Applying Cluster Merging and Dynamic Routing Mechanisms to Extend the Lifetime of Wireless Sensor Networks

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***Abstract*:** In recent years, the applications of wireless sensor networks have increased steadily. Sensor nodes are often scattered outdoors and their energy consumption depends heavily on the area of coverage and network topology. Many studies were focused on saving the energy of sensor nodes to maintain their functionality. This work aims at extending the lifetime of a wireless sensor network by using cluster merging and dynamic routing mechanisms. Cluster merging can increase the number of sensor nodes in a cluster to balance its energy consumption; dynamic routing prevents the cluster heads from exhausting electric power by forwarding data through detoured routes. The simulation results show that cluster merging followed by dynamic routing is more efficient in extending network lifetime. The best combination of the above two mechanisms is to set the threshold of the remaining energy to 90% for applying cluster merging and 10% for applying dynamic routing, which results in the lifetime about 9 times that of a wireless sensor network without using the adaptive mechanisms.

***Keywords*:** wireless sensor networks, energy saving, adaptive mechanisms, cluster merging, dynamic routing, network lifetime.

1. Introduction

As the advance of technologies in microelectronic systems, wireless communication, and embedded processing, a small sensor device combining with the functions of computation and communication in one piece can be used to detect the environmental changes, such as temperature and humidity, and send the data to the base station for analysis through wireless transmission. There have been many applications in wireless sensor networks, e.g., the control and monitoring of battle fields for military purposes. Now these devices can also be applied to commercial applications like manufacturing flow controls, home appliances and office automation [1]. When the sensor devices were first introduced, the major concerns were the cost, size, and energy consumption because of their limited computation speed, memory and power capabilities. Since the transmission distance also affects the energy consumption, it is another factor to be considered.

A wireless sensor network consists of sensor components, microelectronic systems and a wireless network [2]. The sensor devices contain four basic units: power supply, central processing, data communication and sensor component. With the advance of microelectronics, a small and low-power sensor has become more affordable today. Therefore, it is important to deploy the sensor devices using efficient routing protocols for reducing energy consumption. When selecting wireless communication protocols, the compatibility and market acceptance are the major issues under consideration. In home automation, IEEE 802.15.4 (Low-Rate Wireless Personal Area Networks) combined with ZigBee has become the most popular deployment for many manufacturers.

Usually, sensor devices are scattered outdoors and exposed to different weather conditions, and their energy consumption depends heavily on the network topology. For example, when they are deployed on a farm to monitor the growth of crops, the energy consumption has become an important factor affecting their lifetimes. A few studies were conducted to reduce energy consumption using dynamic routing protocols. Chen *et al.* [3] proposed an energy-efficient protocol for wireless sensor networks, which can be applied to a broad spectrum of application environments. Tang and Xu [4] investigated the tradeoff between data quality and energy consumption regarding the lifetime of wireless sensor networks, and they proposed an adaptive scheme to extend network lifetime by adjusting the precision constraints at the sensor nodes.

In general, wireless sensor data can be transmitted in two ways, i.e., direct transmission or forwarding. The former sends data to the base station directly for further processing; the latter sends data by forwarding to some other nodes before reaching the base station. Each method has its merit depending on the applications and routing protocols. From the viewpoint of network topology, the routing protocols can also be classified into general topology and cluster topology. Some routing protocols in clustered wireless sensor networks are described in the following.

Clustered wireless sensor networks are categorized as heterogeneous and homogeneous according to the features and functionality of sensor nodes. In wireless sensor networks with heterogeneous sensor devices, the cluster head has better equipment than the regular sensor node, such as power supply, computing capability, memory, and even with the function of data compression [5]. The major purpose of a heterogeneous system is to reduce the energy consumption of regular nodes by preventing them from sending data over a long distance to the base station. This type of networks is not concerned in this study because it is more expensive and can not tolerate the failure of cluster heads.

A routing protocol was proposed by Schurgers and

Srivastava [6] to enhance the energy efficiency in clustered wireless sensor networks based on a sensor node's location, energy consumption and residual battery capacity. PEGASIS [7] operates by connecting sensor nodes in series, starting from the farthest node to the base station, to form a linked structure. When all nodes are connected, the head of the link structure is selected and data transmission starts by sending data from each node towards the head. The data received by the head will be forwarded to the base station.

The low-energy adaptive clustering hierarchy (LEACH) proposed by Heinzelman *et al.* [8] is a well-known hierarchical routing protocol applied in clustered wireless sensor networks because it can balance energy consumption within a cluster to extend the network lifetime. Its operation contains two stages, i.e., *initial stage* and *stable stage*. In the initial stage, the base station selects a few nodes as cluster heads based on random thresholds, and the other nodes join nearby clusters by sending out signals to discover the nearest cluster heads. When clusters are formed, the network enters a stable stage. Each node starts to sense and transmit data to its cluster head, which will then forward data to the base station along with its own data. Since the cluster head will consume more energy, it must be replaced regularly to prevent power exhaustion.

Handy *et al.* [9] proposed a centralized version of LEACH to replace its distributed operation to extend the network lifetime. During the initial stage, each sensor node sends its position and energy condition to the base station, which will then select cluster heads according to the received information. The selected cluster heads start to transmit data to the base station afterwards. This approach can effectively extend the network lifetime, but its drawback is that distant cluster heads will consume energy quickly.

The Threshold sensitive Energy Efficient sensor Network protocol (TEEN) proposed by Manjeshwar and Agrawal [10] is also based on LEACH to transmit sensor data to the base station periodically. TEEN sets two threshold values, i.e., *hard threshold* and *soft threshold*, to avoid the transmission of duplicated sensor data. This approach can save energy, but it is not suitable for the applications requiring periodical data since the threshold values may not be met in occasion. Therefore, a revised version of TEEN was proposed [11] later to remedy the drawback by reporting data periodically to react to sudden events in real time.

Recently, a number of studies were focused on reducing the power consumption of sensor nodes in wireless sensor networks. This work aims at extending the lifetime of wireless sensor networks by using cluster merging and dynamic routing mechanisms. The selection of cluster heads is based on the high-energy-first scheme proposed by Huang *et al.* [12]. Cluster merging can increase the number of nodes in a cluster to balance the energy consumption of cluster heads; dynamic routing prevents cluster heads from exhausting their electric powers by forwarding data through available detoured routes. In addition, the network lifetime can be further extended by the data aggregation and sleep mode methods.

Data aggregation is an essential and efficient paradigm for wireless routing in sensor networks, and its idea is to combine the data from different sources by eliminating redundancy to reduce the amount of data. Another power-saving technique is used to schedule the sensor nodes to alternate between active and sleep modes. The sensor nodes in a cluster are organized into two sets such that only one set is responsible for monitoring the targets and the other set is in sleep mode. This study uses the data aggregation [13] and sleep mode [14] methods to further reduce energy consumption during data sensing and transmission.

Usually, the cluster-based routing mechanisms try to increase the lifetime of wireless sensor networks. Therefore, saving power is of great importance in a wide-range sensing environment. A static clustering algorithm configures the sensor nodes into a number of clusters of similar size. Usually, the cluster heads near the base station will consume more energy by forwarding data for other clusters. Thus, it is better to increase the cluster size near the base station using cluster merging mechanism to balance energy consumption. However, cluster merging should not be applied too early because sensor nodes may consume more energy by sending data to their cluster head through a longer distance.

The major purpose of a dynamic routing protocol for wireless sensor networks is to find an efficient route for transmitting data to the base station for reducing energy consumption. The dynamic routing mechanism proposed in this study also tries to find the shortest route for sending data by multi-hop forwarding. When a cluster head refuses to forward data due to insufficient electric power, the mechanism will find another feasible route in the direction of base station for transmitting data. When there are no cluster heads in the direction of the base station to be selected as forwarding nodes, the cluster head will transmit data directly to base station if it is within the reachable range, or it will use a detoured route to maintain a high receiving ratio.

The network topology and forwarding routes can be reconfigured by the adaptive mechanisms described above to extend the network lifetime. The simulation results show that cluster merging followed by dynamic routing is more efficient in extending the network lifetime. The best combination for applying the adaptive mechanisms is to set the threshold of cluster merging at the time when the remaining energy of the cluster head equals 90% and the threshold of dynamic routing as 10%, which together can result in the longest network lifetime, about 9 times that of regular networks without using the proposed mechanisms.

The remainder of this paper is organized as the following. Section 2 describes the system model of wireless sensor networks considered in this study and the parameters for calculating energy consumption in a sensor node. Section 3 describes the adaptive mechanisms proposed in this study. Section 4 provides the simulation results and data analysis; Section 5 is the conclusion and future work.

2. System Model

In this study, the wireless sensor network under investigation is divided into several clusters of the same size. Each cluster will select a cluster head to collect and forward data for the other nodes in this cluster. The high-energy-first scheme is used to determine the cluster head and its purpose is to have all nodes play the role of cluster heads in turn to balance energy consumption. When the system starts its operation, regular nodes send out collected data to the cluster head, and then the cluster head forwards data to the base station through its neighbor cluster heads using the dynamic routing mechanism (Figure 1). In the following, the energy consumption for each node and the cluster head is analyzed.

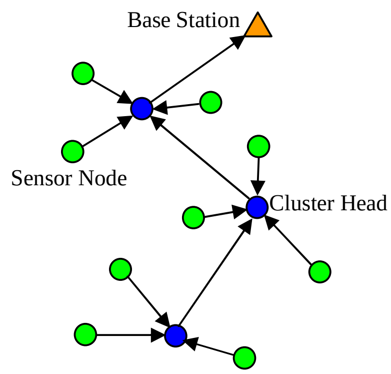

Figure 1. Data transmission in a wireless sensor network

Since routing protocols play an important role in saving the energy of wireless sensor networks, the main objective of this study is to extend the lifetime of wireless sensor networks by using a dynamic routing mechanism. In order to evaluate the lifetime of a wireless sensor network, it is required to analyze the energy consumption of a cluster head and a regular sensor node. The parameters related to energy consumption in sensor nodes [15] are listed in Table 1.

Table 1. Parameters of energy consumption for sensor nodes

n: number of nodes per cluster
f : data records received from neighbor clusters
ε: amplifier consumption
E_t : energy in transmitting data
E_r : energy in receiving data
ℓ : data amount
ℓ_a : data amount after data aggregation
E_a : energy consumption in data aggregation
d_{cc} : distance between cluster heads
d_{nc} : distance between cluster head and sensor node
E_h : energy consumption in deciding cluster head
x: data records per round

In a wireless communication system, the energy loss of a signal is related to its transmission distance. Equation (1) shows the energy consumed when passing through an amplifier. Using d_0 as a threshold, if transmission distance is smaller than d_0, the free-space propagation model is used to calculate the consumed energy, which is proportional to the square of distance; when transmission distance is greater than d_0, the two-ray ground propagation model is used for calculation and the consumed energy is proportional to the fourth power of distance. In that case, the consumed energy has a great influence on the network lifetime.

$$\text{Energy consumption by amplifier} = \begin{cases} \varepsilon_{fs} \times d^2, \text{if } d \le d_0 \\ \varepsilon_{tr} \times d^4, \text{if } d > d_0 \end{cases} \quad (1)$$

In the above equation, ε_{fs} and ε_{tr} are the parameters for the free-space propagation model and two-ray ground propagation model with values equal to 10 pJ/bit/m^2 and 0.0013 pJ/bit/m^4, respectively; d_0, defined as $\sqrt{\varepsilon_{fs}/\varepsilon_{tr}}$, is the threshold of transmission distance and its value is about 87.7 m. Considering the effect of transmission distance, it is assumed that the grid area is 70m×70m when dividing the clusters. In that case, the cluster heads will not consume too much energy in forwarding data even if they are diagonally placed, i.e., d_0 is less than 100m.

For regular sensor nodes, the computation of consumed energy E_{sn} is simpler because the transmission distance is less than 100 m, as shown in equation (2). When the cluster merging mechanism is applied, the cluster size may increase and the energy consumption will become proportional to the fourth power of transmission distance.

$$E_{sn} = (\ell \times E_t) + (\ell \times \varepsilon \times d_{nc}{}^2) + E_h \quad (2)$$

The energy consumed by cluster heads contains two parts: energy consumption in transmitting local data and energy consumption in forwarding data for regular nodes. The energy consumed in deciding cluster heads is negligible because receiving signals from the base station dose not require too much energy; detecting the forwarding cluster head also requires a small amount of energy and thus can be neglected. This study considers mainly the energy consumption in transmitting and receiving data and doing data aggregation within a sensor device. Especially, the distance of transmission is an important factor.

Equation (3) shows the energy consumption of a cluster head, denoted by E_{ch}. Inside the first pair of parentheses is the energy consumption for data aggregation and transmission, and the rest part is the energy consumption for the cluster head to forward *x* records of data for the other nodes.

$$E_{ch} = \{[\ell \times E_r \times (n-1)] + [\ell \times E_t \times n] + [\ell \times \varepsilon \times n \times d_{cc}{}^2] + [\ell \times E_{data} \times n] + E_h\} + x \times \{[\ell_{data} \times E_r \times f] + [\ell_{data} \times E_t \times f] + [\ell_{data} \times \varepsilon \times f \times d_{cc}{}^2] + E_h\} \quad (3)$$

3. Adaptive Mechanisms

In this study, the operation of adaptive mechanisms consists of two stages: initialization stage and operation stage (Figure 2). The initialization stage includes dividing clusters and the distribution of sensor nodes. The operation stage includes: data sensing, collection, and transmission. This study divides the environment into a number of small areas (35m×35m) for the distribution of sensor nodes. Each small area is distributed with a fixed number of sensor nodes and their positions are determined by a pseudo random number generator to simulate the real situations in deployment. During operation stage, the base station uses high-energy-first scheme to select cluster heads, and then the cluster heads determine the forwarding nodes for transmitting data. This study uses *data aggregation* and *sleep mode* to reduce energy consumption in each cluster. In addition, *cluster merging* and *dynamic routing* mechanisms can also be applied to balance energy consumption during operation stage.

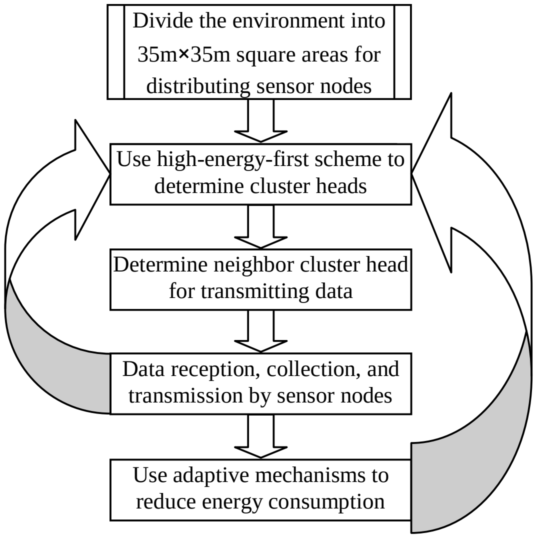

Figure 2. Flowchart of applying the adaptive mechanisms

3.1 High-Energy-First Scheme

In LEACH, a sensor node with a longer time as a regular node has a higher probability to be selected as the cluster head. Although this may initially seem reasonable, a recently retired cluster head still has a chance to be selected again, which may lead to fast exhaustion of its electric power. Therefore, this study adopts the high-energy-first scheme to remedy this drawback. A sensor node will send out data together with the information of its remaining electric power. The base station can then decide which nodes are to be selected as cluster heads in the next round using broadcast messages.

3.2 Determination of Forwarding Nodes

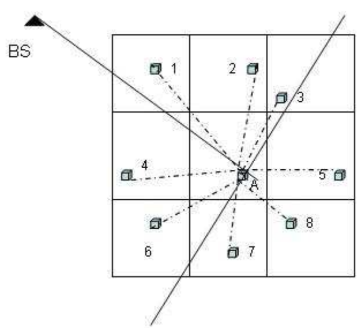

Figure 3. Determination of the forwarding node

In each round, a cluster head has to determine the forwarding node, which is also a cluster head in neighbor clusters. The most direct forwarding route is determined based on the angle between the directions of the base station and the candidate forwarding node. The neighbor cluster head with the smallest angle is chosen first as the forwarding node, and the goal is to use the shortest forwarding route to reduce energy consumption. For example, cluster head ***A*** in Figure 3 will select node 1 as the forwarding node, unless its remaining electric power is below the threshold. If node 1 is not available, node 4 will be selected next. This method can save energy by choosing the shortest route in forwarding data.

3.3 Data Aggregation and Sleep Mode

In wireless sensor networks, the amount of data transmitted can also affect the energy consumption. When a cluster head detects the same or similar data packets are being transmitted, it can use data compression method to filter out similar data packets. This method can reduce the amount of data and therefore save some energy. Sleep mode can also reduce energy consumption effectively in wireless sensor networks. In this study, a grouping method is used to divide sensor nodes into a number of groups in a cluster. The following example shows how to divide the sensor nodes in a cluster into groups for the execution of sleep mode (Figure 4).

- Select the cluster head using the high-energy-first scheme (node 1).
- Combine half of the remaining nodes with the shortest distance as a group (node 3 and node 4)
- The rest nodes form the other group (node 2 and node 5).

In each group, the node with more electric power is selected as the active node, and the other nodes enter sleep mode. For example, node 3 and node 5 are active while node 2 and node 4 are in sleep mode. The cluster head (node 1), the only node to form a group in its cluster, is also in operation.

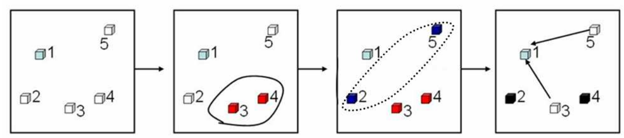

Figure 4. The grouping method and operation of sleep mode

The main objective of the grouping method is to evenly distribute active nodes in each cluster to reduce data repetition. The purpose of sleep mode is to decrease the amount of data transmitted. The ratio of active nodes and group size can be adjusted according to the requirement of data precision.

3.4 Adaptive Mechanisms

In this study, it is assumed all sensor nodes are homogeneous, so they have the same electric power initially. However, the cluster heads have to perform data aggregation and forwarding such that they will consume more energy. In each round, every node will be notified of its role to play, and start to sense the environment no matter what the role is. A regular node will send the obtained data to its cluster head upon the completion of sensing task and then enter the idle state. A cluster head will transmit the collected data within its cluster to the forwarding node; in the mean time, it can also receive data from other cluster heads. In order to preserve some energy for sensing data, a cluster head can refuse forwarding data for other clusters when its remaining energy is below the threshold. Two adaptive mechanisms are proposed in this study for extending the network lifetime, i.e., cluster merging and dynamic routing, and their operation is described in the following.

3.4.1 Cluster merging

The goal of cluster merging is to increase the number of sensor nodes in a cluster to balance the energy consumption of a cluster head by merging neighbor clusters into a larger cluster. When the remaining electric power of a cluster head is below the threshold, the cluster merging process is invoked to combine four adjacent clusters (35m×35m) into a larger cluster (70m×70m). The number of nodes in the merged cluster has increased and the network lifetime can be extended because more nodes have joined to balance the power consumption of the cluster head.

The following example shows the process of cluster merging (Figure 5). Initially, all cluster heads have enough electric power to transmit data to the base station (Figure 5(a)). After a certain time, the electric power of a cluster head drops below the threshold, which invokes the cluster merging immediately. Then, more nodes in the merged cluster with sufficient electric power can be selected as the cluster head to prevent the occurrence of a dead cluster (Figure 5(b)).

After several rounds, the electric power of all sensor nodes in the merged cluster may drop below the threshold again due to heavy workload. As a result, the cluster head will stop forwarding data for other clusters. When the neighbor cluster heads detect this situation, they start transmitting data to base station directly if the distance is within the reachable range. The low-power cluster head only needs to use the remaining energy to transmit data for its own cluster (Figure 5(c)), and thus save the energy in forwarding data for other cluster heads. The cluster merging process continues as required, and the network lifetime can be extended due to balanced energy consumption (Figure 5(d)).

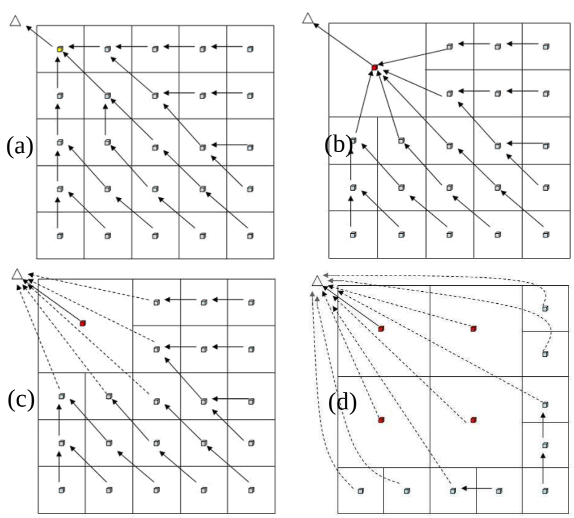

Figure 5. Operation of the cluster merging mechanism

3.4.2 Dynamic routing

As described earlier in this section, a cluster head decides its forwarding node by finding the shortest route for forwarding data to the base station to reduce energy consumption. However, the cluster heads in neighbor clusters may refuse to forward data due to insufficient electric power. In that case, the cluster head initiates the dynamic routing mechanism to forward data through another feasible route when its request is declined by a certain cluster head.

As shown in Figure 3, cluster head ***A*** selects node 1 as its forwarding node initially, but the request is declined due to low electric power in node 1; it then selects the node with the second smallest angle, i.e., node 4, but is declined again. Then, it selects the node with the third smallest angle, i.e., node 2, but still in vain. The process continues until there are no forwarding nodes in the direction of the base station for selection. After that, the cluster head tries to transmit data to the base station directly if it is within the reachable range; otherwise, it will turn to request the nodes in the direction greater than 90 degree as a last resort.

When a cluster head has to request a forwarding node deviating from the direction of the base station, it means most nodes in the direction of the base station are in low-power conditions. Instead of giving up at this moment, the cluster head tries its best by using a detoured route to transmit data to the base station since the goal is to maintain a high receiving ratio. Figure 6 shows the final situation of dynamic routing process when most inner cluster heads around the base station refuse to forward data for the outer cluster heads. The inner cluster heads still reserve some electric power which can be used to send data directly to the base station. In the mean while, the outer cluster heads try to find some feasible routes for sending data to the base station.

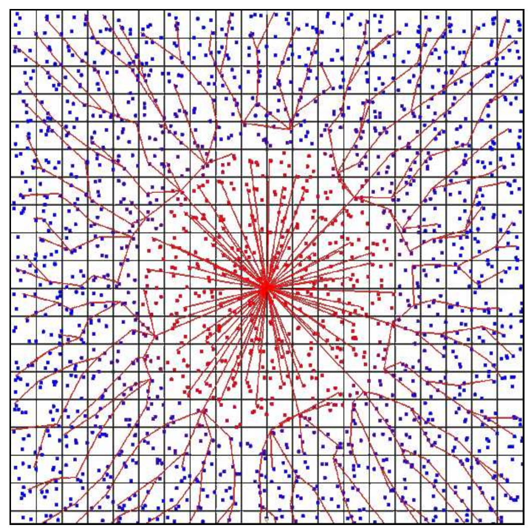

Figure 6. The final situation of dynamic routing process

4. Simulation Results

The goal of this study is to propose two adaptive mechanisms to extend the life time of clustered wireless sensor networks. This study adopts data aggregation and sleep mode to reduce the data amount, and utilizes cluster merging and dynamic routing mechanisms to balance the energy consumption of cluster heads. Simulation experiments were conducted to find out the near optimal threshold values for applying the cluster merging and dynamic routing mechanisms. Other related issues such as finding the suitable locations for the base station and the proper order for applying these two adaptive mechanisms were also investigated.

The simulation was performed on a VB.NET platform. The size of the simulated environment is 700m×700m and there are 2000 sensor nodes distributed in this area. The environment is divided into 400 small areas of size 35m×35m which contains a fixed number of sensor nodes. The longest transmission distance for a senor node is 200m, and the energy consumptions for transmitting and receiving data are the same, both equal to 50nJ/bit. Each data aggregation takes 5nJ/bit with the compression rate equal to 70%. The parameters for transmitting amplifier are ε_{fs} =10pJ/bit/m^2 and ε_{tr} =0.0013pJ/bit/m^4 with the data rate equal to 160 bit/sec. The wireless sensor network is defined as failed when the receiving ratio is below 98% or a dead cluster occurs.

4.1 Location of Base Station vs. Network Lifetime

The location of base station has great influence on the energy consumption of sensor nodes. To find out a better location for the base station, a simulation was performed to investigate the lifetime of a wireless sensor network with three different locations of the base station, i.e., upper left (Figure 7), left (Figure 8), and center (Figure 9). The simulation did not apply the cluster merging and dynamic routing mechanisms, but it compared the results of using or without using data aggregation and sleep mode by the static routing protocol (forwarding data in the direction of the base station) and LEACH without sleep mode or data aggregation as well.

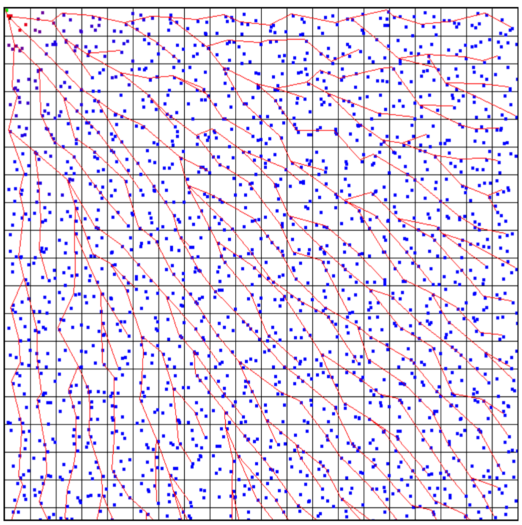

Figure 7. The base station is at the upper left corner

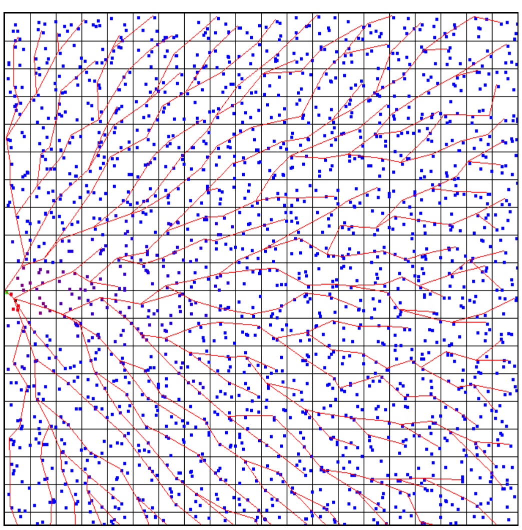

Figure 8. The base station is on the left side

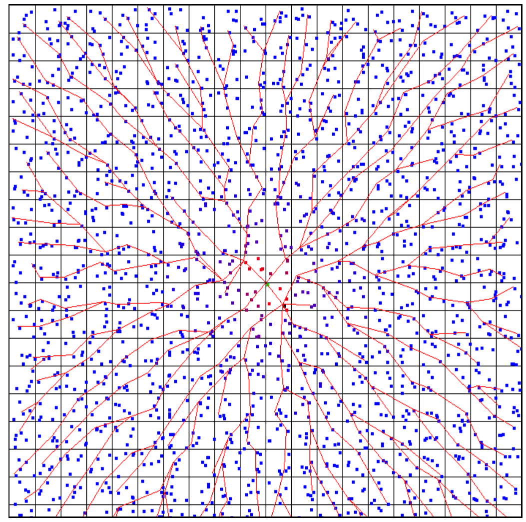

Figure 9. The base station is at the center

As shown in Table 2, the lifetime of the wireless sensor network is longer when the base station is at the center. This is due to balanced energy consumption for the sensor nodes around the base station. In addition, sleep mode and data aggregation can also effectively extend the network lifetime.

Table 2. The location of base station vs. network lifetime

Location of base station	Upper Left	Left	Center
Static routing protocol with sleep mode and data aggregation	1053	1458	2120
Static routing protocol without sleep mode or data aggregation	535	726	1694
LEACH without sleep mode or data aggregation	523	716	1564

4.2 Order of Applying Adaptive Mechanisms

There are two adaptive mechanisms proposed in this study for extending the network lifetime, i.e., cluster merging and dynamic routing. The order and timing for applying these two mechanisms have great influence on network lifetime. Figure 10 shows the simulation result of network lifetime with cluster merging followed by dynamic routing. It can be seen that the effect of dynamic routing is more significant than that of cluster merging. Furthermore, the later dynamic routing is applied, the longer the network lifetime becomes. However, the network lifetime without dynamic routing (or threshold y=0%) is about half that of the network with dynamic routing performed at threshold y=10% (Table 3).

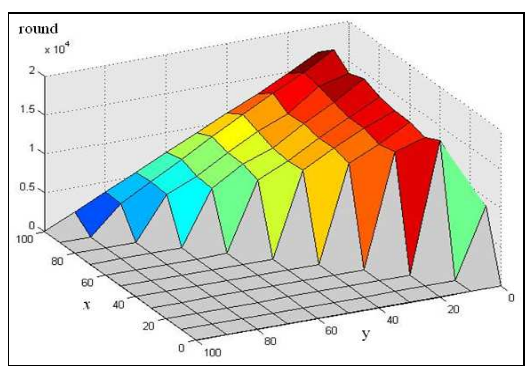

Figure 10. Network lifetime with cluster merging first

Figure 11 shows the simulation result of network lifetime by performing dynamic routing first. If dynamic routing is applied earlier (or its threshold is higher), the number of cluster heads refusing to forward data for other clusters will increase and it will cause more clusters not able to send data to the base station. Therefore, dynamic routing is better to be applied later to maintain a higher receiving ratio. If cluster merging is performed after dynamic routing, its threshold has almost no chance to be met since the network fails at the time when most cluster heads still have plenty of electric power. Therefore, cluster merging can not take place to improve network lifetime when it is applied after dynamic routing.

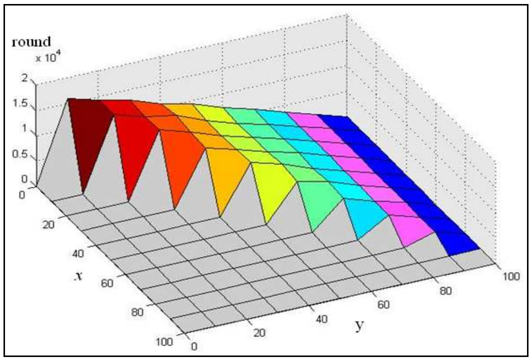

Figure 11. Network lifetime with dynamic routing first

4.3 Thresholds for Applying Adaptive Mechanisms

The above simulation results have suggested that it is better to apply cluster merging before dynamic routing (or to set the threshold of cluster merging higher than that of dynamic routing). Table 3 shows the simulation results of network lifetime with adaptive mechanisms applied under different combinations of threshold values, where *x* and *y* stand for the thresholds of rest energy by cluster heads (in percentage) to apply cluster merging and dynamic routing, respectively. The network lifetime (in rounds) is computed based on the average of 100 simulation results.

Table 3. Network lifetime vs. different threshold values

x	*y*	Lifetime	*x*	*y*	Lifetime	*x*	*y*	Lifetime
10	0	8960	60	40	10503	90	20	16323
20	0	9623	60	50	8773	90	30	14282
20	10	16629	70	0	10427	90	40	12254
30	0	9391	70	10	17575	90	50	10102
30	10	15621	70	20	15210	90	60	7861
30	20	14437	70	30	13175	90	70	5788
40	0	9791	70	40	10804	90	80	3651
40	10	16249	70	50	9398	100	0	11203
40	20	14077	70	60	6954	100	10	16800
40	30	12335	80	0	11034	100	20	14808
50	0	9523	80	10	16895	100	30	12839
50	10	16235	80	20	15955	100	40	11060
50	20	14727	80	30	13084	100	50	9244
50	30	12895	80	40	11531	100	60	7353
50	40	10711	80	50	9514	100	70	5510
60	0	10280	80	60	7187	100	80	3650
60	10	16650	80	70	5496	100	90	1825
60	20	14733	90	0	11351			
60	30	12715	90	10	18553			

The purpose of cluster merging is to increase the number of sensor nodes within a cluster to balance the energy consumption of cluster heads. The above results have shown that a higher threshold for cluster merging can lead to a longer network lifetime. However, if a larger cluster size 70mx70m is used directly at the beginning (or set the threshold of cluster merging to 100%), the regular nodes will consume more energy when sending data to their cluster heads (Figure 12) and thus the network lifetime may not be the longest. On the other hand, if cluster merging is applied too late, the cluster heads near the base station will use up their energy quickly and become unable to forward data for the other clusters (Figure 13).

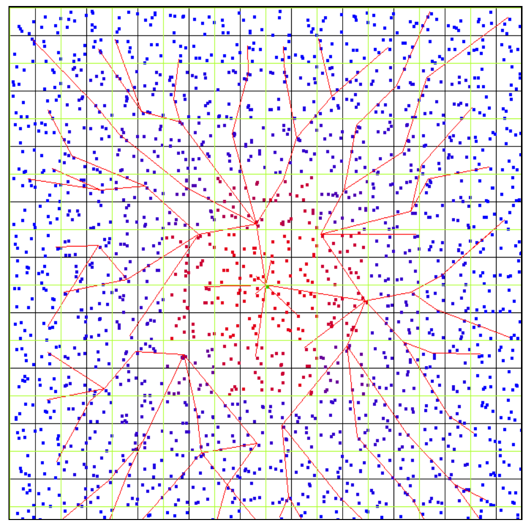

Figure 12. The case of applying cluster merging at the beginning (*x*=100%, *y*=10%, lifetime=16800)

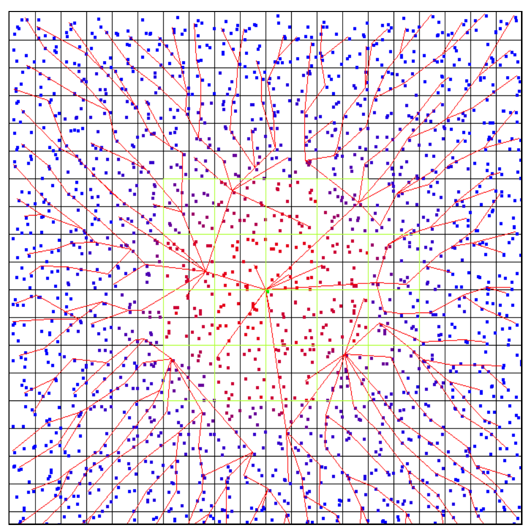

Figure 13. The case of applying cluster merging at a later time (*x*=30%, *y*=10%, lifetime=15621)

Different from cluster merging, dynamic routing is better to be applied at a later time. However, setting the threshold of dynamic routing to 0% (or without applying dynamic routing) is not the best case (Figure 14). On the other hand, applying dynamic routing too early may cause more cluster heads to refuse forwarding data for other clusters such that they must transmit data directly to the base station at a longer distance or forward data using detoured routes and thus consume more energy (Figure 15).

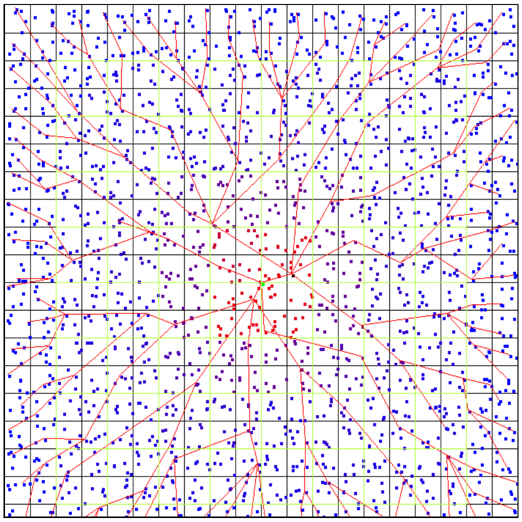

Figure 14. The case of without using dynamic routing mechanism (*x*=90%, *y*=0%, lifetime=11351)

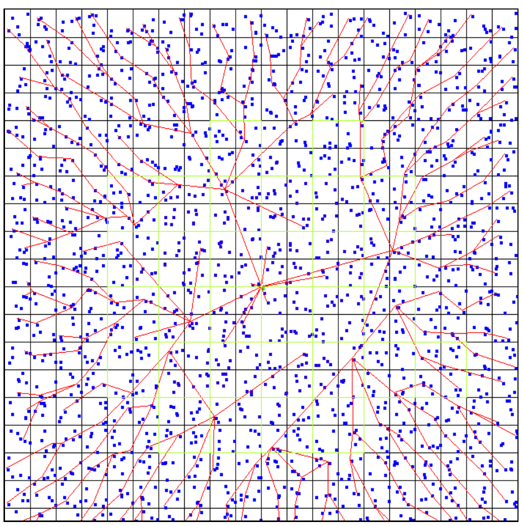

Figure 15. The case of applying dynamic routing at an early time (*x*=90%, *y*=80%, lifetime=3651)

According to the simulation results, the near optimal case for applying adaptive mechanisms is to set the threshold of cluster merging at *x*=90% and the threshold of dynamic routing at *y*=10%, which results in the longest lifetime. As shown in Figure 16, cluster merging near the base station can bring in more nodes to balance the energy consumption of cluster heads such that they can continue to forward data for other clusters. Even after cluster merging, a cluster head can refuse forwarding data for other nodes to save some energy for its own cluster when its energy is below the threshold value. Besides, in stead of giving up transmission when a forwarding request is declined, a cluster head can use detoured routes to forward data to the base station. This helps maintain a higher receiving ratio and extend the network lifetime to 18554 rounds, which is about 9 times that of a wireless sensor network without using the proposed adaptive mechanisms (as shown in Table 2).

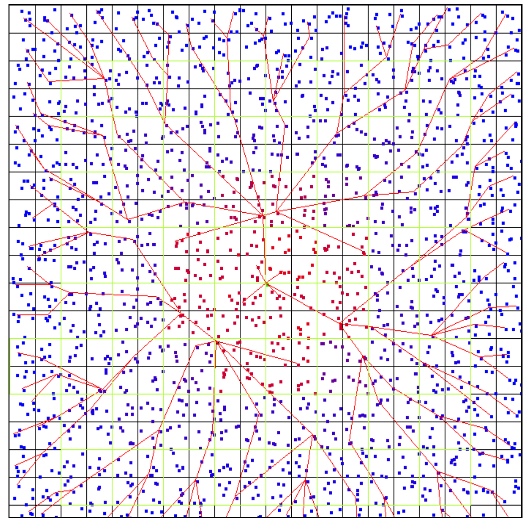

Figure 16. The near optimal case of applying the adaptive mechanisms (*x*=90%, *y*=10%, lifetime=18554)

5. Conclusion and Future Work

Wireless sensor networks enable the reliable monitoring of various environments for both civil and military applications. A number of studies have been conducted to extend the lifetime of wireless sensor networks by using dynamic routing protocols and data aggregation methods. This study proposed the combination of cluster merging and dynamic routing mechanisms as well as data aggregation and sleep mode; the network topology and forwarding routes can be reconfigured by the proposed mechanisms to extend the network lifetime and data receiving ratio. In specific, cluster merging can increase the number of nodes in a cluster to balance the energy consumption of cluster heads near the base station; and dynamic routing prevents cluster heads from exhausting their energy by forwarding data through a detoured route when a direct route is not available.

According to the simulation results, the location of base station has a great influence on the network lifetime, which is longer when the base station is at the center due to balanced energy consumption. In addition, data aggregation and sleep mode can also improve network lifetime by reducing the amount of data. This study investigated the order and energy thresholds for applying the adaptive mechanisms. The simulation results show that cluster merging followed by dynamic routing is more efficient in extending network lifetime. The near optimal combination for applying adaptive mechanisms is to set the threshold of cluster merging at 90% and the threshold of dynamic routing at 10%, which together can result in the longest lifetime of 18554 rounds, about 9 times that of a wireless sensor network without using the proposed mechanisms.

This study considered the lifetime of a wireless sensor network as the time when any sensor node has used up its electric power or can not transmit data to the base station. For practical applications, a wireless sensor network is considered useful if most of the sensor nodes can still operate correctly.

Thus, how to maintain an acceptable data receiving ratio is another issue about extending the lifetime of wireless sensor networks. The future works of this study may include how to increase the coverage area or receiving ratio of wireless sensor networks by balancing the power consumption of sensor nodes. Besides, an important factor affecting the lifetime of wireless sensor networks is the distribution of sensor nodes near the base station. How to change the distribution of sensor nodes to increase the lifetime of wireless sensor networks is another issue to be investigated.

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