Thesis for the Degree of Master of Engineering

A Study on Hierarchical Energy-Aware Routing Algorithm for Heterogeneous Wireless Sensor Networks

by

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A Study on Hierarchical Energy-Aware Routing Algorithm for Heterogeneous Wireless Sensor Networks

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Abstract

Recently, a new concept called ubiquitous computing has been rising to the surface in the process of changing IT paradigm. This concept called Ubiquitous IT has already transcended the simplest conception or technical blind and dumb, and regard as a new paradigm. Especially, this research has been studied under support of government's u-IT839 policy in our country. Ubiquitous Sensor Network (USN) is one of the most important services in the u-IT839 policy and has regard as the core technology in Ubiquitous IT.

To provide USN services, WSN (Wireless Sensor Network) which is a base of USN environment is necessary to research. Especially energy efficiency is considered the crucial issues in WSN due to the sensor nodes are equipped with small, often irreplaceable, batteries with limited power capacity. Therefore, many power saving algorithms have been studied and there has been much work on "energy-aware" routing protocols for WSN.

For surmounting these problems, this thesis proposes a new routing algorithm for reducing the power consumption of each sensor node in WSNs, combining energy aware cluster head election technique with DAG (Directed Acyclic Graph)

concept in TORA (Temporally-Ordered Routing Algorithm) and adapt to heterogeneous networks. The simulation results show that the proposed routing algorithm has better energy efficiency than the existing routing algorithms.

Ⅰ. Introduction

Recently, a new concept called ubiquitous computing has been rising to the surface in the process of changing IT paradigm. This concept called Ubiquitous IT has already transcended the simplest conception or technical blind and dumb, and regard as a new paradigm. Especially, this research has been studied under support of government's u-IT839 policy in our country. Ubiquitous Sensor Network (USN) is one of the most important services in the u-IT839 policy and has regard as the core technology in Ubiquitous IT.

To provide USN services, WSN (Wireless Sensor Network) which is a base of USN environment is necessary to research. WSN is dense networks of low cost, wireless nodes that sense certain phenomena in the area of interest and report their observations to a base station for further analysis. WSN has been predicted to have a wide range of applications in military, environment, health, home and other commercial areas [1].

Many researchers have recently been dedicated to WSN including design issues related to routing, MAC and collaborative data gathering mechanisms. Among these design issues, energy efficiency is a key design objective. Because the sensor nodes are equipped with small, often irreplaceable, batteries with limited power capacity, it is essential that the network be energy efficient in order to maximize the life span of the network [1, 2]. Therefore, many power saving algorithms have been studied. Specially, there has been much work on "energy-aware" routing protocols for WSN.

The routing techniques are classified into three categories based on the underlying network structure [3]: flat, location-based, and hierarchical routing. In flat routing, each node typically plays the same role and sensor nodes collaborate to perform the sensing task. In location-based routing, sensor nodes are addressed by means of their location and these sensor nodes' positions are exploited to route data in the network. On the other hand, in hierarchical routing, nodes play different roles in the network. Thus, hierarchical routing is mainly two-layer routing where one layer is used to select CHs and the other for routing. However, most hierarchical routing protocols have not taken into consideration the routing but rather data aggregation, channel allocation, and so on.

WSN can be classified into two broad types in terms of network state [4]: homogeneous and heterogeneous wireless sensor networks. In homogeneous network all the sensor nodes are identical in terms of battery energy and hardware complexity. On the other hand, in a heterogeneous network, two or more different types of nodes with different battery energy and functionality are used.

In [2], Heinzelman, et al. proposed LEACH as a hierarchical clustering algorithm for WSN. In LEACH, cluster member nodes send information to their CH node. And CH nodes compress data arriving from cluster member nodes and then send an aggregated packet to the remote BS (Base Station). LEACH randomly selects a few sensor nodes as CHs with some predefined probability and rotates this role to evenly distribute the energy load among the sensor nodes in the network. Therefore, LEACH accomplishes significant energy savings and prolongs the network lifetime over fixed clustering and other conventional schemes. But

LEACH has some problems, such that a CH node uses up own energy while it plays a role of CH and cluster member nodes away from the CH node consume much more transmission energy comparing to the nodes close to the CH node.

In order to reduce the transmission energy consumed by cluster member nodes to send information to the CH node in LEACH, we proposed DAUCH algorithm [5]. DAUCH is one of the hierarchical routing protocols in USN, combining the random CH selection technique in LEACH with DAG in TORA [6]. Due to the short propagation distance between a sender and a receiver, DAUCH makes improvements in the energy savings and the network lifetime compared with LEACH. But, DAUCH has the same problem with LEACH in the sense of the energy exhaustion of CH because CH selection algorithm of DAUCH is identical to that of LEACH.

This thesis proposes HERAH that ameliorates the CH selection algorithm of DAUCH and adapt to heterogeneous networks. HERAH consist of two types of nodes: CM (Cluster Member) node, CHC (Cluster Head Capable) node. CM nodes deployed with intensity λ_0 and battery energy E_0, and CHC nodes deployed with intensity λ_1 and battery energy E_1. CM nodes do the basic sensing as well as the data aggregation of packets within each cluster but cannot become CH. CHC nodes can be CH, do the data aggregation within each cluster and directly transmit the aggregated data to BS. HERAH performs CH selection by considering residual energy level of CHC nodes, hence the energy load of being a CH is evenly distributed among the CHC nodes. Since CHC nodes perform long range transmissions to BS, construction DAG and CH election, they have much higher battery energy than CM nodes. Due to heterogeneous nodes and energy-aware CH selection, HERAH makes improvements in the energy savings and the network lifetime compared with LEACH and DAUCH.

The rest of the thesis is organized as follow: in section II, we review the state of previous routing researches in WSN. We define a new routing algorithm for WSN in section III. Experiment results showing effects of new algorithms and our conclusion are presented in section IV and V, respectively.

Ⅱ. Background

1. Ubiquitous Sensor Network Services

USN is drawing a lot of attention as a method for realizing a ubiquitous society. It collects environmental information to realize a variety of functions, through a countless number of compact wireless nodes that are located everywhere to form an ad hoc arrangement, which does not require a communication infrastructure. An example for its application under consideration is forecasting the outbreak of forest fires by monitoring the temperature of the hills and fields.

USN is constructed by allowing an electronic tag, which is attached to objects to sense the surrounding environment. It manages real-time information through a network. The USN expands the information-oriented society from a strictly human centered paradigm to one including objects.

The end result is a unified BcN and ultimately a Ubiquitous Network. In the early phase, USN will be developed from individual identification of an RF tag. In the next phase, the ability to sense its environmental surrounding will be added into the tag. In the final phase, ad hoc network among objects is built and will control the other tags, which are operating at a lower functionality [7].

USN technology is the combination of wired and wireless networks consisting of an electronic tag, reader, middleware, and application platform. Especially, the technologies related with WSN and BcN are the basis of USN services based on BcN. Figure 1 presents point-to-point (P2P) and point-to-multipoint (P2MP) RWA problems of IP/GMPLS over DWDM based BcN backbone network and access networks. The same figure shows the routing problem of WSN for USN services.

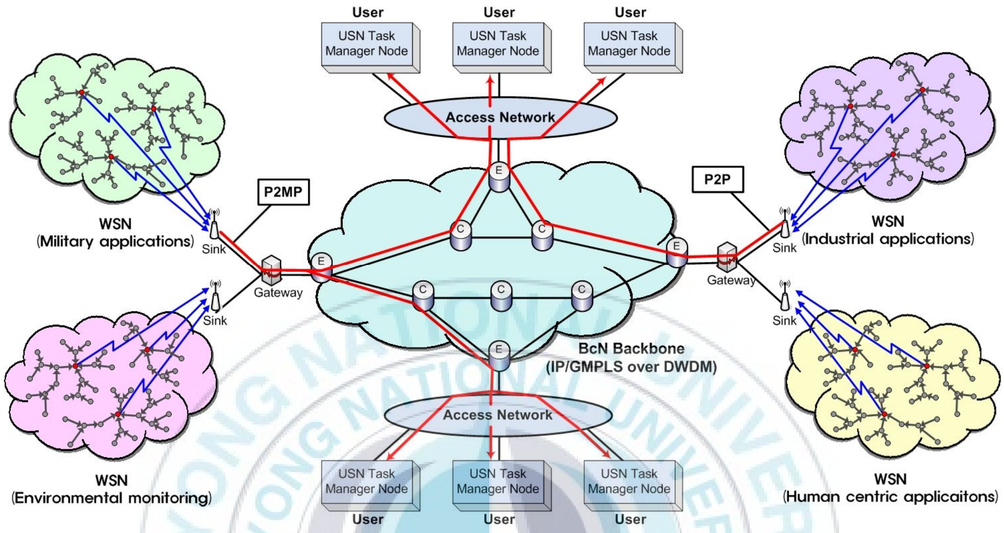


Figure 1. Ubiquitous Sensor Network services based on Broadband convergence Network

There are the numerous USN services that utilize WSNs. Table 1 summarizes applications and research institutions for USN services[1, 8].

Table 1. Applications and research institutions for USN services

Service	Applications	Research institution
Military applications	• Enemy tracking • Target classification • Reconnaissance of opposing forces and terrain • Monitoring friendly forces, equipment and ammunition • Battle damage assessment • Nuclear, biological and chemical attack detection and reconnaissance	University of Virginia, Ohio State University, Palo Alto Research Center, University of Wisconsin-Madison
Environmental monitoring	• Indoor: home automation, optimal control of the indoor environment, mitigation of fire and earthquake damages • Outdoor: forest fire detection, forecasting weather phenomena, habitat monitoring, irrigation management, crop management	SABER (Sensors and Buildings Engineering Research Center), U. C. Berkeley, Intel Research, University of Hawaii, North Carolina State University
Industrial applications	• Inventory control • Detection of faulty parts • Wearable motes • Monitoring the condition of pumps at gas stations	British Petroleum, Intel Research, Helsinki University of Technology, Shell Oil Co.
Human centric applications	• Telemonitoring of human physiological data • Human vision restoration • Tracking and monitoring doctors and patients • Tracking drug usage inside hospitals	Intel Research, UCLA, Wayne State University
Applications to robotics	• Detection of level sets of scalar fields (like isothermal or isobar curves) • Virtual keyboard • Solution to the "coverage problem" • Support the operation of a sensor network: sustaining the energy resources of the sensor network indefinitely, maintaining and configuring hardware, detecting sensor failures, appropriate deployment for connectivity among nodes	University of Southern California, Intel Research, Deakin University, U. C. Berkeley

2. Analysis of Previous Routing Techniques in Wireless Sensor Networks

Due to recent technological advances, the manufacturing of small and low-cost sensors has become technically and economically feasible. These sensors measure ambient conditions on the environment surrounding them and then transform these measurements into signals that can be processed to reveal some characteristics about phenomena located in the area around these sensors. A large number of these sensors can be networked in many applications that require unattended operations, hence producing a WSN. In fact, the applications of WSN are quite numerous. For example, WSNs have profound effects on military and civil applications such as target field imaging, intrusion detection, weather monitoring, security and tactical surveillance, distributed computing, detecting ambient conditions such as temperature, movement, sound, light, or the presence of certain objects, inventory control, and disaster management. Deployment of a sensor network in these applications can be in random fashion (e.g., dropped from an airplane in a disaster management application) or manual (e.g., fire alarm sensors in a facility or sensors planted underground for precision agriculture). Creating a network of these sensors can assist rescuer operations by locating survivors, identifying risky areas, and making the rescue team more aware of the overall situation in a disaster area.

Typically, WSNs contain hundreds or thousands of these sensor nodes, and these sensors have the ability to communicate either among each other or directly to an external base station. One of the main design goals of WSNs is to carry out data communication while trying to prolong the lifetime of the network and prevent connectivity degradation by employing aggressive energy management techniques. Especially, the underlying network structure can play a significant role in the operation of the routing protocol in WSNs. Therefore, the routing techniques are classified into three categories based on the underlying network structure [3]: flat, location-based, and hierarchical routing.

In addition to the routing protocol, data aggregation also plays one of critical factors because the data on the field can be the same information. So data aggregation can reduce the redundant data transfer to save the limited node energies. Figure 2 presents the routing techniques in WSNs.

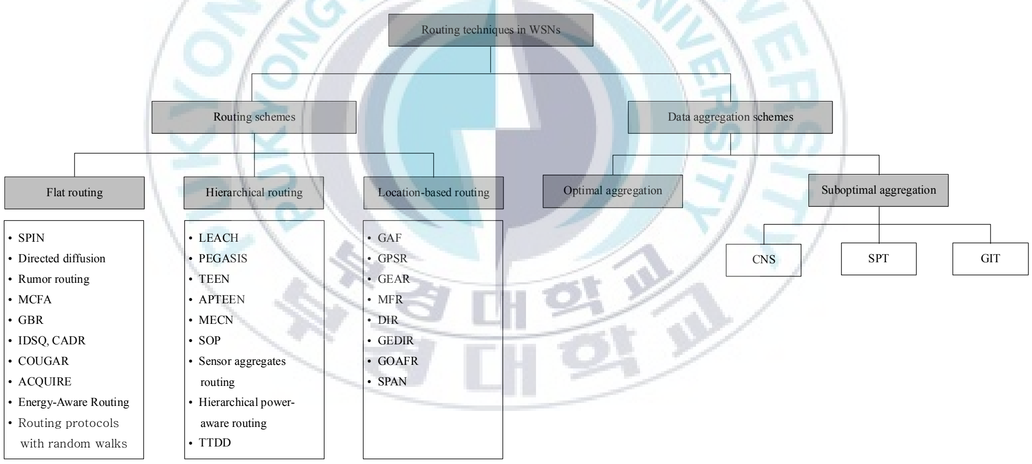


Figure 2. Routing techniques in WSNs

2.1 Routing Challenges and Design Issues in WSNs

Despite the innumerable applications of WSNs, these networks have several restrictions, e.g., limited energy supply, limited computing power, and limited bandwidth of the wireless links connecting sensor nodes. One of the main design goals of WSNs is to carry out data communication while trying to prolong the lifetime of the network and prevent connectivity degradation by employing aggressive energy management techniques. The design of routing protocols in WSNs is influenced by many challenging factors. These factors must be overcome before efficient communication can be achieved in WSNs. In the following, we summarize some of the routing challenges and design issues that affect routing process in WSNs [3].

- Node deployment: Node deployment in WSNs in application dependent and affects the performance of the routing protocol. The deployment can be either deterministic or randomized. In deterministic deployment, the sensors are manually placed and data is routed through pre-determined paths. However, in random node deployment, the sensor nodes are scattered randomly creating an infrastructure in an ad hoc manner. If the resultant distribution of nodes is not uniform, optimal clustering becomes necessary to allow connectivity and enable energy efficient network operation. Inter-sensor communication is normally within short transmission ranges due to energy and bandwidth limitations. Therefore, it is most likely that a route will consist of multiple wireless hops.
- Energy consumption without accuracy: sensor nodes can use up their limited supply of energy performing computations and transmitting information in a wireless environment. As such, energy-conserving forms of communication and computation are essential. Sensor node lifetime shows a strong dependence on the battery lifetime [2]. In a multihop WSN, each node plays a dual role as data sender and data router. The malfunctioning of some sensor nodes due to power failure can cause significant

topological changes and might require rerouting of packets and reorganization of the network.

- Data Reporting Model: Data sensing and reporting in WSNs is dependent on the application and the time criticality of the data reporting. Data reporting can be categorized as either time-driven, event-driven, query-driven, and hybrid [9]. The time-driven delivery model is suitable for applications that require periodic data monitoring. As such, sensor nodes will periodically switch on their sensors and transmitters, sense the environment and transmit the data of interest at constant periodic time intervals. In event-driven and query-driven models, sensor nodes react immediately to sudden and drastic changes in the value of a sensed attribute due to the occurrence of a certain event or a query is generated by the BS. As such, these are well suited for time critical applications. A combination of the previous models is also possible. The routing protocol is highly influenced by the data reporting model with regard to energy consumption and route stability.
- Fault Tolerance: Some sensor nodes may fail or be blocked due to lack of power, physical damage, or environmental interference. The failure of sensor nodes should not affect the overall task of the sensor network. If many nodes fail, MAC and routing protocols must accommodate formation of new links and routes to the data collection base stations. This may require actively adjusting transmit powers and signaling rates on the existing links to reduce energy consumption, or rerouting packets through regions of the network where more energy is available. Therefore, multiple levels of redundancy may be needed in a fault-tolerant sensor network.
- Scalability: The number of sensor nodes deployed in the sensing area may be in the order of hundreds or thousands, or more. Any routing scheme must be able to work with this huge number of sensor nodes. In addition, sensor network routing protocols

should be scalable enough to respond to events in the environment. Until an event occurs, most of the sensors can remain in the sleep state, with data from the few remaining sensors providing a coarse quality.

- Network Dynamics: Most of the network architectures assume that sensor nodes are stationary. However, mobility of both BS's or sensor nodes is sometimes necessary in many applications [10]. Routing messages from or to moving nodes is more challenging since route stability becomes an important issue, in addition to energy, bandwidth etc. Moreover, the sensed phenomenon can be either dynamic or static depending on the application, e.g., it is dynamic in a target detection/tracking application, while it is static in forest monitoring for early fire prevention. Monitoring static events allows the network to work in a reactive mode, simply generating traffic when reporting. Dynamic events in most applications require periodic reporting and consequently generate significant traffic to be routed to the BS.
- Transmission Media: In a multi-hop sensor network, communicating nodes are linked by a wireless medium. The traditional problems associated with a wireless channel may also affect the operation of the sensor network. In general, the required bandwidth of sensor data will be low, on the order of 1-100 Kb/s. Related to the transmission media is the design of medium access control (MAC). One approach of MAC design for sensor networks is to use TDMA based protocols that conserve more energy compared to contention based protocols like CSMA. Bluetooth technology [11] can also be used.
- Connectivity: High node density in sensor networks precludes them from being completely isolated from each other. Therefore, sensor nodes are expected to be highly connected. This, however, may not prevent the network topology from being variable and the network size from being shrinking due to sensor node failures. In

addition, connectivity depends on the, possibly random, distribution of nodes.

- Coverage: In WSNs, each sensor node obtains a certain view of the environment. A given sensor's view of the environment is limited both in range and in accuracy; it can only cover a limited physical area of the environment. Hence, area coverage is also an important design parameter in WSNs.
- Data Aggregation: Since sensor nodes may generate significant redundant data, similar packets from multiple nodes can be aggregated so that the number of transmissions is reduced. Data aggregation is the combination of data from different sources according to a certain aggregation function, e.g., duplicate suppression, minima, maxima and average. This technique has been used to achieve energy efficiency and data transfer optimization in a number of routing protocols. Signal processing methods can also be used for data aggregation. In this case, it is referred to as data fusion where a node is capable of producing a more accurate output signal by using some techniques such as beamforming to combine the incoming signals and reducing the noise in these signals.
- Quality of Service: In some applications, data should be delivered within a certain period of time from the moment it is sensed, otherwise the data will be useless. Therefore bounded latency for data delivery is another condition for time-constrained applications. However, in many applications, conservation of energy, which is directly related to network lifetime, is considered relatively more important than the quality of data sent. As the energy gets depleted, the network may be required to reduce the quality of the results in order to reduce the energy dissipation in the nodes and hence lengthen the total network lifetime. Hence, energy-aware routing protocols are required to capture this requirement.

2.2 Routing Schemes

1) Flat Routing

Flat routing is that all nodes in the fields exchange the information with each other in the equal position. Due to the large number of such nodes, it is not feasible to assign a global identifier to each node. This consideration has led to data-centric routing, where the BS sends queries to certain regions and waits for data from the sensors located in the selected regions. Since data is being requested through queries, attribute-based naming is necessary to specify the properties of data. Early work on data centric routing (e.g., SPIN and directed diffusion [12]) were shown to save energy through data negotiation and elimination of redundant data. These two protocols motivated the design of many other protocols that follow a similar concept. As shown in figure 2, there are several flat routing methods in WSNs.

2) Hierarchical Routing

Flat Routing Method is efficient in the small-scale networks because of its simple routing construction procedure. But the large the scale of network is, the much the quantity of routing information is. And there are long delays in sending the routing information from the remote sensor node and in transferring data from the remote source nodes. Therefore it needs a routing method in which all nodes can waste the equivalent battery in order to guarantee the long lifetime.

Hierarchical routing method was proposed to resolve such a problem, in which all nodes are partitioned into logical groups and each logical group has the head node that control the data traffic in the corresponding group. The creation of clusters and assigning special tasks to CHs (Cluster Heads) can greatly contribute to overall system scalability, lifetime, and energy efficiency.

Hierarchical routing is an efficient way to lower energy consumption within a cluster, performing data aggregation and fusion in order to decrease the number of transmitted messages to the BS. Hierarchical routing is mainly two-layer routing where one layer is used to select CHs and the other for routing. However, most techniques in this category are not about routing, but rather "who and when to send or process/ aggregate" the information, channel allocation, and so on, which can be orthogonal to the multihop routing function. As shown in figure 2, there are several hierarchical routing methods in WSNs.

Table 2 summarizes the comparisons of flat and hierarchical routing methods according to the specific parameters.

Table 2. Comparisons of flat and hierarchical routing methods

	Hierarchical Routing method	Flat Routing method
Scheduling	Reservation-based scheduling	Contention-based scheduling
Collision	Collisions avoided	Collision overhead present
Duty cycle	Reduced duty cycle due to periodic sleeping	Variable duty cycle by controlling sleep time of nodes
Aggregation point	Data aggregation by cluster head	Node on multi-hop path aggregates incoming data from neighbors
Complexity	Simple but non-optimal routing	Routing can be made optimal but with and added complexity
Synchronization	Requires global and local synchronization	Links formed on the fly without synchronization
Overhead	Overhead of cluster formation throughout the network	Routes formed only in regions that have data for transmission
Latency	Lower latency as multiple hops network formed by cluster heads always available	Latency in waking up intermediate nodes and setting up the multipath
Energy dissipation	Energy dissipation is uniform	Energy dissipation depends on traffic patterns
Fairness	Guarantee	Not guarantee

3) Location-Based Routing

In this kind of routing, sensor nodes are addressed by means of their locations. The distance between neighboring nodes can be estimated on the basis of incoming signal strengths. Relative coordinates of neighboring nodes can be obtained by exchanging such information between neighbors [13-15]. Alternatively, the location of nodes may be available directly by communicating with a satellite using GPS if nodes are equipped with a small low-power GPS receiver [16]. To save energy, some location-based schemes demand that nodes should go to sleep if there is no activity. More energy savings can be obtained by having as many sleeping nodes in the network as possible. The problem of designing sleep period schedules for each node in a localized manner was addressed in [16, 17]. As shown in figure 2, there are several location-based routing methods in WSNs.

2.3 Data Aggregation Schemes

1) Data aggregation in sensor networks

Before starting the data aggregation techniques, we should investigate the routing models [18] that are assumed to consist of a single data sink attempting to gather information from a number of data sources. Figure 3 is a simple illustration of the difference between simple models of routing schemes that use data aggregation (which we term Data-Centric (DC)), and schemes that do not (which we term Address-Centric (AC)). They differ in the manner that the data is sent from a source to a sink. In the AC routing, each source independently sends data along the shortest path to the sink based on the route that the queries took (" end-to-end routing”), whereas in the DC routing the sources send data to the sink, but routing nodes on the way look at the content of the data and perform some form of aggregation and consolidation functions on the data originating at multiple sources.

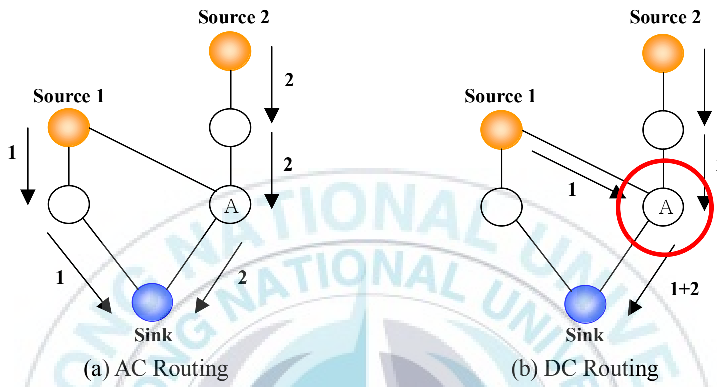


Figure 3. Illustration of AC routing Vs. DC routing

In ad hoc networks, a routing model follows the AC routing, so each source sends its information separately to the sink like the figure 3(a). In sensor networks, a routing model follows the DC routing, so the data from the two sources are aggregated at node A, and the combined data is sent from node A to the sink like the figure 3(b). Therefore in sensor networks, the data aggregation technique is a critical factor different from ad hoc networks to save the power consumptions of the nodes in order to extend the sensor network lifetime.

In sensor networks, the data aggregation tree can be thought of as the reverse of a multicast tree. So optimal data aggregation is a minimum Steiner tree on the network graph. Instead of an optimal data aggregation, sub-optimal data aggregations are proposed to generate data aggregation trees that are aimed to diminish the transmission power. The table 3 summarizes the properties and disadvantages of sub-optimal data aggregation methods.

The prevenient data aggregation methods [18] are efficient to the model where a single point in the unit square is defined as the location of an "event", and all nodes within a distance S (called the sensing range) of this event that are not sinks are considered to be data sources (which we term Event-Radius Model). In the model where some nodes that are not sinks are randomly selected to be sources, e.g. a temperature measurement and environment pollution detection (which we term Random-Source Model), it needs appropriate strategies for an efficient data aggregation.

Table 3. Comparisons of the data aggregation methods

Data aggregation method		Properties	Disadvantages
Optimal	Minimum Steiner Tree	The optimal number of transmissions required per datum for the DC protocol is equal to the number of edges in the minimum Steiner tree in the network.	The NP-completeness of the minimum Steiner problem on graphs
Sub-optimal	CNS (Center at Nearest Source	The source that is nearest the sink acts as the aggregation point. All other sources send their data directly to this source that then sends the aggregated information on to the sink.	The more great the gaps between the aggregation point and sources, the more the batteries consumptions.
	SPT (Shortest Paths Tree)	Each source sends its information to the sink along the shortest path between the two. Where these paths overlap for different sources, they are combined to form the aggregation tree.	The shorter the overlapped paths when the shortest route is established from each source to the sink, the more the batteries consumptions.
	GIT (Greedy Increment-al Tree)	At the first step the tree consists of only the shortest path between the sink and the nearest source. At each step after that the next source closest to the current tree is connected to the tree.	It takes some time for the identical data to arrive to the aggregation point and to aggregate the identical data from other source nodes.

In LEACH, all of the nodes in the field can be the source nodes in sensor networks, so this model can be considered Random-Source Model. The nodes in LEACH organize themselves into local clusters, with one node acting as the cluster head, which allocates the time slot to its cluster members. All non-cluster head nodes directly transmit their data to the cluster head, while the cluster head node receives data from all the cluster members, performs signal processing functions on the data (e.g., data aggregation), and transmits data to the remote BS (Base Station). If the cluster heads were chosen a priori and fixed throughout the system lifetime, these nodes would quickly use up their limited energy because being a cluster head node is much more energy intensive than being a non-cluster head node. Thus LEACH incorporates randomized rotation of the high-energy cluster head position among the sensors to avoid draining the battery of any one sensor in the network. In this way, the energy load of being a cluster head is evenly distributed among the nodes. But LEACH needs clustering formation overheads before performing the task, and the nodes which are away from the cluster head consume much more transmission batteries comparing to the nodes close to the cluster head. So it needs a strategy to eliminate the redundancy power consume in LEACH.

2) Data aggregation in ad hoc networks

Most of the ad hoc networks are based on point-to-point communications, so the data aggregation in ad hoc networks is not considered a critical issue except the multipath routing. In some routing protocols such as DSR [19], AODV [20], LMR [21], TORA [6], and so on, multi-paths can be established from the sources to the destination. In that case the data aggregation can be performed through the overlapped paths en route. But it depends on each routing technique, which is implemented in ad hoc networks. Amongst the multipath routing techniques, TORA builds a directed acyclic graph rooted at the destination in ad hoc networks. So using DAG all data in the field can be assembled at the destination node.

3. Differences of Homogeneous Networks and Heterogeneous Networks

3.1 Homogeneous Networks

In homogeneous networks all the sensor nodes are identical in terms of battery energy and hardware complexity. With purely static clustering (cluster heads once elected, serve for the entire lifetime of the network) in a homogeneous network, it is evident that the cluster head nodes will be over-loaded with the long range transmissions to the remote base station, and the extra processing necessary for data aggregation and protocol co-ordination. As a result the cluster head nodes expire before other nodes. As a result the cluster head nodes expire before other nodes. However it is desirable to ensure that all the nodes run out of their battery at about the same time, so that very little residual energy is wasted when the system expires. One way to ensure this is to rotate the role of a cluster head randomly and periodically over all the nodes as proposed in LEACH [2]. However the downside of using a homogeneous network and role rotation is that all the nodes should be capable of acting as cluster heads, and therefore should possess the necessary hardware capabilities [4].

3.2 Heterogeneous Networks

In a heterogeneous sensor network, two or more different types of nodes with different battery energy and functionality are used. The motivation being that the more complex hardware and the extra battery energy can be embedded in few cluster head nodes, thereby reducing the hardware cost of the rest of the network. However fixing the cluster head nodes means that role rotation is no longer possible. When the sensor nodes use single hopping to reach the cluster head, the nodes that are farthest from the cluster heads always spend more energy than the nodes that are closer to the cluster heads. On the other hand when nodes use multi-hopping to reach the cluster head, the nodes that are closest to the cluster head have the highest energy burden due to relaying. Consequently there always exists a non-uniform energy drainage pattern in the network [4].

Ⅲ. Hierarchical Energy-Aware Routing Algorithm for Heterogeneous Wireless Sensor Networks

1. DAUCH

DAUCH is a hierarchical routing protocol that improves the cluster formation algorithm of LEACH by applying DAG concept in TORA. The operation of DAUCH is divided into several rounds and each round consists of five phases logically: CH selection phase, DAG construction phase, DATA transfer phase, Downlink failure phase, DAG deconstruction phase [5]. Moreover, DATA transfer phase consists of frames when all the nodes send their data to the downlink node or BS once during their allocated transmission slot. Figure 4 shows the operation of DAUCH.

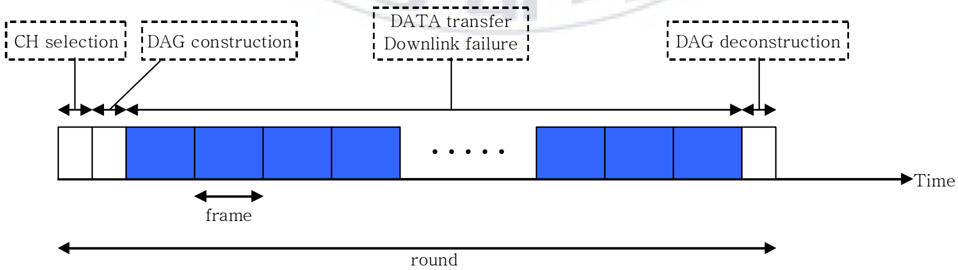


Figure 4. Time line showing the operation of DAUCH

During a round, DAUCH operates as follows. At first, during CH selection phase, CHs are randomly selected as LEACH. And then each CH creates the DAG rooted at itself during DAG construction phase. During DATA transfer phase, the nodes that have more than one uplink node aggregate the data arrived from the uplink nodes and then transmit them to the downlink node. This manner is continued until all data arrive at the CH. The CHs receive and aggregate the data from the adjacent neighboring node, and then transmit them to BS. During Downlink failure phase, reconnecting another node restores the node’s downlink lost. Finally, The CHs deconstruct the DAG rooted at themselves and inform their cluster member of the end of a current round during DAG deconstruction phase. Figure 5 illustrates the data transfer of DAUCH.

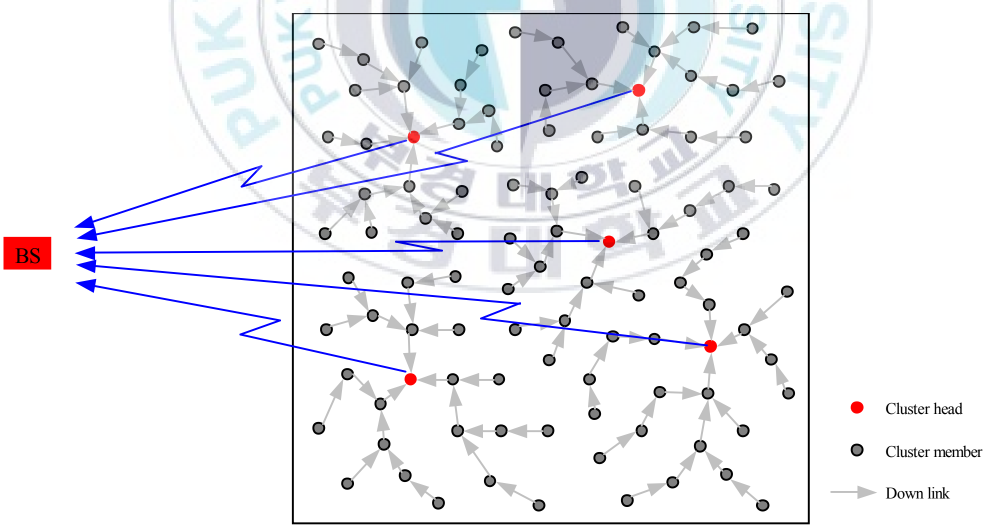


Figure 5. Illustration of the new data aggregation algorithm

When the cluster is formed, LEACH establishes point-to-point connections between a CH node and each cluster member node, while DAUCH constructs DAG centered at CH node. Thus, cluster member nodes in LEACH directly send data to their CH, while cluster member nodes in DAUCH send data to their downlink node close to them. Therefore, DAUCH saves energy compared to LEACH because the cluster member nodes far away from their CH node transmit the data to a node in less distance than LEACH in the way of multi-hop transmission. Moreover, the task effort of data aggregation in the CH is distributed to non-CH nodes because nodes in the overlapped routes perform data aggregation before the whole data within a cluster get to the CH. Consequently, DAUCH provides energy savings and prolongs the network lifetime compared to LEACH.

2. Network and Radio Models in HERAH

2.1 The Network Model and Architecture in HERAH

We consider a heterogeneous network with two types of nodes (CHC node and CM node) that are deployed using a two-dimensional homogeneous Poisson point process for each type of nodes. CM nodes deployed with intensity λ_0 and battery energy E_0, and CHC nodes deployed with intensity λ_1 and battery energy E_1. CM nodes are geographically grouped into clusters but cannot become CH. Therefore, CM nodes perform sensing tasks, aggregates the sensed data and the data arrived from uplink nodes, transmits them to the downlink node. CHC nodes can be CH, hence when CHC nodes serve as CH node, the nodes gather the data from the adjacent neighboring nodes within its cluster, perform data aggregation, and send the data to the BS. A CH is selected based on remaining battery power or residual energy of nodes among CHC nodes. Since the other CHC nodes, which weren't selected CH, enter a sleep state, they can save energy.

Also, we assume a sensor network model with the following properties. First, a fixed BS is located far away from the sensor nodes. Second, all sensor nodes in the network are immobile and energy constrained with a initial energy allocation. Third, the nodes are equipped with power control capabilities to vary their transmitted power. Last, each CM node senses the environment at a fixed rate, and all sensed data always have to be sent to the BS via CH.

2.2 The Radio Model in HERAH

We assume a simple radio model [2] for the radio hardware energy dissipation where the transmitter dissipates energy to run the radio electronics ($E_{Tx\text{-}elec}$) and the power amplifier ($E_{Tx\text{-}amp}$), and the receiver dissipates energy to run the radio electronics ($E_{Rx\text{-}elec}$), as shown in Figure 6. We use both the free space (d^2 power loss) and the multipath fading (d^4 power loss) channel models depending on the distance between the transmitter and the receiver [22], i.e., if the distance is less than a threshold d_t, the free space (f_s) model is used; otherwise, the multipath (m_p) fading model is used. The threshold d_t is cross-over distance for free space and multipath fading model [23]. Therefore, the radio energy dissipation of the transmitter is set as follows:

$$\begin{aligned} E_{Tx}(k,d) &= E_{Tx-elec}(k) + E_{Tx-amp}(k,d) \\ &= \begin{cases} E_{elec} \times k + \varepsilon_{fs} \times k \times d^2, & d < d_t \\ E_{elec} \times k + \varepsilon_{mp} \times k \times d^4, & d \geq d_t \ . \end{cases} \end{aligned} \tag{1}$$

And the radio energy dissipation of the receiver is set as follows:

$$E_{Rx}(k) = E_{Rx-elec}(k) = E_{elec} \times k \tag{2}$$

where E_{elec} is the electronics energy, d is a distance from a transmitter to a receiver, and k is a k-bit message.

The communication energy parameters and the energy for data aggregation E_{DA} are set as those of [2]: E_{elec} = 50nJ/bit, ε_{fs} = 10pJ/bit/m2, ε_{mp} = 0.0013pJ/bit/m4, and E_{DA} = 5nJ/bit/signal. Moreover, the cross-over distance for free space and multipath fading model is set as that of [23]: d_t = 87m.

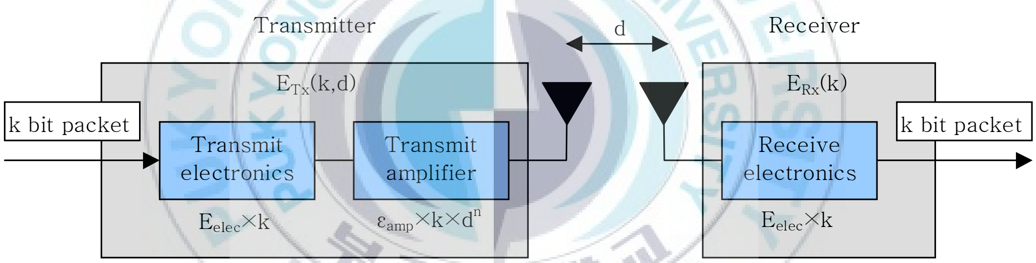


Figure 6. Radio energy dissipation model

3. The Operation of HERAH

HERAH is a hierarchical routing algorithm that uses DAG concept in TORA [5] for transmitting data from sensor nodes to CH. The operation of HERAH is divided into rounds and each round consists of two phases logically: Clustering phase, DATA transfer phase. Moreover, Clustering phase consists of sub-phases which is divided into CH selection, DAG construction, Scheduling. And DATA transfer phase consists of frames when all the nodes send their data to the downlink node or

BS once during their allocated transmission slot. Figure 7 shows the operation of HERAH.

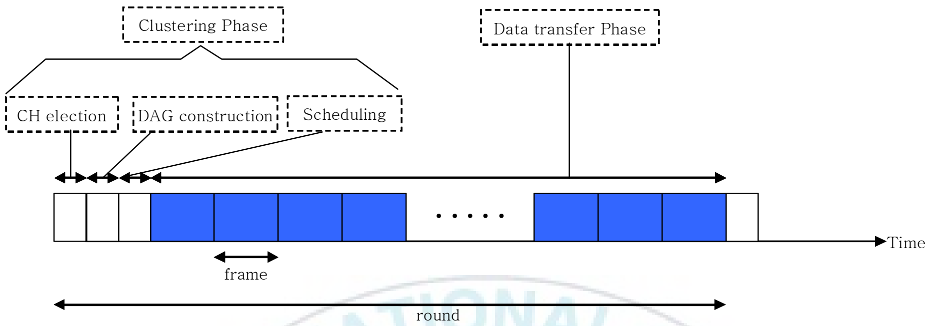


Figure 7. Time line showing the operation of HERAH

During a round, HERAH operates as follows. At first, during Clustering phase, CHs are selected among CHC nodes by considering residual energy level, and then each CH creates the DAG rooted at itself and allocates a timeslot to each node for data transfer. During DATA transfer phase, the nodes that have more than one uplink node aggregate the data arrived from the uplink nodes and then transmit them to the downlink node. This manner is continued until all data arrive at the CH. The CHs receive and aggregate the data from the adjacent neighboring node, and then transmit them to BS.

3.1 CH Election Phase of HERAH

HERAH performs CH selection based on residual energy value of CHC nodes. When CHC nodes initially deployed, they have the same battery energy(E_I). Therefore, we use the CH selection algorithm of LEACH [2] until T_{init} (r) time.

$$T_{init}(r) = T_{round} \times \frac{1}{CH_{prob}} \tag{9}$$

where r is current round, T_{round} is time of one round, and CH_{prob} is the desired percentage to become a CH. After T_{init} (r), since all the CHC nodes have the different energy, the CH is selected by residual energy of CHC nodes. The CH selection algorithm is shown in Figure 8.

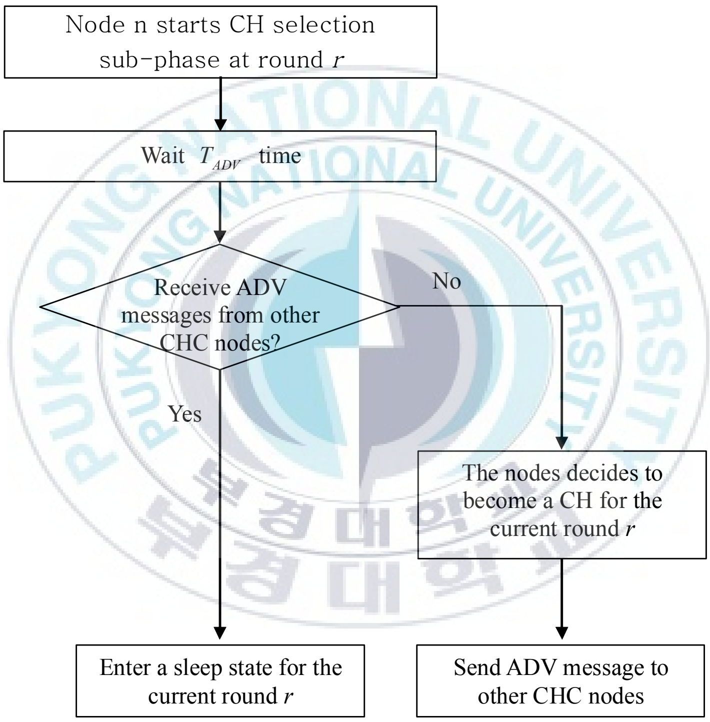


Figure 8. Flowchart of the CH selection algorithm for HERAH

When round r begins, each CHC node waits T_{ADV} time which is defined by its current residual energy as shown in equation (10). Hence, the larger residual energy, the shorter T_{ADV} time. And then, it confirms whether or not to receive ADV messages, which indicate that some neighbor CHC node already became CH, from other CHC nodes. If it receives the ADV message, it enters a sleep state for the current round r. Otherwise, it decides to become a CH for the current round r and sends ADV message to neighbor CHC nodes.

$$T_{ADV} = T_{CH\_E} \times \left(1 - \frac{E_{current}(r)}{E_{init}}\right) \quad (10)$$

where T_{CH_E} is the duration of CH election step, $E_{current}(r)$ is the CHC node's current energy at the beginning of round r, and E_{init} is the CHC node's initial energy.

3.2 Energy Consumption in HERAH

We analyze CHC node's energy consumption by estimating the expected consumption of a CH, since they are naturally selected to be CHs. For the CM nodes' energy consumption, we focus on the critical nodes which are within a distance r from a cluster head. Because they have the heaviest forwarding load among all the CM nodes in the cluster. Hence, they can be considered to be the CM nodes with the most constrained lifetime. Let P_1 be the amount of energy spent by a CHC node during each data gathering cycle. This consists of energy spent on receiving data from other nodes in the cluster (E_{Rx} per packet), aggregating the received data (E_{DA} per packet), and transmitting the aggregated data to the BS (E_{Tx_CHC} per packet). Let P_2 denote the amount of energy spent by a CM node during one cycle. This consists of energy spent on data from the neighboring nodes (E_{Rx} per packet), aggregating the received data (E_{DA} per packet), and transmitting the aggregated data to the CH (E_{Tx_CM} per packet). Hence,

$$P_1 = E[N_v(r)](E_{Rx} + E_{DA}) + E_{Tx\_CHC} \quad (3)$$

$$P_0 = E[N_c(r)](E_{Rx} + E_{DA}) + E_{Tx\_CM} \quad (4)$$

where $E[N_v(r)]$ is the expected number of critical nodes in a typical cluster and $E[N_c(r)]$ is the expected number of a CM node's uplink nodes [24].

The above equations can help us determine a reasonable energy allocation for the heterogeneous case, as we show below. The key issue is that since we have different types of sensors, given a fixed budget and a fixed task, how much energy with which the CM nodes and CHC nodes should be equipped, respectively. One possible criteria is to let the two types of nodes expire at about the same time. Thus by balancing energy allocation, by using (3) and (4), we can maximize the network lifetime for a given fixed amount of energy.

$$\frac{E_1}{P_1} = \frac{E_0}{P_0} \quad (5)$$

From there we get the relation:

$$\frac{E_1}{E_0} = \frac{E[N_v(r)](E_{Rx} + E_{DA}) + E_{Tx\_CHC}}{E[N_c(r)](E_{Rx} + E_{DA}) + E_{Tx\_CM}} \quad (6)$$

Following this, both the CHC nodes and the CM nodes in the network should last

$$T_{lifetime} = \frac{E_1}{E[N_v(r)](E_{Rx} + E_{DA}) + E_{Tx\_CHC}} \quad (7)$$

We use the approach used in [24] to determine the expected number of critical nodes in a cluster.

$$E[N_v(r)] = \frac{\lambda_0}{\lambda_1}\left(1 - e^{-\lambda_1 \pi r^2}\right) \qquad (8)$$

Since it is not easy to draw conclusions directly from these equations for the lack of a closed form solution in some cases, we use a few numerical methods to solve the equations under given circumstances. Our calculations are done in Matlab.

Note that $E[N_v(r)]$ depends on λ_1, the number of CHC nodes. This suggests that we could use (7) to determine how many CHC nodes are needed.

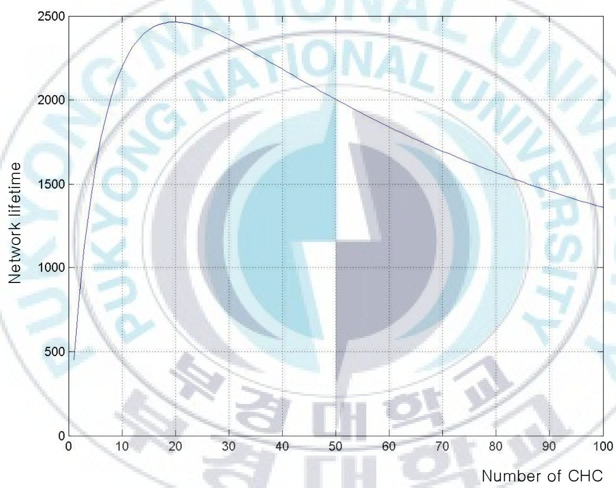


Figure 9. The network lifetime as a function of the number of CHC nodes

Figure 9 is obtained assuming data packets of 500 bytes and control packets of 25 byte. We also assume that the total energy of the network is bounded by 200 joules in each case and the CM node to CHC node energy ratio is 5.5. The energy ratio was determined by considering maximum energy consumption (one-hop communication within a cluster) in each node.

In this experiment we set the total number of nodes to be fixed at 100. Hence, λ_1 varies from 1 to 100. In other words, if the number of CHC nodes is λ_1, the number of CM nodes should be 100-λ_1. Figure 9 shows the expected lifetime that the network can last as a function of number of clusters. It shows that the maximum lifetime is reached when λ_1=18.

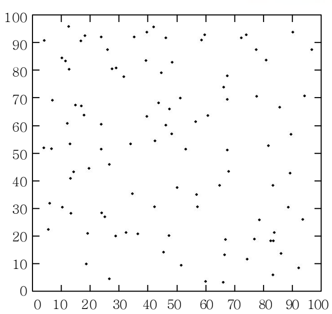
Ⅳ. Simulatin and Performance Evaluation

1. Simulation Setup

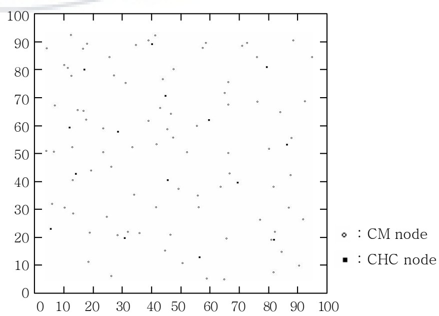
We evaluate the performance of the proposed scheme via C++. The network and radio models described in section Ⅲ are used as the simulation model for our simulation. We conduct simulation with two test networks shown in Figure 10. Table 4 summarizes the characteristics of the test network.

Table 4. Characteristics of test networks

Characteristic	Test network 1 (LEACH, DAUCH)	Test network 2 (HERAH)
Nodes	100	CM node : 82 CHC node : 18
Network size	100m×100m	100m×100m
BS location	(50, 175)	(50, 175)
E_{init}	2J	CM node : 1.1J CHC node : 6.1J



(a) Test network 1



(b) Test network 2

Figure 10. 100-node random test networks for EDAUCH

2. Analysis of Numerical Results

First, we compare the proposed HERAH to LEACH, which is one of the most notable clustering algorithms in WSNs, in respect of the total number of nodes that remain alive over the simulation time. Figure 11 shows that HERAH is operational and remains alive all the nodes for a longer time than LEACH. Futhermore, if network lifetime is defined as the number of rounds for which 75% of the nodes remain alive, HERAH outperforms the network lifetime of LEACH by 14% and DAUCH by 11%.

Next we analyze the number of data signals received at the BS for the two routing protocols under consideration. Figure 12 depicts that HERAH improves approximately 53% and 23% comparing to the number of data signals received at the BS in LEACH and DAUCH.

Finally, we evaluate the performance of HERAH and LEACH in respect of the average energy dissipation per round. Figure 13 shows that HERAH improves approximately 7.5% and 3.1% comparing to the average energy dissipation per round in LEACH and DAUCH.

These simulation results mean that HERAH is more energy efficient than LEACH and DAUCH because HERAH eliminates the case that CH nodes use up their own energy while they play CH's role by using energy aware CH selection algorithm.

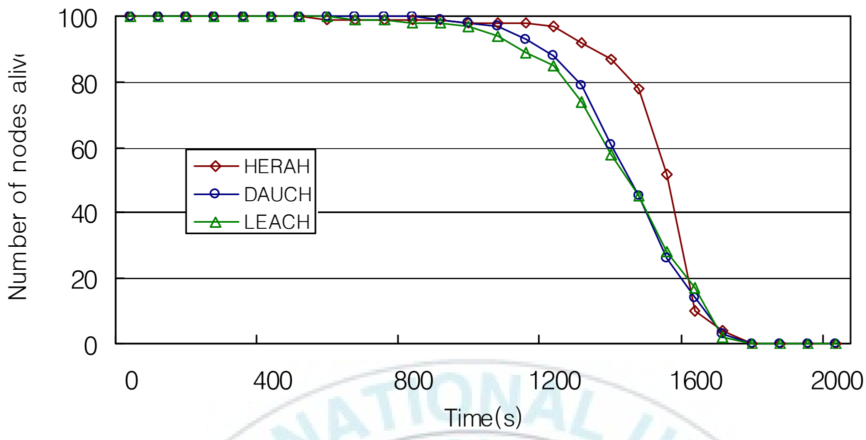


Figure 11. Analysis of the number of nodes alive over time

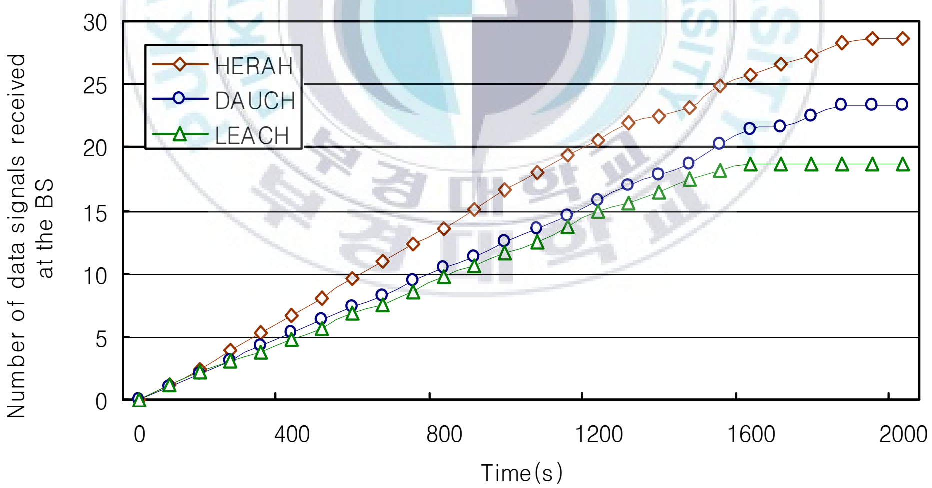


Figure 12. Analysis of the number of data signals received at the BS over time

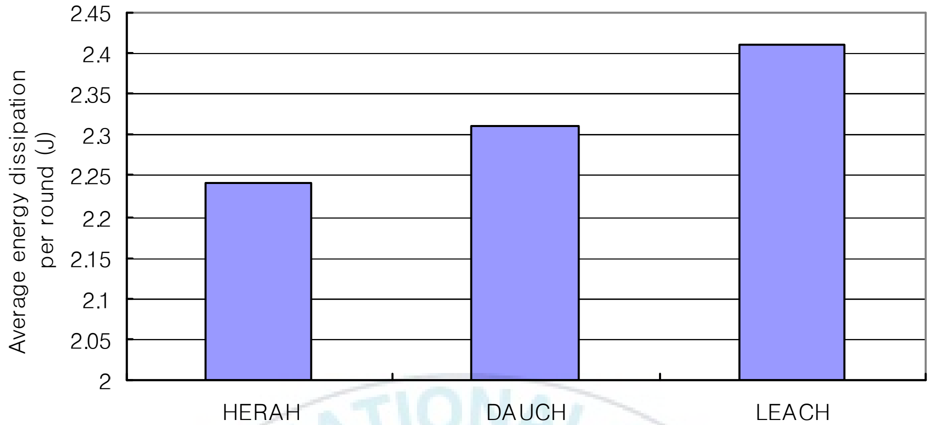


Figure 13. Analysis of the average energy dissipation per round

Ⅵ. Conclusion

This thesis proposes HERAH that is the hierarchical routing algorithm in WSNs and is established on heterogeneous environment. HERAH combines the energy aware cluster head election technique with DAG which constructs an efficient cluster in DAUCH and has two types of nodes: CM (Cluster Member) node, CHC (Cluster Head Capable) node. CM nodes do the basic sensing as well as the data aggregation of packets within each cluster but cannot become CH. CHC nodes can be CH, do the data aggregation within each cluster and directly transmit the aggregated data to BS. And CHC nodes have higher battery energy than CM nodes. The proposed algorithm outperforms DAUCH by eliminating the case that CH node exhausts its own energy while it plays a role of CH. According to simulation results, HERAH improves the number of data signals received at the BS, network lifetime, and average energy dissipation per round comparing with LEACH and DAUCH. These results mean that HERAH has better energy efficiency than LEACH and DAUCH. Therefore, it is concluded that HERAH provides an energy-efficient routing scheme suitable for a vast range of WSN applications.

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이종 무선 센서 네트워크를 위한 계층적 에너지 인지 라우팅 알고리즘 연구

박 진 호

부경대학교 대학원 정보통신공학과

요 약

최근 정보기술 패러다임의 변화과정 속에서 유비쿼터스 컴퓨팅(ubiquitous computing)이라는 개념이 새롭게 부상하고 있다. '유비쿼터스 정보기술'로 일컬어지는 이 개념은 이미 단순한 개념적 구상이나 기술적 맹아의 단계를 뛰어넘어 새로운 패러다임으로 부상하고 있다. 특히 우리나라의 경우 정보통신부에서 진행하고 있는 u-IT839 정책의 지원 아래 이에 대한 연구를 계속하고 있다. 그 중 유비쿼터스 센서 네트워크(USN: Ubiquitous Sensor Network)는 u-IT839 정책에서 가장 중요 기술 중의 하나로써, 유비쿼터스 정보기술의 핵심기술로 여겨지고 있다.

USN 은 전자태그 또는 센서를 이용하여 사물과 환경 정보를 수집하고 네트워크를 통하여 실시간 정보를 구축·관리할 수 있는 환경을 제공한다. 또한, USN 은 다양한 분야에 대해 자동화가 가능하게 하며, 이러한 기술을 통해 텔레매틱스, 홈네트워크, 제고관리, 환자관리, 동물관리, 자연재해관리, ITS 시스템 등 인간에게 편리한 다양한 서비스를 제공할 수 있다. 이러한 USN 서비스를 제공하기 위해서는 USN 환경의 기반이 되는 무선 센서 네트워크(WSN: Wireless Sensor Network)에 대한 연구가 필수적이다. 특히 제한된 에너지 자원들을 가지는 센서 노드들로 구성된 WSN 의 특징으로 인하여 망 수명에 직접적으로 영향을 끼치는 에너지 효율성이 핵심 연구 과제로 부각되고 있다. 그에 따라 많은 종류의 에너지 절약 알고리즘들이 연구되고 있으며, 특히 여러 에너지 효율적인 라우팅 기술들이 WSN 을 위해 개발되고 있다.

이에 본 논문에서는 이종 센서 노드를 사용하여 전체적인 노드 생존시간을 동일하게 하는 기법을 적용하고, 클러스터를 형성 후 해당 클러스터 내의 수집된 데이터를 클러스터 헤드를 통해 BS 로 전송하는 새로운 알고리즘을 제시한다. 특히 클러스터 내의 센서 노드에서 클러스터 헤드로 데이터 전송 시 멀티 홉을 이용하

여 데이터 통합을 수행하고, 클러스터 헤드 선택 시 잔여 에너지의 양에 따라 클러스터 헤드를 선택함으로써 에너지 효율성을 향상시킨다. 그리고 시뮬레이션 결과를 통해 BS 에서 수신된 시그널 수, 시간에 따른 생존 노드의 수, 라운드당 평균 소비 에너지 분석을 통해 제안한 알고리즘의 성능이 우수함을 평가한다.

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