energy dissipated during data aggregation in the CH nodes is also taken into account. In order to evaluate the energy dissipation, this work accepts the same radio model used in [13, 14] as shown in Figure 3.1.

Figure 3-1 Radio energy dissipation model

The transmit and receive energy costs for the transfer of a k -bit data message between two nodes separated by d meters are given by

$$E_T(k, d) = E_{elec} \times k + E_{amp}(d) \times k \quad (3.1)$$

$$E_R(k) = E_{elec} \times k \quad (3.2)$$

where $E_T(k, d)$ in equation (3.1) denotes the total energy dissipated in the transmitter of the source node, and $E_R(k)$ in equation (3.2) represents the energy cost incurred in the receiver. The parameters E_{elec} in equations (3.1) and (3.2) are the per bit energy dissipations for transmission and reception,

respectively. $E_{amp}(d)$ is the energy required by the transmit amplifier to maintain an acceptable signal-to-noise-ratio in order to transfer data messages reliably. Similar with [13, 14], both the free-space propagation model and the two-ray ground propagation model are adopted to approximate the path loss occurred in data transmission. Given a threshold transmission distance of d_0 , the free-space model is employed when $d \leq d_0$, and the multi-path model is applied when $d \geq d_0$. Using these two models, the energy required by the transmit amplifier $E_{amp}(d)$ is given by

$$E_{amp}(d) = \begin{cases} \varepsilon_{FS} \times d^2, & d < d_0; \\ \varepsilon_{MP} \times d^4, & d \geq d_0; \end{cases} \quad (3.3)$$

where ε_{FS} and ε_{MP} denote transmit amplifier parameters corresponding to the free-space and the multi-path models, respectively, and d_0 is the threshold distance given by

$$d_0 = \sqrt{\varepsilon_{FS} / \varepsilon_{MP}} \quad (3.4)$$

A set of parameters used in [13] for all experiments throughout this work are: $E_{elec} = 50 \text{ nJ/bit}$, $\varepsilon_{FS} = 10 \text{ pJ/b/m}^2$, and $\varepsilon_{MP} = 0.0013 \text{ pJ/b/m}^4$. Moreover, the energy cost for data aggregation is set as $E_{DA} = 5 \text{ nJ/b/message}$ and all sensor nodes are deployed with an initial energy of $2J$.

3.2.3 Communication and Address Architectures

Communication Architecture: CBERRP classifies the communications in the WSN into three classes:

- 1) Level-I-Cluster communication that is between sensor nodes and CH.
- 2) Level-II-Cluster communication that is between CHs in the same chain.
- 3) Long Distance Communication that is between chain leaders and the BS.

Note that data communications in the level-I clusters are direct, while data communications in the level-II cluster are multi-hop forwarding among the CHs with the chain leader as the destination. Unlike other approaches, the integration of single-hop and multi-hop routing in CBERRP reaps the benefits from the two mechanisms. Single-hop routing is used for the short distance communication in the level-I cluster to avoid the collision and the long latency; while multi-hop routing is suited to the medium distance communication where power consumption is significant if the single-hop routing is used.

Communication utilizing the CDMA modulation technique in a cluster needs to address the radio interference caused by the transmission in the neighboring clusters [13]. In CBERRP, each cluster is assigned a pseudo code to distinguish the data transmission inside the home cluster from the transmission in other clusters. Furthermore, once the data gathering process is complete, the CH uses another pseudo code dedicated to the chain to forward data to the chain leader or the BS. In addition, TDMA is incorporated with CDMA to avoid transmission collision within a cluster and a chain. The schedules of the time slots in TDMA are determined at the BS.

Address Architecture: After having an insight on the WSN network model that is used in this thesis, it is clear that the traffic pattern on this WSN model is “many-to-one”. That is, the data traffic in the WSNs flows in one direction: from all sensor nodes to the BS. This unique feature that differs from many other computer networks, like MANETs and Internet, implicates the

difference on the network layer's address scheme for WSNs.

In most distributed systems, naming of sensor nodes for low-level (Layer 3 in the OSI network model) communication leverages topological location (such as node addresses) and is independent of any application [19]. An example of this is the Internet where IP addresses provide the low-level names suitable for routing. IP addresses are assigned topologically, this topological assignment is essential for scaling the routing system. Meanwhile, higher-level (Level Three Up), location-independent naming and communication in this kind of network are built upon these low-level communications through mapping the higher-level names to topological names, the low-level naming. For example, DNS provides a mapping of text-based hierarchical node name to an IP address. However, as an emerging class of distributed systems, the low-level communication of the WSNs does not rely on network topological location. Rather, it is based on attributes that are external to the network topology and relevant to the application [19]. Simply put, the application of the WSNs will not know the topological information about the specific sensor nodes before the application initiates. By contrast, the topological information of those sensor nodes of interest might be the exact information that is required by the application.

Work in [19] demonstrates that there exists a simple architecture (The attribute-based naming scheme with flexible matching rules grounded in a shared framework of attributes) that uses topology-independent naming for low-level communications to achieve flexible, yet highly energy efficient application designs. Such an approach is also suitable for the WSN model studied in this thesis. Furthermore, unlike the sensing applications discussed in [19], the WSN applications targeted in this work are taking the WSN as a whole to carry out the sensing tasks. Thus, all sensor nodes will act exactly same way corresponding to the sensing demands from the BS. There is no need of the

matching rules to filter out those irrelevant sensor nodes for the sensing tasks. Therefore, this work can eliminate the network layer's address assignment for the WSN. Such an approach to address or naming provides two kinds of efficiencies. First, it eliminates the overhead of communication required for resolving name bindings. Second, it enables Data Aggregation inside the network, allowing data reduction near where data is generated. As a result, the upper layer data in this work could be directly encapsulated by the MAC layer header, skipping the encapsulation of the network layer.

3.3 Definitions

Before going into the details of CBERRP, some terms used in the operation of CBERRP are defined as following:

- 1) Cluster: In general, a cluster is a group of objects with similar attributes. The cluster in this work is a group of sensor nodes classified into the same category with respect to the geography. That is, the distance of the sensor node away from the CHs.
- 2) Cluster Head: Cluster head is a sensor node that not only senses the phenomena, but also collects the data from other members of its home cluster and performs data aggregation. Note that each sensor node takes turn to be CH in order to distribute power dissipation evenly throughout the whole WSN.
- 3) Ring: Ring is a term which describes the virtual topology of sensor field. Each ring is an arch strip that is the part, covering the sensor field, of the concentric circle with the BS as the center.
- 4) Chain: Chain is used to describe the topology formed by the CHs. All

the CHs within the same ring will form a chain, thus, the number of rings determines the number of chains in CBERRP. Chain is also referred to as the second level cluster.

- 5) Chain leader: Chain leader is a designated CH responsible for delivering the data back to the BS on behalf of the entire chain. Thus, the chain leader collects the data not only from its home cluster but also from other CHs of its home chain. Similar to the fact that each sensor node has chance to be a CH, each CH has chance to be a chain leader.
- 6) Data fusion: In this work, data fusion and data aggregation are interchangeably used. Techniques of data aggregation are used to combine several correlated data signals into a smaller set of information that maintains the effective data (i.e., the information content) of the original signals [19]. For example, the appropriate CH will aggregate K data packets generated from K sensor nodes of one cluster into one packet.
- 7) Round: The whole lifetime of WSN in CBERRP is divided into rounds, and one round is equivalent to a period. The end user can determine the duration of one round. Following the LEACH, it is also 20 seconds in this work. In this sense, the number of rounds the WSN lasts indicates the lifetime of the WSN. Meanwhile, it is the round operation that makes the rotation of the CHs and chain leaders possible among all sensor nodes. Since each time one round finishes, a new set of CHs and a new set of chain leaders will be selected for the upcoming new round. Therefore, the power dissipation in the whole life of the WSN is distributed evenly among all the sensor nodes.
- 8) Frame: This term describes the structure of the data transferred in the wireless channel. Frame is composed of the TDMA slots and is the

basic component of the round. The TDMA time slots are assigned for communications for each sensor node in the cluster and each CH in the chain. Within each frame, a sensor node has a designated slot for transmitting data to its CH. In addition, each CH in the chain is also assigned one time slot for transmitting the aggregated data of its cluster to the chain leader. Thus, at the end of one frame, the BS will receive an aggregated packet from each of the CHs. The number of frames that can be transmitted in one round, N_f , is determined by three factors: the number of bits in a frame (B_f), the duration of the round (T_r) and the wireless channel throughput bandwidth (BW), and is given by the following equation:

$$N_f = \frac{BW \times T_r}{B_f} \quad (3.5)$$

Note that the number of bits in a frame is the product of the length of the packet (L_p) and the number of time slots in the frame (N_s). Equation (3.5) can be rewritten to

$$N_f = \frac{BW \times T_r}{L_p \times N_s} \quad (3.6)$$

Figure 3.2 shows the frame structure in the operation of CBERRP corresponding to the time line.

Figure 3-2 The frame structure in CBERRP

- 9) Wireless Channel Throughput Bandwidth: This term can also be called the fundamental capacity of a wireless channel. It dictates the maximum data rate that can be transmitted over the channel with arbitrarily small probability of error.

3.4 Operation of CBERRP

CBERRP is a hierarchical WSN routing protocol that utilizes the BS as a central controller to perform most of the control tasks. Therefore, there is no need for sensor nodes to exchange the fancy routing protocol messages, thus reducing CBERRP workload and improving its energy efficiency. CBERRP operates in two major phases: Initialization Phase and Data Transmission Phase. The second phase is further divided into the Setup sub-phase and the Data Delivery sub-phase. In this section, the details of these phases are described.

3.4.1 Initialization Phase

The Initialization Phase accomplishes three activities. The first step in this phase is to partition the sensing area of WSN into a number of rings that

are concentric circles with the BS as the center. These rings are the basis where the chains are constructed. The second activity is to calculate the optimal number of the level-I clusters by following the formula in [13], given both the size of the sensor area and the number of sensor nodes in the WSN. In [13], a formula is derived to calculate the optimum number of the clusters, given that N sensor nodes are randomly distributed in a $K \times K$ region, to minimize the energy dissipation. Thirdly, CBERRP will form a hierarchical topology of the WSN with the combination of clusters and chains. Afterwards, the whole sensor region obtains a logical grid view, and each grid is a cluster region. For example, Figure 3.3 illustrates a WSN's topology with six clusters and two rings.

Figure 3-3 An example of ring topology in CBERRP

CBERRP will then calculate the location of the center point for each grid. This location is referred to as a reference point (RP). The RP will be used in the data transmission phase for CH selection. It is always a challenging issue for the clustering-based algorithm to find an optimal subset of sensor nodes to be CHs in terms of power consumption. Many schemes proposed in the literature so far have tried to address this problem. In [13], a simulated annealing algorithm is used to solve the NP-hard problem of finding k optimal clusters is used. Other schemes choose the CHs or chain leaders based on other considerations rather than the power consumption such as the random probability [21] and load-balance [16]. However, these schemes are either too complicated or suboptimal in terms of power consumption. By using the clustering architecture, CBERRP can utilize the cluster formation in order to minimize the power dissipation in the WSN. Thus, how to form the cluster is also a key issue in CBERRP. Ideally, the clusters are expected to have following properties: the shape of the cluster is regular; the CHs are distributed evenly throughout the WSN and the sum of power consumption on the data communications in the cluster could be optimized. It is encouraging that CBERRP with the help of the RP can meet these challenges desirably with a small amount of computation.

By choosing the center of each grid as the RP, we gain two advantages. First, using RPs can make the distribution of the CHs as uniform as possible throughout the whole WSN. Second, taking the center of the grid as the RP makes the expectation of the sum of the square distance between sensor nodes and CH minimum. Since this sum is approximately proportional to the energy consumption required for the data communications between the sensing nodes and the CH [13], the power consumption during the data communication of the Level-I cluster will reach the optimal minimum value. It is proved as following.

If it can be proved that the sum of the square distance between all the sensor nodes and the RP is minimal when compared with the sum of the square distance between all the sensor nodes and any other sensor node rather than the RP, this proof then indicates choosing the sensor node at RP as the CH will minimize the power dissipation in the cluster since the power consumption on the data communication between two sensor nodes is proportional to the square distance between them. Now the proof is given as following.

In our proof, it is assumed that N sensor nodes are uniformly distributed in a cluster of a square area (square region is applied in the analysis for simplicity) as shown in Figure 3.4.

Figure 3-4 A generic cluster

The j th sensor node is located at the center with coordinates $(0, 0)$. First we calculate the expectation of the sum square distance between the i th sensor node ($i=1 \dots N, i \neq j$) and the j th sensor node, given as

$$S_c = E \left[\sum_{i=1, i \neq j}^N (x_i^2 + y_i^2) \right] \quad (3.7)$$

where (x_i, y_i) is the coordinates of the i th sensor node. Now we randomly choose a sensor node rather than the j th sensor node, namely sensor node n th ($n \neq j$), with coordinates (x_n, y_n) , as the CH. The expectation of sum square distance is given as

$$S_n = E \left[x_n^2 + y_n^2 + \sum_{i=1, i \neq j, i \neq n}^N [(x_i - x_n)^2 + (y_i - y_n)^2] \right] \quad (3.8)$$

where $x_n^2 + y_n^2$ is the square distance of the j th sensor node to the n th sensor node. From (3.7), we have

$$S_c = E \left[x_n^2 + y_n^2 + \sum_{i=1, i \neq j, i \neq n}^N (x_i^2 + y_i^2) \right] \quad (3.9)$$

By manipulating the expected summation in (3.8), S_n can be written as

$$S_n = E[x_n^2 + y_n^2] + E \left[\sum_{i=1, i \neq j, i \neq n}^N 2E[X^2] - 2E^2[X] + 2E[Y^2] - 2E^2[Y] \right] \quad (3.10)$$

Considering the fact that $E[X] = 0$ and $E[Y] = 0$, S_n can be written as

$$S_n = E \left[x_n^2 + y_n^2 + 2 \sum_{i=1, i \neq j, i \neq n}^N (x_i^2 + y_i^2) \right] \quad (3.11)$$

From (3.9) and (3.11), we can readily have

$$S_c < S_n \quad (3.12)$$

As a result, the RP can be thought as the preferred location of the CH for each cluster. However, it is not realistic for a sensor node to be located at the exact RP position in a real deployment of the WSN. Then, the sensor node that is nearest to the RP can take on the role. The proof for this case is given below.

The same diagram (Figure 3.4) is used for the proof. Let sensor node 1, (x_1, y_1) be the point that is the closest to the cluster center $(0, 0)$. Hence, we have

$$x_1^2 + y_1^2 < x_n^2 + y_n^2, \quad 1 < n \leq N. \quad (3.13)$$

The expectation of the sum square distance between the i th sensor nodes ($i=2, \dots, N$) and the 1st sensor node is:

$$S_1 = E \left[\sum_{i=2}^N \left[(x_i - x_1)^2 + (y_i - y_1)^2 \right] \right]. \quad (3.14)$$

Now we randomly choose a sensor node rather than the 1st sensor node, namely node n ($n \neq 1$), with coordinates (x_n, y_n) , as the CH. The expectation of the sum square distance is given as

$$S_n = E \left[\sum_{i=1, i \neq n}^N (x_i - x_n)^2 + (y_i - y_n)^2 \right]. \quad (3.15)$$

By manipulating (3.14) and (3.15) with the fact $E[X] = 0$ and $E[Y] = 0$, we have

following two equations, respectively:

$$S_1 = \sum_{i=2}^N E(x_i^2 + y_i^2) + (N-1)E(x_1^2 + y_1^2). \quad (3.16)$$

$$S_n = \sum_{i=1, i \neq n}^N E(x_i^2 + y_i^2) + (N-1)E(x_n^2 + y_n^2). \quad (3.17)$$

and then one step further:

$$S_1 = \sum_{i=1}^N E(x_i^2 + y_i^2) + (N-2)E(x_1^2 + y_1^2). \quad (3.18)$$

$$S_n = \sum_{i=1}^N E(x_i^2 + y_i^2) + (N-2)E(x_n^2 + y_n^2). \quad (3.19)$$

Based on the prerequisite of (3.13), we have

$$S_1 < S_n, \quad 1 < n \leq N. \quad (3.20)$$

Thus, the center point of the grid is always an ideal RP for the CH.

Moreover, the clusters' formation is based on the locations of the RPs by using this method, resulting in another important feature in CBERRP: the integration of the physical topology and cluster formation. This feature enhances the performance of CBERRP when the topology is well engineered (more analysis will be given in the simulation section).

With the necessary topology information, CBERRP is able to assign

each sensor node in WSN into appropriate cluster and data communication schedule, which is done in the Data Transmission Phase.

3.4.2 Data Transmission Phase

The operation of Data Transmission Phase in CBERRP iterates by rounds. Each round begins with a Setup sub-phase followed by a Data Delivery sub-phase. In Setup sub-phase the clusters and chains are organized and the schedules for data transmissions are created, and in the Data Delivery sub-phase the data are transferred from the sensor nodes to the CH, and then hopped to the chain leader and the BS.

Setup Sub-Phase: The main tasks in the Setup sub-phase are CH selection, chain formation and schedule creation. At the beginning of the Setup sub-phase, the BS receives information on the current energy status and location information from all the nodes in the WSN. Only sensor nodes with the energy high enough to communicate directly with the BS and having not been CH in the previous rounds can be the candidates for the CH in the current round. In order to ensure that all sensor nodes are CHs the same number of times, a flag is used to mark whether a sensor node has been CH or not. If all the sensor nodes have been the CHs once, these flags will be reset and the process of CH selection continues. This strategy keeps the random rotation of the CHs throughout the WSN to achieve the fairness among the sensor nodes on the selection of CHs, then further achieve the even power dissipation among all the sensor nodes.

The CH selection in CBERRP is based on the following sorting and searching algorithm. The BS sorts all the sensor nodes based on the distance from each sensor node to those RPs that are obtained in the initialization phase. The sensor node nearest to each RP of a cluster is preferred as the CH for the

cluster. If the nearest sensor node either has been the CH in the previous rounds or without sufficient power, then the second nearest one to the RP is considered. The procedure continues until a qualified sensor node is found. The Figure 3.5 shows the logic of this process.

After the selection of the CHs, the BS forms the chains by following the rule that the CHs falling in the same ring form a chain. The selection of the chain leader is based on the locations of the CHs. Specifically, the CH with the smallest distance to the BS is selected as the chain leader. This chain leader selection achieves the minimum power consumption in the Data Delivery sub-phase without loss the random rotation of chain leaders. It is clear that taking the CH closest to the BS in the chain as the chain leader makes the sum of the squared distance in the level-II cluster minimal. Meanwhile, the location of this CH is random, either. In other words, each CH has the chance to be closer to the BS than others in the same chain, which guarantees the randomness of the chain leaders' selection. It is this feature that makes CBERRP attractive since many other proposed routing protocols in the literature are not able to make the balance between the rotation of the chain leaders and the optimum of power dissipation.

It is also clear that the clusters in CBERRP have such characters as following. The RPs and Rings are fixed for a certain initialization setup. As the time passing by, the CHs change round by round. Consequently, the level-I clusters also change the cluster associations, which indicate the membership between a certain CH and a certain sensor node. Meanwhile, as the CH moves away from the nearest node to the RP, the power consumption within the cluster will not be minimal any longer. However, this more energy cost trades off the fairness of the power dissipation among all sensor nodes in the cluster. As a result, the power is evenly distributed throughout the whole network to prolong the lifetime of the WSN in the long run.

Figure 3-5 The selection of CHs in CBERRP

The BS will advertise the resulting topology information including cluster's formation, CHs and chains to all sensor nodes through broadcast. Thus, by letting the BS carry on most of the control tasks of the routing protocol, CBERRP minimizes the energy consumption of running the routing protocol in the WSN. Along with the topology information broadcasted to the sensor nodes are the TDMA time slot schedules, one schedule for one cluster. Hence, each schedule specifies the slots used within each level-I cluster and each level-II cluster (chain). The sensor nodes deliver the sensed data to the BS in the Data Delivery sub-phase according to these schedules.

Table 3.1 demonstrates what the schedule might typically look like for one sensor node, for example, the CH3 in the chain topology shown in Figure 3.6.

Figure 3-6 A chain with four CHs

First, the "ON" at the right side of the "TDMA slot" means wake or sleep of the sensor node; T (True) stands for wake and F (False) for sleep. Because the CH3 is the CH, it will be awake all the time during the period of the level-I cluster communications in order to receive the sensed data from the sensor nodes in its home cluster. It is assumed that the size of CH3's cluster is 6

(including it) in this example, thus, the TDMA slots from 1 to 5 are the TDMA schedule of the level-I communications, and then the rest of the slots is the TDMA schedule of the level-II communications for sensor node CH3.

TDMA slot	ON	CDMA code	Destination	No. of iterations
1	T	pl-3	rx	21
2	T	pl-3	rx	
3	T	pl-3	rx	
4	T	pl-3	rx	
5	T	pl-3	rx	
6	T	pll-1	rx	
7	T	pll-1	CH2	
8	F	pll-1	-	

Table 3.1 The TDMA schedule of CH3

Here, the number of slots for the chain is 3 as the maximum number of hops to the chain leader from a CH is 2, and then plus the final hop to the BS. In the slot 6, CH3 will receive the data from the CH4. At this same time slot, CH1 can also transmit data to CH2 if the distances between CH1 and CH3, CH2 and CH4 are large enough to avoid the transmission collision. Otherwise, there should be one more time slot reserved for the transmission between CH1 and CH2.

Next, CH3 will send this data and its own data to the chain leader, CH2, during the slot 7. The slot 8 is reserved for CH2 to deliver all the data from the chain to the BS. In one extreme case, the role of the chain leader will keep the CH2 awake for the whole duration of the level-II communications. Certainly, it is the BS that works out the specific slot numbers for both parts in the schedule

according to the setup of clusters and chains. The number of the level-I TDMA slots is up to the maximum level-I cluster size out of the same chain. It is easy to derive that there may be more slots with False value in the field of “ON” for some other sensor nodes. Another extreme case is the normal sensor node that is not the CH. The schedule table for this kind of sensor nodes will be all F but one T in the “ON” field.

The field of “CDMA code” indicates the pseudo code used in the CDMA modulation for the corresponding time slot. Typically, the number of the pseudo codes used in CBERRP equals to the sum of the number of the level-I and level-II clusters since each level-I or level-II cluster uses a particular pseudo code for itself. For example, if there are 6 level-I clusters and 2 level-II clusters in the WSN, the set of pseudo codes can be, namely, pl-1 for cluster 1, pl-2 for cluster 2... pl-6 for cluster 6, and pll-1 for chain 1 and pll-2 for chain 2. In Table 3.1, we assume sensor node CH3 is located in cluster 3 and ring 1, thus, it will use the pseudo codes of pl-3 and pll-1, respectively. This assignment guarantees the elimination of the interference between all the concurrent transmissions.

The next hop that the sensor node will forward the sensed data to is specified in the field of “Destination”. As a CH, CH3 is expected to receive the data only for the level-I cluster communications, hence the rx means just waiting for the data arrival. While for the level-II cluster communications, the value for this field should be the real address of the next hop towards the BS. It is CH2 in the example that is the next hop to the BS for sensor node CH3. Note that the address of the BS has been known by every sensor node after the Initialization Phase.

The field “No. of iterations” tells the repeat number of the usage of this schedule. Since the operation about the Data Transmission Phase is counted by round, when a round is finished, a new schedule will be setup and advertised

by the BS. By knowing this value, each sensor node will know where to stop the old schedule and wait for the new schedule, and then move into the operation of the new round. From the definition of Frame, we know this number is exact the number of frames in a round. In this example, one data packet is transmitted for each time slot from 1 to 6; two aggregated packets are transmitted at time slot 7 and three at time slot 8 since CH3 and CH2 do not do data aggregation over the packets in the chain. Thus total number of packets in one frame is 11. In addition, each packet is 525 bytes long and the channel throughput bandwidth is 1 Mbps, it can be derived that the number of iterations for such an assignment is 21.

In addition, integrating the level-II cluster's schedule and the level-I cluster's schedule together into one schedule assignment addresses another great challenge not well overcome by other hierarchical clustering-based routing protocols, such as [16] and [21]. The issue is the synchronization of the communications associated with the level-I cluster routing and the CH-to-CH routing in the situation where the data aggregation happens. For example, in [16] a minimum spanning tree is deployed on all the CHs to route and forward the data back to the BS. As a result, during the process of data forwarding, it is possible for data sensed from different frame time to be aggregated together on a certain CH due to the latency of data transmission. This will introduce severe problems for some certain sensor applications. For instance, one of the sensor applications could request the extent of the humidity over a certain area. Then all the sensor nodes start to sense over the area around them. After the sensed data is collected and aggregated by each CH, the aggregated data will be passed on along the path of CH-to-CH towards the BS. At each hop, the data aggregation happens again to reduce the raw data to be received by the BS. Hence, it is not surprising that the data sensed some substantial time ago at the further CH will be mixed with the data sensed at most recent time when it

arrives at the nearer CH, resulting in very low Data Aggregation Quality (DAQ). In the worst case, it may even lead to incorrect information at the end user.

An alternative way to avoid the above problem is to divide the operation of the routing protocol into two separate time phases. The first phase is for the level-I cluster communication, while in the second phase, the data is forwarded among CHs when all the communications inside level-I clusters are stopped. However, this method will add much more latency to the data transmission in addition to the control messages exchanged between CHs. The same issue also exists in CBERRP in that it has two levels' clusters. Therefore, how to synchronize the communications associated with level-I and level-II clusters is the issue that should be addressed in order to guarantee only the data sensed from the same frame time to be aggregated together and then forwarded to the BS correctly. Integrating the two level's transmissions into one TDMA schedule is a desirable way to address this issue because of the inherent synchronization feature of TDMA technique.

Data Delivery sub-phase: The Data Delivery sub-phase consists of three major activities: data gathering, data aggregating and data forwarding.

When the sensor nodes receive the schedule information, they will sleep and wake up based on the schedule assigned to them to transmit the sensed data to its own CH. Not only will the transmission collision be avoided, but also the power can be saved through this schedule. The CH in turn aggregates the data and forwards the aggregated data to the chain leader hop by hop along with the path of the chain based on its schedule. Multi-hop routing used for level-II-Cluster communication is for the sake of power conservation because typically the distance between CH and chain leader is very long. Since large numbers of sensor nodes are densely deployed, neighbor nodes might be quite close to each other. Thus, multi-hop communication in WSNs is expected to

consume less power than the single hop communication. Furthermore, the transmission power levels can be kept low, which is highly desired in covert operations. Multi-hop communication can also effectively overcome some of the signal propagation effects experienced in long-distance wireless communication. After that, the chain leader delivers the data to the BS. The communications from different chain leaders to the BS can be simultaneous and independent; however, they are synchronized by the round. Since sensor nodes are geographically grouped into clusters, the transmissions in the level-I cluster consume minimal energy due to small spatial separations between the CH and the sensor nodes. Compared with multi-hop routing, the single-hop transmission for the Level-I-Cluster communication makes CBERRP less latency on the data delivery. As a result, the hybrid routing method of single-hop and multi-hop benefits CBERRP for both the power efficiency and the low latency. Once the data from all sensor nodes have been received, the CH performs data aggregation on the collected data, and reduces the amount of raw data that needs to be sent to the BS. The aggregated data are then routed to the BS via the chain path.

Moreover, since the number of the chain leaders is much less than the number of the CHs, the interference for the Long Distance Communications decreases dramatically compared with the situations in LEACH [13], where all CHs communicates directly with the BS. Also in each round, unlike other routing protocols, which designate only sensor node, CH or chain leader, which is responsible for transmitting data towards the BS, CBERRP utilizes several chain leaders at one time. Intuitively, it seems worse by using more than one designated sensor node in each round to transmit data to the BS as more energy consumption incurs. However, in a long run, the whole performance of the network will be improved by preventing all data traffic from converging at a single sensor node in each round. Meanwhile, the latency can be decreased

significantly by utilizing multiple designated sensor nodes compared with only one sensor node utilized in each round, especially in a large scale WSN.

Chapter 4

Simulation and Analysis

4.1 Simulation

Like in the table 4.1, for our simulations, we use a 121-node (N) network where sensor nodes are randomly distributed in a $100\text{ m} \times 100\text{ m}$ (M) region from $(0,0)$ to $(100,100)$ with the BS coordinate (BS) $(50,200)$.

Energy		Topology		Operation		Message	
E_{elect}	50 nJ/bit	N	121	round	20 s	BW	1 Mbps
ϵ_{fs}	10 pJ/b/m ²	M	10 ⁴ m ²	--	--	Payload	500 bytes
ϵ_{mp}	0.0013 pJ/b/m ²	BS	(50,200)	--	--	Header	25 bytes
E_{da}	5 nJ/bit/message	K	6	--	--	--	--
Initial E	2 J	R	2	--	--	--	--

Table 4.1 The parameter table in the simulation

Some other parameters similar to those used in [13] are: the throughput bandwidth of the channel (BW) is set to 1 Mbps, the payload of the data packet is 500 bytes long, and the packet header (Header) for each type of packet is 25 bytes long. The duration of round is 20 seconds. We also assume that the aggregated data from a given CH does not perform further aggregation as it hops along the chain path. In addition, the number of rings (R) equals 2 with equal width and the number of clusters (K) is 6 which is the optimal number

derived from the formula in [13] for the network setup in this work. The electronic energy (E_{elec}) for both transmission and receive is 50 nJ/bit, the transmission amplifier energy is 10 pJ/b/m² for free space mode (ϵ_{FS}) and 0.0013 pJ/b/m⁴ for multiple path mode (ϵ_{MP}), respectively. Moreover, the energy cost for data aggregation (E_{DA}) is set as 5 nJ/b/message and all sensor nodes are deployed with an initial energy (Initial E) of 2J.

To obtain the performance of CBERRP, we simulate 30 different network topologies in the MatLab and compare the average performance with that of LEACH and LEACH-C [13] in terms of the lifetime or the number of rounds, the average power dissipation and the throughput of the WSN.

(a) Average energy dissipation vs. number of rounds.

(b) Vestigial Energy after the operation of WSN.

Figure 4-1 Energy dissipation and vestigial energy

Figure 4.1(a) shows the average energy dissipation of CBERRP vs. number of rounds. The average energy dissipation calculates the power consumption in each round for both communication and data aggregation. This

graph clearly shows that CBERRP achieves significant improvement in reducing average energy dissipation over LEACH and LEACH-C. It also shows that the energy consumptions of LEACH and LEACH-C are very similar. This is due to the same nature of these two schemes although LEACH-C can maintain the optimal number of clusters, producing better formation of clusters. This observation is consistent with the explanations in [13] that the energy performance will not be significantly different between LEACH and LEACH-C. In average, CBERRP exhibits a reduction in energy consumption of more than 50% over LEACH and LEACH-C. This is mainly because CBERRP utilizes a sub-set of the CHs, the chain leaders, to forward the data to the BS, instead of all the CHs are used to communicate with the BS like in LEACH and LEACH-C.

The power conservation in CBERRP is also in evidence as shown in Figure 4.1(b) where the *vestigial energy* in the sensor nodes running CBERRP is the highest. The *vestigial energy* is defined as the remaining energy from all the sensor nodes when there is no single sensor node in the WSN with high enough energy to communicate to the BS directly. The operation of the WSN comes to a halt. At this moment, we compute the sum of energy in all the sensor nodes in which some power still remains. This can verify the efficiency of power dissipation of a certain algorithm. CBERRP presents a better performance over the other two by 266 percent and 500 percent, respectively. The beauty about this is that all the energy saved by CBERRP can be used by other components of the sensor nodes, for example, the sensing unit or data processing, thus making the WSN more power-effective.

The main idea of CBERRP is the chain formation where the number of chain leaders communicating with the BS can be well controlled. The advantages gained from this scheme are threefold. First, compared with LEACH-C, not all CHs communicate directly to the BS in each round resulting in less power consumption in the data delivery phase due to both fewer number of

long distance (from CHs to the BS) transmissions and less interference coming from simultaneous communications between multiple CHs and the BS. Second, CBERRP decreases the average number of hops the data has to undergo before it arrives at the BS, compared to the algorithm that runs multi-hop routing protocol over all the CHs, such as the algorithm in [23]. Third, it is not surprising to see such a scenario in the WSN that the sensed data goes back and forth along the path in the course of data delivery to the BS from the original sensing node. This is due to the suboptimal shortest path decision made by most of the WSN routing protocols, in which the power conservation is the single highest priority metric of interest. Moreover, the necessity of the rotation of CHs among all the sensor nodes does not always utilize the nearest node to the BS as the CHs, thus more power is “wasted” on the way delivering the data to the BS, like the schemes proposed in [16] and [21].

CBERRP remedies this in some extent by the ring architecture where the BS is the center of each ring. That is, the maximum range that the sensed data can go back and forth is limited by the width of the ring. Hence the energy will be saved since the data coming from CH other than the chain leader will not suffer a long round trip before it is forwarded to the BS through the chain leader. This is exactly another advantage of the ring architecture. Therefore, in CBERRP, the desirable balance between minimizing the power consumption and keeping chain leaders randomly rotating among all the CHs can be achieved.

The improvement gained by CBERRP is further exemplified by the system lifetime shown in Figure 4.2. Since each round is fixed at 20 seconds in the simulation, the lifetime of the whole network can be worked out by the product of the number of rounds and the 20 seconds. The curve of CBERRP falls much more gradually to the X-axis than those of LEACH and LEACH-C. The number of the rounds, which can be interpreted as the system lifetime, is

near 80 rounds for CBERRP, while LEACH and LEACH-C are 33 rounds. The improvement of the lifetime of CBERRP over LEACH and LEACH-C is near to 200 percent.

Figure 4-2 System lifetime

In addition, in our simulation, we take into account the power consumption associated with the overhead of each algorithm; the BS is also located further away from the WSN than the RF distance threshold (r_0). As a result, some sensor nodes will be dead after the first several rounds' operations due to lack of power.

Figure 4-3 Cumulated data signals received at the BS vs. number of rounds

Next, we analyze the number of aggregated-data signals received by the BS in Figure 4.3. The aggregated data signals, which can also be interpreted as the number of aggregated packets received at the BS, are counted in CBERRP in such a way: if the sensed packet received by the CH are equal to or more than half of the cluster size, the number of aggregated data signals received by the BS is two for one frame; otherwise, the number of aggregated data signals is one for one frame. Thus, this measurement is affected by the data aggregation.

It clearly illustrates the effectiveness of CBERRP in delivering significantly more aggregated-data signals than its counterparts. This results from both the less power consumption in each round and the longer system lifetime. Besides the measure of the aggregated data signals, it is also

interesting to observe the absolute signals sensed by the sensor nodes during the lifetime of the WSN. This absolute signal can also be interpreted as the number of non-aggregated packets sensed by the sensor nodes. The number of aggregated data signals received at the BS is only a relative quantity that highly depends on the aggregation algorithm. However, the absolute signals can indicate the capability of the WSN of gathering the phenomena signals regardless of which kind of data aggregation scheme is used. Hence, these two measures are mainly different at whether the data aggregation happens. The first one, which highly relies on the data aggregation algorithm, can be named *relative throughput*; while the later, which has nothing to do with data aggregation, can be called *absolute throughput*. The performance of *absolute throughput* is shown in Figure 4.4.

Figure 4-4 Cumulated data signals sensed by the sensors vs. number of rounds

Intuitively, when each sensor node has sufficient power to participate in the sensing application, the totally number of data signals sensed by the sensor nodes should be roughly same for any routing protocol. The curves in Figure 4.4 fit in with what is predicted that the number of signals sensed by the sensor nodes at the beginning period is the same for all kinds of routing schemes because this quantity has nothing to do with the data aggregation, which is significantly diversified for different routing protocols. When the number of dead sensor nodes reaches a certain percentage, the *absolute throughput* diverges for the different schemes. CBERRP gains more than 60% improvement over the other two schemes. Another point of interest here is nearly the same simulation performance of LEACH and LEACH-C. Compared with LEACH, LEACH-C has no significant change in terms of the power dissipation. However, due to its more regular formation of the clusters than that of LEACH, the *relative throughput* in LEACH-C is better, which is showed in Figure 4.2. No more signals are received at the BS at about 30th round for LEACH and LEACH-C because none of the sensor nodes in the WSN has sufficient power to deliver the data to the BS. It is also apparent that in the last several rounds of these two schemes, the growth of the signals is almost negligible. This results from the fact that when about 75% of the sensor nodes died (according to the turning points in the plots both Figure 4.2 and Figure 4.3), the sensing capability of the WSN decreases dramatically for LEACH and LEACH-C. In contrast, the performance of CBERRP is more desirable in terms of both system lifetime and the effective transmission.

Figure 4-5 Number of data signals received at BS vs. energy consumption

Figure 4-6 Data signals sensed by sensors vs. energy consumption

The efficiency of energy consumption in CBERRP also can be verified from Figure 4.5 and Figure 4.6. Figure 4.5 shows the improvement of CBERRP over LEACH and LEACH-C on the *relative throughput* vs. energy consumption. CBERRP offers the improvement in aggregated data signals delivered per unit energy by a factor of 60% and 40% over LEACH and LEACH-C, respectively. Figure 4.6 shows the performance of the *absolute throughput* sensed by the sensors vs. energy consumption about three schemes. It verifies that the CBERRP gains a significant advantage with respect to power dissipation over the other two.

In the case of the WSN with deterministic topologies mentioned in Section 4.1, the CBERRP shows a stable and overwhelming improvement over the other two protocols. We simulate the engineered topology by deterministically distributing 121 sensor nodes in a $100\text{ m} \times 100\text{ m}$ region from $(10, 10)$ to $(110, 110)$ with the BS coordinate $(60, 210)$ as shown in Figure 4.7.

Figure 4-7 An engineered topology

(a) Data signals sensed by sensor vs. energy consumption.

(b) Data signals sensed by sensor vs. energy consumption.

Figure 4-8 Topology Factor

LEACH and LEACH-C both present the similar performance when the network topology of the WSN changes to the deterministic topology from the randomly distributed topology, as shown in Figure 4.8. This is because LEACH and LEACH-C do not take into account the factor of the physical topology into their schemes. However, as shown in Figure 4.9, it is very clear that the performance of CBERRP is improved significantly over that of its randomly distributed topology by around 20 percent, since the selection of CHs in CBERRP is influenced by the RPs that are associated with the physical topology. Hence, when the physical topology of the WSN can be engineered, like in Figure 4.7, the cluster, the chain and the distance between two sensor nodes can all be optimized, which results in a better performance.

Figure 4-9 Data signals sensed by sensor vs. energy consumption

The longer lifetime of WSNs is gained in CBERRP by trading off the transmission delay and channel throughput. For example, the aggregated data generated by one CH in a chain needs to go through multiple hops to reach the BS. Unlike in LEACH-C, the aggregated data will directly be forwarded to the BS from the CH. Thus, the transmission delay is increased.

In addition, it is normal in CBERRP that the sizes of the level-I clusters in a chain are not exact same. As a result, the frame size for each level-I cluster will be different, either. Since the TDMA time slot assignment is based on the frame size, the different frame sizes will result in the different number of TDMA time slots for each level-I cluster. Hence, the CH with smaller number of TDMA time slots must wait the offset period to the largest size cluster for going into next round. This waiting also makes the appropriate cluster stop data sensing

and data aggregation in the offset time, resulting in the non-sufficient usage of the channel throughput.

4.2 Analysis

Adopting the clustering architecture for the WSN provides many desirable properties. For example, with the clustering technology, the WSN is able to do the data aggregation and localized control. Clustering also provides a great scalability and the self-configuration ability. However, only having clustering architecture is still not enough, many issues must be explored further to achieve the desirable goals for the applications of WSNs. Power efficiency is one of the most important aspects that need to be addressed in WSNs.

CBERRP is a scheme trying to meet the critical challenges arising from the WSN, such as limited energy consumption, routing issue and the quality of data aggregation, by following a cross-layer design concept at the very beginning. Typically, the cross-layer design indicates that the feedback information should be exchanged across all layers in the protocol stack. This information exchange allows the protocol to adapt in a global manner to the application requirements and underlying network conditions. In addition, all protocol layers must be jointly optimized with respect to global system constraints and characteristics. However, the way to fulfill the cross-layer design in traditional networks is not well suited for the WSN since vast overhead will be generated by cross-layer messages and this overhead will degrade dramatically the performance of the WSN due to the limited resources of computation, memory and power on the tiny sensor. As a result, an alternative for the cross-layer design is incorporating the factors from different layers into the protocol. This method can eliminate the fancy overhead involved

in the cross-layer design while retaining the benefits of it.

We would like to emphasize some features in CBERRP in details in addition to those that were already described in previous chapters. First, the two-phase operation in CBERRP allows it to adapt to the change of the Data Aggregation Quality (DAQ) introduced in [19]. Since the DAQ varies proportionally with the number of clusters and inversely with the number of sensor nodes in each cluster, CBERRP can make a balance between the optimal power consumption and the specific level of the DAQ by manipulating the number of the rings. For example, the Data Aggregation Quality of 12 clusters with 4 rings will be better than that of the same number of clusters with 2 rings. While in general, this benefit is obtained with the price of the higher power consumption. CBERRP adapts to different DAQ requirements by setting up the appropriate number of rings in the initialization phase in such a way: When the DAQ for the sensed data changes, another initialization phase can be triggered. Furthermore, when the sensed data are passed along with the chain, whether it is aggregated further or not can also be fine-tuned without significantly affecting the power consumption. It is clear that the requirement from the application layer such as DAQ can be met by manipulating the parameters at network layer in CBERRP, which shows the cross-layer design concept between the application layer and network layer.

The scalability of CBERRP is also enhanced through the ring topology. In fact, when the number of the rings is equal to or greater than the optimal number of the clusters, CBERRP in fact treats the WSN as a kind of topology like LEACH-C, where each CH communicates directly to the BS. When the number of the rings decreases to one, CBERRP converts the WSN to a kind of topology like C-PEGASIS in [19], where all the CHs form a single chain then only one of them acting as the chain leader delivers the data signals to the BS. Thus, CBERRP can also be reviewed as a general case for the two above

schemes in the extent of level-II cluster communication.

Second, CBERRP shows flexibility in the sense of topology type of the WSN. In some cases, it is a necessity for the end users to do topology engineering about the WSN in order to accomplish some sensor missions. Instead of scattering a large number of sensor nodes from a plane or other approaches in a random manner, the topology engineering of the WSN normally is done manually by placing the sensor nodes one by one over a certain area, like some fixed significant locations in a building. For example, in one of the most important applications of the WSN, automatic control and monitoring of the building environment [22], sensor nodes are placed in certain rooms manually. Since the selection of the CHs in CBERRP follows a certain sorting algorithm in accordance with the RPs as described in Section 3.4, the rotation order of the CHs among the sensor nodes will then depend certainly on the location of each sensor node. Thus in a WSN with the deterministic topology or engineered topology, the rotation order of the CHs during the whole lifetime of the WSN will be fixed as well. This feature will make possible the task-driven design of the WSN for the particular sensor application. The combination between the network layer routing protocol and deployment of the sensors enhances the applied scope of CBERRP. The performance of CBERRP in the deterministic topology is presented and compared in the simulation results section already; it shows CBERRP has a close connection between the throughput performance and physical topology.

Chapter 5

Conclusion and Future Work

In this thesis, we proposed a cluster-based routing protocol, CBERRP, which utilizes the high-energy BS to perform most energy-intensive routing tasks, such as cluster setup, CH selection, chain formation, and TDMA schedule assignment, making the sensor nodes relieved from performing heavy routing tasks. CBERRP departs with LEACH-C and other clustering-based routing protocols at the hierarchical cluster architecture and simple algorithm of CH selection. In CBERRP, the level-I clusters and level-II clusters (chain) make up the hierarchical architecture, which improves the power consumption and management over the WSN. The RPs introduced in CBERRP for CHs selection greatly reduce the complexity of the computation of the CH selection in addition to the accomplishment of achieving optimal power dissipation and even power distribution. The simulation results show that the significant improvement can be achieved compared with the LEACH and LEACH-C schemes in terms of the power consumption, lifetime and throughput of the WSN.

CBERRP adopts a particular approach of the cross-layer design especially for WSNs. The benefits and improvements gained by CBERRP come from the implementation of the various integrations that run through the whole protocol. For example, the integration of ring and cluster, the integration of two level communication schedules, the integration of single-hop and multi-hop routing, the integration of ring architecture and multiple DAQs, and the integration of the RP and the physical topology. These integrations are designed to meet the challenges coming from the WSN, which possesses many particular characteristics, such as “many-to-one” traffic pattern, low and limited

energy, limited process capability and memory, which are different from those in the traditional network. Utilizing the global information to operate WSNs at network layer is necessary to address the new challenges associated with WSNs. The best practice for designing routing schemes for WSNs is to apply the cross-layer design concept to the protocol.

While the current CBERRP addressed some important issues on the WSN routing protocol, there is still room for improvement to make the protocol more widely applicable. In the current implementation of CBERRP, the level-I cluster formation is determined totally by the BS according to the distance information feedback from the sensor nodes. It is based on the assumption that the strength of the communication signal is uniquely specified by the square distance. However, in practice, communication energy does not exactly change monotonically with the square distance while considering the impact of shadowing and fading occurred in wireless channel. Furthermore, gathering information about the communication channel between sensor nodes is impractical [13]. It is more realistic to let each sensor node make autonomous decisions without any centralized control. What can be done to improve it is, after the CHs are elected, let the BS advertise only this CH information to WSNs without performing the level-I cluster formation. Sequentially, the CHs advertise the information of being CHs to all the sensor nodes, and then the sensor nodes in turn make the decision of which cluster to join based on the real characteristics of the wireless communication channel. It could be called controlled self-configuration of the clustering architecture.

Meanwhile, death of the sensor nodes makes the optimal number for the level-I clusters calculated at the very beginning of the protocol not always correct based on the algorithm in [13]. This dynamic character of the WSN can be leveraged by re-computing the optimal number every several rounds, which will exclude the dead sensor nodes from the calculations and then the result

should be more accurate in accordance with the algorithm. It is this observation particularly more significant for the WSN with a large scale in terms of geography and number of sensor nodes.

Another issue in this work is that the size of a level-I cluster can be as large as possible. Normally, this is not recommended from the power reservation point of view since much higher energy is required for the communications with longer distance between the CH and the sensor node. It can be relaxed by setting up the communication range threshold of the sensor nodes. Because there is a high probability that the sensor nodes within the same area of a certain scale have correlated data, it is safe to ignore those sensor nodes that are out of the communication range threshold, thus decreasing the power consumption as typically the longer distance communication will occur at these sensor nodes. In addition, we can achieve the load balance among clusters or comply with the capacity of the CH by this threshold on the communication range. For example, by adjusting the range of sensor nodes' RF, each cluster will cover almost the same number of members, regardless of the location of the CH. Meanwhile, the DAQ is expected not to be affected significantly since the size of the level-I cluster can also be determined by taking into account the factor of DAQ measurement. Furthermore, the benefits of the load balance and the power conservation can be achieved. Once the size of each level-I cluster is almost same, each CH will also process almost same amount of data load. Preventing the nodes that are out of the RF range from participating in the cluster saves the power on these nodes, and then the saved energy can be used for other components or the communication in the later round where the sensor nodes are close enough to participate in the cluster again.

In addition, near to the end of the operation of CBERRP, it is inevitable that the chains further away from the BS will be drained out of power faster than

those nearer from the BS, resulting in an unbalanced sensing. That means some parts of the sensing region are able to sense the data, while other parts are not able to do so. This issue can be solved by introducing some extra processes that deal with the inter-chain traffic forwarding. Using the approaches mentioned above, it can be expected that CBERRP can be applied for the WSN scalable to a large number of sensor nodes and a large sensor network area, and be able to handle dynamic network topology change in support of multiple Aggregated Data Qualities. All these features of CBERRP are valuable for it to be a desirable routing protocol for the WSN.

In current version of CBERRP, it does not take into account the load balance and controlled self-configuration cluster's formation. A new version of CBERRP will be studied to adopt these features. We will also consider a larger scale WSN in the later study to evaluate the ability of CBERRP to support the multiple DAQs, while observing the tradeoff among the gains of the DAQ, the influence of the different DAQs on the power dissipation and the associated latency. Overall, we will make CBERRP a desirable routing protocol for the WSN carrying on multiple applications in terms of scalability, availability and power efficiency in the clustering-based routing category.

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