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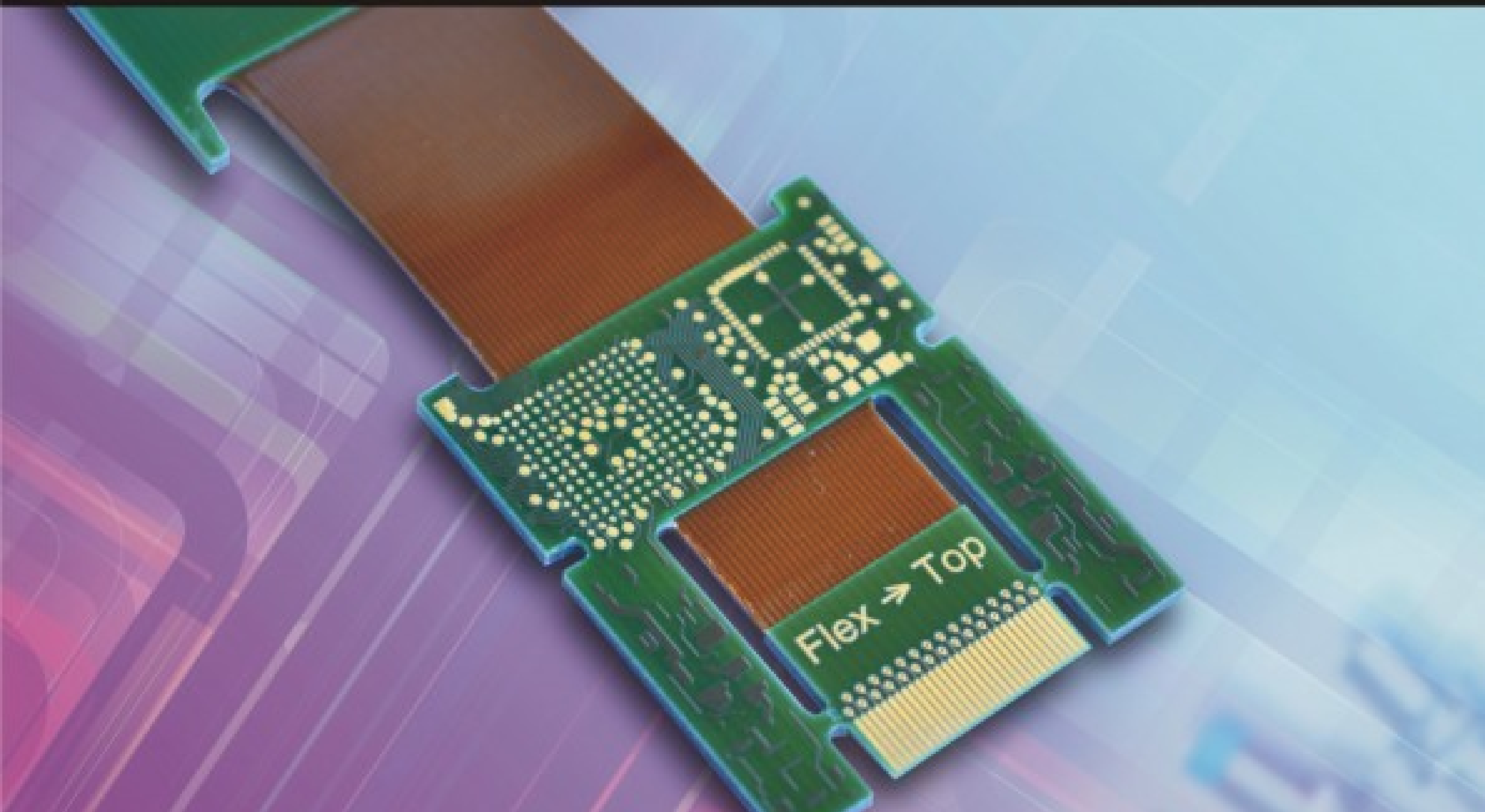

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Editor-in-Chief
Sergey Y. YURISH

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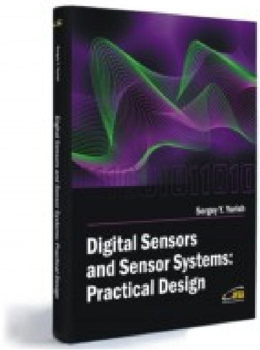
Digital Sensors and Sensor Systems: Practical Design

Sergey Y. Yurish



The goal of this book is to help the practicians achieve the best metrological and technical performances of digital sensors and sensor systems at low cost, and significantly to reduce time-to-market. It should be also useful for students, lectures and professors to provide a solid background of the novel concepts and design approach.

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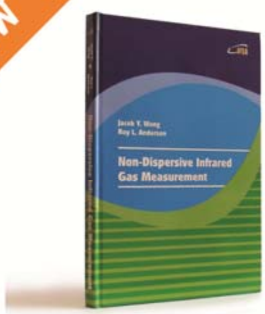
NEW BOOK

Jacob Y. Wong, Roy L. Anderson

Non-Dispersive Infrared Gas Measurement



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An Energy-Efficient Adaptive Clustering Protocol for Wireless Sensor Network

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Abstract: An energy-efficient adaptive clustering hierarchy EEACH in wireless sensor networks based on LEACH and LEACH-C is proposed in this paper. The main consideration is the LEACH cluster structure, each cluster is not uniform energy consumption; LEACH-C using a centralized algorithm can achieve better clustering, but do not contribute to the implementation of distributed. In EEACH, we analyzed the effects of different numbers of cluster member node on the network energy consumption; and re-planning time slice to balance the energy consumption of each cluster; and avoid the energy hole problem by reasonable cluster head selection algorithm. Its objective is to balance the energy consumption and maximize the network lifetime. Analysis and simulation results show that EEACH provides more uniform energy consumption among nodes and can prolong network lifetime compared to LEACH and LEACH-C. *Copyright © 2013 IFSA.*

Keywords: Wireless sensor network, Clustering protocol, EEACH, Energy-efficient.

1. Introduction

With the rapid development of mobile communication technology, embedded computing technology and sensor technology, people are getting more and more attention on a variety of application scenarios of wireless sensor networks (WSN). These sensor nodes can be formed self-organizing network and use the wireless interface to communicate with each other. Self-organization and Initiation Protocol about the energy efficient use are in the literature [1, 2]. Each node has a transmission power control and an all-directional antenna, so its coverage could be adjusted through a wireless communication. The represent meaning is that the sensor node collects sound, earthquakes and other types of data and then combines them so as to complete the work of high-level sensor networks. For example, sensor networks can investigate potential danger in the military conflict.

Since wireless communications need to consume large amounts of power energy, the sensor nodes must achieve the efficient use of energy in the process of transferring data. As how to use energy efficiently in sensor networks to communicate has gotten more and more attention [3-7], for WSN energy consumption could be minimized. In recent years, researchers have proposed efficient MAC protocol [8] [9] and efficient routing protocol [10, 11]. Energy consumption in WSN includes communication energy consumption, perception of the energy consumption and calculating the energy consumption. Communication energy consumption occupies the largest share. Therefore, to reduce communication energy consumption is an effective means to extend the network lifetime. A large number of studies have shown that the major energy waste in the communication process exists in that retransmission led by the conflict and waiting for the retransmission, to receive non-destination node and process the data to form cross-talk, transmitter/receiver is not synchronous leading empty transferring with divided groups, control the spending of grouping, the channel idle listening of non communication task node.

The remote base station collected sensor data is a typical application in sensor networks. Fig. 1 shows that sensor network with 100 randomly placed node in a 100 m × 100 m size of the scene, and the base station is located on a network remote. Receive or send a packet has the energy loss, and in accordance with the transmission distance, there is a corresponding variable energy loss. There are r^2 or more of the radio signal attenuation due to the distance r, so it must control the transmission distance for energy savings. As a clustering protocol, for saving the network energy, it is also needed to consider the number of cluster head, the number of nodes of the cluster members, node frequency etc.

In this paper, we have the following settings:

Each sensor node is subject to energy constraints and can transfer data to any other node or directly transmit data to the base station

As a model of sensor networks, it should have the same energy -constrained sensor nodes which have uniform initialization energy.

All nodes are in a quiescent state.

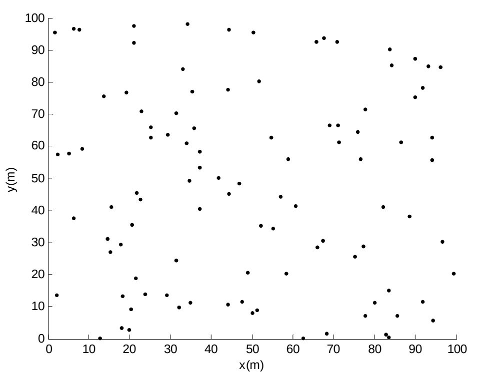

Fig. 1. 100 nodes randomly distributed within the scene of 100 m × 100 m.

2. Summarization

There is a simple program to complete this data collection, and each node transfers data directly to a base station, namely direct transmission. The stations are generally far away from each other, and energy loss of any node transferring data to the base station is very high. Thus requiring the transmission the node to the base station is as little as possible, and reducing the necessary amount of data for transmission to the base station. Further speaking, if all nodes in the sensor network energy consumption level are consistent, Network would be in normal operation for a long time and does not occur to any node of the death. In sensor networks, data aggregation can reduce the total transmission of data that node transferring to the base station [14]. The process of data fusion is combined from one or more packets of different sensors to generate a single data packet. For example: The sensor can collect temperature, pressure, humidity and signal data in the region, and we may only be interested in the maximum or minimum values of these parameters. Then you can use data fusion to combine one or more data packets to generate a data packet with the same size. LEACH protocol [15] is a simple example to solve the program of the data acquisition and the agreement is to generate a small amount by self-organizing clusters. The good performance of LEACH is that it is completely randomly distributed to integrate data by sensor nodes forming a network hierarchy, which are ultimately transmitted to the base station. In LEACH, a selected node in each cluster (cluster head) collection and integration of data is from other nodes in the cluster, and the integration results are transmitted to the base station.

In LEACH, about 5 percent of nodes in the network were randomly selected a cluster head. These cluster head send a strong signal to all the nodes, and sensor nodes decided to join that cluster, based on the received signal strength. In LEACH, each round of the dispersion of the cluster structure may not be able to form a good cluster, and thus it can not effectively use the energy [14]. The LEACH-C protocol [16] of the improvements in this program complete the cluster structure through the base station by centralized algorithm at the beginning of each round. Although LEACH-C cluster structure requires a higher energy loss, but the improved cluster structure, through the improved network hierarchy, makes its overall performance better than LEACH. If each node communicates with neighbors, and only one node selected in each round transmit integration of data to a base station in order to reduce the energy, so you can further improve the program. Based on the foregoing ideas a new protocol EEACH (Energy-Efficient Adaptive Clustering Hierarchy) is proposed in this paper, which has significantly reduced the energy loss and improved the life of the sensor network. The overall planning of EEACH are the network initialization phase, establishment phase and stable phase. The network initialization phase is executed only once for accessing the adjacent nodes collection and other information. After that, the operation of the network is divided into several rounds, and each round is set up by the establishment phase and stable phase, and the time of stable phase is much larger than the establishment phase.

In the network initialization phase, the base station determines the depth, Di from the i-th node to the base station by flood way (Depth of base station is defined as 0, node depth from the base stations 1 jump is 1, and node depth from the base stations 2 jump is 2, and other depths of nodes from the base stations are following this discipline).Each node in turn send node information to the adjacent nodes and each node can get the its own depth Di and the collective depth of adjacent nodes. Unless the node dies of energy depletion, or the adjacent node collection for each node are fixed.

Distributed selection algorithm selects each round of cluster head. Each cluster head using the CSMA MAC agreement, broadcast an ADV (advertisement message). This message contains a node ID and a statement different from other news. Each non-cluster head node, based on received signal strength, decided to select a cluster head based on its minimum communication energy.

After each node determines which cluster it belongs, using CSMA MAC protocol sends a join message (a join-request message clusters (Join-REQ), which contains ID and ID cluster head node.

Each cluster head using the CSMA MAC protocol broadcast a request to relay news Fw-REQ (forward-request message), and the message contains cluster head ID , cluster head depth information. The adjacent cluster member nodes decide whether to send the information for the cluster, according to the depth of information in the message and the received signal strength. And send an acknowledgement message (forward-confirm Fw-COF message) to establish the chain inter- cluster routing to base station.

In order to ensure only one node was sent data to the base station, the depth 1 of a node generates a chain, and send data to the adjacent node and integrate them; node in the chain turns to the base station to send data. Nodes in the chain are either as a cluster head, nor used as a cluster member node. When all the nodes in the chain were dead, generate a chain from a depth of two to complete the task sending data to the base station, and so on, until all nodes died.

Cluster head in EEACH, as a local control center, coordinate communication in the cluster. The cluster-head creates a TDMA schedule, and then distributes the table to each node in the cluster. This will ensure that there is no data collision and each non- cluster head nodes can turn off the wireless module and reduce energy consumption in idle. After all nodes in the cluster receive a TDMA schedule, the establishment phase is completed, the stable phase starts.

3. Clustering Algorithm Based on Energy Efficiency

3.1. The Energy Model

Assume that the energy of the sender including signal processing and power amplification of two parts, and the receiving end of energy is only for signal processing, and assume that when the distance d between two nodes is less than d_0, using free space model, and when it is greater than equal to d_0 using multipath fading model. Therefore, when the two nodes with distance d to send 1 bits of data, the energy consumed by the sender is:

$$E_{tx}(l,d) = E_{elec}(l) + E_{tx-amp}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2, d < d_0 \\ lE_{elec} + l\varepsilon_{mp}d^4, d \geq d_0 \end{cases}, \quad (1)$$

The energy consumed by the receiver is:

$$E_{rx}(l) = lE_{elec}, \quad (2)$$

where E_{elec} is the energy what signal processing needs, determined by digital coding, modulation, filtering and expansion signals and other factors. Amplifier power consumption ε_{fs} and ε_{mp} are decided by transmission distance and the receiver bit error rate etc.

3.2. The Influence of the Number of Cluster Members on the Network Energy Consumption

In the network, the cluster head is usually randomly generated according to certain rules, and the number of cluster head directly affects the energy consumption of the whole network. Whether clustering is too much or too little, it will exacerbate the energy consumption of the whole network. Excessive number of cluster head will increase the operating frequency of nodes and cluster head, so that the energy consumption of the whole cluster would be intensified. The number of cluster head is too small causing the cluster head of the burden is too heavy, and the cluster head premature death is not conducive to the balanced energy consumption. Optimized for the most number of cluster head of the whole network, minimum of the network 's overall energy consumption in a way could be reached. But whether it is using the base station to run the central control or coordinates communication among the cluster heads to achieve the most optimized, it will increase additional energy consumption of cluster head, especially in larger scenarios. Regardless of the network, the number of clustering, the energy consumption cluster head and the entire clusters in nature are determined by the number of nodes and the operating frequency of the cluster members. Therefore, the following number of cluster members on the network energy consumption is considered that the energy consumption of nodes in a stable phase is much larger than the establishment phase, the following derivation ignores the energy consumption of the node to establish the stage.

Suppose a total of N nodes are uniformly distributed in the region of the M × M，If the number of cluster head is N_{CH}, each cluster in average has $k = N/N_{CH} - 1$ nodes. Each cluster head and member nodes in the cluster allocate of time slices, and node in the time allocated send sensor data to the cluster head. To set tdata as the required time for node the send l_{data} length, $t_{data} = l_{data}/s$, s is the rate of the channel. After all members of the cluster nodes send a data to the cluster head, the cluster head data is sent by data fusion, which is called one frame. energy consumption for one frame of one node is:

$$E(node - frame) = (k-1)t_{data}E_{sleep} + E_{tx}(l_{data}, d_{toCH}) \tag{3}$$

where d_{toCH} is the distance from the node to the cluster head, and each cluster area is about M^2/N_{CH} . Typically, a node $\rho(x, y)$ locates in a region of arbitrary shape. Distance variance from node to the cluster head is

$$E[d_{toCH}^2] = \iint (x^2 + y^2)\rho(x,y)dxdy = \iint r^2 \rho(r,\theta) r dr d\theta \tag{4}$$

If we assume that this region is circular, The radius $R = M/\sqrt{\pi N_{CH}}$, $\rho(r,\theta)$ is constant of r and θ, it is simplified as follows:

$$E[d_{toCH}^2] = \rho \int_{\theta=0}^{2\pi} \int_{r=0}^{R} r^3 dr d\theta = \frac{\rho}{2\pi} \frac{M^4}{N_{CH}^2} \tag{5}$$

The density of nodes in the cluster region is a unified, then $\rho = N_{CH}/M^2$, so

$$E[d_{toCH}^2] = \frac{1}{2\pi} \frac{M^2}{N_{CH}} = \frac{1}{2\pi} \frac{M^2(k+1)}{N} \tag{6}$$

Each cluster receives sensor data from head node, then integrates it and sends data to next cluster, the energy consumption of one frame of cluster is:

$$E(CH - frame) = kE_{rx}(l_{data}) + kl_{data}E_{eda} + E_{tx}(l_{data}, d_{toNext}) \tag{7}$$

d_{toNext} is the distance that a cluster to the next cluster head, from above derivation of $E[d_{toCH}^2]$ we can get

$$E[d_{toNext}^2] = 2E[d_{toCH}^2] \tag{8}$$

If the cluster allocates the time for each node is the Slot time, and The duration of each round is Round time, so the energy consumption of node is

$$E(node - round) = \frac{round\_time}{k \cdot slot\_time} \bullet E(node - frame) \tag{9}$$

Similarly, the energy consumption of a cluster head is

$$E(CH - round) = \frac{round\_time}{k \cdot slot\_time} \bullet E(CH - frame) \tag{10}$$

The simulation parameters are set as shown in Table 1.

Table 1. Simulation parameter settings.

Parameter	Value
E_{elec}	50 nJ/bit
l_{data}	500 Byte
E_{eda}	5 nJ/bit/signal
E_{sleep}	15 uW
Slot time	100 ms
Round time	20 s
channel speed	125 kbps
ε_{fs}	10 pJ/bit/m2

As shown, when k = 13, and the communication distance is 15m, the whole cluster of energy consumption is the lowest. When the k value is smaller (k <7), node of the cluster members and cluster head will more frequently send and receive data in the time of a round, so energy consumption of cluster heads and clusters are bigger. When the k value is bigger, the node operating frequency reduces, the main work of the cluster head in each round is to receive data, and the number of sending data decreases, Therefore, the energy consumption of cluster head decreases as k increases; However, the energy consumption of the whole cluster increases with the increase of k.

As shown, the clustering with the k value increases, the network will reduce, so when the carve cluster in network reduces, although the energy of a single cluster is higher, the energy consumption of the entire network is lower. Then is the value of k larger, the better for sensor networks, the main purpose of sensor data ultimately is to send to base station, Therefore, we treat the node energy consumption as the network cost, so the data received by the base station is the benefits derived from the network. We can find, from the Table 2 below, that with the k value increases, although the average energy consumption of cluster head is quite similar, and the overall power consumption of the network is quite similar, the interests obtained by the base station reduces value.

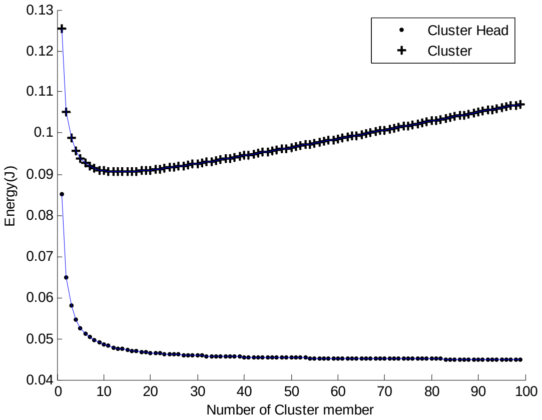

Fig. 2. The influence of the number of cluster members *k* on cluster heads and cluster energy loss.

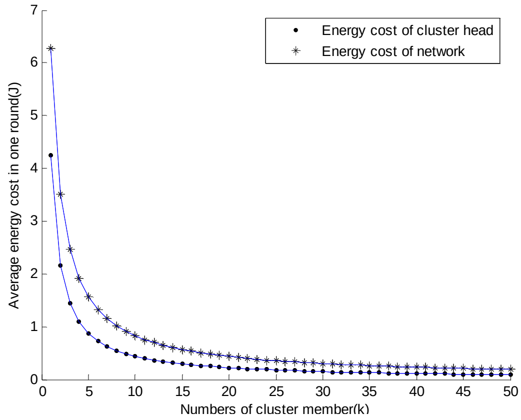

Fig. 3. The influence of the number of cluster members, *k* on cluster head of the whole network and the energy loss of the entire network.

Table 2. The statistics of *k* values to different indicators in the operation of the network.

K Value	Number of cluster head	Energy consumption in the whole network cluster head	Average energy consumption of the cluster head	Cluster head to receive / send data(Byte)	Cluster head to receive / send data(Byte)
4	20	1.0927J	0.0546J	100000/25000	500000
13	7	0.3402J	0.0486J	91000/8400	58800
19	5	0.2332J	0.0466J	95000/5000	25000
32	3	0.1387J	0.0462J	96000/3000	9000
48	2	0.0926J	0.0463J	98000/2000	4000

If the *k* value is set to 13, the whole cluster of energy consumption is the lowest, is it the best number of cluster members. If the entire network of each cluster of nodes is set to the same value of *k*, as using the CSMA MAC protocol, then all the cluster head will send data in the same time. Competing with each other to send data between the cluster head will bring additional energy consumption, and ideally, if each adjacent cluster set different values of *k*, the cluster head will send data at different times, without affecting the other nodes. Combined with the simulation results of the previous values of *k*, in later experiments, we set $7 \le k \le 20$, which will ensure that the number of cluster head in the entire network does not appear too much or too little , and also ensures that the cluster head only send data in conflict consuming less energy. At this point, we define the cluster that the value of *k* is less than 7, as very small clusters, and for *k* value is greater than 20, will be defined as a great cluster.

3.3. The Cluster Head Selection Algorithm

In the stable phase, node sends data to the cluster head according to the allocation of time slices; however, the node does not know whether the cluster head has successfully received the data. If in the stable phase, a cluster head suddenly dies of energy depletion, and the cluster nodes in the cluster head does not know it has died, it will continue to send data in accordance with the prior allocation of time slice until the end of current round. Then the collected data from the cluster actually did not reach the base station after the death of cluster head, resulting in unnecessary loss of the energy of the cluster members. The reliable transmission by ACK can easily solve the problem. Cluster head node will wait for the ACK message after sending the data. When it is timeout, retransmit data or directly identify that the cluster head has died, and then going into a sleep state, waiting for the next round of re- started. However, this will increase the energy loss of the node and cluster head, while increasing the delay of the entire network. Therefore consider to resolve the issue by way of node energy estimates.

All nodes had plenty of energy in the early operation of the network, so the standard to choose the cluster head is the number of nodes becoming a cluster head. Running over a period of time, some nodes due to energy consumption, the remaining energy is not sufficient to ensure the operation of a round. By the energy savings calculations in 3.2, when *k* value is determined for a cluster, the cluster head can estimate the energy consumption of the next round of the stable stage, and check whether there is enough energy to complete the round operation. Before the *k* value determined, it could be estimated according to the simulation results of the previous $k = 13$.

Each node in the establishment phase generates a random number between (0, 1), and then compare to probability pi that the node becomes a cluster head. If the generated random number is greater than p_i, then the node is set to the cluster head. E_{NP} is the residual energy of the node after the current round, and estimate this value by $k = 13$.

E_P is the current residual energy of the node, and E_{init} is the initial energy of node, E_T is threshold energy of the node, meaning node energy is not enough to complete one turn, r is the rounds of network operation. When node E_{NP} is less than 0, it means the energy of the node is not enough to complete a run, then the probability of becoming a cluster head is determined by the current ratio of the residual energy and initial energy; When the energy is less than the threshold, the node energy is insufficient to complete a run, meaning this is not suitable for a cluster head, and at this time the probability is 0.

For the second case, cluster head need to calculate the time slice based on energy depletion time point and release the respective nodes, avoiding unnecessary energy loss because of the death of the cluster head node. Cluster head could be estimated, after entering the stable stage, that how many frames the working hours its energy can be maintained, which could be the base of members stop work into hibernation.

$$p_i = \begin{cases} \dfrac{N_{CH}}{N - N_{CH}(r \mod k)}, & E_{NP} \geq 0 \\ \dfrac{E_P}{E_{init}}, & E_{NP} < 0, E_P > E_T \\ 0, & E_P \leq E_T \end{cases} \tag{11}$$

4. Energy-efficient Adaptive Data Transmission

4.1. Data Transmission between Clusters

In order to make a balanced energy consumption of the nodes in the network, similar to the cluster head election, relay node should be assumed by all the network nodes by turns. The easiest method is to make the cluster head assume the relay task directly, and that after collecting node data each time, the cluster head will directly send data to the next cluster head. However, it has two drawbacks: firstly, because the cluster head itself is responsible for much data transceiver task, if it takes charge of extra data forwarding task again, the cluster head will be exacerbated energy consumption and be accelerated to death; Secondly, as each node in the network can not be informed of their location information, communication distance becomes an important issue to consider when a node is sending and receiving data. In order to make cluster heads communicate with each other, communication distance must be set as twice as the distance between the node and the cluster head, which undoubtedly will increase the energy consumption of cluster head sending data.

Therefore, we consider making each cluster node assume the data relay task in turn. In this way, network node energy consumption can be balanced. We suppose the node depth as i, and define the depth of the adjacent node i-1 as this node's upstream node, i+1 as downstream node.

After clustering, the cluster head broadcasts a request for relay messages Fw-REQ, which includes cluster head ID and depth information of the cluster head; after receiving this message, the adjacent cluster node first determines the depth of the cluster head, and then agree to the forwarding request of the cluster head if located in its downstream. If you want multiple nodes to receive Fw-REQ, you can decide and send a confirmation message Fw-COF according to the strength of the received signal. The message includes cluster he ad ID and depth as well as forwarding node ID and depth, and other nodes will no longer forward the information to the cluster head after receiving Fw-COF. After sending the Fw-REQ message, if not receiving the confirmation message, the cluster head should adjust the communication distance step by step until receiving the reply.

If there is a relay node in the cluster, after finishing data sensing and sending within the allocated time slice the node is in the receiving state in the rest of the time slice, to receive the adjacent clusters' forwarding data.

4.2. Data Transmission of the Base Station

The base stations are usually far from the network nodes, so the cluster head directly sending data to the base stations will only consume more energy. Therefore, we consider making a subset of nodes take turns sending data to the base station, and each time only one node sends data. Here we assume that the entire base station has all the information of the whole network, and suppose the depth of node subset nearest the base station as 1.

In the process of chain construction, the base station randomly selects a node as the chain head. Through sending the join-chain message, chain head node notifies an adjacent node with the depth 1 of entering the chain. The adjacent node receives the message and sends the confirmation message and passes the number of nodes that have entered the chain. When the total number of nodes entering the chain that the chain head receives is equal with the statistics that the base station sends, the operation of entering the chain ends; when JCH that the node sends has not been confirmed, this node becomes the chain tail.

Because the node does not know its location in the chain, we adopt simple controlled token communication protocol started by the chain head, transmitting data from the chain tail.

The token size is very small, so the loss is small. In Fig. 4, the node c2 is the chain head, and c2 will first pass the token to the node c0 along the chain head. And the node c0 transfers data to the direction of c2. When the node c2 receives the data from c1, it passes the token to the node c4. So the node c4 transmits the data to the direction of c2 and integrate data along the chain in the transmission process.

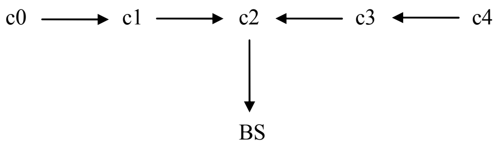

Fig. 4. Chain-style token transmission.

Except for the node in the chain tail, all the nodes perform data integration. Each node integrates its data with its neighbor' thus generating an independent data packet with the same length, and transmits the packet to its another data node (each node has two neighboring nodes). In the instance above, the node c0 transmits data to the node c1, and the node c1 integrates the data from the node c0 and transmits it to the chain head. When the node c2 passes the token to the node c4, the node c4 passes the data to the node c3, and the node c3 integrates the data from the node c4 and passes it to the chain head. The node c2 waits for receiving the data of the two neighbors and then integrates with its own data, and finally the node c2 sends a message to the base station. In this way, except for the chain head and tail, each node only receives and transmits one packet in every turn.

To ensure the transmission reliability, we need add confirmation mechanism. It is that after sending a data packet, each node in the chain needs to wait for the confirmation of the adjacent nodes. If not receiving the confirmation message, we believe that the adjacent nodes have died and re-adjust the communication distance and send.

In each turn the base station in turns determines the chain head node. If the chain nodes were all dead, the base station informs the entire network nodes of reducing 1 off respective depths.

4.3. The Planning of Time Slice

To make energy consumption of clusters in the network tends to the same, we adjust the operating frequency of the node by the planning of time slice. After clustering in the network, the cluster head can determine its *k* value. It generates a random number *q* between [7, 20] if a minimal cluster. When the cluster completes one frame of work, all the nodes (except for the relay node) continue to sleep for (*q*-*k*) time slices. If judging to be the maximal cluster, it generates a random number *q* between [7, 20], and the cluster node takes *q* as a cycle, and by turns sends data using the time slice. The working condition is shown as follows.

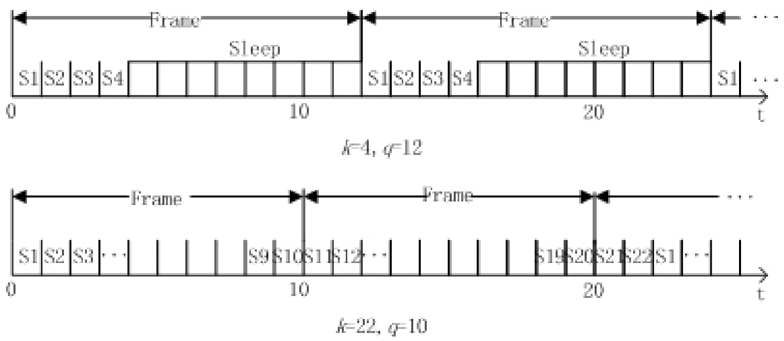

Fig. 5. The time slice planning of the minimal and maximal clusters.

5. The Experimental Results

In order to analyze the effectiveness of EEACH, the simulation environment we use is 100 nodes randomly distributing in the area of 100 m x 100 m (Fig. 1). Each node's initial energy is 2 joules, and the base station location is (50, 200). We make a comparison of surviving nodes, nodes mortality and energy consumption per turn on average of Direct, LEACH, LEACH-C in the environment.

Fig. 6 shows the four protocols' network lifetime as well as the surviving nodes for each protocol. As the figure shows, Direct can make the node survive longer, because the node closer to the base station always sends data with the minimal cost, but the node further from the station will die earlier. Because of Direct data collision and the lack of data integration, the protocol always consumes more extra energy to transmit data. LEACH and LEACH - C use the same transmission mechanism in the stable phase, so their network lifetime is almost the same. However, the cluster head in LEACH-C is generated by the central control, and can produce better clusters compared with LEACH. So the data LEACH-C delivering to the base station is more than LEACH. Compared with the other three protocols, EEACH has a distinct advantage in the network lifetime and the death time of the first dead node in network.

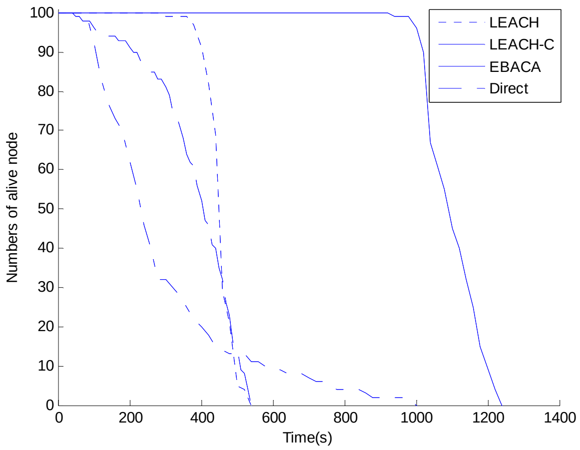

Fig. 6. The comparison of network lifetime.

Fig. 7 shows the node death time of the four protocols at 5 %, 25 %, 50 % and 100 %. From the node mortality, the death rate of direct node is the fastest, at 240 seconds the nodes have lost more than a half, and at 400 seconds, the nodes dead have over 75 %.

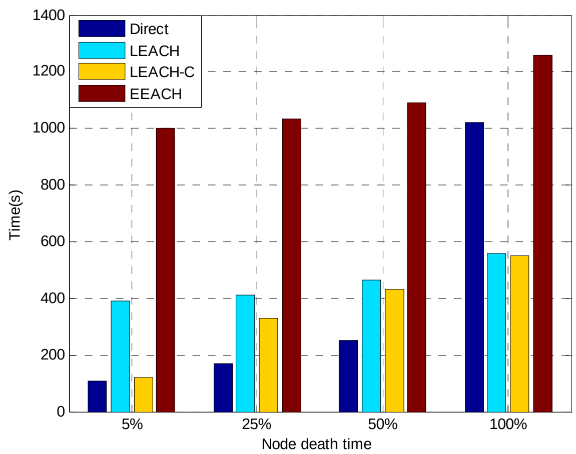

Fig. 7. The comparison of node death time.

For the other three Clustering protocols, as the figure shows, 95 % of the nodes at about the last 200 seconds (10 turns), all die. It is that we can use node energy with balance, making most of the nodes intensively die in the late period of network run. Compared to the other two clustering protocols, EEACH's improvement lies on using fewer nodes to send data to the base station, and each node only sends data to the adjacent nodes, so the nodes have lower energy consumption.

Fig. 8 shows the energy consumption of the four protocols in each turn during the network operation. For Direct, the worst one, with the continued death of nodes, energy consumption in each turn declines sharply. For LEACH, as the cluster head is randomly generated, so the energy consumption in each turn fluctuates greatly according to the quality of clusters generated. For LEACH-C, through the central control, the quality of clusters is relatively good, so energy consumption tends to be even. EEACH's improvement lies on, through the planning of the time slice, making the frequency of each cluster node similar, so the balance of energy consumption is good, and energy consumption in each turn is also lower than the other two clustering protocols.

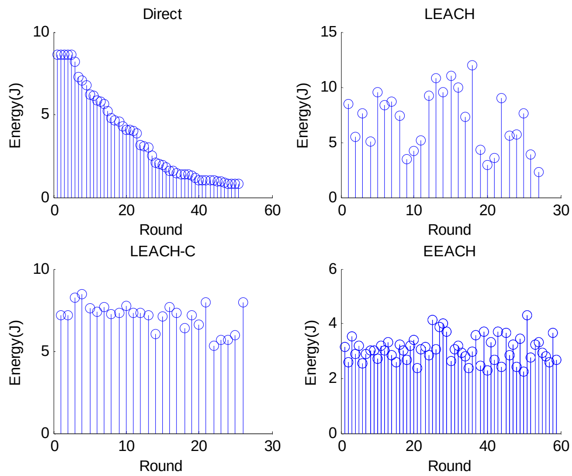

Fig. 8. The comparison of the average energy consumption in every turn.

It can be seen from the above analysis, EEACH's performance in the same scene is better than the other three protocols. Below, by setting different base station locations, different packet sizes and different node density, let's analyze the impact on EEACH.

Base station location is respectively set as (50, 200) (50, 300) (50, 400). As there is only one node in each turn communicating with the base station, the distance over the base station has no big effect on the total energy consumption of the network. According to the statistics, when the node sends the same data amount to the base station, in each turn on average, (50, 300) and (50, 400) have 0.026J and 0.416J of additional consumption compared to (50, 200), accounting for 1.3 % and 20.8 % of the communication node energy, only 0.013 % and 0.208 % of the energy of the whole network. From the overall network energy consumption, to adjust the position of the base station will not affect EEACH's performance.

Fig. 9-A shows the network lifetime when the packets are 500 Byte , 1000 Byte and 2000 Byte, and Fig. 9-B shows energy consumption when the packets are 500 Byte , 1000 Byte and 2000 Byte. As the basic unit of communication between nodes, packet size is an important factor to affect the network energy consumption. As Fig. 9-A shows, the packet size determines the network lifetime of EEACH, but does not change the balance of the network energy consumption. Fig. 9-B shows that, the packet sizes are different, but the overall of the network tends to be

linear, that is power consumption in each turn is similar. Therefore, packet size does not affect the balanced use of node energy for EEACH.

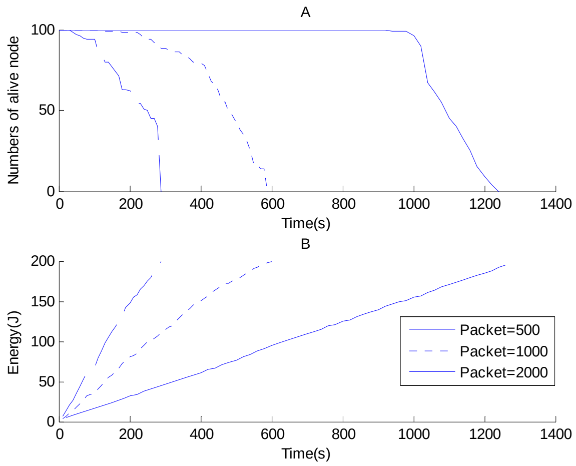

Fig. 9. The impact of different packet sizes on EEACH.

Fig. 10-A shows the minimal energy, the maximal energy and the average energy in each turn of network run when the numbers of nodes are set as 50, 100, 200. Fig. 10-B shows the network lifetime when the numbers of nodes are set as 50, 100, 200.

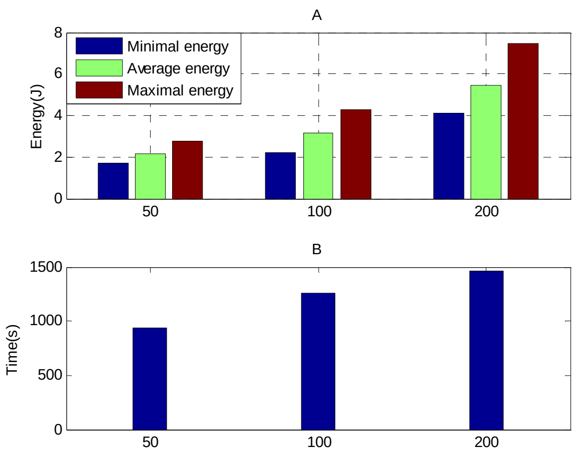

Fig. 10. The impact of the different node numbers on EEACH.

By the previous derivation, we find that, to guarantee EEACH's performance under different node densities, we need to adjust the optimal communication distance of the node. When the number of nodes is 50, the optimal communication distance is 21 m, and the average energy consumption per turn is 2.13 J; when the number of nodes is 100, the optimal communication distance is 15 m, and the average energy consumption per turn is 3.17 J; when the number of nodes is 200, the optimal communication distance is 10 m, and the average energy consumption per turn is 5.45 J. With the increase of node density, the lifetime of the network will increase, and the base station will receive more data. As the optimal communication distance is deduced from the total number of nodes, so we need to write it into nodes in advance. Therefore, EEACH does not apply to a dynamic network.

6. Summary and Outlook

Based on Clustering protocols in wireless sensor networks, by analyzing some factors of the effect of the number of cluster members on the network energy consumption, the optimal communication distance of nodes, additional energy consumption of multiple nodes competing to communicate, we propose an energy-efficient adaptive clustering hierarchy EEACH. The protocol is mainly achieved through the nodes only communicating with adjacent nodes, reducing the nodes communicating with the base station, and adjusting node frequency by the time slice, the design goal is to balance the network energy consumption, and to maximize the network lifetime. Analysis and simulation results show that, compared to the clustering protocols LEACH and LEACH-C, EEACH has the superior performance in balancing node energy and prolonging the network lifetime.

In the further research work, we still have a lot of work that need to be analyzed in details. The theoretical model of the simulated network transmission that the paper constructs only considers the most important energy consumption, and does not analyze the impact of different transmission mechanisms and delay on node energy. In the future work, we will establish an energy consumption correction mechanism to ensure that each node 's energy consumption judgment is more accurate.

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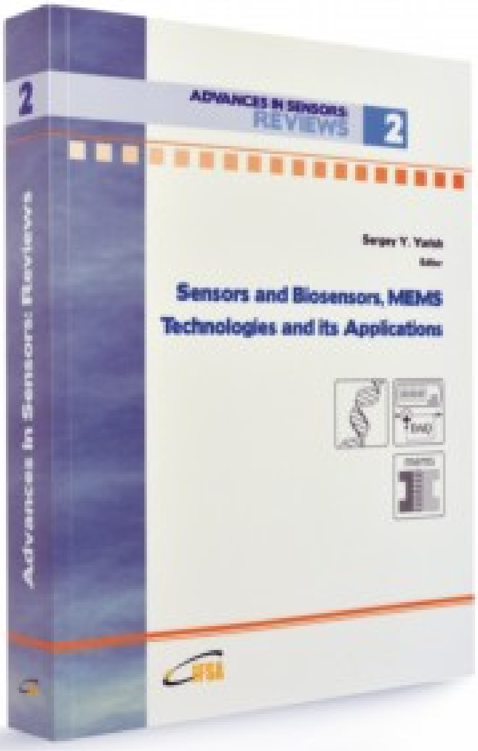

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