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Double Cluster Head-based Fault-tolerant Topology Control Algorithm for Wireless Sensor Networks

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Abstract. Topology control is an effective method that can enhance the power efficiency and fault tolerance in WSNs and the goal of it is to extend the life of the network. As a result, double cluster head-based fault-tolerant topology control algorithm for WSNs (DCHFT) is presented which takes both network life and fault tolerance into consideration. Firstly, the algorithm uses AGNES algorithm based on nodes' location for optimizing the distribution of cluster heads to divide the network into several subareas; secondly, the main cluster head and the vice cluster head which are respectively responsible for communication of clusters and the inter-cluster are elected to form a network topology according to the distance between nodes; Finally, the simulation results show that DCHFT can reduce energy consumption, prolong the network lifetime and improve the fault tolerance, compared with the typical clustering algorithm like LEACH and EEUC.

Keywords: AGNES, double cluster head, fault tolerance, topology control, wireless sensor networks

1 Introduction

Wireless sensor networks (WSNs) has an important and practical value in military, environmental monitoring, industrial control, smart home and urban transportation, etc., and has become one of research focus filed [1]. For different application requirements, WSNs has a great difference in the hardware platform, software systems and communication protocols. From the perspective of network topology, WSNs can be divided into two categories: the plane structure and the clustering structure. The status of nodes in WSNs is equal in the plane structure, and in the clustering structure, nodes in the network are divided into a few sets which are called clusters, and each cluster usually consists of a cluster head node and a plurality of member nodes, and cluster head is responsible for management and control of the member nodes, and is also responsible for intra cluster data collection and inter cluster data forwarding. Compared with the planar structure, the WSNs has the advantages of high energy efficiency, good scalability and so on by using the clustering structure [2-3].

WSNs has been studied extensively for their broad range of potential monitoring and tracking applications [1]. WSNs is typically composed of a large number of tiny sensor nodes that are capable of sensing, processing and transmitting data via wireless links, however, sensor nodes are powered by limited disposable batteries and deployed arbitrarily in a two (or three) dimensional region [4]. The limited energy of nodes and the instability of the environment are the main problems to be solved urgently. WSNs is generally used to monitor an unmanned area, so environmental or other external

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factors will enable sensor nodes failure, and maintenance or replacement of the invalid sensor node is very difficult, therefore this requires that the network topology must have a certain fault tolerance to ensure that the system has the high reliability [3-5]. Besides the energy depletion, hardware failures, communication link failure or adverse environmental conditions may occur frequently in WSNs, however, topology control can still ensure the normal operation of the network in these unfavorable conditions. Therefore topology control is one of the important technologies to reduce energy consumption, maintain network connectivity and tolerate node failures.

In many scenarios, we have to face such a complicated real networks which suffer from the resource limitations or node failures that the traditional clustering methods cannot be suitable for them. Thus, we focus on how to design an energy-efficient and fault-tolerant algorithm for WSNs to maximize the network lifetime while considering the energy consumption, link or node failures and any other complex scenarios. This paper put forward a kind of double cluster head (main, vice cluster-head) topology control method, can reduce energy consumption of cluster, thus can effectively prolong the lifetime of network and balance the network load, and can provide a certain redundancy of network by constructing multi-path from member nodes to double cluster head and having main and vice cluster head. This algorithm not only keeps the advantages of clustering method but also ensures redundancy, not like many clustering algorithms which only focus on the optimization of a single goal instead of multiple targets. This paper turned to reducing energy consumption and ensuring fault tolerance in order to prolong the network lifetime as long as possible.

2 Related Work

In the architecture of wireless sensor networks, network based on clustering has the advantages of convenient topology management, high energy efficiency, simple data fusion and so on [6, 8]. A low energy adaptive clustering hierarchy algorithm (LEACH) [7] is a classical clustering algorithm, and randomly selects cluster head in a circular way, and cluster heads communicate with sink node directly in a single hop. Because LEACH does not consider the node’s residual energy, Younis [9] proposed a hybrid energy efficient distributed clustering algorithm (HEED), first selected cluster heads according to the node’s residual energy, and then competed to select the final cluster heads in accordance with cluster communication cost, due to the need for repeated iterative message within the radius of the clusters, the communication overhead is remarkable. Li et al. [10] proposed an energy efficient uneven clustering algorithm (EEUC), the algorithm selected nodes as candidate cluster heads in accordance with a certain probability. The candidate cluster heads set the election radius according to the distance of candidate cluster heads to the sink node, and then determined the final cluster head through comparing with the residual energy of candidate cluster heads. Ye et al. [11] proposed the energy efficient clustering scheme (EECS), by considering the distance of candidate cluster head to sink node, uneven clusters are constructed to balance the load of cluster heads. This just compares with local residual energy and is not in harmony with node energy consumption on the whole, and the inter cluster communication uses the same single hop communication, limiting the scalability of algorithms, so it is not suitable for large-scale networks. Miao et al. [12] inherited uneven clustering structure, and combined with ant colony algorithm to optimize, but such a strategy is easy to fall into the local optimum. Li et al. [13] designed an uneven grid network partition method to solve the hotspot and improve the reliability of the data. Heinzelman et al. [14] first proposed to solve the problem of energy hole by using non-uniform clustering, but it is considered to put to use in a heterogeneous network, and cluster head is super node, calculating the node deployment location in advance. [15] proposed a method of combining the node residual energy with node degree to control cluster head selection, which can effectively balance the energy consumption of nodes.

Clustering algorithm is one of the effective ways to manage energy consumption and improve the network performance, and the fault tolerance is the important property of topology control [15]. In this paper, clustering and fault tolerance are effectively combined with together, and we put forward the double cluster head -based fault-tolerant topology control algorithm, and the algorithm elects two cluster heads which are responsible for the task of intra cluster and inter cluster to reduce the energy consumption of cluster heads and to provide a certain redundancy of network. The goal of the algorithm is to reduce the network’s energy consumption, prolong the network lifetime and improve fault tolerance and robustness, and the algorithm has a good application foreground.

The main difference between what we mentioned in above and our solution described in the following lies in network model. In this paper, a double cluster head-based fault-tolerant topology control algorithm is introduced for WSNs in order to solve the problem that is how to save energy and solve the problem of nodes failure. Forecasting the energy consumption per round during the network lifetime and the actual lifespan of the network is greatly important. We propose DCHFT algorithm for solving this problem in an efficient way and compare with other clustering algorithms according to energy consumption and network lifetime. On the one hand, this algorithm employed clustering algorithms to save energy consumption and prolong network lifetime. On the other hand, it constructed multi-path from member nodes to double cluster head nodes to solve nodes failure which caused by limited energy or hostile environment. The clusters are formed by combining with the factors of the distance and link quality, while the cluster heads are selected depending on the location of nodes and their distance. Moreover, to reduce the burden of the cluster-head, vice cluster head nodes in each cluster are chosen as the relay nodes for transmitting data through multi-hop communication. The performance of DCHFT is evaluated and found better than other typical clustering algorithms via simulation.

3 Model Assumption

3.1 Assumptions

(1) Nodes distribute uniformly in the square of the monitoring area, and all nodes know their location information and are motionless, and sink node is located at the lower left of the region;

(2) Every node has the same maximum transmission power, and its coverage is the circular area of the radius, and it can adjust the transmission power according to the communication need;

(3) When the nodes communicate at the maximum transmission power in the network, the network is connected;

(4) Nodes have the same initial energy, and can obtain the residual energy of their own, and can communicate with the base station directly.

3.2 Energy Consumption Model

In WSNs, the energy consumption of the nodes mainly is data acquisition, fusion and transmission, and the energy consumption of data transmission is much greater than other parts of energy consumption [14]. Therefore, this paper mainly considers the data transmission energy consumption in the network, and uses the typical wireless communication energy consumption model. In the model, the energy consumption of sensor nodes transmitting l-bit data is:

$$E_{tx} = \begin{cases} l \times E_{elec} + l \times e_{fs} \times d^2 & d \le d_0 \\ l \times E_{elec} + l \times e_{mp} \times d^4 & d > d_0 \end{cases} \quad \textbf{(1)}$$

The energy consumption of sensor nodes receiving l-bit data is:

$$E_{rx} = l \times E_{elce} \quad \textbf{(2)}$$

Where E_{elce} is a fixed energy value spent for sending l-bit data; d is the transmission distance; e_{fs}, e_{mp} are the energy coefficients; $d_0 = \sqrt{e_{fs} / e_{mp}}$.

4 Algorithm

Selecting the appropriate number of clusters and ensuring inter-cluster load balance are crucial in clustering algorithms for WSNs. The cluster head nodes will be responsible for all affairs of intra cluster and inter cluster, so two clusters can be elected, and one is responsible for intra cluster communication, and the other is in charge of inter-cluster communication. Cluster head selection is based primarily on the distance between nodes, that is, considering the energy consumption of nodes. Because reducing nodes' and cluster head nodes' energy consumption can extend lifetime and improve the utilization efficiency of energy networks, and double cluster head also ensures network fault tolerance and enhances network survivability. Thus double cluster head-based fault-tolerant topology control algorithm is proposed (DCHFT), and each cluster has a master cluster head and vice cluster head, master cluster head is responsible for the data collection in intra-cluster, vice cluster head is responsible for the data transmission between clusters [18].

4.1 Network Partition

WSNs is relatively large, and clustering algorithm can effectively manage energy consumption and improve network performance. However, the number of clusters can also affect the network performance, too much or too little clusters will lead to decrease network performance [3].

The network can be divided by hierarchical clustering algorithm to form a plurality of sub-areas called clusters, and cluster head nodes are elected independently among regions. In the network partition, a node sends its location information to sink node, and the network will be divided into a plurality of sub-regions according to the distance between the nodes and sink node, and hierarchical clustering algorithm requires that each node can only belong to a region [16]. According to the energy consumption model, energy consumption of the data transmission is closely related to distance between nodes, so the network partition uses agglomerative nesting method (AGNES) that only considers the factor of distance [17]. Nodes are separated into clusters by agglomerative nesting method to complete network partition based on the distance between nodes, and nodes within each sub-region are relatively uniform distribution after division. As shown in Fig. 2, through clustering, the network in Fig. 1 is divided into five different sub-regions. In the process of data transmission, the nodes within the sub-region transfer the data to the cluster head nodes and then to the sink node. Nodes outside the sub-region are called outliers, and outlier node transmits its data to its nearest node in its nearest cluster or directly to the sink in the data transmission process.

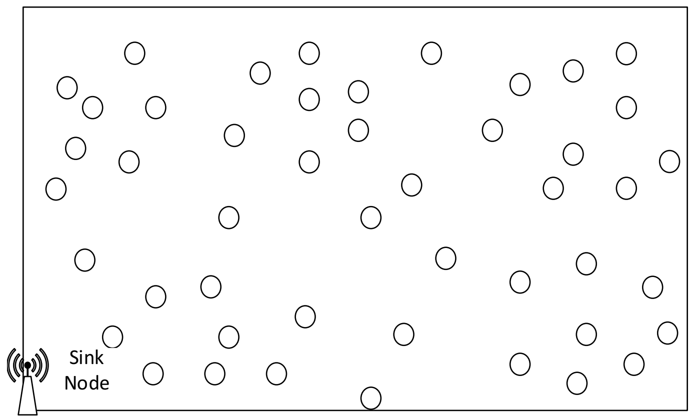

Fig. 1. Network diagram

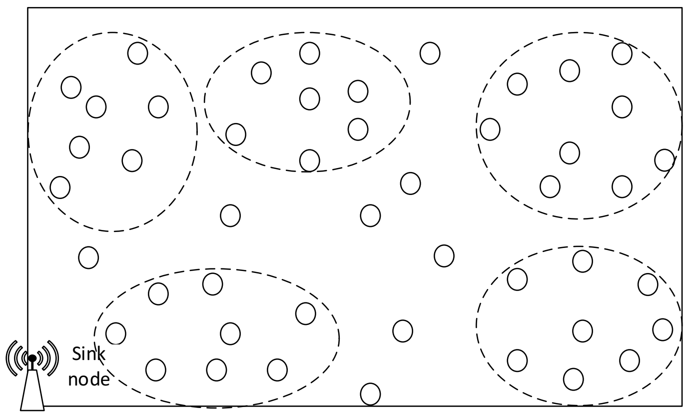

Fig. 2. Network partition

4.2 Master and Vice Cluster Head Selection

4.2.1 Optimal Number of Cluster Heads

The number of clusters also affects network performance. Too many clusters are not easy to manage the cluster head nodes and will increase the energy consumption. If the number of cluster head nodes is too small, the number of member nodes in the cluster will be too many, and it is difficult to manage the member nodes and the responsibility of cluster head nodes is greatly heavy. Therefore, The number of clusters is extremely important in the cluster algorithm. And the network must reasonably determine the number of clusters to improve network performance. According to literature [19], the optimal number of cluster heads in network was given by

$$K_{opt} = \sqrt{\frac{N}{2\pi}} \sqrt{\frac{e_{fs}}{e_{mp}}} \frac{M}{d_{toBS}^2} \tag{3}$$

where K_{opt} is the optimal number of cluster heads; N is the number of sensor nodes in the network; e_{fs} and e_{mp} are the energy coefficients; M is the side length of sensor network distribution area; d_{toBS} is the distance of the cluster head to sink node.

4.2.2 Cluster Head Election

Cluster head nodes in WSNs have an important role [20-22]. In order to reduce energy loss of cluster head election and prolong the network life, we should offer reasonable cluster head election program. The cluster head election should be considered the following aspects [18]:

(1) Cluster election algorithm should be as simple as you can to save energy consumption, and nodes in the network can choose the cluster heads independently;

(2) Try to make the cluster head evenly distributed throughout the network, and the cluster head can monitor the operation of the entire network;

(3) The number of cluster heads should be close to the optimal number of cluster head, and cluster head election process should be less energy consumption as much as possible.

The main cluster head. Whether the node can serve as the main cluster head is mainly affected by the location of the node in the cluster and the distance between the node and the base station. The probability that a node becomes the main cluster head is given by

$$\omega_{S_{ij}} = \alpha \frac{\overline{d^1}}{d_{S_{ij}}^1} + \beta \frac{\overline{d^2}}{d_{S_{ij}}^2} \tag{4}$$

Where $d_{S_{ij}}^1$ is the distance from the node to sink node; $\overline{d^1}$ is the average distance from cluster member nodes to sink node; $d_{S_{ij}}^2$ is the average distance of the node to the remaining nodes in the cluster; $\overline{d^2}$ is the average distance of cluster member nodes to the remaining nodes in the cluster; α and β are weighted coefficients and satisfy $\alpha + \beta = 1$.

The first item of formula (4) is to select the node whose distance is small to sink node. A large part of energy consumption is forwarding data to sink node, and energy consumption is becoming more with the distance farther away from the base station. Therefore, the smaller the distance to the base station node is, the more suitable the main cluster head is. The second option is to select nodes with a smaller average distance to nodes in the cluster as the master cluster head. Cluster member nodes will send data to the cluster head, if the distance between cluster head and members of the cluster is large, then the cluster members will consume more energy. In order to reduce the energy consumption, prolong the life of the network, we can elect the main cluster head according to the formula (4).

The vice cluster head. The selection of the vice cluster head mainly considers the connection among clusters. We only need to make inter-cluster communication, and the energy consumption of vice cluster head nodes is the least, namely, the total distance among vice cluster head nodes is minimum, so we can obtain the location information of the vice cluster head nodes according to the formula (5). The objective of selecting vice cluster head nodes is to establish the inter cluster communication with the minimum energy consumption in the network, and the redundancy is generated and the fault tolerance of the network is improved.

$$\mu=\min\left(\sum_{i,j=1\sim m,i\neq j} d_{ij}\right) \quad \textbf{(5)}$$

4.3 Cluster Communication

After the clustering is completed and the master and vice cluster head is determined, nodes in the cluster to master and vice cluster heads utilize Dijkstra algorithm to form a local minimum spanning tree, and it is the shortest distance to communicate, hence this can reduce the energy consumption of the nodes in the cluster. The main cluster head nodes can directly communicate with the sink node and can also reach the sink node by multi-hop transmission. The vice cluster head can directly communicate with the main cluster head in own cluster, and vice cluster head’s information can also be transmitted directly to the sink node. When the main cluster head node fails or its energy is exhausted in the network, the vice cluster head is enabled to communicate.

5 Simulation

In this paper, the simulation experiment is under MATLAB environment. DCHFT, LEACH and EEUC are compared and analyzed in the residual energy, the number of survived nodes and the fault tolerance in the network. 100 nodes are distributed randomly in 500m× 500m monitoring area, and the initial energy of every node is 0.5J. And more simulation parameters are shown in Table 1.

Table 1. Simulation parameters

parameters	Value
The size of the monitoring area	500m×500m
The total number of nodes	100
Maximum radius of the transmission	85m
Initial energy of nodes	0.5J
The total energy of network	50J
E_{elec}	50 nJ/b
e_{fs}	10 pJ/(b*m^3)
e_{mp}	0.013 pJ/(b*m^3)

5.1 Survival Nodes

The network lifetime can be expressed by the relationship between the number of survived nodes and the number of rounds, and the time when the first node’s energy is exhausted is defined as the network lifetime. Lifetime span is an important index for evaluating network, and long lifetime is the goal of our pursuit.

As shown in Fig. 3, among LEACH, EEUC, DCHFT, the lifetime of LEACH is the shortest, because this algorithm elected cluster head nodes entirely based on random probability in LEACH algorithm, resulting nodes with low energy premature death. The lifetime of EEUC is longer than LEACH, and survived nodes are more than LEACH, and this is because the EEUC can better balance the energy consumption of nodes in the network. Compared to LEACH and EEUC, the network lifetime of DCHFT is greatly extended obviously. In the figure of network lifetime, the network lifetime in LEACH is more than 220 rounds, and network life in EEUC is about 430 rounds, while network lifetime in DCHFT is about 610 rounds. So compared to LEACH and EEUC, the network lifetime of DCHFT raises about 64% and 30%, but the number of DCHFT’s survival node is not always more than LEACH and EEUC, which shows that the energy consumption of DCHFT is not uniform, and DCHFT can balance the energy consumption of nodes not better than EEUC, so there is still much room for improvement.

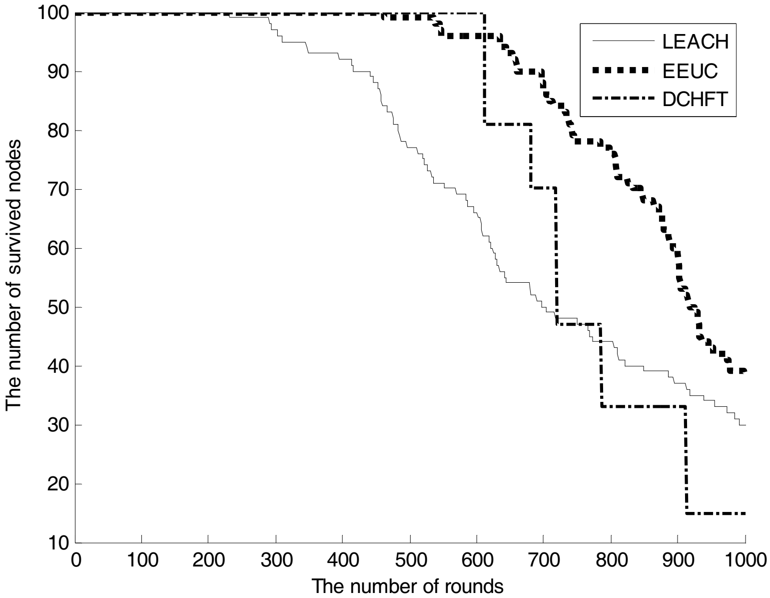

Fig. 3. Network lifetime

5.2 Residual Energy

Another main objective of topology control is to reduce the energy consumption of the network in WSNs. The remaining energy in networks reserves more and the lifetime of such a network may be longer. As shown in Fig. 4, the residual energy of LEACH in the first 700 rounds was the least, namely, the energy consumed by LEACH was the most, but after the 700 rounds, the residual energy of EEUC is the least, and the energy consumption of EEUC is the most, because at this time, only half of the original LEACH nodes are survived, and the number of failures is only about 10% of the original in EEUC, so the energy consumption of EEUC is higher than LEACH and this can be predictable. Compared with LEACH and EEUC, the residual energy of DCHFT is higher than both, because cluster communication of DCHFT is minimum spanning tree, apparently with less energy consumption, and DCHFT is beneficial to energy saving.

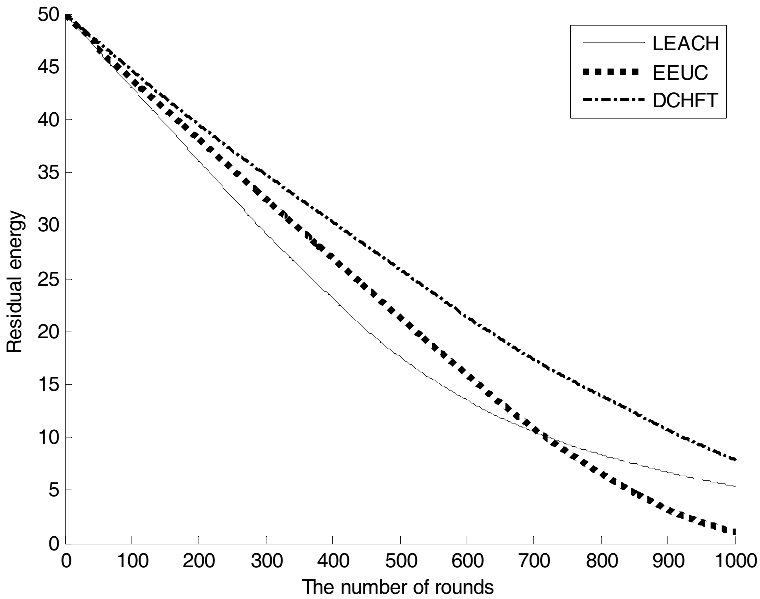

Fig. 4. Network energy consumption

5.3 Fault Tolerance

Fault tolerance is the ability that in case of failure of the sensor nodes, the system can still run the program correctly and give the correct result. Good fault tolerance refers to having a certain network redundancy. On the one hand, DCHFT is a double cluster head algorithm, from the number of cluster head perspective, apparently there are redundant cluster head. On the other hand, due to the protection of double cluster head, communication paths from the cluster member nodes to the cluster head are not the only one, so there are redundant paths compared with LEACH and EEUC, apparently DCHFT have some fault tolerance.

6 Conclusion

In this paper, the double cluster head-based fault-tolerant topology control algorithm for WSNs is presented, and it mainly introduces the idea of double cluster head, and there are two cluster head nodes within each cluster, and it can make two tasks of data acquisition and data forwarding assign master and vice cluster heads. The coordinates of nodes and distance determined the location of main and vice cluster head nodes, and the cluster head nodes are in the proper position, which can balance the energy consumption of intra cluster and inter cluster to a certain extent, and can prolong the lifetime of the entire network. So the energy consumption of master and vice cluster head nodes is much slower than a cluster head node, and the network not only achieves energy savings but also makes the network fault-tolerant. In addition, due to the intra-cluster communication based on the minimum spanning tree, the energy consumption will be relatively small. So DCHFT can effectively improve the energy efficiency of data transmission, reduce energy consumption and extend the lifetime of the network. Because the sensor node and link transmission quality is strongly influenced by environmental factors, which can bring instability to clustering topology control, now topology control should consider the optimization of multiple goals, especially fault tolerance which can solve the instability of network to some degree. DCHFT algorithm satisfied the characteristics of low energy consumption, long lifetime and fault tolerance.

The algorithm proposed in this paper did not consider the external signals interference that may bring calculation errors. This issue will be addressed in the future in-deep researches. And the selection of cluster head nodes did not consider the residual energy, so we should take other factors that affect network lifetimes into consideration then. Now heterogeneous wireless sensor networks is more practical, we should consider that how the idea of double cluster head is applied in heterogeneous wireless sensor networks in the next step.

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References

[1] V.W. Mahyastuti, A.A. Pramudita, Energy consumption evaluation of low energy adaptive clustering hierarchy routing protocol for wireless sensor network, in: Proc. 2013 IEEE International Conference on Communication, Network and Satellite (COMNETSAT), 2013.

[2] Z. Hong, R. Wang, X. Li, A clustering-tree topology control based on the energy forecast for heterogeneous wireless sensor networks, IEEE/CAA Journal of Automatica Sinica 3(2016) 68-77.

[3] Y. Lv, Z. Miao, D. Zhang, A low energy uneven clustering topology control algorithm for wireless networks, in: Proc. 2016 3rd International Conference on Information Science and Control Engineering (ICISCE), 2016.

[4] L. Zheng, L. Gao, T. Yu, An energy-balanced clustering algorithm for wireless sensor networks based on distance and distribution, in: Proc. the 6th International Asia Conference on Industrial Engineering and Management Innovation, 2016.

[5] S.PSingh, K. Bhanot, S. Sharma, Critical analysis of clustering algorithms for wireless sensor networks, in: Proc. Fifth International Conference on Soft Computing for Problem Solving, 2016.

[6] J. Su, W. Guo, Z. Yu, Fault tolerance clustering algorithm with load balance aware in WSNs, Chinese Journal of Computer 37(2014) 445-456.

[7] J. Guo, Y. Han, Load balancing algorithm for non-uniform clustering with distributed hierarchical structure, Journal of Computer Applications 35(2015) 332-335.

[8] W.R. Heinzelman, A. Chandrakasan, H. Balakrishnan, Energy-efficient communication protocol for wireless microsensor networks, in: Proc. the 33rd Annual Hawaii International Conference on System Science, 2000.

[9] O. Younis, S. Fahmy, Heed: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks, IEEE Transactions on Mobile Computing 3(4)(2004) 366-379.

[10] C. Li, G. Chen, M. Ye, An uneven cluster-based routing protocol for wireless sensor networks, Chinese Journal of Computers 30(2007) 27-36.

[11] M. Ye, C. Li, G. Chen, Eecs: an energy efficient clustering scheme in wireless sensor networks, in: Proc. 24th IEEE International Performance, Computing, and Communications Conference, 2005

[12] C. Miao, Q. Chen, J. Cao, Energy balanced uneven clustering algorithm based on ant colony for wireless sensor network, Journal of Computer Applications 33(2013) 3410-3414.

[13] C. Li, G. Chen, M. Ye, An uneven cluster-based routing protocol for wireless sensor networks, Chinese Journal of Computers 30(2007) 27-36.

[14] W.B. Heinzelman, A.P. Chandrakasan, H. Balakrishnan, An application-specific protocol architecture for wireless microsensor networks, IEEE Transactions on Wireless Communications 1(4)(2002) 660-670.

[15] C. Wang, C. Li, An ad-hoc network clustering algorithm based on relative mobility, Computer Application and Software 33(2016) 151-155.

[16] J. Le, W. Zhang, W. Xiao, Balanced energy consumption and reliable clustering algorithm for wireless sensor network, Journal of Communication 2(2012) 11-96.

[17] Y. Wang, T. Zhang, Z. Song, Regional cluster-based lifetime optimization strategy for large-scale wireless sensor networks, Journal of Computer Applications 35(11)(2015) 3031-3037.

[18] J. Lian, K. Naik, G.B. Agnew, Data capacity improvement of wireless sensor networks using non-uniform sensor distribution, International Journal of Distributed Sensor Networks 2(2)(2006) 121-145.

[19] S. Long, D. Chen, G. Jian, Clustering topology control algorithm for wireless sensor networks, Transducer and Microsystem Technologies 33(2014) 143-145.

[20] F. Li, Research on cluster head selection algorithms for wireless sensor networks cluster routing, [dissertation] Changsha University of Science and Technology, 2012.

[21] T. Zhang, L. Yan, X. Li, Energy-efficient and balanced unequal clustering nodes scheduling in wireless sensor networks, Computer Engineering and Applications 52(19)(2016) 128-133.

[22] H. Bagci, I. Korpeoglu, A. Yazici, A distributed fault-tolerant topology control algorithm for heterogeneous wireless sensor networks, Parallel and Distributed Systems 26(4)(2015) 914-923.