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A Study on the Low-power Clustering Algorithm of Timeslot-based WSN Nodes

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Abstract: A Wireless Sensor Network (WSN) is a wireless network consisting of a set of self-organizing micro sensor nodes. In WSN, most nodes are stationary except a few nodes that are required to move. A core issue in prolonging the lifetime of WSN is to work out the effective protocol and algorithm. In this study, network nodes are clustered according to the timeslot and the protocol keeps some nodes in the working state and the rest in the dormant state, thus resulting in the low power consumption of the nodes and in the prolonged lifetime of the network. Simulation experiment shows the system can meet the design specifications and can extend the lifetime of the WSN, improving the viability of the network.

Key words: WSN, clustering algorithm, low-power consumption

INTRODUCTION

To prolong the lifetime of WSN, clustering is regarded as one of the most effective method. A node is partitioned into a number of clusters. Clusters are divided into the Cluster Heads (CHs) and Member Nodes (MNs). Mns report the sensed data to their respective CHs. After fusing the collected data, CHs transmit the fused data to the Sink Nodes (SNs) to reduce the data flow in the network. Because different CHs are different in distance from the SNs, those CHs farther away from the SNs connect SNs through multi-hop communication. But the method causes uneven energy consumption; that is, in the one-to-many communication in the sensor network, nodes close to the SNs must transmit a large quantity of data from other clusters resulting in the quick depletion of their energy till their death which in turn causes the disconnection of the network and the reduction of its lifetime. Many energy-saving methods of topology control make prolonging the service life of the network as their ultimate purpose and of those method, LEACH (Nori *et al*., 2011) is the most influential and representative algorithm. However, when simulation is conducted in the TOSSIM simulator with energy awareness in TinyOS, LEACH protocol may cause a few nodes to die prematurely, greatly reducing the lifetime of the network, while there is still much energy in the global network.

AN ANALYSIS ON LEACH PROTOCOL

Network model: The network model adopts the typical settings of the WSN topology control that are the same as those settings of LEACH. N isomorphic nodes with weak communications capabilities, computing power and limited energy are randomly but evenly distributed in a square area A. After deployment, the nodes are no longer in mobility and generate self-organizing peer-to-peer network without manual intervention. In the network, there is a base station deployed somewhere outside the area A. The sensor network has the following properties: (1) In each round, different nodes consume energy differently; (2) The nodes do not need to know the information of their specific locations; (3) A weak synchronization clock is maintained in the network; (4) All the sensors sense their surrounding environment at a fixed rate, therefore there are always data transmitted to the end user; (5) The network lifetime refers to the period from the time when network boots up to the time when the first node dies.

In terms of the communicative means, the same assumptions with those for LEACH algorithm are proposed in this study: By the symmetrical communication channel model and the free-space model, in the threshold distance d0 (d0 is a constant, in relation to the specific application environment) the energy consumed by the data-sending amplifier is in direct proportion to the square of the distance between the sending node and the reception node. Energy consumed by data sending can be given in Equation 1 (Liu *et al*., 2013; Wang *et al*., 2009; Zhuang *et al*., 2013):

$$E_{TX}(L,d) = E_{elec}L + \varepsilon_{amp}Ld^2 \tag{1}$$

Energy consumed by data reception can be given in Eq. 2:

$$E_{Rx}(L,d) = E_{elec}L \tag{2}$$

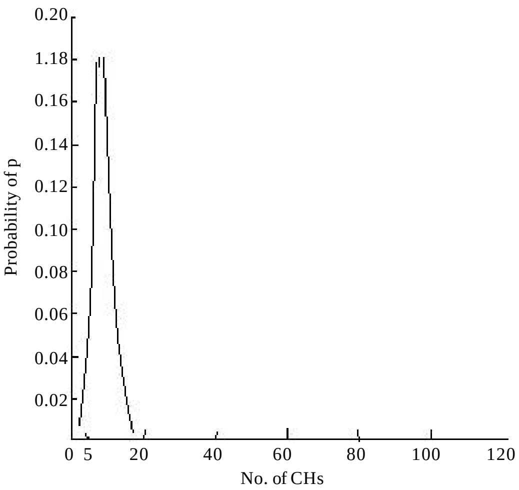

Fig. 1: Probability distribution of CHs

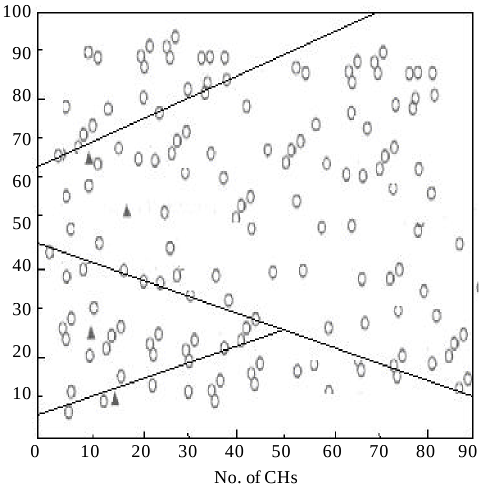

Fig. 2: LEACH cluster distribution

where, L represents the length of data frame, E_{elec} the energy consumption of the wireless signal processing circuits in the sender and the receptor and ε_{amp} the energy consumption of the transmission amplifier circuits. Equation 1 shows that the energy loss of transmission in the channel is O (d^2), where d is the distance between nodes. Therefore, the transmission distance and the times of reception should be minimized.

Number of Chs: The number of CHs generated by LEACH is random. This randomness causes non-ignorable probability of too many or too few CHs. In each round, the number of CHs elected by LEACH obeys binomial distribution and if the CH ratio is assumed to be p = k/N and the elected CHs number in each round to be X, Eq. 3 can be established:

$$P\{X=K\}=\binom{N}{k}p^k(1-p)^{N-k} \tag{3}$$

According to Eq. 3, Fig. 1 indicates, where N = 100, the optimal number of CHs is k = 5; namely the probability distribution of X at p = 0.05. In Fig. 1 the probability of the optimal value k=5 in terms of the number of CHs is 0.18002. Concerning the case of too few CHs, the probability of the number of CHs below 3 is 0.1183 which means there is a probability of 0.1183 for an overlarge size of clusters since the number of CHs determines the cluster size. In this way, only after collecting information from all nodes do the CH nodes fuse and forward data, thus effectively reducing the times of forwarding data by the CHs in one cycle, yet in the meantime reducing the quality of information service. The probability of CH number above 7 is 0.128 which means the cluster size is too small to allow an effective fusion of data within the cluster, leading to the high frequency of communication between CHs and the base station and resulting in increased energy consumption during communication within the globe network and in the reduced network lifetime.

Ddistribution of Chs: The distribution of the CHs generated by LEACH is random and this randomness causes different size of each cluster in the round, as is indicated in Fig. 2. Through analysis, it is believed that the inconsistency of cluster sizes makes it difficult to secure the validity of the two preconditions for LEACH algorithm.

The two preconditions for LEACH validity can be described as follows: one is, at the initial stage of CHs, all nodes have the same amount of current energy; the other is, after the formation of clusters, nodes have consumed roughly the same amount of energy. In the first working cycle of the initial deployment in the network, the first precondition can be satisfied in the first round of CH election. But, when there is a different size of each cluster, the second precondition cannot be secured. This is because, in the assumption for the network model (namely, all sensors sense the surrounding environment at a fixed rate, therefore there are always data sent to users), nodes are believed to transmit data at the same rate. In this way, the different sizes of CHs decide the workloads on CHs are quite different. The random way for LEACH to generate CHs causes large difference in cluster size and salient difference of the energy consumption by the CHs in different clusters. At the same time, much variation of the distance among intracluster nodes to the

CH causes much difference in communicative power, resulting in much difference in energy consumption. Consequently, it is possible in each election of the later rounds the clustering algorithm selects the node that has consumed more energy to continue to serve as the CH which undoubtedly accelerates the death of the node.

ALGORITHM IMPLEMENTATION

To deal with the problems caused by the randomness of the distribution and the random number of CHs caused by LEACH protocol, at the stage of cluster generation, the residual energy is taken into consideration and the method to generate energy-aware CHs is raised to make nodes with remaining energy serve as CHs and at the stage of cluster maintenance, rotating active nodes within the cluster based on time-division multiplexing is adopted to make active nodes apportioned for node depletion in order to reduce the depletion of CHs. In this way, the lifetime of clusters in their rounds can be increased, the times of cluster generation within the lifetime of the entire network are reduced and accordingly the depletion in the global network is reduced and the lifetime of the network is prolonged.

Method to elect energy-aware CHs: Clustering includes two stages: the first stage is CH election; then the rest of the nodes choose to join appropriate CHs according to their interactions with the CHs. The key issue is the distributed election of the peer-to-peer nodes in large quantity. LEACH provides an effective distributed algorithm but has not taken into account the randomness of cluster sizes which leads to different remaining energy of different nodes. The assumption that every node has the same amount of remaining energy may cause the non-ignorable probability of those nodes with very low energy to be elected as CHs and this leads those nodes to premature death. To deal with this problem, an energy factor is brought into the stage of CH election. Given the threshold value Function T(i):

$$T(i) = \begin{cases} \dfrac{1}{1-p[r \bmod (1/p)]} \cdot \dfrac{1}{\sqrt{\lambda}}, i \in G \\ 0, \text{other} \end{cases} \tag{4}$$

where, the parameter p refers to preset proportion of CH nodes to total nodes, r to current round of CH election, i to the ID of the current node, G to the convergence of nodes that have not been elected so far to the current round, λ to adaptive adjustment parameter decided by the remaining energy of nodes, the value of which can be calculated by Eq. 4:

$$\lambda = \frac{E_{i-init}}{E_{i-current}} \tag{5}$$

where $E_{i\text{-init}}$ is the initial energy of the node and $E_{i\text{-current}}$ is its current energy.

The proportion factor should not approximate zero too quickly along with the energy decrease of nodes, nor should the proportion factor decreases too slowly; otherwise the energy factor cannot be reflected. Based on the above considerations, simulations of the 1/λ, 1/λ½ and several other situations are conducted. Under the same network settings, extensive analyses and comparisons of the results allow the proportion factor 1/λ½ to be selected.

At the stage of CH generation, each node individually decides whether to be the CH in the current round. A node generates a random number from 0 to 1; then the threshold value T(i) is obtained according to Eq. 3. If the random number is smaller than the threshold value, the node becomes a CH. When the node has become the CH, from Eq. 4 it can be known that along with the increase of rounds the threshold value increases gradually and the node with the most remaining energy in the rest of the nodes has the most probability to be elected as the CH.

At the stage of CH formation, by the non-persistence CSMA MAC protocol, CHs send advertisement message by the same energy to remaining nodes. At this stage, non-CH nodes turn on their receptors to receive the message and decide which cluster to join in the current round according the strength of the received message. Non-CH nodes receive many advertisement messages. The cluster whose CH sends the strongest message will be the selected cluster. This is in agreement with the Nearest Neighbor Clustering which can effectively avoid intracluster interference. The node, having decided to join a certain cluster, needs to inform the CH which cluster it belongs to. According to the assumption of the symmetric communication channel, this node sends response messages to the CH with minimum communicative power according to the energy-awareness of the messages and sends feedback message to the CH by the non-persistent CDMAMAC protocol to indicate to join the cluster.

Timeslot-based rotating method of intracluster energy consumption: In a given cycle in LEACH, several nodes are elected to be CHs in the first round. After one cycle, new CHs are elected to form new clusters. As clustering consumes too much energy, the cycle should be prolonged as far as possible. Because CHs consume far more energy than member nodes, the overlong cycle causes the premature death of intracluster CHs. Therefore, it is proposed to develop a cluster scheduling mechanism so that each node rotates to take its duty as the CH.

After the CH nodes receive the feedback from the nodes intending to join the cluster, the CH node establishes, on the basis of number of intracluster nodes, the TDMA scheduling for a centralized decision that individual nodes take turns to serve as active nodes which in turn take the role of the CH. In the scheduling process, 3 parameters of time will be used, namely, S_B, S_A and T_{round}, of which S_B is a network parameter, with the least value being the frame length divided by channel ratio; S_A is a cluster parameter, referring to the time duration of a certain node as an active node, the value of which is S_B multiplies the number of its members (the total intracluster nodes -1); the time of round T_{round} is a preset value; a certain intracluster node in one round can determine how many times to be an active node according the value of T_{round} and thus the difference in the times for all nodes to serve as active nodes is less than 1.

After the formation of the cluster, the elected CH determines the allocation of timeslot according the number of intracluster nodes N. In the current round, the first-tier timeslot S_A should be the multiplication of the product of the second-tier timeslot S_B times N. Each node forwards message to active nodes in its assigned timeslot, so that all sensor nodes can avoid message collision through TDMA. All the intracluster nodes in timeslot S_A take turns to be elected as active nodes. In the implementation of the algorithm, the deployment of the second-tier timeslot S_A can be omitted, instead, after N SA timeslots, the current active node probabilistically transfer its leadership to one of its N members so that the new active node proceeds to undertake the work in the next S_A timeslot. The transfer of the leadership is conducted by $P = 1/N_{current}$, where $N_{current}$ is the number of the intracluster nodes which have not currently taken the role of the active node and the value of which may included in the network control frame.

After its generation, the cluster enters the stable working stage. According to the preset interval of the second-tier timeslot S_B and the number of current intracluster nodes, the CH can determine the interval of the first-tier timeslot S_A. Then, according to the preset time duration in each round T_{round}, the CH determines N_A, the number of the first-tier timeslot S_A in the current cluster. Assuming that the energy consumption of the active node in S_A is E_{SA} (energy consumption of communication), the energy consumption of the CH is $E_{SA}N_A$. In this round of implementation, energy consumption is apportioned approximately equally to each intracluster node; that is, to be more exact, the energy consumption of each node of N_A mod N nodes is $[1+(N_A/N)]E_{SA}$ and the energy consumption of each node of (N-N_A mod N) nodes is $[N_A/(N+1)]/E_{SA}$. It is thus clear that within the cluster this algorithm can apportion energy consumption approximately equally to all intracluster nodes, therefore the energy consumption of each intracluster node is approximately equal, thus preventing a single CH from to much load of data forwarding which leads to its premature death.

Data transmission service: After the timeslot is established in the cluster, data transmission can proceed. When it is assumed that the node always has data to forward in the assigned timeslot to active nodes, the node needs only less energy because of the shorter distance. In other timeslot it turns off the radio signal to reduce energy consumption. During work, the active node must turn on the radio signal continuously in order to receive information from its members. Having received all the data, it processes the data by fusion, compresses data into the single signal and forwards it to the base station. Because of the longer distance, the active node consumes much energy. When the time given for this round is due, the next round of CH election and cluster generation is initiated.

Analysis of simulation experiment and the comparison of relevant work: In consideration of the criteria for appraising the performance including well-proportioned energy consumption, energy efficiency, network lifetime, the dying speed of the system and the impact of mobility of the base station on the performance, comparisons of relevant work in the simulation experiment have been conducted.

Parameter settings and the appraisal indexes: The process of simulation is described as below:

- Simulation startup. The simulator starts with main.exe and the simulation scenario is set with energy parameters added to it
- Simulation initialization. The queue of global tasks is initialized and the settings of the system initialization are completed
- Processing cycling of the queued-up events to realize corresponding functions
- The concluding stage of simulation

The parameters used in the experiment are indicated in Table 1. The network with 100 nodes randomly and equally distributed is shown in Fig. 3, the base station is positioned 50 m to the closest node and at (50, 150 m) which is not shown in Fig. 3. Based on the energy

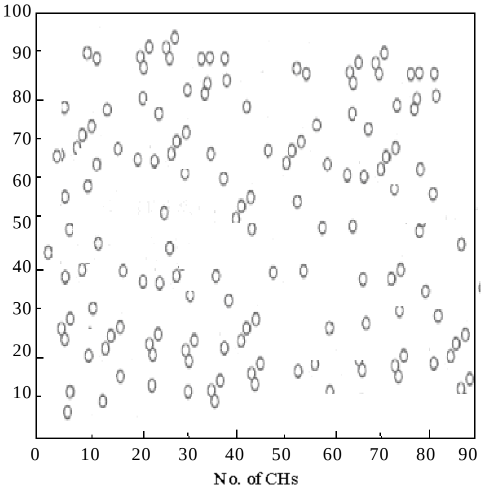

Fig. 3: Network with 100 nodes randomly distributed

Table 1: Parameters used in the simulation

Parameters	Value
Network size	100×100 m
Location of base station	50 m.150 m
No. of nodes	100
Energy consumption of radio receiver and transmitter circuits	50 nJ/bit
Energy consumption of transmitting amplifier	100 pJ/(bit.m2)
Initial energy	0.5 J
Size of data frame	400 Byte
Size of broadcast frame	40 Byte
Threshold value of distance	300 m
Energy consumption of data fusion	5 nJ/bit
Duration of one cycle	18 sec
Brand width of communication channel	1 M bit/s
Second-tier timeslot	3.2 ms

parameters in Table 1, it can be figured out that the value of the second-tier timeslot SB (L/Cbw) is 3.2ms. When the energy of the node becomes 0.002J and below, the node is considered dead according to the algorithm.

In the simulation, LEACH, HEED (Nori *et al.*, 2011) DCHST (Wang *et al.*, 2013) and low-power timeslot-based algorithm are achieved and their performances are compared. Below are the main criteria used to analyze and appraise the low-power timeslot-based algorithm:

- The equality of energy consumption
- Network lifetime, namely, the time that the first node dies
- The dying speed of the system which refers to the time from the death of the first node to the death of all nodes
- Energy efficiency
- The relationship between the energy consumption of the network and the number of frames received by the base station

Experiment results and comparison of relevant work: After 600 rounds of simulation, it is found that the numbers of nodes with energy consumption more than 10% and less than 90% are 20 and 30%, respectively, while the numbers of nodes at other segments of energy consumption are not more than 10%. This indicates there are cases that some nodes consume energy excessively, so they may die prior to other nodes. This demonstrates LEACH cannot obtain satisfactory results although its original intention is to balance energy consumption by random rotation.

The timeslot-based protocol proposed in this study mainly intends to balance the energy consumption of intracluster nodes so that most the nodes consume approximately equal amount of energy. Compared with LEACH, DCHS and HEED, this protocol obtains greater escalation in its performance and the simulation effects are in accordance with its expected performance. This protocol balances the energy distribution well in that nodes with about 40% energy consumption take up nearly 80% of all nodes; in the meanwhile, nodes with 40, 50 and 60% energy consumption occupy about 95% of all nodes. Therefore this protocol has solved the problem of unequal energy consumption caused by the unreasonable number of CHs and unequal distribution in LEACH.

CONCLUSION

In summary, this study proposes the timeslot-based topology clustering control protocol. The protocol self-adaptively elects CHs according to the current remaining energy of nodes. Within the cluster, MNs are made through timeslot to take turns to serve as active nodes in order to achieve equal energy consumption. In terms of improving the lifetime of the network, this new topology control algorithm has the following features: The time of the death of the first node is postponed much significantly and the lifetime of the network is prolonged; the increased stability of topology with good fault tolerance can guarantee service quality in the early period of node death; the distributed CH election and centralized generation of intracluster active nodes ensure both resilience and operational efficiency and reliability.

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