Grid Clustering and Routing Protocol in Heterogeneous Wireless Sensor Networks (Short Paper)

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Abstract. In wireless sensor network, sensor nodes usually use batteries to provide energy, and energy consumption have very strict restrictions. High demands about the efficient use of energy are put forward. However typical multi to one communication mode in the wireless sensor network will lead to the uneven consumption of sensor nodes in the whole network. So it will greatly shorten the lifecycle of the entire network. As for this problem this paper optimize the model of heterogeneous chessboard clustering of sensor network and propose a grid clustering mechanism and propose an effective node routing protocol to achieve the goal of prolonging the network lifecycle by balancing the energy consumption of nodes. Simulation experiments show that the grid clustering protocol greatly improves the lifecycle of wireless sensor networks and has better performance compared with LEACH and LRS.

Keywords: Grid clustering · Routing protocol · Heterogeneous · Sensor network

1 Introduction

Recent advances in microprocessor, VLSI and wireless communication technologies have enabled the deployment of large-scale sensor networks where many low-power, low-cost small sensors are distributed over a vast field to obtain fine-grained, high-precision sensing data. These sensor nodes are typically powered by batteries and communicate through wireless channels, and are usually scattered densely and statically.

Sensor nodes usually operate on a nonreplaceable battery. A large proportion of a node'senergy resource is consumed in forwarding data. A major design challenge in sensor networks is to increase the operational lifetime of the network as much as possible by employing energy efficient routing. Many routing protocols have been proposed for sensor networks, such as Directed Diffusion, TTDD, and so on. However, most of the routing protocols did not consider the Uneven Energy Consumption problem in sensor networks. In typical sensor networks, the many-to-one traffic pattern is dominant, a large number of sensor nodes send data to the sink. Thus sensor nodes near the sink have much heavier traffic burden and run out of power much faster than other nodes. The short lifetime of these critical nodes dramatically reduces sensor network lifetime.

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Recently deployed sensor network systems are increasingly following heterogeneous designs, incorporating a mixture of sensors with widely varying capabilities. For example, in a smart home environment, sensors may be powered by AA batteries, AAA batteries or even button batteries. Some recent work starts considering heterogeneous sensor networks. Some paper studied the optimum node density and node energies to guarantee a lifetime in heterogeneous sensor networks, Du presented an energy efficient differentiated coverage algorithm (which can provide different coverage degrees for different areas in a sensor network) for heterogeneous sensor networks. Duarte-Melo and Liu analyzed energy consumption and lifetime of heterogeneous sensor networks.

Clustering-base schemes are promising techniques for sensor networks because of their good scalability and performance. Several clustering-based routing protocols have been proposed for sensor networks, like LEACH, TTDD, and LRS. LEACH and LRS include redundancy in the system by periodically selecting a cluster-head from the sensors in the network. However, these schemes suffer from overhead of frequent re-clustering. In addition, they did not solve the UEC problem near the sink.

2 The Uneven Energy Consumption Problem

Several existing routing protocols based on cluster take into account the problem of uneven energy consumption of nodes. In LEACH and LRS, periodically a cluster head is elected from the sensors to solve the uneven energy consumption in cluster heads. However, these schemes suffer from overhead of frequent re-clustering. Further more, rotating cluster-head among sensors does not solve the uneven energy consumption. Because no matter how to transform cluster-head nodes, the nodes around them always have a lot of communication pressure. Usually these nodes near cluster-head nodes are the key nodes. For example in Fig. 1, the base station node is located in the upper-right corner of the network. All nodes send data packets to the base station nodes by one hop or multi-hops. The sensors within one hop to the base station are the critical nodes and need to relay packets from all other nodes. When all the critical nodes fail, other sensor nodes will be disconnected from the base station, and the sensor network becomes unavailable. The uneven energy consumption problem exists no matter where the base station is located.

For a heterogeneous sensor network, it is reasonable to let the more powerful H-sensors become cluster-head nodes. Each L-sensor sends data to its cluster-head node, and cluster-head nodes forward data to the base station node. If H-sensors have sufficient energy supply, the heterogeneous sensor network solves the uneven energy consumption near the base station. Unfortunately, there is another uneven energy consumption problem in schemes with fixed cluster-head nodes. As for a typical cluster in Fig. 2, cluster-head nodes have a transmission range of r. The nodes within this distance from the cluster-head node are referred to as critical nodes. Every transmission of L-sensors in the cluster to the cluster-head node has to go through these critical nodes. Because these critical nodes are the last hop nodes for every communication link. Hence the critical nodes have the highest burden of tansmission, then these critical nodes will run out of their power much faster than other nodes. When the critical nodes

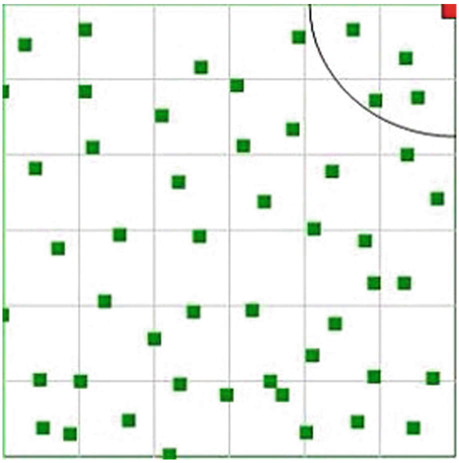

Fig. 1. Nodes near the base station consume more energy

drain out their energy and become unavailable, other L-sensors will not be able to send packets to the cluster head, and the entire cluster becomes unavailable even though the remaining energy in many sensor nodes are still high. The remaining energy in most nodes is wasted.

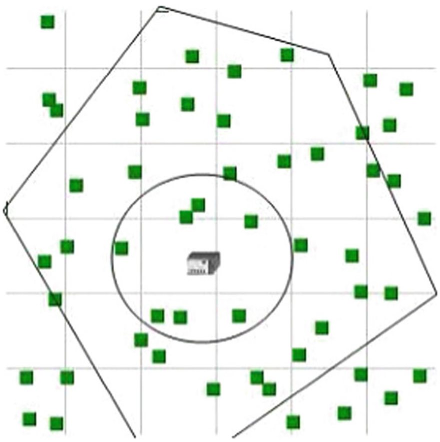

Fig. 2. Typical cluster stricter of sensor network, critical nodes in the circle

Simulation demonstrates the uneven energy consumption among sensor nodes in a cluster. The results are shown in Fig. 3. In the simulation, there are totally 73 sensors in the cluster. The number of sensor nodes that are 1-hop, 2-hop, 3-hop, and 4-hop away from cluster-head node is 7, 22, 29, 15. Each sensors sends to the cluster-head node one packet per second. Each node has a fixed amount of energy, and the nodes die when the energy is run out. The routing protocol used is the greedy geographic routing algorithm. Figure 3 shows the remaining energy in the sensors when all critical nodes run out of energy, where the x-axis signifys the remaining energy percentage. We can see that more than half nodes have higher than 50% energy left from Fig. 3, and this energy will be wasted in a real sensor network. The sum of all the remaining energy is equivalent to 38 sensores with full energy. This simulation demonstrates that there is still the problem of uneven energy consumption with fixed cluster-head nodes.

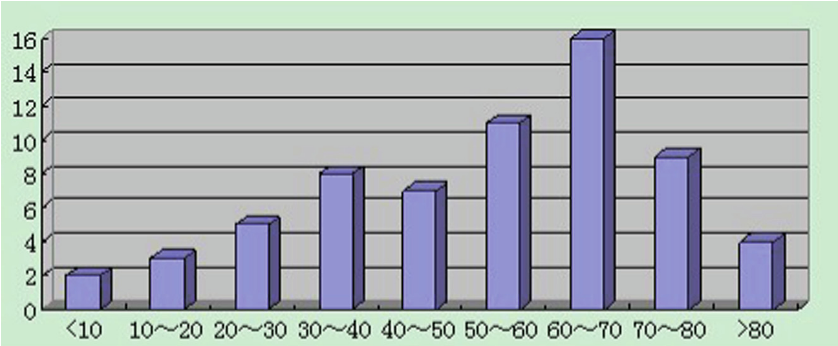

Fig. 3. The remaining energy of sensor nodes

In order to solve the uneven energy comsumption problem and prolong network lifecycle, while at the same improve the performance and measurability of routing mechanism based on clustering. We propose a novel chessboard clustering scheme for sensor network. The details are presented in next section.

3 The Chessboard Clustering Routing Protocol

In this section, we present the Chessboard Clustering routing protocol for heterogeneous sensor networks. We consider a heterogeneous sensor network consisting of two types of nodes: a small number of powerful High-end sensors (H-sensors) and a large number of Low-end sensors (L-sensors). Each sensor node is aware of its own location. Sensor nodes can use location services to estimate their locations, and no GPS receiver is required at each node.

First, we briefly present the idea of our chessboard clustering. The sensor network is divided into several equal-sized cells, adjacent cells are colored with different colors such as white and black. Figure 4 shows the struct of sensor network divided. The H-sensors and L-sensors are uniformly and randomly distributed in the field. Based on location information, H-sensors can determine if it is in a white cell or a black cell. During the initialization phase, only the H-sensors in white cells are active, and the H-sensors in black cells sleep. All L-sensors are active. Clusters are formed around the H-sensors in white cells, and these H-sensors become cluster heads. After a period of time when the H-sensors in black cells wake up and become new cluster heads. The network form a different set of clusters. Previous critical sensors become non-critical sensors, and previous non-critical sensors become critical sensors. Since critical sensors consume much more energy than other sensors, this shift balances the energy comsumption among sensors prolonging the network lifecycle.

Compared with the original chessboard, the improvement of the grid clustering has the following points:

(1) In the initial stage of cluster partition, in order to avoid the broadcast storm of ACK messages, the ACK message interruption mechanism is designed, which reduces the unnecessary forwarding of ACK messages, thus saving the energy cost of nodes.
(2) Based on the black and white grid transformation, a new scheme of partial adjustment of cluster structure based on the real-time congestion degree of communication links is put forward. This scheme improves the flexibility of cluster structure and transformation, reduces the data communication pressure in designated area timely and efficiently, and avoids unnecessary energy consumption of nodes.
(3) Chessboard clustering is used to convert black and white networks passively when the energy of the existing cluster heads is consumed, but it is often unreasonable. Because when cluster head nodes and the surrounding key nodes suddenly decrease in energy, it indicates that the existing cluster structure is no longer suitable for the data transmission pressure of the current communication link, resulting in the excessive consumption of cluster head nodes and key nodes. To solve this problem, the nodes in the grid cluster will monitor the energy usage of cluster heads in real time. When these situations happen, the black-and-white grid transformation will take the initiative to make changes based on the data communication pressure and avoid excessive energy consumption of some nodes.

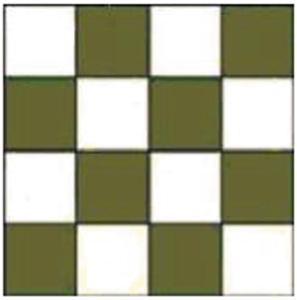

Fig. 4. Chessboard clustering scheme

3.1 Initial Cluster Formation

The initial division describe the following several steps:

(1) During the initialization phase, all H-sensors in white cells broadcast Hello messages to nearby L-sensors with a random delay. The random delay is to avoid the collision of Hello message from two neighbor H-sensors.
The hello message includes the ID of the H-sensor and its location. The transmission range of the broadcast is large enough so that most L-sensors can receive Hello message from at least one H-sensor.
(2) Then each L-sensor chooses the H-sensor whose hello message has the best signal ratio as the cluster head. Each L-sensor also records other H-sensors from which it receives the hello messages, and these H-sensors are listed as backup cluster heads in case the primary cluster head fails.
(3) If a L-sensor does not receive any hello message during the initialization phase, the node will broadcast an explore message to seek the nearest H-sensor.
(4) When the neighbor L-sensors receive the Explore message, they will response an ack message with a random delay. The ack message includes the location and ID of these L-sensors's cluster head.
A L-sensor will not send ack message again if it receive an ack response from neighbors. This mechanism reduces the number of messages and the comsumed energy.
(5) Then L-sensor can select a cluster-head node based on the ack message. This ensures all L-sensors have a cluster head.

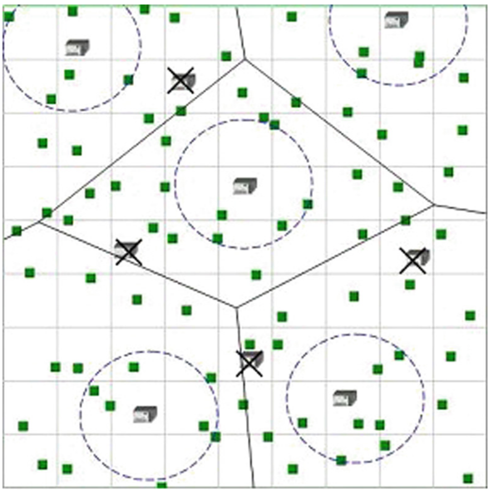

Fig. 5. Shows the initial cluster formation, the rectangle nodes are

Figure 5 shows the initial cluster formation, the rectangle nodes are H-sensors, and the square nodes are L-sensors. The L-sensors within circles are the critical nodes. The H-sensors with a cross are the H-sensors located in black cells, and they are not active until the second half period of the sensor network.

3.2 Re-formation of Cluster

In order to solve the problem of uneven energy consumption of nodes in sensor network, this paper adopts the method of re-formation of cluster while breaking the limit of the traditional cluster structure. The re-formation of cluster can achieve balanced energy consumption of nodes. The tansformation of cluster structure needs certain preconditions that can avoid more additional energy costs from too much transformation of cluster. Usually when the base stations find the following conditions, cluster will re-formate.

(1) The base station will real-time monitor the energy consumption of the working H-sensors. Base station nodes take into account the residual energy of these H-sensors. When the remaining energy is lower than a certain value, the base station node will start the transformation of the cluster.
(2) Base station nodes also monitor the data processing and transmission of communication links and sensor nodes in real time, when there is a high transmission rate of data in one area of the network, it is shown that the sensor nodes in this area have a large number of data to be transmitted to the cluster head nodes. At this point, the base station node will specify a H-sensor as a cluster-head node in the region.

According to the two cases above, the corresponding measures for the two kinds of transformation of clusters are given here. The first one is the black and white grid transformation under the sensor network. It involves the transformation of the cluster structure which is carried out in a whole network range and at a certain time interval. The second one is the adjustment of the cluster structure based on the real-time communication pressure of the communication link in the sensor network, which is the adjustment of the cluster structure in a certain area under the sensor network. The aim is to avoid the effect of uneven energy consumption on nodes of high data communication pressure in the region.

The first cluster transformation: For each active H-sensor in white cells, there is a pairing and sleep H-Sensor in the neighbor black cell. After a period of time, the base station node sends query information to the working H-sensors, asking the remaining energy in the nodes. Based on the overall energy usage of these nodes, the base station will decide whether to go on cluster tansformation. When the transformation is needed, the base station node sends the wake-up message to the H-sensor in the black grid and closes the working H-sensors. The wake-up H-sensors will build their own cluster structure according to the same process. After this transformation of cluster, before the L-sensor as a key node becomes the common node, the original ordinary L-sensor is likely to become a key node, so the transformation of the role can well balance the node energy consumption, to avoid the problem of the entire network failure due to the excessive consumption of energy.

After a series of operations mentioned above, new clustering results are formed in the network. Previously, the H-sensor in white grid was transformed into a sleep state by working state. Instead, the H-sensor in the black grid starts to work as the cluster-head node of the new cluster. Figure 6 gives the results after the grid cluster transformation. As you can see in Fig. 6, as a result of the formation of a completely different set of grid clustering results, most of the previous critical nodes become ordinary nodes with less energy consumption. The reformation of the cluster is equivalent to the reversal of the energy consumption pattern before, so it plays a role in the use of balanced energy.

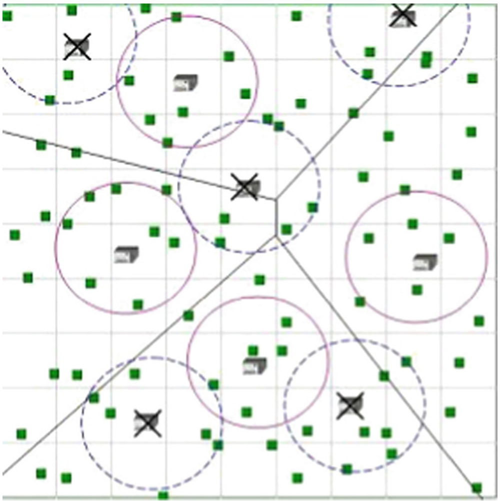

Fig. 6. The results of the grid clustering after the whole cluster transformation

The second cluster transformations: the base station node monitors the communication link in the sensor network in real time. If we find that the data transmission rate in the communication link is higher than the set value, it means that the sensor nodes on the communication link have large amounts of data to transmit to the cluster-head nodes. If these nodes are far away from the cluster head node, it needs a large number of intermediate nodes forwarding data, which leads to unnecessary energy cost of the intermediate nodes, and critical nodes located around the cluster-head nodes will have to bear the pressure of communication more, which leads to the excessive consumption of energy.

In order to solve these problems, the distance between the nodes of these high data transmission rates and their cluster-head nodes needs to be shortened. A simple and feasible method is specifying a nearest cluster-head node which is specially responsible for data transmission of nodes in this area by the base station node, the process of building cluster structure by cluster-head node is the same as that of the initial process of cluster. Only the nodes in this area retain the information of original cluster-head nodes. When the temporary cluster structure is cancelled, these nodes can use these information to establish links with the original cluster head nodes.

The adjustment of the local cluster structure can effectively reduce the data transmission pressure in the above area in a timely and effective way, thereby avoiding unnecessary overhead and uneven use of energy. When the communication link in this area has passed the peak period of the data transmission, at this time the communication pressure of the sensor nodes in the region will be much less. Before the specified cluster head node will be sleeping by the base station node, the sensor nodes in the cluster will re-select the original cluster head node as its cluster head node.

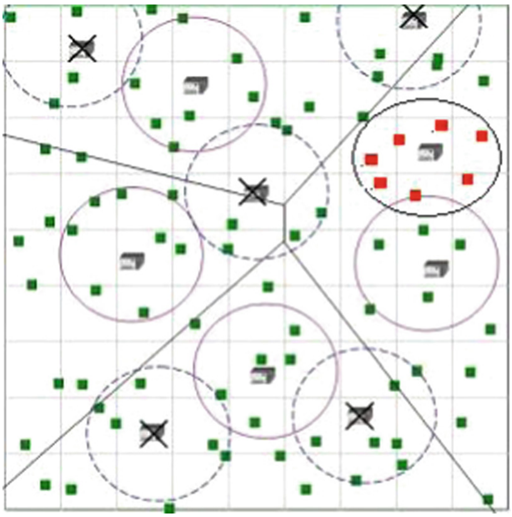

Fig. 7. The result of the adjustment of the local cluster structure (Color figure online)

Figure 7 is the clustering structure of sensor network obtained after second kind of cluster transformation. The red square is used to identify the sensor nodes with high data transmission rate. These nodes are located in the cluster structure represented by the black ellipse. This temporary cluster structure effectively reduces the data communication pressure in the region, thus solving the problem of the imbalance of energy consumption.

3.3 Routing Protocols of Intra-cluster and Inter-cluster

Here we discuss the routing scheme inside a cluster. Each L-sensor sends data packets to its cluster head. Since the location of the cluster head is known from the Hello message, a greedy geographic routing protocol can be used for intracluster routing. A L-sensor sends the data packet to the neighbor that has the shortest distance to the cluster head, and the next node performs the similar thing, until the data packet reaches the cluster head. Since nodes within a cluster are not far away from the cluster head, the greedy geographic routing should be able to route data packets to cluster head with high probability.

Cluster heads know the location of the base station node, and communicate with the base station node via multi-hop transmissions over other cluster heads. If enough number of H-sensors are uniformly and randomly deployed in the network, then with high probability a cluster head can directly communicate with a neighbor cluster head. After cluster formation in the network, each cluster head sends its location information to the base station node. Then the base station node broadcasts the locations of all cluster heads to each cluster head. When a cluster head wants to send data packets to the base station node, it draws a straight line L between itself and the base station node. Line L intersects with several cells, and these cells are denoted as C0, C1, …, Ck, which are referred to as relay cells. The packet is forwarded from the source cluster head to the sink via the cluster heads in the relay cells. The Inter-Cluster routing scheme is presented in the following. The cluster head initiating the transmission is referred to as source node S.

(1) Based on the location of source cluster-head node S and base station node, the source node determines the relay cells C0, C1, …, Ck, starting from the cell with node S. S records the relay cells in a cell_list field, which is stored in the header of the packet. The header contains the following fields: session_id, source_id, sink_id and cell_list. session_id plus source_id uniquely determines a data transmission session.
(2) First the data packet is sent from source node S to the cluster head H1 in cell C1. H1 gets the next hop relay cell based on the header information of the packet, where the next hop relay cell is C2. The packet which includes a next_cell field is broadcast to neighbor cluster heads. The neighbor node receives the broadcast packet and compares the next hop relay cell to its own cell. If it matches, it sends the response message to the broadcast node, letting the broadcast node know that it is the cluster head node of next relay cell.
(3) In each of the following forwarding processes, the following steps are carried out in turn. In order to ensure the reliability of each forwarding, every forwarding cluster head node should be responsible for confirming that its next hop forwarding cluster head node can successfully receive packet packets. This security mechanism needs to be implemented by every transmission node, and it needs to monitor whether the packets arrive at the next node in a certain time after the transmission. Of course, if the acknowledgement mechanism on the link is supported by the MAC layer protocol, for example, 802.11 has this function. The security mechanism mentioned above is not necessary. Because, under the MAC layer protocol, every packet that needs to be forwarded is saved in the buffer until the acknowledgement of the receiver is received, so as to prevent the failure of data packet transmission. This acknowledgement mechanism can reduce the impact of channel error.
(4) If a cluster head Hi does not get any acknowledgement within a time period, Hi will re-transmit the data packet to the next hop relay node once. And if the retransmission fails, Hi will find a backup path.

(5) A backup path is set up as follows. The current cluster head draws a straight line between itself and the base station node, and the line intersects with several cells $C'_1, C'_2, \ldots, C'_{k-1}, C_k$. If the next cell is the cell with the failed cluster head, the cluster head will use a detoured path to avoid the cell. Otherwise, the sequence of new cells $C'_1, C'_2, \ldots, C'_{k-1}, C_k$ will be the new relay cells. And the data packet is forwarded to the base station via the new relay cells.

An example of inter-cluster routing is shown in Fig. 8, where cluster head in cell C0 wants to send data packets to the base station, which is the square in the top-right corner. A straight line from the source cluster head to the base station is used to determine the original relay cells: C_o, C_1, C_2, C_3. If the cluster head in cell C2 is not available, the cluster head in cell C1 will use a backup path C'_2, C_3 to connect the base station.

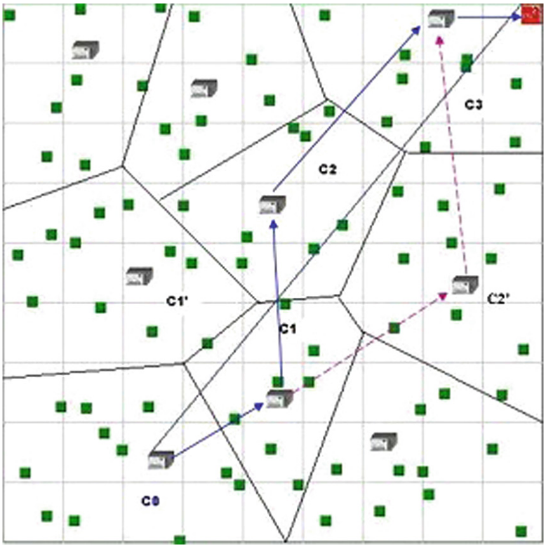

Fig. 8. An example of inter-cluster routing

4 Performance Evaluation of Protocol

We evaluate the performance of the chessboard clustering routing protocol through experiments, and compare chessboard clustering with two other clustering-based routing schemes: LEACH and LRS. LRS is a chain-based 3-level hierarchical protocol proposed. In this protocol, sensor nodes are initially grouped into clusters based on their distances from the base station. A chain is formed among the sensor nodes in a cluster at the lowest level of the hierarchy. Gathered data, moves from node to node, gets aggregated, and reaches a designated leader in the chain. At the next level of the hierarchy, the leaders from the previous level are clustered into one or more chains, and the data is collected and aggregated in each chain in a similar manner.

In the same simulation environment, the performance of the three protocols are compared, the default simulation testbed has 1 base station,1000 L-sensors and 40 H-sensors randomly, uniformly distributed in a 300 m × 300 m area. The transmission range of a H-sensor and a L-sensor is 80 m and 20 m respectively. Both H-sensors and L-sensors hava a fixed amount of energy supply-10 J and 2 J respectively.

4.1 Sensor Network Lifetime

First we compare the network lifetime for different sensor node density. The network lifetime here is defined as the time that no sensor can send packet to the base station. For the fixed 300 m x 300 m routing area, the number of L-sensors in chessboard clustering varies from 500 to 2000 with an increment of 500, while the number of H-sensors remains 40 for all cases. The numbers of L-sensors in LEACH and LRS are always 1.5 times the number of L-sensors in chessboard clustering, varying from 750 to 3000 with an increment of 750. The network lifetimes under the three routing protocols are plotted in Fig. 9, where the x-axis represents the number of L-sensors in chessboard clustering.

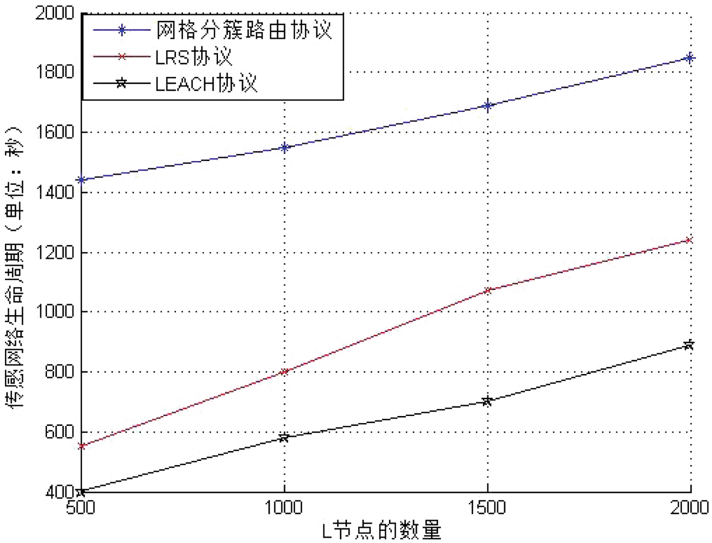

Fig. 9. Lifetime under different node density

As we can see, the network lifetimes under all the routing protocols increase as sensor density increases. With higher node density, more sensors are available to forward packet to the base station, and hence the network lifetime increases. Figure 9 also shows that chessboard clustering has much longer lifetime than both LRS and LEACH. In LRS and LEACH, L-sensors serve as cluster heads in turn to balance node energy consumption and to ensure the availability of cluster heads. However, since L-sensor has limited energy supply, the cluster heads need to re-elected periodically.

Even if each L-sensor only serves as cluster head once, there will be 2000 elections in a 2000-node network.

Each cluster head election introduces large overhead in the network and drains lots of energy from nearby sensor nodes. Large number of cluster head elections cause sensor nodes to die out quickly. Thus, the network lifetimes in LRS and LEACH are much shorter than CC. In CC, the chessboard clustering scheme balances the energy consumption among different L-sensors very well, avoid causing some nodes being out of energy too soon. In addition, only the more powerful H-sensors serve as cluster heads in chessboard clustering, and there is only one election for each H-node, which means there are only 40 elections in total. Thus, in chessboard clustering the overhead from cluster head election is very small. Because of the above two reasons, chessboard clustering prolongs network lifetime.

4.2 Total Energy Consumption

H-sensors have more initial energy than L-sensors, also H-sensors consume more energy than L-sensors for transmitting or receiving data. To fully understand the energy consumption in chessboard clustering, we measure the total energy consumption in the network, including energy spent by both H-sensors and L-sensors. In the experiments, there are 1000 L-sensors in chessboard clustering, and 1500 L-sensors in LRS and LEACH. All the measures are taken before 500 s simulation time, during which the network is connected for all the three routing protocols. The results are shown in Fig. 10. As we can see, the total energy consumption in LRS and LEACH are close to each other, and they are much larger than the total energy consumption in chessboard clustering. In LRS and LEACH, the large number of L-sensors communicate with each

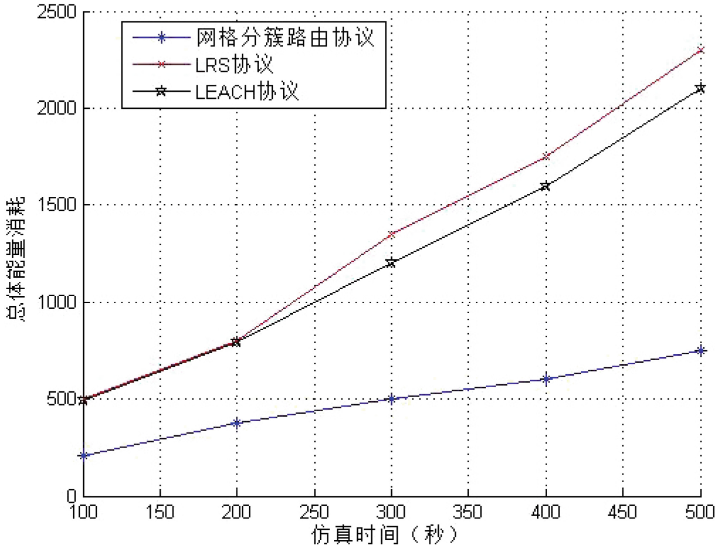

Fig. 10. Comparison of the total energy consumption of the three protocols

other and cause interferences and consume lots of energy, also the frequent re-clustering consumes significant amount of energy. So LRS and LEACH consume more total energy than chessboard clustering.

4.3 Remaining Energy of Node

Figure 11 reports the distribution of the remaining node energy when the sensor network became unavailable. The x-axis is the remaining energy in terms of the percentage of initial L-sensor energy. We can see that most nodes in chessboard clustering have remaining energy below 20%, while in LRS most nodes have remaining energy between 20% and 50%, and in LEACH most nodes have 30% to 70% energy left. Figure 11 shows that chessboard clustering balances the energy consumption among nodes better than both LRS and LEACH, and LRS performs better than LEACH. In typical sensor networks, sensors send packets to the base station via multi-hop communications. The failure of any node in the path will cause the route unavailable. If the node energy drain is not balanced well, then some nodes will die too soon and may cause the network disconnected and become unavailable. Besides minimizing the total energy consumption in the network, balancing node energy consumption is also very important for maximizing sensor network lifetime.

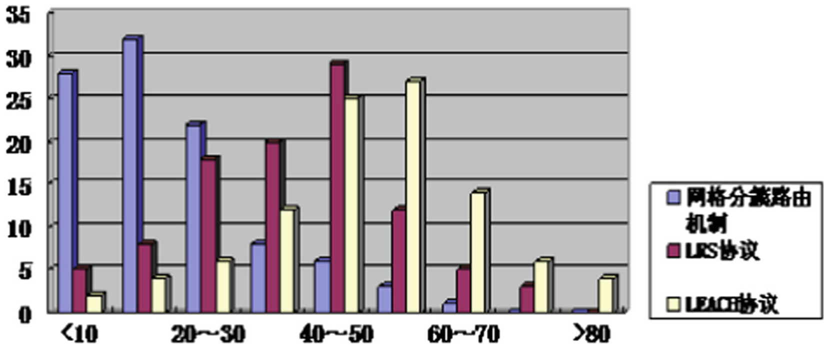

Fig. 11. The distribution of remaining node energy

5 Conclusions

In this chapter, based on the existing chessboard clustering routing protocol, we propose an energy-efficient grid clustering routing protocol, which aims to extend the network lifecycle by balancing the energy consumption of nodes. Because there are a few high performance H-sensors in the heterogeneous sensor network, the energy efficiency of the routing protocol is improved by this isomerism. Simulation experiments show that the grid clustering protocol greatly improves the lifecycle of the network. Compared with LEACH and LRS, it has better performance.

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