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Research on the Energy Hole Problem Based on Non-uniform Node Distribution for Wireless Sensor Networks

TangLiu[1,2,3], JianPeng[1,2], Xiao-fen Wang[4], Jin Yang [5] and Bing Guo[1]
[1] College of Computer Science, Sichuan University
Chengdu 610065, China
[2] State key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunications
Beijing 100876, China
[3] College of Fundamental Education, Sichuan Normal University
Chengdu 610068, China
[4] School of Computer Science and Engineering, University of Electronic Science and Technology of China
Chengdu 610054, China
[5] Department of Computer Science, Leshan Normal University
Leshan 614000, China
[e-mail: penguest@163.com, guobing@scu.edu.cn, crikey@163.com, wangxuedou@sina.com, jinnyang@163.com]
*Corresponding author: JianPeng

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Abstract

Based on the current solutions to the problem of energy hole, this paper proposed a nonuniform node distribution clustering algorithm, NNDC. Firstly, we divide the network into rings, and then have an analysis and calculation on nodes' energy consumption in each ring of the network when clustering algorithm is applied to collect data. We also put forward a scheme of nonuniform node distribution on the basis of the proportion of nodes' energy consumption in each ring, and change nodes' active/hibernating states under density control mechanism when network coverage is guaranteed. Simulation shows NNDC algorithm can satisfyingly balance nodes' energy consumption and effectively avoid the problem of energy hole.

Keywords: WSN, energy hole, non-uniform node distribution, network lifetime

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1. Introduction

Over recent years, energy hole problem [1][2][3] have become a research hotspot in wireless sensor networks (WSN) [4]. Sensor nodes carry out mutual communication usually by means of multiple hops, and some sensor nodes behaves as both data originator and data router, so the nodes near the sink tend to have more energy consumption because they are burdened with heavier relay traffic, and these areas are named as hotspots [1]. Nodes in hotspots die of energy exhaustion when nodes in other potions have more residual energy and eventually there forms some areas without sensor nodes near the sink, which is called energy hole. When energy hole emerges in the network, data collected by surviving nodes may not able to be sent to the sink, when the survival period of the network ends and considerable energy which has not yet been used is wasted.

If nodes are distributed uniformly, the simulation [5] show that when the network lifetime is over, up to 90% of the total initial energy is left unused. If some nodes exhaust their energy too early, that will lead to the deficiency of the original network coverage area and the failure to send data to the sink, which is a phenomenon called energy hole.

Now, many researchers balance the energy consumption and prolong the network lifetime by adding more nodes to the areas with heavier traffic, thus creating different node densities in different areas. This is what is called nonuniform node distribution[6]. Stojmenovic and S. Olariu **[7]** first discussed the energy hole problem in WSN with nonuniform node distribution. They believe that if the node's density of the ith ring is proportional to $\left(k+1-i\right)$, energy hole in the network can be avoided. k is the optimal number in which a circular network is divided into rings of equal width.

Based on the existing research, this paper proposes a nonuniform node distribution clustering algorithm (NNDC) to effectively avoid the energy hole problem. The main contributions of this paper are listed as follows:

(1) Data are collected and transmitted by means of clustering. Different from traditional nonuniform clustering, NNDC divides the network into rings, each of equal width and clusters are limited within the ring;

(2) This paper proposes and proves a method to calculate energy consumed by all nodes for one inner- and inter-cluster data processing and puts forward a nonuniform deployment strategy based on the energy consumption proportion in every ring.

(3) Different rings have different node's density, so we propose a corresponding density control mechanism. The network coverage is guaranteed under this condition, part of nodes become active nodes and the remaining are hibernating so as to save energy costs. Optimal cluster-radius values under different network parameters are obtained by means of simulation.

Simulation results indicate that the proposed algorithm NNDC can effectively avoid the energy hole problem, decrease the dead speed of the nodes and prolong the network lifetime. Compared with DIRECT, LEACH and EADC, NNDC has even uniform node energy consumption within each network ring. Therefore, when there is dead node in the network, the rate of nodes' average residual energy in different network rings is near 10%. Under different radius, NNDC has stable network lifetime. This superiority is particularly evident in a bigger network.

2. Related Work

Li and Mahapatra [8] first proposed a mathematical model for the analysis of energy hole in wireless sensor network. But it is not discussed in the paper whether the energy hole problem can be avoided in WSN. Olariu and Stojmenovic [2] for the first time proved under certain conditions, energy hole in WSN is unavoidable.

In order to avoid energy hole, researchers have proposed many effective methods. Some researchers proposed that sensor nodes use different transmission power levels to transmit data. Mhatre and Rosenberg [9] proposed an alternate transmission scheme between single hop and multiple hops. Zeng et al. [10] proposed sends part of data which are supposed to be sent to areas with high energy consumption to areas with lower energy consumption ahead of time, so as to balance the amount of data undertaking and energy consumption of nodes. Furthermore, nodes with lower energy consumption can send data at higher data transfer rate and nodes with higher energy consumption send data at lower data transfer rate, which can balance the energy consumption. The similar studies can be found in Song et al. [11]’s paper and so on.

Many researches concern about how energy holes can be avoided by means of nonuniform distribution of nodes. In such networks with nonuniform node distribution, considering the network coverage problem, Soro and Heinzelman [12] proposed some good cluster head election techniques. Considering the node distribution, the authors in [13] proposed a hierarchical architecture of sensor network with cluster formation and cluster head selection algorithm. Yu et al. [14] proposed a cluster-based routing protocol for wireless sensor networks with nonuniform node distribution to avoid energy hole, which includes an energy-aware clustering algorithm EADC and a cluster-based routing algorithm. Because of the unbalanced energy depletion among nodes in the network, Lian et al. [5] explicitly propose the nonuniform node distribution strategy in WSN. In their strategy more nodes are added to those areas with heavier energy load. Wu and Chen [6] proved that if nodes in a circular WSN are nonuniformly distributed and continuously send data to the sink, energy hole is unavoidable. But if the network is divided into concentric rings of equal width, the networks obtain sub-optimal energy efficiency.

Some other researchers apply non-uniform clustering algorithm to make network energy uniformly consumed. As different as the classical uniform clustering algorithms such as LEACH [15] and HEED [16], in order to avoid energy hole, some researchers focus on non-uniform clustering algorithm. For example, Chen et al. [17] proposed an Unequal Cluster-based Routing(UCR) protocol. It groups the nodes into clusters of unequal sizes. Liu et al. [18] proposed a strategy to avoid the energy hole problem. Employing an unequal cluster-radius and alternating between dormancy and work is the core idea of the strategy.

It is a comparatively ideal scheme to adopt density control[19] to lower network energy consumption. Density control means that on the condition that the networks connection is guaranteed and the whole area is covered, some nodes are put into hibernating state. Currently, the research on density control is mainly focused on network coverage and connectivity so as to reduce network energy consumption and prolong network lifetime. For instance, Jiang and Sung [20] proposed a density control algorithm for WSN to keep as few as possible sensors in active state to achieve a connected coverage of a specific area of interest.

3. Network Model

3.1 Network Model

In this paper, we assume N sensor nodes are randomly distributed in a circular area whose radius is $\overline{R}$ and all nodes are all stationary after deployment. The only sink in the network is located at center O. The network is divided into k rings from the inside out and each ring is of equal width. Nodes in the network are organized into clusters and get monitoring data periodically. After clusters finish data fusion, multi-hop communication between cluster heads is adopted to send data to the sink. Every cluster has identical radius and the range of every cluster is limited in one ring, satisfying the requirement that the minimum node's density for network coverage is ρ. The network structure is shown in **Fig. 1**.

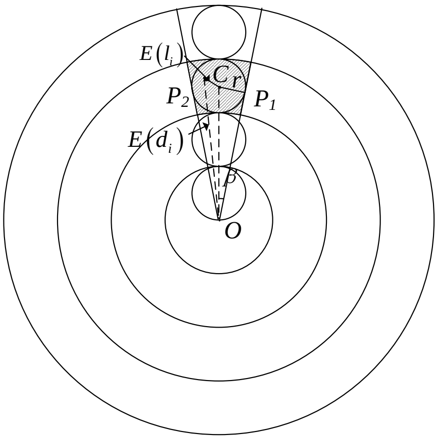

Fig. 1. Network structure model

From the inside out to the R_ith ring in the network, draw a circle C_i centered at C with radius r, then draw a line from network center O and contact C_i at P_1 and P_2. The area for the cluster CR_i with C being the cluster center to collect data is the fan-shaped area formed by the intersection of OP_1 and OP_2 and the R_i. If CR_i is not located at the outmost ring, CR_i is responsible for transferring data collected in outer ring area to the cluster head node in the R_{i-1}. The cluster angle of CR_i is the angle between OP_1 and OP_2. Set the cluster angle is 2β, the area of cluster CR_i is S_i. In R_i, n_i is the number of nodes, ρ_i is the node's density and S_{Ri} is the area of this region. The average expected distance from all nodes in the monitoring area to the network center O is $E(d_i)$ and the average expected distance from these nodes to the cluster center C is $E(l_i)$. To enable readers to more easily understand this paper, **Table 1** summarizes the notations used in this paper.

Table 1. Notation

Symbol	Definitions
$\overline{R}$	The radius of network
N	The number of sink nodes
O	The center of network
R_i	The *ith* ring from the network center out
n_i	The number of nodes in the R_i

S_{Ri}	The area of the R_i
ρ	The minimal node's density required by network monitoring
ρ_i	The node's density of the R_i
CR_i	The cluster in the R_i
r	The cluster-radius
S_i	The area of the cluster CR_i
φ	The rate of data fusion
$E(d_i)$	The average distance expectancy from all nodes in the monitoring area to the network center O
$E(l_i)$	the average distance expectancy from all nodes in cluster CR_i to the cluster center
τ	Node's sensing distance
E_{i_in}	The energy consumption for cluster CR_i to complete data processing within the cluster in one cluster period
E_{i_ex}	The energy consumption for cluster CR_i to complete data processing between clusters in one cluster period
E_i	The total energy consumption of cluster CR_i in one cluster period

3.2 Energy Models

This paper uses simple energy consumption model [21]. In the process of transmitting l bits message across distance d, the energy consumption of the sender is:

$$E_{Tx}(l,d) = E_{Tx\_elec}(k) + ET_{Tx\_amp}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2, d < d_0 \\ lE_{elec} + l\varepsilon_{mp}d^4, d \ge d_0 \end{cases} \quad (1)$$

Receiver's energy consumption is:

$$E_{Rx}(l) = E_{Rx\_elec}(l) = lE_{elec} \quad (2)$$

Where E_{elec} is the energy consumption to send or receive one bit data, $\varepsilon_{fs}d^2$ and $\varepsilon_{mp}d^4$ are respectively the energy required by power amplifier to send one bit data. The rate of data fusion is φ, and E_{df} is the energy consumption for the fusion of one bit data:

$$E_F(l) = lE_{df} \quad (3)$$

4. Analysis on Nodes' Energy Consumption

This section sets that nodes in the same ring are distributed uniformly and node's density in the network is ρ. In this situation, we carry out analysis on energy consumption from the angle of energy. The total energy consumption of cluster CR_i in one cluster period is the total of E_{i_in} and E_{i_ex}. So, there are some theorems about energy consumption based on the network model above.

Theorem 1. In R_i, the monitoring range of cluster CR_i is $4\beta r^2(2i-1)$, and cluster CR_i is responsible for transmitting data received from the region whose area is $4\beta r^2(k^2-i^2)$. The area of the region which is responsible for transmitting data sent by cluster CR_i is $4\beta r^2(2i-3)$.

Proof. Nodes randomly distributed can be regarded as a Poisson point process [22]. Set the locations of all nodes within cluster CR_i are mutually independent random variables and they are uniformly distributed within the ring. The average distance expectancy from all nodes within the cluster to network center is:

$$E(d_i)=\iint_A \sqrt{x_i^2+y_i^2}\,\rho(x_i,y_i)\mathrm{d}x\mathrm{d}y \tag{4}$$

Since a ring is formed by radius rotating around the center, consider the distribution of nodes on a random radius. Nodes are uniformly distributed within the cluster, and it can be obtained that the density of nodes is proportional to radius squared, so the probability density of nodes on a random radius is:

$$f(x)=\frac{2x}{RA^2} \tag{5}$$

Where *RA* is the radius of the ring.

So the average distance expectancy of every node within the ring to the network center is:

$$E(d_i)=\int_{RA_{i-1}}^{RA_i} xf(x)\mathrm{d}x=\int_{RA_{i-1}}^{RA_i} x\frac{2x}{\left(RA_i-RA_{i-1}\right)^2}\mathrm{d}x+RA_{i-1}=\frac{2}{3}\left[2r\times i-2r\times\left(i-1\right)\right]+2r\times\left(i-1\right)=r\left(2i-\frac{2}{3}\right) \tag{6}$$

Nodes in the cluster take turn to be the cluster head so as to evenly share energy consumption, so the average distance expectancy of the cluster head of every cluster period to network center is $r\left(2i-\frac{2}{3}\right)$.

d_i, the length of segment $\overline{OC}$, is $2r\left(i-1\right)+r$, and the length of radius $\overline{CP_1}$ is r, thus the length of $\overline{OP_1}$ is $2r\sqrt{i^2-i}$. Therefore, we can calculate the cluster angle of the cluster in R_i

$$\cos\beta=\frac{2r\sqrt{i^2-i}}{2r\left(i-1\right)+r}=\frac{2\sqrt{i^2-i}}{2i-1}\Rightarrow\beta=\arccos\left(\frac{2\sqrt{i^2-i}}{2i-1}\right) \tag{7}$$

The cluster angle of cluster CR_i is 2β and the area of R_i is $\pi R_i^{\ 2}-\pi R_{i-1}^{\ \ 2}=4\pi r^2(2i-1)$.so the area S_i of the fan-shaped region covered by CR_i is $4\pi r^2(2i-1)\times\frac{2\beta}{2\pi}=4\beta r^2\left(2i-1\right)$.

Cluster CR_i is responsible for transmitting data collected from regions whose angle is 2β in rings out of the R_i, the area of the region is $\frac{2\beta}{2\pi}\left(\pi R_k^{\ 2}-\pi R_i^{\ 2}\right)=4\beta r^2(k^2-i^2)$. The region whose angle is 2β in cluster CR_i ' neighboring inner ring R_{i-1} is responsible for receiving and transmitting data sent by cluster head of CR_i . The area of this region is $\frac{2\beta}{2\pi}\left(\pi R_{i-1}^{\ \ 2}-\pi R_{i-2}^{\ \ 2}\right)=4\beta r^2(2i-3)$.

Theorem 2. The energy consumption E_{i_in} for cluster CR_i to complete inner-cluster data processing in one cluster period is equation 14.

Proof. In one cluster period, energy consumed for completing inner-cluster data processing includes the energy consumption E_{node} for nodes within the cluster to send collected data to the cluster head, the energy consumption E_{re} for the cluster head to receive data sent by inner-cluster nodes and the energy consumption E_f for the cluster head to complete data fusion. So:

$$E_{i\_in}=E_{node}+E_{re}+E_f \tag{8}$$

Set every node sends *l* bits data to the cluster head in one cluster period and the node's density in CR_i is ρ. Then the total number of nodes in the cluster is:

$$n_i = S_i \times \rho = 4\beta\rho r^2 \left(2i-1\right) \tag{9}$$

The average expectancy of the angle formed by nodes in CR_i and the cluster center is $\frac{\beta}{2}$, so the average distance expectancy from nodes to the cluster center is:

$$E\left(l_i\right) = \sqrt{E\left(c_i\right)^2 + E\left(d_i\right)^2 - 2E\left(c_i\right)E\left(d_i\right)\cos\left(\frac{\beta}{2}\right)} = \sqrt{4r^2\left(2i-\frac{2}{3}\right)^2\left(1-\cos\left(\frac{\beta}{2}\right)\right)} \tag{10}$$

According to equation 2, the energy consumption for inter-cluster nodes to send collected data to the cluster head in a cluster period is:

$$E_{node} = \begin{cases} n_i\left(lE_{elec} + l\varepsilon_{fs}E\left(l_i\right)^2\right) = 4\beta\rho r^2\left(2i-1\right)\left(lE_{elec} + l\varepsilon_{fs}4r^2\left(2i-\frac{2}{3}\right)^2\left(1-\cos\left(\frac{\beta}{2}\right)\right)\right), & E\left(l_i\right) < d_0 \\ n_i\left(lE_{elec} + l\varepsilon_{amp}E\left(l_i\right)^4\right) = 4\beta\rho r^2\left(2i-1\right)\left(lE_{elec} + l\varepsilon_{amp}\left(4r^2\left(2i-\frac{2}{3}\right)^2\left(1-\cos\left(\frac{\beta}{2}\right)\right)\right)^2\right), & E\left(l_i\right) \geq d_0 \end{cases} \tag{11}$$

The energy consumption E_{re} for the cluster head to receive data sent by inter-cluster nodes is:

$$E_{re} = n_i lE_{elec} = 4\beta\rho r^2\left(2i-1\right)lE_{elec} \tag{12}$$

After the cluster head has received these data, which is responsible for the data fusion. The energy consumption for the cluster head to complete data fusion is:

$$E_f = n_i lE_{df} = 4\beta\rho r^2\left(2i-1\right)lE_{df} \tag{13}$$

Bring equation 11, 12, 13 into equation 8, then:

$$E_{i\_in} = \begin{cases} 4\beta\rho lr^2\left(2i-1\right)\left(2E_{elec} + \varepsilon_{fs}4r^2\left(2i-\frac{2}{3}\right)^2\left(1-\cos\left(\frac{\beta}{2}\right)\right) + E_{df}\right), & E\left(l_i\right) < d_0 \\ 4\beta\rho lr^2\left(2i-1\right)\left(2E_{elec} + \varepsilon_{amp}\left(4r^2\left(2i-\frac{2}{3}\right)^2\left(1-\cos\left(\frac{\beta}{2}\right)\right)\right)^2 + E_{df}\right), & E\left(l_i\right) \geq d_0 \end{cases} \tag{14}$$

Theorem 3. The energy consumption E_{i_ex} for cluster CR_i to complete inter-cluster data processing in one cluster period is equation 20.

Proof. The energy consumption for clusters in the outmost ring R_k to complete inter-cluster data processing only includes the energy consumption E_{cl} for the cluster head to send data to the cluster head in the R_{k-1}. While for the clusters in the other rings, the energy consumption should also include the energy consumption E_{o_re} taken to receive data sent from the outer regions. So:

$$E_{i\_ex} = \begin{cases} E_{cl} + E_{o\_re}, & i \neq k \\ E_{cl}, & i = k \end{cases} \tag{15}$$

According to Theorem 1, if CR_i is not in the outmost ring R_k, CR_i should also be responsible for receiving data sent from the regions whose areas are $4\beta r^2(k^2-i^2)$. So the total energy consumption for the cluster head to receive data from these regions is:

$$E_{o\_re} = 4\beta\rho r^2(k^2-i^2)l\varphi E_{elec} \tag{16}$$

The total number of data l_{total_i} the cluster head node in CR_i needs to send to the inner region is:

$$l_{total\_i} = \begin{cases} 4\beta\rho r^2 (2i-1) l\varphi, i = k \\ 4\beta\rho r^2 (2i-1) l\varphi + 4\beta\rho r^2 (k^2 - i^2) l\varphi = 4\beta\rho r^2 l\varphi \left(k^2 - i^2 + 2i - 1\right), i \neq k \end{cases} \tag{17}$$

The energy consumption for the cluster head to send data to the neighboring inner cluster head or the sink is also related to the average sending distance expectancy $E\left(d_{send}\right)$. The sending distance of the cluster head in the non-inner rings is the distance from it to the nearest cluster head in neighboring inner rings, when $E\left(d_{send}\right) = 2r$; The sending distance of the cluster head in the innermost rings is the distance from it to the sink, when $E\left(d_{send}\right) = \frac{4}{3} r$.

So, we can calculate the energy consumption E_{cl_i} for the cluster head of CR_i to send all received data:

$$\begin{cases} E_{cl\_i} = \begin{cases} 4\beta\rho r^2 (2i-1) l\varphi E_{elec} + 4\beta\rho r^2 (2i-1) l\varphi \varepsilon_{fs} (2r)^2, i = k \\ 4\beta\rho r^2 l\varphi \left(k^2 - i^2 + 2i - 1\right) E_{elec} + 4\beta\rho r^2 l\varphi \left(k^2 - i^2 + 2i - 1\right) \varepsilon_{fs} (2r)^2, 1 < i < k \\ 4\beta\rho r^2 l\varphi \left(k^2 - i^2 + 2i - 1\right) E_{elec} + 4\beta\rho r^2 l\varphi \left(k^2 - i^2 + 2i - 1\right) \varepsilon_{fs} \left(\frac{4r}{3}\right)^2, i = 1 \end{cases} , E\left(d_{send}\right) < d_0 \\ E_{cl\_i} = \begin{cases} 4\beta\rho r^2 (2i-1) l\varphi E_{elec} + 4\beta\rho r^2 (2i-1) l\varphi \varepsilon_{amp} (2r)^4, i = k \\ 4\beta\rho r^2 l\varphi \left(k^2 - i^2 + 2i - 1\right) E_{elec} + 4\beta\rho r^2 l\varphi \left(k^2 - i^2 + 2i - 1\right) \varepsilon_{amp} (2r)^4, 1 < i < k \\ 4\beta\rho r^2 l\varphi \left(k^2 - i^2 + 2i - 1\right) E_{elec} + 4\beta\rho r^2 l\varphi \left(k^2 - i^2 + 2i - 1\right) \varepsilon_{amp} \left(\frac{4r}{3}\right)^4, i = 1 \end{cases} , E\left(d_{send}\right) \geq d_0 \end{cases} \tag{18}$$

Bring equation 16 and 18 into 15, we can obtain the energy consumption E_{i_ex} for cluster CR_i to complete inter-cluster data processing in one cluster period:

$$E_{i\_ex} = \begin{cases} \begin{cases} 4\beta\rho l\varphi r^2 \left((k^2 - i^2 + 2i - 1) E_{elec} + (2i-1) \varepsilon_{fs} (2r)^2\right), i = k \\ 4\beta\rho l\varphi r^2 \left((2k^2 - 2i^2 + 2i - 1) E_{elec} + \left(k^2 - i^2 + 2i - 1\right) \varepsilon_{fs} (2r)^2\right), 1 < i < k \\ 4\beta\rho l\varphi r^2 \left((2k^2 - 2i^2 + 2i - 1) E_{elec} + \left(k^2 - i^2 + 2i - 1\right) \varepsilon_{fs} \left(\frac{4r}{3}\right)^2\right), i = 1 \end{cases} , E\left(d_{send}\right) < d_0 \\ \begin{cases} 4\beta\rho l\varphi r^2 \left((k^2 - i^2 + 2i - 1) E_{elec} + (2i-1) \varepsilon_{amp} (2r)^4\right), i = k \\ 4\beta\rho l\varphi r^2 \left((2k^2 - 2i^2 + 2i - 1) E_{elec} + \left(k^2 - i^2 + 2i - 1\right) \varepsilon_{amp} (2r)^4\right), 1 < i < k \\ 4\beta\rho l\varphi r^2 \left((2k^2 - 2i^2 + 2i - 1) E_{elec} + \left(k^2 - i^2 + 2i - 1\right) \varepsilon_{amp} \left(\frac{4r}{3}\right)^4\right), i = 1 \end{cases} , E\left(d_{send}\right) \geq d_0 \end{cases} \tag{19}$$

5. Density Control Mechanism Under The Condition of Nodes' Non-uniform Distribution

5.1 Nodes' Nonuniform Deployment Strategy

Ideally, the network can obtain optimal energy efficiency if the nodes in every ring can use up their energy at the same time.

Theorem 4. In order to achieve the goal that the energy in every ring can be used up at the same time, it is needed to deploy different initial total energy to every different ring, that is to say, the number of initial nodes in different rings is not equal.

Proof. To avoid energy hole, it is necessary to use up all nodes' energy at the same time. All the nodes in the network are homogeneous and have equal initial energy, so those regions with higher energy consumption should have more initial energy. According to Theorem 2,3, clusters in inner rings have higher energy consumption in one cluster period, so inner rings should have higher initial total energy. To equalize the cluster periods of nodes' survival in every ring, it should satisfy:

$$\frac{n_1\varepsilon}{E_{R1}}=\frac{n_2\varepsilon}{E_{R2}}=\cdots=\frac{n_k\varepsilon}{E_{Rk}} \tag{20}$$

Where E_{Ri} is the total energy consumption of R_i in one cluster period, $E_{Ri}=\frac{E_i\times S_{Ri}}{S_i}$.

That is, for any two neighboring rings, if the following equation is satisfied, these two rings have optimal energy efficiency.

$$\frac{n_i}{n_{i+1}}=\frac{E_{Li}}{E_{Li+1}},1\le i\le k \tag{21}$$

According to Theorem 4, to avoid energy hole, the initial number of nodes and node's density in every ring is different. ρ is the lowest node's density which can satisfy network monitoring. Mao *et al.* [23] discusses the calculation of the lowest node's density which can satisfy coverage. Nodes' coverage is shown by **Fig. 2**. Node A's 6 neighbors form a hexagon. The distance between any two nodes is $\sqrt{3}(\tau-\sigma)$ where τ is the node sensing radius and σ is any decimal($\sigma \ll 1$). If the distance between any two nodes is more than $\sqrt{3}\tau$, a blind spot results. The coverage area of node A is $\frac{3\sqrt{3}\tau^2}{2}$, and the lowest node's density is $\rho=\frac{2}{3\sqrt{3}\tau^2}$.

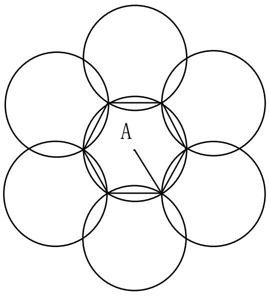

Fig. 2. 'A'Largest possible occupation

According to equation 21, the following can be obtained:

$$\rho_i = \begin{cases} \dfrac{E_{Li} S_{Li+1} \rho_{i+1}}{E_{Li+1} S_{Li}}, 1 \le i < k \\ \rho, i = k \end{cases} \tag{22}$$

5.2 Density Control Mechanism

Obviously, except the outermost ring, the node's density of every ring is more than that needed by network monitoring. If all nodes in the network are made working, it is inevitable that some regions will be monitored repeatedly, so the waste of energy is caused and this will affect the network lifetime. At the same time, the repeated coverage of the monitored region will cause considerable redundant message. One solution lies in density control mechanism: making some nodes in working state and others in hibernating state and they take turn to work. This ensures information collection in monitored regions and prolongs network lifetime. When network coverage is ensured to the greatest extent, active nodes are generated by election. Those that fail are put into hibernation state to save energy.

First, relative definitions in this section are given as follows:

Definition 1. Node coverage area (NCA): for any sensor node *i* in the R_i, its coverage region is $cover_i$, and the area of the coverage region is $Area(cover_i)$. Set node sensing radius is τ. For node *i*, its coverage area is $Area(cover_i) = \pi\tau^2$.

Definition 2. Node repeated coverage area (NRCA): for any sensor node *i* in the same ring, $Niegh(i)$ is the collection of *i*' s neighboring nodes which share the same coverage area with *i*. The repeated coverage area of *i* is the union of intersections of node *i* and its neighboring node's coverage area, expressed by $Area_{\cup}(i)$.

Definition 3. node valid coverage area (NVCA): NVCA is NCA subtract NRCA.

Definition 4. Node valid coverage rate (NVCR): for any sensor node *i* in the network, the valid coverage rate $C(i)$ is the ratio of NVCA and NCA, $C(i) = \dfrac{Area(cover_i) - Area_{\cup}(i)}{Area(cover_i)}$.

Definition 5. Node active probability (NAP): to ensure uniform energy consumption within the cluster, it's necessary to make all nodes take turn to become active nodes under the condition that the monitored regions are validly covered. Thus, nodes with higher NVCR and more residual energy are given higher probability to become active nodes: $PA(i) = C(i) \times \dfrac{\varepsilon_{cur\_i}}{\varepsilon}$, where $PA(i)$ is the NAP of node *i*, ε_{cur_i} is the current energy of *i* and ε is node initial energy.

Nodes can perceive their mutual distance according to attenuation of signal strength in the process of transmission. For instance, node *i* broadcasts messages, including its message sending period t_i, message length l_i and its energy ε_{cur_i}, to other nodes by energy E_i^{tran}. At the same time when node *j* receives messages, it also detects the strength of the received signals strength $E_{j,i}^{rec}$. The relationship between transmission energy and reception energy is as follows [20]:

$$E_{j,i}^{rec} = \frac{K}{d_{i,j}^{\alpha}} \times E_i^{tran} \tag{23}$$

Where *K* is a constant, $d_{i,j}^{\alpha}$ is the relative distance between node *i* and node *j*. α is distance-energy gradient, and its value varies from 1 to 6 according to the physical environment in which the sensor networks operate. Thus, the distance between *i* and *j* is:

$$d_{i,j} = \sqrt[\alpha]{\frac{K \times E_i^{tran}}{E_{j,i}^{rec}}} \tag{24}$$

According to the detected distance $d_{i,j}$ between node *i* and *j*, equation 25 can be obtained by Pythagoras Theorem:

$$\left(\frac{l_{i,j}}{2}\right)^2 + \left(\frac{d_{i,j}}{2}\right)^2 = \tau^2 \tag{25}$$

So, we can calculate the length of the connection $l_{i,j}$ of the intersection of two circles:

$$l_{i,j} = 2\sqrt{\tau^2 - \left(\frac{d_{i,j}}{2}\right)^2} \tag{26}$$

Furthermore, we can calculate the central angle θ corresponding to the intersection of the two circles:

$$\theta = 2\arcsin\left(\frac{l_{i,j}}{2\tau}\right) \tag{27}$$

The half of the area of the intersection of node *i* and node *j*'s coverage region is: the area of the fan-shaped region formed by the intersecting of two circles subtracts the area of the triangle formed by the circle center and the two intersecting points of the two circles.

$$Area(cover_i \cap cover_j) = \theta\tau^2 - \sin\theta\tau^2 \tag{28}$$

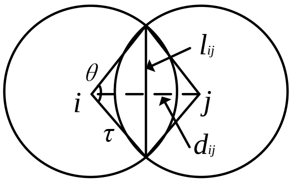

Fig. 3. Sample of the calculation of the area of incremental zone

When the intersection of node *i* and its neighbor *j*'s coverage regions intersects other neighboring coverage areas, set this neighbor is $neigh_n$. The shared part is a region formed by intersecting of a number of arcs, which can be regarded as the total of the areas of the arches of each sub-arc and the area of the inner convex polygon. For instance, the coverage area of node *i* intersects two circles at the same time, $Area_{\cup}(i)$ is:

$$Area_{\cup}(i) = Area(cover_i \cap cover_j) + Area(cover_i \cap cover_{neigh_n}) - Area\left(cover_i \cap cover_j \cap cover_{neigh_n}\right) \tag{29}$$

When the union of the intersection of multiple circles is a continuous area, we can calculate nodes' NRCA step by step according to equation 29.

Thus, in the initialization phase, any node *i* can obtain the node active probability by one broadcast and then sends the NAP to the sink:

$$PA(i) = C(i) \times \frac{\varepsilon_{cur\_i}}{\varepsilon} = \frac{Area(cover_i) - Area_{\cup}(i)}{Area(cover_i)} \times \frac{\varepsilon_{cur\_i}}{\varepsilon} \tag{30}$$

For $R_i\,(1 \le i < k)$, the number of nodes which need to hibernate in the initialization phase is the total number of nodes in the ring subtracts the minimal number of nodes satisfying the requirement of network monitoring.

$$nsleep_{Ri} = S_i \times (\rho_i - \rho) \tag{31}$$

For nodes in the networks are homogeneous, the sink sends hibernation order to $nsleep_{Ri}$ nodes with lower NAP in $R_i\,(1 \le i < k)$ in the initialization phase. When these nodes receive the order, they begin hibernating and the other nodes start working.

To balance the energy consumption of all nodes, nodes in the network need to shift states and take turn to work according to NAP at the end of each cluster period. For $R_i\,(1 \le i < k)$, the number of nodes which need to shift states is determined by the total number of nodes and the number of hibernating nodes in this ring.

$$nalter_{Ri} = \left\lceil \left(n_i - nsleep_{Ri}\right) \times \left(1 - e^{-\frac{nsleep_{Ri}}{n_i - nsleep_{Ri}}}\right) \right\rceil \tag{32}$$

At the end of each cluster period, sink give work order to $nalter_{Ri}$ nodes among the hibernating nodes with the highest active probability. In the meantime, sink gives hibernation order to $nalter_{Ri}$ nodes with the lowest active probability, and these nodes shift to the hibernating state.

5.3 Cluster Selection Strategy

Cluster head nodes are responsible for inner-cluster data collection and fusion and also data transmission of the relative area in the outer rings, so the energy consumption of cluster head nodes is much higher than the other nodes. In order to balance load, active nodes in the cluster take turn to become the cluster head node so as to share energy consumption. Here define the probability P_{CH_i} for any active node i in the R_i to become the cluster head node as:

$$P_{CH\_i} = \frac{1}{n_i \times \rho} \times \frac{\varepsilon_{cur\_i}}{\varepsilon} \times \left(1 - e^{\frac{-1}{D_{CH\_i}+1}}\right) \tag{33}$$

Where D_{CH_i} is the times for node i to become the cluster head node in the past.

In the clustering phase of a cluster period, nodes with the highest P_{CH_i} become the cluster head.

6. Simulation

To evaluate performance of the algorithm proposed in this paper, we have made a simulation experiment on it with the help of MATLAB simulation software. The parameters of the simulation are shown as **Table 2**. Through simulation, this paper observes how the value of the optimal cluster-radius and the density control mechanism affect the network performance in different network environment. Furthermore, the experiment compares NNDC, DIRECT, LEACH and EADC in the following 3 indexes:① the energy consumption of the rings in the network;② when the first dead node appears, what the nodes' residual energy rate in each ring would be like;③ network lifetime period.

Table 2. Network Parameters

Parameter	**Value**

Network radius $\overline{R}$ (m)	720
Sensing radius τ (m)	15
Threshold distance d_0(m)	87
Initial energy (J)	0.5
φ	0.5
E_{elec}	5 nJ/bit
ε_{fs}	10pJ/bit/m2
ε_{mp}	0.0013pJ/bit/m4

6.1 The Analysis on the Value of the Optimal Cluster-Radius

Definition 6. Optimal cluster-radius(OCR): according to the network model proposed by this paper, the height of each ring of the network is twice cluster-radius *r*, so the value of *r* is directly relevant to the number of the rings. The fact that there is an extreme point for *r* results that nodes finishing one data collection has the lowest average energy consumption, which means this value of *r* meets the requirement of maximal network lifetime, so the value of *r* is OCR .

Fig. 4 gives the average energy consumption for processing inter-cluster and inner-cluster data and the average total energy consumed by active nodes in the process for the active nodes to finish one data collection in a default network environment, when cluster radius are different.

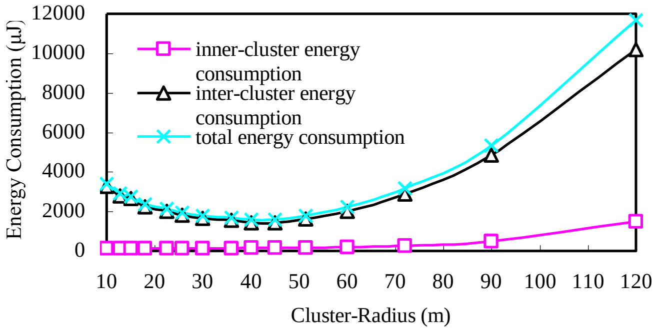

Fig. 4. Active nodes' average energy consumption under different *r*

From **Fig. 4**, it can be seen that under different *r*, the average energy consumed by active nodes is different. With *r* increasing, there are more active nodes in the cluster and the amount of data transmitted is larger, so the energy consumption taken by the sensor nodes to process inner-cluster data increases gradually. The energy consumption taken for inter-cluster data processing and the total energy consumption are two concave curves on the two sides. When *r* lengthens from 10m, nodes' average total energy consumption decreases. The reason is that when *r* is very short, the network will be divided into more rings. At this moment, the amount of data transmitted between clusters is maximal and hence, the energy consumption taken for inter-cluster data processing is relatively large. According to **Fig. 4**, when *r* is 40m, active nodes' average total energy consumption is minimal. With *r* increasing, the distance between cluster heads become longer, so the energy consumption taken for inter-cluster data processing begins increasing. The increase is more obvious especially when the distance to transmit data between nodes is more than d_0 .

Fig. 5 gives active nodes' average energy consumption under different *r* in a default network environment when φ is changed. **Fig. 5** shows the lower φ is, the smaller the amount of data sent by cluster head would be, so nodes have even lower average energy consumption. According to **Fig. 5**, the change of φ does not affect the value of OCR. Under different φ, active nodes' average energy consumption is minimal when *r* is 40m.

Fig. 6 gives active nodes' average energy consumption in a default network environment when τ and the *r* are changed.

From **Fig. 6**, under different τ, there is little difference in active nodes' average energy consumption. When the value of τ is different, OCR is always 40m. Therefore, it can be obtained that the change of τ not only has no effect on the value of OCR, but also little effect on network performance.

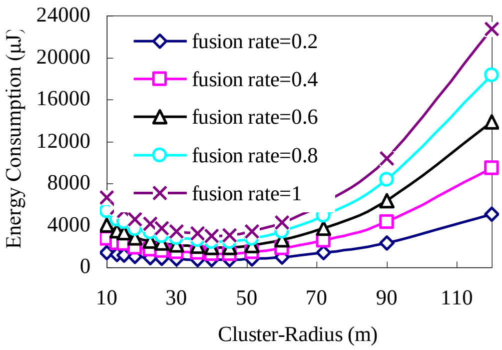

Fig. 5. Active nodes' average energy consumption under different *r* and φ

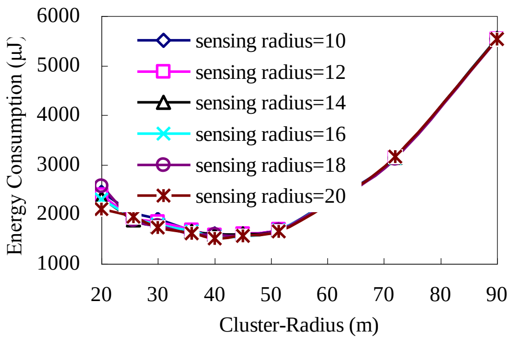

Fig. 6. Active nodes' average energy consumption under different *r* and τ

Sum up the experiment results from **Fig.4**, **Fig. 5** and **Fig. 6**, and we can obtain that when $\overline{R}$ is 720m, the value of OCR is 40m, when the network is divided into 9 rings.

Further the observation on the value of OCR under different network size. **Fig. 7**. Gives the value of OCR when $\overline{R}$ respectively is 400m, 450m, 500m,550m, 600m,650m,700m, 750m and 800m. **Fig. 7** Shows that under different $\overline{R}$, the value of the OCR changes little, varying from 40m to 46m.

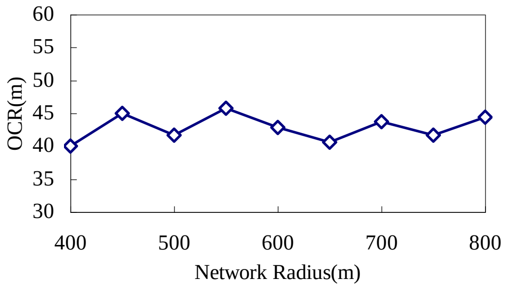

Fig. 7. The value of the OCR under different $\overline{R}$

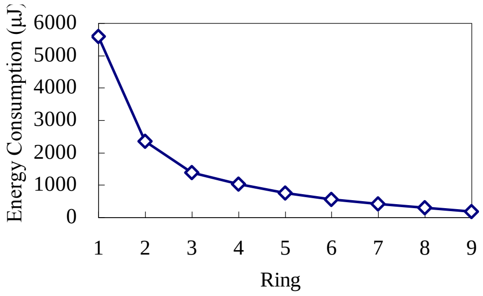

Fig. 8. Active nodes' average energy consumption

Fig. 8 Gives the energy consumption taken by nodes in every ring when *r* is 40m in a default network environment. From **Fig. 8**, nodes in the innermost ring are responsible for transmitting data collected from nodes in the other ring to the sink, so nodes' average energy consumption in this ring is far larger than those in the other rings. With the distance from the sink increasing, nodes' average energy consumption in every ring gradually decreases. Nodes in the outermost ring are not responsible for transmitting other data, so they have the lowest average energy consumption. According to the experiment result of **Fig. 8** and equation 23, the node's density in every ring can be obtained when *r* is 40m in a default network environment. **Fig. 9** shows that the more inner rings have higher node's density.

Fig. 10 gives the distribution of the number of nodes in every ring when *r* is 40m in a default network environment. It is shown that the nodes in the outermost ring have minimal energy consumption, so the number of nodes in this ring is the lowest. With the increase of node's density, the number of nodes increases gradually from R_9 to R_4. But nodes in R_2 and R_3 are less than those in R_4 because the areas of the more inner rings are smaller. And the decease of the area of R_1 is obvious, so nodes in R_1 are only more than those in R_9.

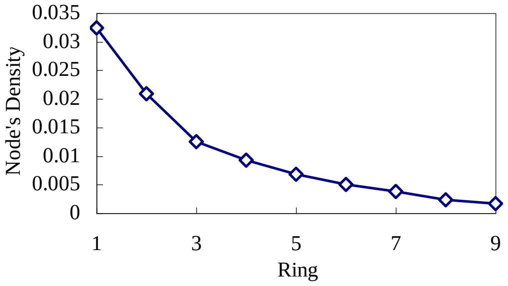

Fig. 9. The node's density in every ring.

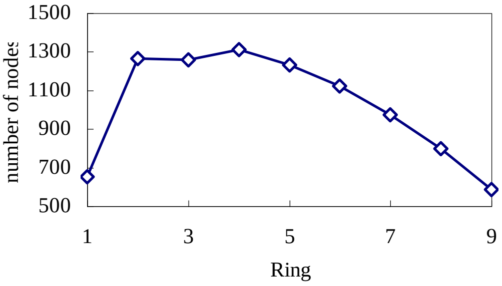

Fig. 10. The number of nodes in every ring.

6.2 Impact of Density Control Mechanism on the Network Performance

Definition 7. Network energy efficiency(NEE): NEE is defined as the ratio of network lifetime and the total energy deployed in the network.

According to the experiment result from **Fig. 10**, nodes shift between active and hibernating states under density control mechanism. There are 9196 sensor nodes deployed in the network, but if they are distributed uniformly in the whole network, 2785 nodes need to be deployed. The experiment result shown by **Fig.11** has compared the death time of the first node respectively under density control mechanism and uniform nodes distribution in a default network environment when the radius is 40m.

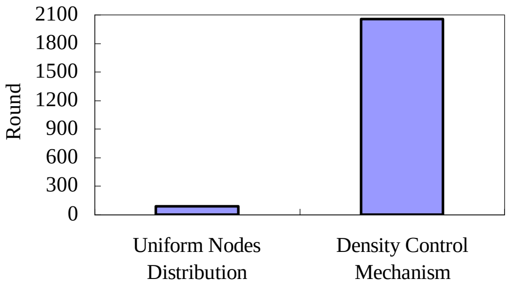

Fig. 11. The death time of the first node respectively under density control mechanism and uniform nodes distribution

When density control mechanism is adopted, 9196 nodes are deployed and the total energy of the network is 4598J. The death time of the first node is at the 2056th round, when the NEE is 0.4472; when nodes are distributed uniformly, 2785 nodes are distributed and the total energy of the network is 1392.5J. The death time of the first node is at the 89th round, when the NEE is 0.0639. Although the number of nodes under density control mechanism is 3.31 times more than that under uniform nodes distribution, network lifetime improves by 22.1 times and NEE improves by 599.77%.

Furthermore, we change the network size and observe the improvement of NEE brought about by the adoption of density control mechanism when $\overline{R}$ is 400m-800m.

Fig. 12 shows the improvement of NEE brought by the adoption of density control mechanism compared with uniform nodes distribution when $\overline{R}$ increases from 400m to 800m. It can be seen that in networks of different sizes, the adoption of density control can effectively improve the load balance of node energy and in the network of a bigger size, the improvement of network performance is more obvious. The reason, according to **Fig. 7**, is that the OCR are between 40m-46m under different network sizes and when the network radius lengthens, the network is divided into more rings, and thus, there is more difference in node's density between inner rings and outer rings. Hibernation algorithm can make more redundant nodes turning into hibernating state so as to save energy.

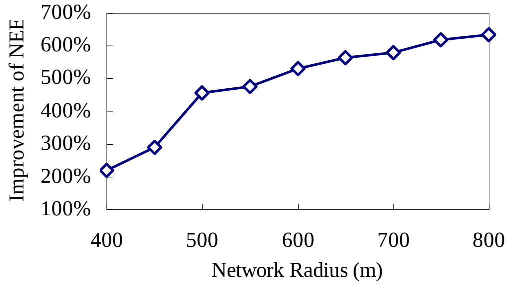

Fig. 12. Improvement of NEE under different $\overline{R}$

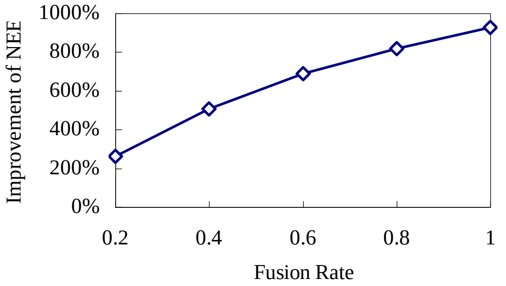

Fig. 13. Improvement of network energy efficiency under different φ

Further observe the improvement of network performance brought by node's density control mechanism when φ is changed. **Fig. 13** gives the improvement of NEE in a default network environment when r is 40m and φ is changed from 0.2 to 1.0.

From **Fig. 13** no matter φ is high or low, the adoption of density control mechanism can all bring about the improvement of NEE, compared with uniform nodes distribution. Furthermore, with φ increasing, the adoption of density control mechanism can bring about higher improvement. The reason is that when φ is relatively low, compression ratio of data message is higher and the amount of data transmitted in the network is less after data messages collected by clusters are fused by cluster heads, while when φ is relatively high, compression ratio of data message is lower and the amount of data transmitted and energy consumed by nodes is more. Therefore, there is more improvement in NEE produced by the adoption of density control mechanism.

6.3 Comparison on Network Performance with Other Algorithms

Through simulation, we have compared NNDC, EADC, DIRECT and LEACH on such performances as energy consumption, nodes' residual energy rate when the first node dies and network lifetime.

Based on the network environment provided by this paper, DIRECT and LEACH are respectively defined as:

DIRECT：nodes in the network are uniformly distributed. When nodes in every ring have finished data collection, they directly send data to the sensor nodes in the neighboring inner ring and the inner rings are responsible for forwarding the data to more inner ones.

LEACH：nodes in the network are uniformly distributed. The nodes in the same cluster send their data to the cluster head and the cluster head transmit data to the sink directly after data fusion. And it is known as single hop clustering network.

Fig. 14 gives the average energy consumption taken for one data collection for nodes in every ring in a default network environment. According to **Fig.14**, NNDC deploys more nodes in those regions with more energy consumptions and makes nodes take turn to work, so the energy consumptions in every ring is lowest. For EADC, nodes' energy consumption is relatively even, but nodes' average energy consumption is more than NNDC for the lack of density control. For DIRECT, nodes energy consumption is very low in the areas far from the network center. But with the distance of nodes to the network center shortening, energy consumption gets increasingly higher, because of the growing amount of data needed to be transmitted; while for LEACH, the energy consumption for nodes in the two rings nearest to the network center is considerably low, but when the cluster head nodes' sending distance is longer than d_0, energy consumption taken by nodes in every ring increase radically.

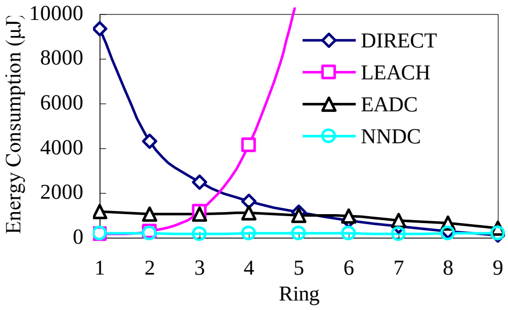

Fig. 14. Energy consumption in different ring

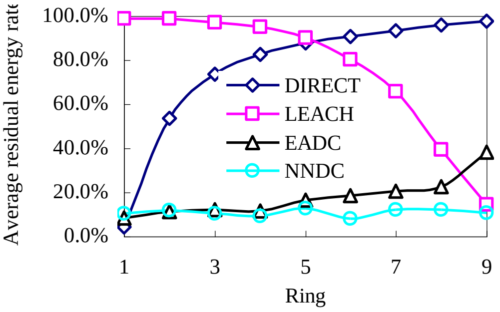

Fig. 15. Average residual energy rate in every ring of the network

Fig. 15 gives the rate of nodes' average residual energy in every ring in a default network environment. It is shown that NNDC can best ensure balanced energy consumption in every ring. When the first node dies, nodes in every ring all have relatively low average residual energy rate, so the network can make good use of nodes' energy. Because EADC constructs clusters of even sizes using competition range in order to balance the energy consumption among cluster members, so EADC can also better balance energy consumption. For DIRECT, the energy of nodes that are far away from the sink cannot be well used. When the first node in the network dies, nodes residual energy rate in the outermost rings is all over 90%, and there is an energy hole near the sink. While for LEACH, the energy of nodes that are nearer to the sink cannot be well used. When the first node dies, nodes residual energy rate in the innermost rings is all over 90% and there is an energy hole far away from the sink. The experiment result in this section is consistent with the result in ref. [5].

Fig.16 gives the comparison of network energy efficiency of DIRECT, LEACH, EADC and NNDC in a default network environment. In a default network environment, DIRECT, LEACH and EADC need to deploy 2785 nodes to satisfy the requirement of network minimal coverage, while NNDC need to deploy 9196 nodes. It is shown from **Fig.16** that DIRECT and LEACH have very low NEE; Because EADC can balance the energy consumption among cluster heads by adjusting the intra-cluster and inter-cluster energy consumption of cluster heads, so the network lifetime is 439th round and NEE is 0.315, which is an obvious improvement compared with DIRECT and LEACH. NNDC has the maximal NEE which is 0.4472.

Fig. 17 gives the comparison of network lifetime of DIRECT, LEACH, EADC and NNDC under different network radius. DIRECT, LEACH and EADC have deployed a number of nodes which can satisfy the requirement of network coverage, while NNDC has deployed a number of nodes which can satisfy the requirement of both network coverage and density control. It is shown in **Fig.17** that under different $\overline{R}$, NNDC can achieve stable and better network lifetime, while DIRECT and LEACH both have very short network lifetime, EADC's performance is better than DIRECT and LEACH, but With $\overline{R}$ increasing, network lifetime shortens to some degree. The performance of EADC is between DIRECT, LEACH and NNDC.

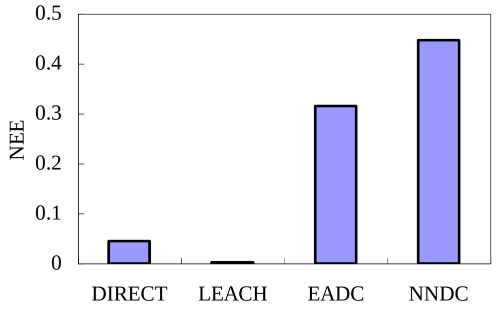

Fig. 16. Network energy efficiency

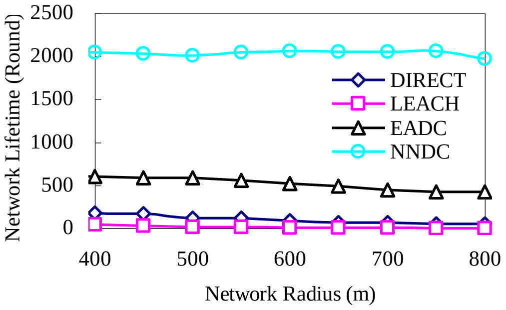

Fig. 17. Network lifetime under different $\overline{R}$

7. Conclusion

To more effectively avoid the phenomenon of energy hole, this paper proposes a nonuniform node distribution clustering algorithm (NNDC). Firstly, we have an analysis on nodes' energy consumption in the network during one data collection. Then, based on the energy consumption of nodes in different places in the network, we deploy more initial energy to those regions where there is more energy consumption and furthermore we introduce density control mechanism, under which redundant nodes take turn to hibernate to save energy under the condition that the valid coverage of the network is guaranteed. Simulation shows NNDC algorithm can satisfyingly balance nodes' energy consumption and effectively avoid the problem of energy hole.

References

[1] A.F. Liu, P.H. Zhang, and Z.G. Chen. "Theoretical analysis of the lifetime and energy hole in cluster based wireless sensor networks", *Journal of Parallel and Distributed Computing*, vol.71, no.10, pp.1327-1355, Oct.2011. Article (CrossRef Link).

[2] S. Olariu, and I. Stojmenovic. "Design guidelines for maximizing lifetime and avoiding energy holes in sensor networks with uniform distribution and uniform reporting", in *proc. of IEEE INFOCOM*, pp.1–12, Apr.2006. Article (CrossRef Link).

[3] A. Eksim, and M.E. Celebi. "Performance Improvement of Binary Sensor-Based Statistical Space-Time Block Code Cooperative Diversity Using Limited Feedback", *IETE Technical Review*, vol.27, no.1, pp.60-67, Jan.2010. Article (CrossRef Link).

[4] F. Akyildiz, W. Su, Y.Sankarasubramaniam, and E.Cayirici. "Wireless sensor network: a survey", *Computer Networks*, vol.38, no.4, pp.393-422, Mar.2002. Article (CrossRef Link).

[5] J. Lian, K. Naik, and G. Agnew. "Data capacity improvement of wireless sensor networks using non-uniform sensor distribution", *International Journal of Distributed Sensor Networks*, vol.2, no2 , pp.121–145. Feb.2006. Article (CrossRef Link).

[6] X.B. Wu, G.H. Chen, and S. K. Das. "Avoiding Energy Holes in Wireless Sensor Networks with Nonuniform Node Distribution", *IEEE Transactions on Parallel and Distributed Systems*, vol.19, no.5, pp.710-720, May.2008 Article (CrossRef Link).

[7] I. Stojmenovic, and S. Olariu. *Handbook of Sensor Networks : Algorithms and Architectures*, Wiley, New York, pp.417-456, 2005. Article (CrossRef Link).

[8] J. Li J, and P. Mohapatra. "An analytical model for the energy hole problem in many-to-one sensor networks", in *Proc. of the IEEE Vehicular Technology Conference*, pp.2721-2725, Sep.2005 Article (CrossRef Link).

[9] V. Mhatre, and C. Rosenberg. "Design guidelines for wireless sensor networks: communication, clustering and aggregation", *Ad Hoc Networks*, vol.2, no.1, pp.45-63. Jan.2004 Article (CrossRef Link).

[10] Z.W. Zeng, Z.G. Chen, and A.F. Liu. "Energy-hole avoidance for WSN based on adjust transmission power", *Chinese Journal of Computers*, vol.33, no.1, pp.12-22, Jan.2010. Article (CrossRef Link).

[11] C. Song, J.N. Cao, M. Liu, Y. Zheng, H.G. Gong, and G.H. Chen. "Maximizing network lifetime based on transmission range adjustment in wireless sensor networks", *Computer Communications*, vol.32, no.11, pp.1316–1325, Nov.2009. Article (CrossRef Link).

[12] S. Soro, and W.R. Heinzelman. "Cluster head election techniques for coverage preservation in wireless sensor networks", *Ad Hoc Networks*, vol.7, no.5, pp.55–72, Jul.2009. Article (CrossRef Link).

[13] O. Rahman, B.G. Choi, M. Monowar, and C.S. Hong. "A density based clustering for node management in wireless sensor network". in proc. of *APNOMS '07 Proceedings of the 10th Asia-Pacific Network Operations and Management Symposium on Managing Next Generation Networks and Services*, pp:527–530, Oct.2007. Article (CrossRef Link).

[14] J.G. Yu, Y.Y. Qia, G.h. Wang, and X. Gu. "A cluster-based routing protocol for wireless sensor networks with nonuniform node distribution". *International Journal of Electronics and Communications (AEÜ)*, vol.66, no.1, pp.54-61, Jan.2012. Article (CrossRef Link).

[15] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan. "An application-specific protocol architecture for wireless microsensor networks". *IEEE Transactions on Wireless Communications*, vol.1, no.4, pp.660–670, Oct.2002. Article (CrossRef Link).

[16] O. Younis, and S. Fahmy. "HEED: A hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks", *IEEE Transactions on Mobile Computing*. vol.3, no.4, pp.660–669, Oct.2004. Article (CrossRef Link).

[17] G.H. Chen, C.F. Li, M. Ye, and J. Wu "An unequal cluster-based routing protocol in wireless sensor networks", *Wireless Networks*, vol.15, no.2, pp.193-207, Feb.2009. Article (CrossRef Link).

[18] A.F. Liu, X.Y. Wu, Z.G. Chen, and W.H. Gui. "Research on the energy hole problem based on unequal cluster-radius for wireless sensor networks", *Computer Communications*, vol.33, no.3, pp.302-321, Feb.2010. Article (CrossRef Link).

[19] M.H. Chiang, and T.B.Gregory. "Neighborhood-aware density control in wireless sensor networks", in *Proc. of 2008 IEEE International Conference on Sensor networks, Ubiquitous, and Trustworthy Computing*, pp:122-129, Jun.2008. Article (CrossRef Link).

[20] J.R. Jiang, and T.M. Sung. "Energy-Efficient Coverage and Connectivity Maintenance for Wireless Sensor Networks", *Journal of Networks*, vol.4, no.6, pp.403-410, Jun.2009. Article (CrossRef Link).

[21] S.Doshi, S. Bhandare, and T.Brownl. "An on-demand minimum energy routing protocol for a wireless ad hoc network", *ACMSIGMOBIL E Mobile Computing and Communications Review*, vol.6, no.3, pp.50-66,Jul.2002. Article (CrossRef Link).

[22] V. Mhatre, and C. Rosenberg, "Design guidelines for wireless sensor networks: communication, clustering and aggregation", *Ad Hoc Network Journal*, vol.2, no.1, pp.45−63, Jan.2004. Article (CrossRef Link).

[23] Y.C. Mao, M. Liu, L.J. Chen, D.X. Chen, and L. Xie, "A Distributed Energy-Efficient Location-Independent Coverage Protocol in Wireless Sensor Networks", *Journal of Computer Research and Development*, vol.43, no.2, pp.187-195, Feb.2006. Article (CrossRef Link).

Tang Liu received his Bachelor from College of Computer Science and Engineering, University of Electronic Science and Technology of China, in 2003, and received his M.S. degree from College of Computer Science, Sichuan University, China, in 2009. He is a PhD student at the College of Computer Science, Sichuan University, Chengdu, China. Since 2008, he has been a instructor in College of Fundamental Education, Sichuan Normal University. His research interests are in the area of wireless sensor networks.

Jian Peng received his Ph.D. degrees from College of Computer Science and Engineering, University of Electronic Science and Technology of China, in 2004. Now, he is a professor in Sichuan University. His research interests are in the area of wireless sensor networks and parallel computing.

Xiao-fen Wang received her M.S. and Ph.D degree in Xidian University in 2006 and 2009. She is a lecturer in the School of Computer Science and Engineering, University of Electronic Science and Technology of China. Her research interest include network security and cryptography.

Jin Yang received his M.S. degree and the Ph.D. degree in computer science from Sichuan University. Now, he is a associate professor in Leshan Normal University. His research interests are in the area of network security and artificial immune.

Bing Guo received his BS degree in Computer Science from the BeiJing Institute of Technology, China, and MS and PhD degrees in Computer Science from the University of Electronic Science and Technology of China, China, in 1991, 1999, and 2002, respectively. He is currently a Professor in the School of Computer Science and Engineering at the SiChuan University, China. He is a Member of IEEE. His current research interests include embedded real-time system, Green Computing and SoC.