http://ansinet.com/itj

ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 12 (22): 6783-6788, 2013
ISSN 1812-5638 / DOI: 10.3923/itj.2013.6783.6788
© 2013 Asian Network for Scientific Information

Research on the Mechanism of Avoiding Energy Hole in Wireless Sensor Networks

[1, 2]Tan Xiao-Bo, [1]Zhao Hai and [2]Zhang Wen-Bo
[1]School of Information Science and Engineering, Northeastern University, Shenyang, 110819, China
[2]School of Information Science and Engineering, Shenyang Ligong University, Shenyang, 110159, China

Abstract: Clustering can extend network lifetime of wireless sensor networks but uniformed clustering makes the nodes closer to the sink take on excessive energy consumption, leading to the energy hole problem. This study analyzes the energy hole problem and proposes a new non-uniform clustering routing protocol (NUCR) based on layered structure. In clustering phase, NUCR makes the number of clusters in different layers more reasonable on the basis of non-uniformed clustering. In inter-cluster routing establishment phase, the cost function balances energy consumption of different layers. The simulation results show that NUCR prolongs the network lifetime greatly. Furthermore, it makes the cluster size of different layers more reasonable.

Key words: Wireless sensor networks, clustering, routing protocol, network lifetime

INTRODUCTION

With the development of wireless sensor networks, it has been widely used in many domains, such as medical care, environmental protection and transportation applications. A sensor network is composed of a large number of sensor nodes and a sink. The sink typically serves as a gateway to some other networks. It provides powerful data processing, storage center and an access point to the sensor nodes in its network (Kumar *et al*., 2009).

Due to the energy limitation, how to improve the utilization efficiency of the node's energy to prolong the network lifetime is an important content in the research of wireless sensor networks. Heinzelman *et al*. (2002) proposed Low-energy Adaptive Clustering Hierarchy algorithm (LEACH). In LEACH, nodes make clustering in self-organized manner and cluster heads are rotated periodically to balance the energy depletion. Although the network lifetime is prolonged greatly, there is only one hop communication from each head to the sink. Moreover, the distribution of cluster heads is uneven. TEEN (Manjeshwar and Agrawal, 2001), HEED (Younis and Fahmy, 2004) and so on were proposed to further reduce energy depletion based on LEACH. Clustering has been studied originally to extend the network lifetime and has been proven to be an effective approach to prolong the network lifetime (Rundel *et al*., 2009).

In the network where it uses clustering structure and multi-hop routing strategy, lots of sensory data are transferred to the single sink in multi-hop manner, which causes nodes near the sink taking on more data forwarding. So the region near the sink becomes "hot region" due to higher energy depletion. The nodes in hot region prematurely consume energy and cause network failure, which is called energy hole. In the energy hole phenomenon, the network lifetime has ended prematurely, although there are lots of surviving nodes. How to solve the energy hole problem has become a hot research. Wu and Chen (2008) and Huang *et al*. (2011) use non-uniform distribution strategy to solve the energy hole problem from the perspective of node deployments. The core idea is to deploy more nodes near the sink. Zhang *et al*. (2010) and Liu *et al*. (2009) avoid energy hole from the perspective of adjusting power. Jiang *et al*. (2012), Bagci and Yazici (2013) and Taheri *et al*. (2012) propose non-uniform clustering method. Clusters near the sink have smaller size, so cluster-head energy used to process the intra-cluster communications is saved for inter-cluster data forwarding, which balances the energy depletion. Li *et al*. (2013) constructs optimal clustering architecture to maximize sensor network lifetime based on non-uniform clustering method.

This study theoretically proves the energy-hole problem in wireless networks which use clustering structure and multi-hop routing mechanism. Furthermore, we discuss the relationships of cluster numbers in different layers and propose a new non-uniform clustering algorithm to alleviate the energy hole problem. The simulation results show that the new algorithm not only balances the energy depletion of the whole network, prolongs the network lifetime greatly but also makes the cluster size of different layers more reasonable.

Corresponding Author: Tan Xiao-Bo, School of Information Science and Engineering, Northeastern University, Shenyang, 110819, China

NETWORK MODEL

Network model: In this study, we assume that all sensor nodes are deployed with uniform distribution in a very large rectangular sensing area and the nodes' deployment density is sufficient to ensure that the initial network has good connectivity to satisfy the related applications, as illustrated in Fig. 1. All sensing nodes except the sinks are homogenous and each sensor node has unique ID. The energy of all nodes except the sinks is limited and can't be recharged after being deployed. All nodes don't have location-aware capability but they can calculate the approximate distance to another node based on the received signal strength. All sensing nodes can adjust their transmission powers according to the transmission distance.

Some sinks are deployed regularly outside the sensing area. There is only one data center responsible for optimizing multiple query tasks and assigning them in parallel to other sinks according to their geometric locations. After query optimization process, the sink will disseminate each query to a subset of the sensor nodes which belong to it. Upon the receipt of a query, the sensors will transmit data to the sink by multi-hop routing mechanisms. We think this model can improve the scalability of the networks. In order to simplify the energy hole problem, we consider a subset of the network, as illustrated in Fig. 2.

In Fig. 2, the sub-rectangle area is divided into equal-size layers. Clusters within a layer have the same size. There is one cluster head in a cluster. It receives data from its members and aggregates them. Meanwhile, the cluster head also receives data from other cluster heads (these cluster heads belong to other layers), then it forwards all the data to the sink by multi-hop mechanism.

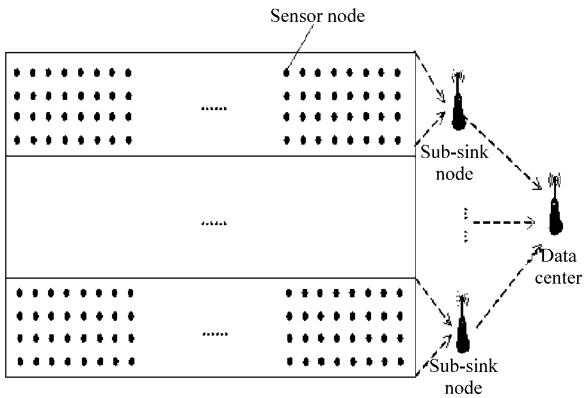

Fig. 1: Network model

Energy consumption model: In this study, energy consumption model only considers the energy consumption of communication. The energy spent for transmission of a q-bit packet over distance d is defined as below:

$$E_s(q,d) = \begin{cases} q(\xi + \varepsilon_f d^2), & d < d_0 \\ q(\xi + \varepsilon_m d^4), & d \geq d_0 \end{cases} \quad (1)$$

The energy spent for receiving a q-bit packet is defined as below:

$$Er(q) = q\,\xi \quad (2)$$

where, ξ is RF energy consumption coefficient, $\epsilon_f d^2$ and $\epsilon_m d^4$ are the amplifier energies for free space and two-ray ground propagation models respectively. ϵ_f and ϵ_m are constants which value are 10pj+/bit/m^2 and 0.0013 pJ/bit/m^4, respectively. The value of d_0 can be calculated by the formula:

$$\sqrt{\varepsilon_f / \varepsilon_m} \approx 87\text{m}$$

ENERGY HOLE ANALYSIS

In this study, we divide network lifetime into rounds. Each round begins with a set-up phase, followed by a steady data transmission phase. In set-up phase, all the nodes in each layer select cluster heads by some certain clustering algorithm and then each cluster head constructs its inter-cluster routing. After set-up phase ends, sensing data are transferred from the ordinary nodes to the cluster heads and so on to the sink. Data transmission time is much longer than the set-up time and energy consumption is mainly caused by the data transmission phase. So we only consider the energy consumption of data transmission phase to analyze the energy hole.

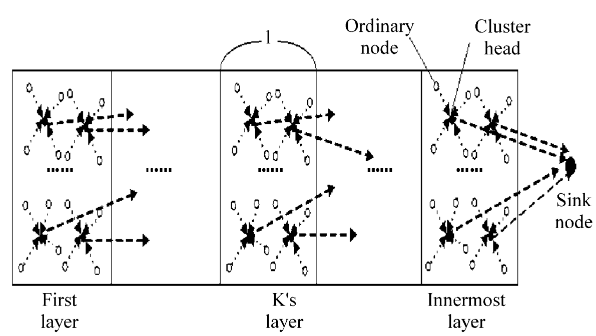

Fig. 2: Subset network model

Table 1: Symbol definition

Symbol	Definition
ω	Per bit aggregation energy cost
m_k	No. of cluster heads in the k's layer
q^r_{ki}	The number of bytes that cluster i in the k's layer received from the k-1's layer
q^s_{ki}	The number of bytes that cluster I in the k's layer sending to the k-1's layer
a	Data aggregation ratio of cluster head
L	Width of each layer
q	The No. of bytes that each cluster member sending to its head
$\bar{d}_{intra}$ (k)	The average distance of intra-cluster communication in the k's layer
$\bar{d}_{inter}$ (k)	The average distance of inter-cluster communication in the k's layer
n	The No. of nodes in each layer

Energy consumption of the network consists of energy consumption for ordinary nodes and energy consumption for cluster heads. Energy consumption for ordinary nodes is mainly caused by sending sensing data from ordinary node to the sink. Energy consumption for a cluster head contains three parts: (1) Energy cost for receiving data from its cluster members and for receiving relayed data from other cluster heads; (2) Energy cost for aggregating intra-cluster data; (3) Energy cost for transmitting its aggregated data and the relayed data to the next head or to the sink. We assume that the energy consumption for intra-cluster communication follows the free-space model and that for inter-cluster communication follows the two-ray ground model (we can realize it by adjusting the width of the layer). We assume that every cluster head has the same aggregation ratio a. In order to calculate the energy consumption, we define symbols, as illustrated in Table 1.

So we get the energy consumption of the k's layer:

- The energy cost that cluster heads in the k's layer receive data from their cluster members:

$$E^r_{intra}(k) = (n-m_k)\, q\xi \tag{3}$$

- The energy cost that cluster heads aggregate data in the k's layer:

$$E_a(k) = nq\omega \tag{4}$$

- The energy cost that cluster members send data to cluster heads in the k's layer:

$$E^s_{intra}(k) = (n-m_k)(\xi+\varepsilon_f\, \bar{d}_{intra}^{\,2}(k))q \tag{5}$$

- The energy cost that cluster heads receive inter-cluster data:

$$E^r_{inter(k)} = \sum_{i=1}^{m_k} q^r_{k_i}\xi \tag{6}$$

- The energy cost that the cluster heads send inter-cluster data:

$$E^s_{inter(k)} = \sum_{i=1}^{m_k} q^s_{k_i}(\xi+\varepsilon_m\, \bar{d}_{inter}^{\,4}(k)) \tag{7}$$

- We get the total energy cost of the k's layer from the formula above:

$$\begin{aligned} E_{total}(k) &= nq\omega + (n-m_k)q\xi + (n-m_k)(\xi+\varepsilon_f\, \bar{d}_{intra}^{\,2}(k))q \\ &+ \sum_{i=1}^{m_k} q^r_{k_i}\xi + \sum_{i=1}^{m_k} q^s_{k_i}(\xi+\varepsilon_m\, \bar{d}_{inter}^{\,4}(k)) \end{aligned} \tag{8}$$

Theorem 1: The energy hole must exist if uniform clustering is adopted and cluster head only sends data to the adjacent layer in the network model proposed in this study.

Because each cluster head only sends data to the adjacent layer and each layer has the same width, we can get:

$$\sum_{i=1}^{m_k} q^s_{k_i} = \sum_{i=1}^{m_{k-1}} q^r_{k_i} \tag{9}$$

$$d_{inter}(k) = d_{inter}(k+1) \tag{10}$$

For each cluster, the relationship between the number of bytes the cluster head sends and that it receives is:

$$q^s_{k_i} = \frac{n}{m_k} qa + q^r_{k_i} \tag{11}$$

If uniform clustering is adopted, we can get:

$$d_{inter}(k) = d_{inter}(k+1) \tag{12}$$

$$m_k = m_{k+1} \tag{13}$$

So we get:

$$E_{total}(k+1) - E_{total}(k) = na(2\xi+\varepsilon_m\, \bar{d}_{inter}^{\,4}) > 0$$

So theorem 1 is founded.

In order to avoid energy hole, namely $E_{total}(k+1) - E_{total}(k) = 0$. There are three solutions:

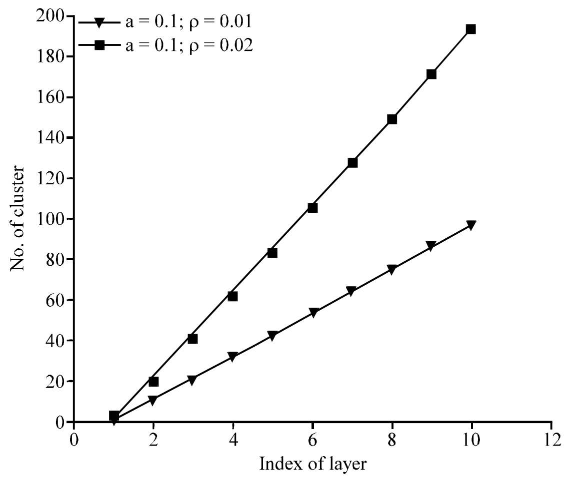

Fig. 3: Number of clusters in different density

- $n_k < n_{k+1}$
- $d_{inter}(k) > d_{inter}(k+1)$
- $m_k < m_{k+1}$

The first method is to make the layers closer to the sink have more nodes by non-uniform deployment, which is hard to practical application. Some researchers use the second method by adjusting the transmission power but these algorithms are almost centralized. The third method is to make the layers near the sink have more cluster heads by non-clustering. Li *et al.* (2013) get the relationship of the m_k and m_{k+1}:

$$(m_{k+1} - m_k)(2\xi + \frac{n\varepsilon_f l^2}{2\pi m_k m_{k-1}}) = na(2\xi + \varepsilon_m \lambda^4 l^4) \quad (l \approx 80m) \tag{14}$$

Meanwhile, the number of the outermost layer (layer 1) is obtained:

$$m_1 = \frac{1}{\lambda^2}\sqrt{\frac{\rho\varepsilon_f}{2\pi\varepsilon_m}}, \lambda = 1.088 \tag{15}$$

From the formula above, m_1 can be calculated if the density and aggregation ratio is known and then the number of clusters in other layers can also be obtained through the Eq. 14. In Fig. 3, we get the numbers of clusters in different layers when $\rho = 0.01$ and $\rho = 0.02$, $a = 0.1$.

Analyzed from Fig. 3, the energy consumption of each layer is balanced when the number of layer is less than 7. But the layers closer to the sink have much more clusters, which causes the cluster heads in these layers owning very few nodes. Even cluster heads in the inner most layer only have one or two nodes, which seriously affects the data fusion and even destroys the cluster structure. The optimal number of a cluster is (Heinzelman *et al*., 2002):

$$k_{opt} = \frac{\sqrt{N}}{\sqrt{2\pi}}\sqrt{\frac{\varepsilon_f}{\varepsilon_m}}\frac{M}{d^2 toSink} \tag{16}$$

We assume that the distance of the network to the sink is between 50 and 136 m, so we get the optimal number of cluster heads is between 1 and 8. When the density is 0.01, the number of m_1 is 1. So we should control the number of clusters in different layers within the range of optimal number.

NON-UNIFORM CLUSTERING ROUTING PROTOCOL (NUCR)

This study proposes a new non-uniform clustering routing protocol to solve the energy-hole problem. Its main thought is to use both non-uniform and auto-adjusting transmission power method to alleviate the energy hole problem.

Non-uniform clustering: In the network initialization stage, the sink broadcasts a "hello" message to all the nodes. According to the signal strength received, each node calculates the approximate distance to de sink. Through the distance each node knows the layer it belongs to.

In clustering phase of every round except the first, all nodes contest cluster head independently according to the local information. Every node broadcasts COMPETE_HEAD_MSG message to its neighbors with a calculated competition radius (R^i_{cmp}). COMPETE_HEAD_MSG message contains information of node ID, the number of layer the node belongs to and its residual energy. In the study, we assume that the nodes in one layer have the same competition radius and R^i_{cmp} is calculated by the Eq. 17:

$$R^i_{cmp} = \left[1 - c \times \frac{d_{max} - (d_{min} + i \times l)}{d_{max} - d_{min}}\right] \times R_{cmp} \tag{17}$$

In the equation, c is a control parameter which value is between 0 and 1. i is the current layer number the node belongs to. d_{max} and d_{min} are the maximum and minimum distance to the sink, respectively. R_{cmp} is the maximum competition radius which is predefined. Each node processes this information after it receives a COMPETE_HEAD_MSG message: if both of the nodes belongs to the same layer, it update information to its neighbor information list.

After each node finishes updating all its neighbor information (we assume that each node complies with the time synchronization strictly), it will broadcast FINAL_HEAD_MSG to its neighbors in a time delay announcing itself as a cluster head. Each node calculates the time delay according to Eq. 18.

$$t_i = \begin{cases} \frac{\bar{E}N_i}{E_{s_i}} \times \frac{T}{2} \times k, & E_{s_i} > \bar{E}N_i \\ T - \frac{E_{s_i}}{\bar{E}N_i} \times \frac{T}{2} \times k, & E_{s_i} \le \bar{E}N_i \end{cases} \tag{18}$$

In the equation, k is a random number which is uniformly distributed between 0.9 and 1. T is a predefined duration time of cluster-head competition. $\bar{E}N_i$ is average residual energy of the s_t's neighbors. $\bar{E}_{si}$ is s_t's residual energy. On the analysis of the formula, we know that cluster-head's broadcasting time is divided to two stages: (0, T/2) and (T/2, T). If $\bar{E}_{si}$ is greater than $\bar{E}N_i$, s_t's broadcasting time is between 0 and T/2 and it has higher probability to be cluster head. Otherwise, s_t's broadcasting time is between T/2 and T, which avoids monitoring blind spots.

When a node receives a FINAL_HEAD_MSG, it will have no chance to be cluster head in this round and then it becomes a member of the cluster head if it hasn't been a member of a cluster head. Finally, non-uniform cluster structure is formed.

The algorithm described above doesn't fit the first round because each node has the same energy initially. We make different layers select cluster heads randomly according to different probabilities in the first round. The probability of the i's layer (P_t) is defined as Eq. 20:

$$P_i = \frac{S_i}{2\times\pi\times(R^i_{cmp})^2\times\rho\times S_i} = \frac{1}{2\times\pi\times(R^i_{cmp})^2\times\rho} \tag{19}$$

S_t is the area of the layer i. ρ is the density of the layer i. We can also form the non-uniform cluster structure.

Inter-cluster multi-hop routing: The purpose of inter-cluster multi-hop routing is to find an optimal routine which further balances the energy consumption of different layer on the basis of reducing the energy consumption of inter-cluster data transmission and avoiding fast energy consumption in some area. Firstly, each cluster head broadcasts a NE_SEARCH_MSG message which contains ID, residual energy, the amount of its members and distance to the sink. Each cluster head adjusts its broadcasting power to satisfy that transmission distance is δ times of its competing radius. After receiving the message, a cluster head calculates the distance and saves the information if it is farther than the node that sends the message.

Each cluster head finds its next-hop node through the cost function, as illustrated in Eq. 20 (Jiang *et al*., 2012):

$$\text{cost}(i,j) = \begin{cases} \alpha\frac{\bar{E}_n(h_i)}{E_{h_j}} + \beta\frac{N_{non-CH}(h_j)}{\bar{N}_{non-CH}(h_i)} + \gamma\frac{d^2_{h_i-h_j}+d^2_{h_j-sink}}{d^2_{h_i-sink}}, & i \ne j \\ \alpha\frac{\bar{E}_n(h_i)}{E_{h_j}} + \beta\frac{N_{non-CH}(h_j)}{\bar{N}_{non-CH}(h_i)} + \gamma, & i = j \,\&\, d_{h_i-sink} \le d_0 \\ +\infty, & i = j \,\&\, d_{h_i-sink} > d_0 \end{cases} \tag{20}$$

After inter-cluster routing establishes, stable data transmission phase starts.

SIMULATION AND ANALYSIS

In order to evaluate the performance of the algorithm proposed in this study, we simulate EEUC, LEACH and NUCR with MATLAB in the same conditions. In the experiment, we set the number of layers from 3 to 10. i.e. the area is from 1.92×10^4-6.4×10^4. Because cluster head sends data to the sink directly in LEACH, we only simulate Leach in the network with 3 layers. Other parameters in the experiment are set as Table 2.

In this study, network lifetime is defined as continuing from the beginning to the first node energy is depleted. Figure 4 shows the network lifetime comparison of LEACH, EEUC and NUCR in the network with 3 layers.

Figure 4 shows that the lifetime of EEUC and NUCR are much longer that of LEACH. Cluster heads are selected randomly without considering the residual energy in Leach and it's more important that cluster heads send data directly to the sink which causes the energy of nodes farther to sink depletes quickly.

From Fig. 5, we can find that with the increasing of network size, network lifetime reduced in EEUC and NUCR. But the drop speed of NUCR is lower than that of EEUC. Cluster size in NUCR is more reasonable and with

Table 2: Experiment parameters

Parameter	Value
d_{min}	50 m
ρ	1 node/100 m^2
$E_{initial}$	0.5 J
C	0.9
D_0	246 m
R_{cmp}	90 m
a	0.1
Aata packet size	4000 bytes
α	0.3
β	0.3
γ	0.4

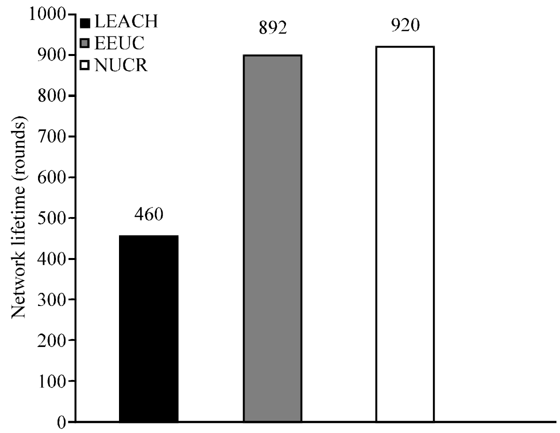

Fig. 4: Network lifetime in the network with 3 layers

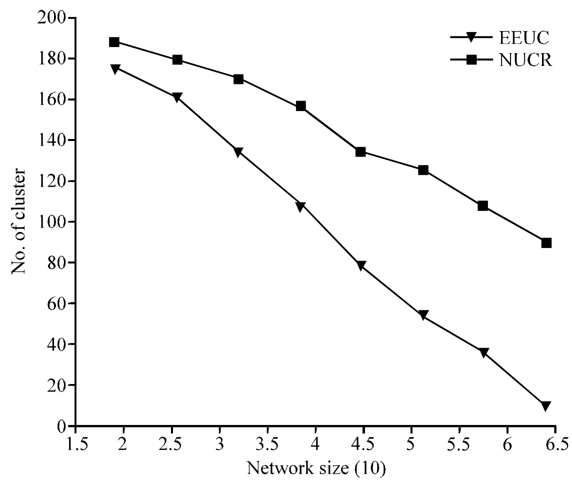

Fig. 5: Network lifetime in different network size

the increasing of layer, the number of clusters in the layers closer to the sink also increases. But in EEUC the number of the clusters closer the sink doesn't change. Furthermore, the inter-cluster routing method adopted in NUCR balances the energy consumption of different layers.

CONCLUSIONS

This study firstly analyzes the energy hole problem of the wireless networks and the relationships of cluster numbers in different layers. Then a new non-uniform clustering algorithm based on layer is proposed to alleviate the energy hole problem. The simulation results show that the new algorithm balances the energy depletion of the whole network and prolongs the network lifetime greatly. Furthermore, it makes the cluster size of different layers more reasonable.

REFERENCES

Bagci, H. and A. Yazici, 2013. An energy aware fuzzy approach to unequal clustering in wireless sensor networks. Applied Soft Comput., 13: 1741-1749.

Heinzelman, W.B., A.P. Chandrakasan and H. Balakrishnan, 2002. An application specific protocol architecture for wireless microsensor networks. IEEE Trans. Wireless Commun., 1: 660-670.

Huang, S.B., Z.Q. Wang and Q.S. Wang, 2011. Energy-balanced routing algorithm for uneven distributed node wireless sensor network. J. Comput. Appl., 11: 2887-2890.

Jiang, C.J., W.R. Shi, X.L. Tang, P. Wang and M. Xiang, 2012. Energy-balanced unequal clustering routing protocol for wireless sensor networks. J. Software, 23: 1222-1232.

Kumar, D., T.C. Aseri and R.B. Patel, 2009. EEHC: Energy efficient heterogeneous clustered scheme for wireless sensor networks. Comput. Commun., 32: 662-667.

Li, H., Y. Liu, W. Chen, W. Jia, B. Li and J. Xiong, 2013. COCA: Constructing optimal clustering architecture to maximize sensor network lifetime. Comput. Commun., 36: 256-268.

Liu, A.F., X.Y. Wu and Z.G. Chen, 2009. An energy-hole avoidance routing algorithm for WSN based on PSO. J. Comput. Res. Dev., 46: 575-582.

Manjeshwar, A. and D.P. Agrawal, 2001. TEEN: A protocol for enhanced efficiency in wireless sensor network. Proceedings of the 15th International Parallel and Distributed Processing Symposium, April 23-27, 2000, IEEE Computer Society, San Francisco, CA., USA., pp: 2009-2015.

Rundel, P.W., E.A. Graham, M.F. Allen, J.C. Fisher and T.C. Harmon, 2009. Environmental sensor networks in ecological research. New Phytol., 182: 589-607.

Taheri, H., P. Neamatollahi, O.M. Younis, S. Naghibzadeh and M.H. Yaghmaee, 2012. An energy-aware distributed clustering protocol in wireless sensor networks using fuzzy logic. *Ad hoc* Networks, 10: 1469-1481.

Wu, X.B. and G.H. Chen, 2008. The energy hole problem of nonuniform node distribution in wireless sensor networks. Chin. J. Comput., 2: 253-261.

Younis, O. and S. Fahmy, 2004. HEED: A hybrid, energy-efficient, distributed clustering approach for *ad hoc* sensor networks. IEEE Trans. Mobile Comput., 3: 366-379.

Zhang, Z.W., Z.G. Chen and A.F. Liu, 2010. Energy-hole avoidance for WSN based on adjust transmission power. Chin. J. Comput., 1: 12-22.