Research Article

Heterogeneous Node Deployment Model Based on Area Topology Control in WSNs

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1. Introduction

Wireless sensor networks (WSNs) have the advantages of low cost, flexible deployment, and so forth and have been widely used in varied fields, such as environmental monitoring [1, 2], intelligent control [3], and military reconnaissance [4, 5]. In WSNs, energy efficiency is very important and also a challenge. The data traffic follows a many-to-one pattern [5], which makes nodes nearer to the sink node carry heavier traffic loads. Therefore, the nodes around the sink deplete their energy faster, leading to what is known as an energy hole around the sink node [6].

In order to avoid energy hole and prolong network lifetime of WSNs, optimization deployment model of WSNs is one of the main methods. Because nodes lack power and are weak in computing capacity, node deployment models adopt some optimization measures to make best use of node resources, such as adjusting number and location of nodes, changing data transmission path, and altering transmission radius. Earlier researches about optimization deployment model are mainly concentrated in the homogeneous sensor networks. Researchers focus on the optimal transmission path, adjustment transmission radius of nodes and optimal selection on position and number of nodes, and so forth. With the development of WSNs, the requirements of service in WSNs present heterogeneous characteristics, such as the various service function and different prices of nodes [5]. For example, when nodes are used for seismic monitoring with high resolution of images and videos, the price of sensing module is more expensive, and if homogeneous nodes are used to balance the energy consumption in such scenarios, resources will be wasted seriously. As the requirements of WSNs become variant, it is of more practical significance to study WSNs deployment model with heterogeneous nodes [7–9].

Halder and Bit [9] proposed heterogeneous node deployment scheme (HNDS) by location-wise predetermined sensor nodes (SNs) and relay nodes (RNs). HNDS enhanced network lifetime while maintaining coverage effectively. However, the SNs and RNs in HNDS should be placed at the precise location, which brought a heavy workload to deployment implement. Additionally, it assumed that
the initial energy of nodes was identical and there was nonnormal energy consumption or accidental death. However, the possibility of nodes with identical initial energy is very small in practical application and abnormal energy consumptions or unexpected deaths of nodes often occur.

To overcome the above shortcomings, we propose a heterogeneous node deployment model based on area topology control in this paper. The simulated experimental results showed that our model could effectively maintain the same energy consumption ratio (ECR) in various areas of WSNs under the premise of maintaining desired sensing coverage and connected coverage. The main contributions of this paper are listed as follows.

(1) We have analyzed the influencing factors of energy consumption based on the hexagonal structure [3] and deduce the internal laws between the number of nodes and the area energy consumption ratio.

(2) Based on the analysis, we proposed a heterogeneous node deployment model, in which sensor nodes and relay nodes are deployed based on energy balancing strategy.

(3) Topology control algorithm based on area energy consumption ratio is designed to maintain dynamic equilibrium energy consumption, which effectively maintains the same ECR in different areas and prolongs the network lifetime.

The rest of the paper is organized as follows. In Section 2 literature review is elaborated. Hexagonal coverage architecture is presented in Section 3 and analysis on lifetime is presented in Section 4. Section 5 presents the node deployment model based on area topology control. In Section 6, the performance of coverage scheme is evaluated. We conclude and discuss future research directions in Section 7.

2. Related Works

The goals of research on deployment model of WSNs are mainly to decrease the cost and improve the QoS of WSNs. Energy is one of the scarcest resources in WSNs, so how to balance loads and average energy consumption is one of the important goals of optimal deployment model. According to the mobility of sink node, there are stationary sink node deployment model and movable sink node deployment model.

In the former models, the energy consumption of nodes closer to sink node is much more than the far ones; therefore, the solutions are mainly in balancing energy consumption among the nodes in different positions. Wu et al. [6] proposed a nonuniform node distribution strategy (NNDS) to resolve energy hole problem, but they did not mention anything about the minimum number of nodes required to be placed in the farthest layer from the sink to maintain connectivity and coverage. Shi et al. [10] proposed a topology control algorithm for data collection in sensor network towards achieving goal of prolonging network lifetime by adjusting transmission range of each sensor node. They have considered collaborative multipath data delivery and formulated the lifetime maximization problem as a max-fair-flow problem. Zhang and Shen [11] proposed a fully localized zone-based routing scheme to resolve problem of intracorona energy consumption balancing and designed an energy balanced data gathering protocol (EBDG) to achieve balanced energy consumption among nodes. Lin and Chen [12] proposed a corona division strategy to guarantee the energy equilibrium in WSNs and designed an energy equilibrium routing based on corona structure (EERCS). Regardless of adopting data fusion or data slice, EERCS can be used to realize the maximum energy equilibrium for a given area. Song et al. [13] proposed a circular node deployment scheme to maximize the network lifetime by analyzing energy consumption ratio and consultation mechanisms. Azad and Kamruzzaman [14] proposed a topology control algorithm for data collection in sensor network towards achieving longer network lifetime by changing transmission range of each sensor node. Jeon et al. [15] proposed a joint control scheme to maximize network lifetime in wireless sensor networks with joint contention and sleep control. Prabh et al. [16] proposed a distributed algorithm to form semilogical hexagonal topology in WSN deployments, which formed the hexagonal topology backbone in an arbitrary but sufficiently dense network deployment.

Because nodes near stationary sink node have excessive energy consumption, some researchers have proposed movable sink node deployment model. Wu et al. [17] proposed an energy consumption solution by changing sink node’s position to balance the nodes’ workload in different areas. Luo and Hubaux [18] proposed an energy balanced program based on mobile agent cluster; the mobile agent could predict the energy consumption of the cluster and balance energy consumption by the cluster-route. Lin et al. [19] took researches on theoretical performance limits about mobile base station and proposed a theoretical solution to fill theoretical gap regarding the optimal movement of a mobile base station. Although moving sink node scheme can balance the consumption, it should add one and more moving sink nodes, which significantly increases deployment cost and additional energy consumption for moving sink nodes.

A variety of service requirements in different scenarios arouse heterogeneous characters of WSNs, and researches on heterogeneous node deployment model have become a hot topic. Smaragdakis et al. [20] proposed a heterogeneous node deployment with two-level energy, which would prolong network lifetime by clustering topology control algorithm. Cardei [21] proposed heterogeneous node deployment scheme with two types of nodes equipped with finite or infinite resource to prolong network lifetime. Sun et al. [8] proposed heterogeneous distributed sensor network topology control algorithm and constructed a heterogeneous node metric function to evaluate and adjust energy consumption ratio. Halder and Bit [9] proposed heterogeneous node deployment scheme (HNDS) by precisely deploying location-wise predetermined sensor nodes and relay nodes, but the deployment of a lot of nodes with precise location is very difficult in practice; additionally, HNDS can resolve some unbalanced energy consumption, such as abnormal energy consumptions or unexpected death of nodes.
3. Heterogeneous Coverage Model

3.1. Coverage Model. Hexagonal coverage architecture is one of the best coverage models to do exhaustive monitoring in WSNs applications circumstance [16], so we adopt it as basic coverage architecture in our model. A sink node is deployed in the center of the whole monitoring area, and its geometry location is defined as (0, 0). Then six hexagonal cells will be tiled around the sink node, which forms the first layer of the coverage model. Next, twelve hexagonal cells will be tiled on the outside of the first layer to form the second layer. And then more hexagonal cells form the third layer and fourth layer, until the entire monitoring area has been covered. The number of hexagonal cells in the i-th layer is 6i, as shown in Figure 1.

In order to facilitate implementation of the node deployment strategy, the cells are labeled as \(C_{i,j}\), where \(i\) is the number of layers and \(j\) is the cell index in the \(i\)-th layer. The sink cell is labeled as \(C_{0,0}\); cells in the first layer are labeled as \(C_{1,1}, C_{1,2}, C_{1,3}, C_{1,4}, C_{1,5}, C_{1,6}\) counter-clockwise; cells in the second layer are labeled as \(C_{2,1}, C_{2,2}, \ldots, C_{2,12}\) counter-clockwise; similarly, cells in other layers are labeled in the same way. In particular, the centers of all cell \(C_{i,j}\) in the \(i\)-th layer are on the extension line of the centers of \(C_{0,0}\) and \(C_{1,1}\), as shown in Figure 1.

In this coverage structure, there are six center lines of cells presenting such properties: the center lines of cells lie in six rays with source on sink node, as dotted line shown in Figure 1; \(i\) and \(j\) meet \(j = (\mu - 1)i + 1, 1 \leq \mu \leq 6\), in \(C_{i,j}\); the cells have one adjacent inner-layer cell and three adjacent outer-layer cells. We define them as Main Line Cell (MLC). The whole coverage area is divided into six extended coverage areas by MLC. There are \(i - 1\) cells in each extended area in the \(i\)-th layer; we define them as Expansion Area Cells (EAC). Each cell of EAC has two adjacent outer-layer cells and two adjacent inner-layer cells; \(i\) and \(j\) meet \(j = (\mu - 1)i + \nu, 1 \leq \mu \leq 6, 2 \leq \nu \leq i\), in \(C_{i,j}\).

In order to obtain much better resource utilization, a heterogeneous node deployment strategy is adopted in this paper. There are two types of nodes, that is, sensor nodes (SNs) and relay nodes (RNs). SNs are placed in the center of hexagonal cells and responsible for monitoring and sensing data and send data to the sink at constant time-interval via RNs; if SNs are of the innermost layer, that is, the first layer of network, they will send data directly to the sink node; RNs are randomly placed in the cell and responsible for relaying data and ensuring network connectivity. The number of RNs in a cell according to energy balanced consumption will launch the analysis in Section 4.3.

3.2. Coverage Analysis. There are two kinds of coverage specifications in WSNs, that is, sensing coverage and connected coverage. We denote \(R_s\) as node’s communication radius, \(R_c\) as sensing radius of SNs, and \(r\) as outer radius of cell.

Definition 1. Sensing Coverage Ratio (SCR) refers to the ratio of the being monitored area by sensor nodes and the whole required being monitored area \([22]\). Let \(\eta\) denotes SCR, \(\eta = \frac{\text{area}(\bigcup_{j \in \phi} S_j \cap M)}{M}\), where \(\phi\) denotes the set of all working sensor nodes, \(M\) denotes the required being monitored area, \(S_j\) denotes the being monitored area by the \(i\)-th sensor node, and area\((\bigcup_{j \in \phi} S_j \cap M)\) denotes the intersection among all the being monitored areas by sensor nodes and \(M\). The network will get more sensing coverage quality when \(\eta\) is bigger, and it will achieve the full sensing coverage quality when \(\eta\) is 1.

For simplicity, assume a SN with sensing radius \(R_s\) is deployed in the center of a cell. When \(R_s\) is bigger than the outer radius of cell, one SN will be enough to meet the requirement of monitoring services in one cell. At this moment, the SCR of a cell \(\eta_{cel} = \frac{\text{area}(\pi R_s^2) \cap r^2 \sqrt{3}/2)}{\text{area}(r^2 \sqrt{3}/2)} = 1\); the SCR of the \(i\)-th layer \(\eta_i = \frac{\text{area}(\bigcup_{\mu=1}^{6} \pi R_s^2) \cap 6i \times r^2 \sqrt{3}/2)}{\text{area}(6i \times r^2 \sqrt{3}/2)} = 1\). So the network will get the best sensing coverage quality regardless of the size of network.

According to coverage model, the sensing data are forwarded layer by layer to sink node via RNs. In order to ensure that data can be relayed to sink node smoothly, it should ensure the connected coverage to meet the requirement of network.

Definition 2. Connected coverage refers to the fact that any node in the WSNs can communicate with another node via single-hop or multihop relaying \([23]\). It reflects the ability of data relaying and communication in WSNs.

The connected coverage in our coverage model can focus on the fact that the data can be relayed layer by layer. Each cell has one or two adjacent cells of inner layer as shown in Figure 1. If \(R_c\) and the outer radius of cell meet the requirement of \(R_c \geq r \sqrt{7}\), the entire network is connective.

4. Lifetime Analysis

4.1. Lifetime. In presence of several existing definitions of network lifetime \([5, 9, 11, 24]\), we consider network lifetime in terms of coverage of the network.
**Definition 3.** Lifetime is the time period till the proportion of dead nodes exceeds a certain threshold, which may result in loss of coverage of a certain area. Let LT denote lifetime, LT = \( \sum q \Delta t \) when \( q \Delta t \geq \eta d \), where \( \Delta t \) denotes the time period of the \( q \)th round data acquisition period, and \( \eta q \geq \eta d \) denote that SCR \( \eta q \) of the \( q \)th round is bigger than or equal to SCR threshold \( \eta d \).

In our deployment model, SNs are deployed in the center of cells to sense information and RNs are randomly deployed in cells to forward the sensing data to next layers until the sensing data reaches sink node. Therefore, according to the coverage analysis in Section 3.2, one can get the following conclusions.

1. Only when SCR of each cell is not less than \( \eta q \), can it achieve the goal of all areas being monitored; otherwise it cannot. According to our coverage model, some area can not be monitored when \( \eta q < \eta d \); that is, the network lifetime is terminated.
2. When the energy of RNs in one layer is depleted, the sensing data of its outer layer can not be forwarded to sink node, which means it is impossible to achieve connectivity of all nodes and network lifetime is terminated.

**4.2. Energy Consumption Analysis.** Without loss of generality, energy consumption model adopts rules with data acquisition periodically in this paper. We denote \( q(t) \) as the \( t \)th round fixed time-interval data acquisition period. SNs uniformly generate and transmit \( L \)-bits data in \( q(t) \). The other notations and their corresponding descriptions used for energy consumption analysis are listed in Notations and Descriptions.

The energy consumption on data processing and node dormancy are much less than data transmitting and sensing [24, 25], so we adopt the energy consumption with four parts: energy consumption for SNs to sense and transmit data, that is, \( e_{\text{sen}} \) and \( e_{\text{tra}} \); energy consumption for RNs to receive and transmit data, that is, \( e_{\text{rec}} \) and \( e_{\text{tra}} \).

The energy consumption [24] for a node to transmit \( L \)-bits data over a distance \( R_c \) is

\[
e_{\text{tra}} = (\beta_1 + \beta_2 R_c^\alpha),
\]

where \( \alpha = 2, 4 \).

The energy consumption [24] for a node to receive \( L \)-bits data from distance \( R_c \) is

\[
e_{\text{rec}} = \beta_3 L.
\]

The energy consumption [24] for a node to sense \( L \)-bits data around distance \( R_p \) is

\[
e_{\text{sen}} = \beta_4 L.
\]

The major energy consumption of SNs for \( L \)-bits data in \( q(t) \) includes \( e_{\text{tra}} \) and \( e_{\text{sen}} \). We denote \( e_s \) as it; \( e_s \) is

\[
e_s = e_{\text{tra}} + e_{\text{sen}}.
\]

The major energy consumption of RNs for \( L \)-bits data in \( q(t) \) includes \( e_{\text{tra}} \) and \( e_{\text{rec}} \). We denote \( e_t \) as it; \( e_t \) is

\[
e_t = e_{\text{rec}} + e_{\text{tra}}.
\]

Denote \( ECR_i(t) \) as the ECR of a SN in \( q(t) \); \( ECR_i(t) \) is

\[
ECR_i(t) = \frac{e_t}{q(t)}.
\]

Denote \( e_r(i, t) \) as the energy consumption of RNs of the \( i \)th layer in \( q(t) \). There are \( 6i \) cells in the \( i \)th layer, so \( e_r(i, t) \) is

\[
e_r(i, t) = 6ie_r.
\]

Denote \( ECR_i(i, t) \) as the ECR of SNs of the \( i \)th layer in \( q(t) \); \( ECR_i(i, t) \) is

\[
ECR_i(i, t) = \frac{e_r(i, t)}{6iq(t)} = \frac{e_r}{q(t)}.
\]

Denote \( ECR_i(t) \) as the average ECR of SNs of whole network in \( q(t) \); \( ECR_i(t) \) is

\[
ECR_i(t) = \frac{e_r}{q(t)}.
\]

Obviously, \( ECR_i(t) \), \( ECR_i(i, t) \), and \( ECR_i(t) \) are equal. It can demonstrate that each area or cell of our coverage model takes the same energy consumption ratio regardless of layer index and cell index.

RNs are responsible for relaying data and ensuring network connectivity in \( q(t) \). Denote \( ECR_i(t) \) as the ECR for RN to relay \( L \)-bits data in \( q(t) \); \( ECR_i(t) \) is

\[
ECR_i(t) = \frac{e_r}{q(t)}.
\]

Assume the number of RNs in the \( i \)th layer is \( \lambda_i \). According to Section 3.2, RNs in the \( i \)th layer should relay the data produced by SNs in all its outer layers in each \( q(t) \). Denote \( D_i \) as the amount of data required to be relayed by RNs of \( i \)th layer. As analysis in Section 3.1, there are \( N - i \) outer layers of the \( i \)th layer and \( 6k \) cell in the \( k \)th layer, so \( D_i = \sum_{k=i+1}^{N} 6k \cdot L \).

Denote \( e_r(i, t) \) as the energy consumption of RNs of the \( i \)th layer in \( q(t) \); \( e_r(i, t) \) is

\[
e_r(i, t) = D_i e_r.
\]

Denote \( ECR_i(i, t) \) as the ECR of RNs of \( i \)th layer in \( q(t) \); \( ECR_i(i, t) \) is

\[
ECR_i(i, t) = \frac{e_r(i, t)}{q(t)} = \frac{D_i e_r}{q(t)}.
\]
Denote $e_r(t)$ as the total energy consumption of RNs of whole network in $q(t)$. As analysis in Section 3, no data need to be relayed by RNs in $N$th layer, so $e_r(t)$ is

$$e_r(t) = \sum_{i=1}^{N-1} e_r(i, t). \quad (14)$$

Denote $\text{ECR}_r(t)$ as the average ECR of RNs of whole network in $q(t)$; $\text{ECR}_r(t)$ is

$$\text{ECR}_r(t) = \frac{e_r(t)}{q(t)} = \frac{\sum_{i=1}^{N-1} e_r(i, t)}{q(t)} = \frac{\sum_{i=1}^{N-1} D_i e_r}{q(t)}. \quad (15)$$

4.3. Energy Consumption Balancing Strategy. If the energy of SNs in a cell has exhausted, it will arouse SCR below $\eta_d$ and the network lifetime is terminated. Thus, the focus on the energy balance strategy for SNs is that each cell has the same $\text{ECR}_r$ to maximize network lifetime. Energy consumption analysis in Section 4.2 shows that each cell of this coverage model has the same $\text{ECR}_r$ in each $q(t)$ and the $\text{ECR}_r$, is equal to the $\text{ECR}_r(t)$. So the $\text{ECR}_r$ can stand for the $\text{ECR}_r(t)$ during whole network lifetime. Assume that when SN's energy is smaller than threshold $\sigma_r$, its lifetime is terminated. Denote $\text{LT}_s$ as SN's lifetime and $\text{LT}_s$ can be computed by

$$\text{LT}_s = \frac{(E_0 - \sigma_r)}{\text{ECR}_s}. \quad (16)$$

The sensing data are sent to sink node via RNs layer by layer in our node deployment, so when the energy of RNs in one layer is depleted, the data of outer layer cannot be sent to sink node, which means the network lifetime is terminated. The energy consumption balance strategy for the RNs focuses on the fact that each layer has the same $\text{ECR}_r$. Assume that when a RN's energy is smaller than threshold $\sigma_r$, it is dead and can not work for relaying data. Assume that there are $\lambda_1$ RNs in ith layer. Denote $\text{LT}_r(i)$ as the lifetime of RNs in the ith layer. $\text{LT}_r(i)$ can be computed by

$$\text{LT}_r(i) = \frac{\lambda_1 (E_0 - \sigma_r)}{\text{ECR}_r(i)} \quad \text{where } i < N. \quad (17)$$

The ideal network lifetime is that the energies of all nodes are exhausted simultaneously. Therefore, three conditions should be met for the goal: (1) $\sigma_0 = 0$, $\sigma_r = 0$; (2) lifetimes of RNs in each layer are identical; (3) lifetimes of RNs in each layer and lifetimes of SNs are identical. That is,

$$\text{LT}_r(i) = \begin{cases} \text{LT}_s & \forall i \in [1, N-1] \\ \text{LT}_r(j) & \forall i, j \in [1, N-1]. \end{cases} \quad (18)$$

Substituting (1), (2), (3), (16), and (17) into (18), we can get

$$\lambda_i = \frac{E_0}{\sigma_0} \times 3 \left( \frac{\beta_3 + \beta_1 + \beta_2 R_c^a}{\beta_4 + \beta_1 + \beta_2 R_c^a} \right) \left( N + i + 1 \right) \left( N - i \right), \quad (19a)$$

$$\lambda_i \frac{\lambda_j}{\lambda_j} = \frac{(N + i + 1) (N - i)}{(N + j + 1) (N - j)}, \quad (19b)$$

where $1 \leq i < N$ and $i$ and $j$ meet $\forall i, j \in [1, N-1] \cup i \neq j$.

It can be concluded that, (1) to keep lifetimes of RNs and SNs being equal, the number of RNs, that is, $\lambda_1$, should meet the requirement of (19a); that is, the number of RNs is relevant to its initial energy and $N$; (2) to keep consistent ECR of RNs in different layers, the number of RNs in each layer should meet the requirement of formula (19b).

5. Node Deployment Based on Area Topology Control

5.1. Node Deployment Strategy. The advantage of heterogeneous deployment model is that the capabilities of nodes can be utilized completely by adjusting the number and location of heterogeneous nodes. As in the previous analysis, the deployment of SNs strategy is that one SN is placed in the center of cell. According to Section 3.2, the center position $(x, y)$ of each cell $C_i,j$ can be calculated by the following formulas:

$$X = \sqrt{3} r (i - v + 1) \cos \left( \frac{(u - 1) \pi}{3} \right)$$

$$+ \sqrt{3} r (v - 1) \cos \left( \frac{u \pi}{3} \right),$$

$$Y = \sqrt{3} r (i - v + 1) \sin \left( \frac{(u - 1) \pi}{3} \right)$$

$$+ \sqrt{3} r (v - 1) \sin \left( \frac{u \pi}{3} \right),$$

where $u$ and $v$ meet $j = (\mu - 1)i + v$, $1 \leq \mu \leq 6$, $1 \leq v \leq i$, $u$ represents the $u$th partition, and $v$ represents the cell index in the $i$th layer.

According to analysis in Section 3.2, RNs in the $i$th layer are deployed randomly and the numbers of RNs in each cell layer are roughly equal in the same layer. The number of RNs in the $i$th layer $\lambda_i$ can be calculated by (19a). If initial energies of the SNs and RNs are consistently certain value, the number of RNs will be determined by layer index $i$ and the total number of network layers $N$.

5.2. Topology Control Algorithm. Accurate deployment on part of RNs and all of SNs was adopted to balance the energy consumption of each coverage area in HNDS [9], which greatly increased the difficulty to implement their node deployment. Meanwhile, the energy consumptions of nodes sometimes are dynamic and unpredictable, such as abnormal energy consumption and sudden failure of node, which bring new problem to balance ECR.

In order to reduce deployment difficulty, our coverage model adopts a simple deployment strategy as shown in Section 5.1. According to known coverage structure in Section 3.1, RNs in MLC are responsible for relaying data from three cells of the next outer layer and have only one cell of the next inner layer to receive their forwarding data. Thus, RNs of MLC will be overweighed and consume excessive energy and then are premature to die. Meanwhile, dynamic unbalanced energy consumption may make some areas take abnormal ECR and be premature to die. To resolve the problem of nodes’ premature death in some area, topology
control algorithm based on area energy consumption ratio is proposed in this paper.

**Definition 4.** Area energy consumption ratio is the ratio of total energy consumption in one coverage area $CA$ in $q(t)$ and total residual energy before the $t$th round data acquisition period; it can be expressed as the following:

\[
ECR_A(\text{CA}) \quad \frac{(\sum_{RN_k \in u} E_{RN_k}(t) - \sum_{RN_k \in u} E_{RN_k}(t + 1))}{\sum_{RN_k \in u} E_{RN_k}(t)},
\]  \quad (21)

where $ECR_A$ denotes the area energy consumption rate, $E_{RN_k}(t)$ denotes the total residual energy of RN$_k$ before $t$th round data acquisition period, and $E_{RN_k}(t + 1)$ denotes the total residual energy of RN$_k$ before $(t + 1)$th round data acquisition period.

Topology control algorithm based on area energy consumption ratio is divided into three parts.

First, information initialization: after nodes deployment, each node will confirm its geometry position by positioning algorithm proposed in [26] and then can obtain information as following list:

\[
\begin{array}{c}
\text{ID}_k \quad E_{RN_k} \quad i_{\text{cell}} \quad j_{\text{cell}} \quad X_k \quad Y_k,
\end{array}
\]  \quad (22)

where $\text{ID}_k$ is ID of node, $E_{RN_k}$ is the current residual energy of $\text{ID}_k$, $i_{\text{cell}}$ and $j_{\text{cell}}$ are index of $\text{ID}_k$, and $X_k$ and $Y_k$ denote coordinates of the center of cell.

Second, selection of cell active node: in order to get optimum energy utilization of RNs, the strategy that one RN is active and other RNs are asleep in one cell is proposed in our model. The active node is randomly generated. When a RN is selected as active node, it gets residual energy of all RNs and computes $ECR_A$ by (21) and then constructs the information list of active node in adjacent cell as follows:

\[
\begin{array}{c}
\text{ID}_p \quad i_{\text{cell}} \quad j_{\text{cell}} \quad ECR_A \quad X_p \quad Y_p,
\end{array}
\]  \quad (23)

where $\text{ID}_p$ is the ID of node $p$, $E_p$ is the residual energy of $\text{ID}_p$, $i_{\text{cell}}$ and $j_{\text{cell}}$ denote the index of cell, and $X_p$ and $Y_p$ denote the coordinates of ID$_p$.

Then information list is transmitted to nodes in adjacent cell and receivers renew their information list. When the energy of current active node is less than $\sigma_s$, the active node will release a notice of a new round selection of active nodes.

Third, connected sets creation: the active nodes establish increment sequence of connection according to $ECR_A$ of adjacent inner cell. When nodes establish new connection, they broadcast a connection request and then get connection confirmations from other nodes in adjacent cell and select the smallest one in inner cells as a new connected node. Thus, the optimal energy consumption connection set is established.

The algorithm progress of topology control algorithm based on area energy consumption is shown in Figure 2.

### 6. Simulation Experiments

To verify the performance of our proposed deployment model, OMNet++ is adopted as the simulation platform for experiments and analysis, and the energy consumption parameters of [24] are adopted in the simulation experiments. Each SN can get 1000 bits data in a $q(t)$; the other parameters and their corresponding values are listed in Table 1.

#### 6.1. Energy Consumption Ratio

#### 6.1.1. ECR in Different Layer. The ECR is one of the important indicators to evaluate superiority of deployment mode. If the $ECR_s$ of each cell and the $ECR_r$ of each layer are equal to each other during every data acquisition period, the network will achieve the goal of optimal energy consumption. We
plot simulations with five layers in two simulation scenarios: Ideal Model and Realistic Model. In Ideal Model, all simulation parameters are ideal: the initial energy of nodes is equal; the communication progression is ideal; there are no unexpected situations, such as mechanical failure, electric leakage, and accidental death. In Realistic Model, there are some unexpected situations that occurred randomly, such as data retransmission and RN's death, and there are a few RNs with different initial energy. The average ECR, and ECR, of each layer during every data acquisition period are recorded until the network lifetime is over.

Table 2 shows the average ECR of each layer during the whole network lifetime. The average of each network layer’s ECR is $2.345 \times 10^{-6}$ J/s and $2.430 \times 10^{-6}$ J/s in Ideal Model simulation scenario and Realistic Model simulation scenario, respectively. RNs have the same results with SNs. It can prove that our model can effectively balance energy consumption of various areas of the network.

Figure 3 shows the ECR, of layer during each $q(t)$. Figures 3(a) and 3(b) show the ECR, of layer 2 and layer 4 in different $q(t)$, respectively. Prompt: the average ECR of other layers is listed in Table 2; we just select ECR of two layers shown in Figures 3 and 4 for simplicity. IM, ECR and RM, ECR denote the ECR, in Ideal Model and Realistic Model simulation environment, respectively. As shown in Figure 3, the ECR, of layer in $q(t)$ is about $2.340–2.350 \times 10^{-6}$ J/s in the Ideal Model simulation scenario, the variation of energy consumption ratio is about 0.4%, and to the best of our knowledge, it will not affect the network lifetime. The average ECR, of layer during every data acquisition period is about $2.412–2.448 \times 10^{-6}$ J/s in the Realistic Model simulation scenario, and the variation of energy consumption ratio is 0.7%. Compared with the Ideal Model, it is slightly increased but does not make a significant impact on network lifetime.

![Figure 3: ECR, of SNs in different layer.](image)

**Table 2: Average ECR during whole network lifetime.**

| ECR ($10^{-6}$ J/s) | Layer number |
|----------------------|--------------|
|                      | 1 | 2 | 3 | 4 | 5 |
| Ideal Model          | SN | 2.345 | 2.345 | 2.345 | 2.345 | 2.345 |
|                      | RN | 2.340 | 2.340 | 2.340 | 2.340 | 2.340 |
| Realistic Model      | SN | 2.430 | 2.430 | 2.430 | 2.340 | 2.340 |
|                      | RN | 2.340 | 2.340 | 2.340 | 2.340 | 2.340 |

Figure 4 shows the ECR, of layer 2 and layer 4 during each $q(t)$. Figures 4(a) and 4(b) express the ECR, of layer 2 and layer 4 in every $q(t)$, respectively. In each subgraph, the Ideal MLC and Ideal EAC express the ECR, of layer RNs of Main Line Cell and Extension Area Cell in Ideal Model simulation scenario, respectively, and the Realistic MLC and Realistic EAC express the ECR, of layer RNs of Main Line Cell and Extension Area Cell in Realistic Model simulation scenario, respectively.

As shown in Figure 4, under Ideal Model simulation scenario, each layer’s RNs’ ECR of our model is $2.32–2.37 \times 10^{-6}$ J/s in a data acquisition period, and their average is $2.345 \times 10^{-6}$ J/s and rippled rate is about 1.07%. Under Realistic Model simulation scenario, each layer’s RNs’ ECR of our model is within $2.412–2.448 \times 10^{-6}$ J/s in a data acquisition period, and their average is $2.430 \times 10^{-6}$ J/s and rippled rate is 0.7%; its rippled rate is higher than under Ideal Model. However, all layers have approximately identical ECR, which means that our node deployment model can effectively balance the energy consumption of networks and prolong the networks lifetime.
6.1.2. Influence on ECR by Topology Control Algorithm.

In order to verify influence on ECR by topology control algorithm based on area energy consumption, we plot a group of experiments under Realistic Model Scenario. There are two routing algorithms in experiments, that is, random routing algorithm and topology control based on area energy consumption ratio. We recorded RN’s ECR of the second layer in each \( q(t) \) during the network lifetime, as shown in Figure 5. MLC-R and EAC-R denote RN’s ECR of the second layer in MLC and EAC, respectively, under the first routing algorithm; MLC-E and EAC-E denote RN’s ECR of the second layer in MLC and EAC, respectively, under the second routing algorithm.

As shown in Figure 5, because RNs in MLC take excessive relaying tasks, the ECR of MLC-R is significantly higher than others and is depleted on 380 thousand seconds; contrarily, ECR of EAC-R is lower than MLC-R, and when RNs’ energies of MLC are depleted, the RNs of EAC take more relaying tasks and their ERC becomes higher suddenly. However, MLC-E and EAC-E have the approximately equal ECR, which proves that our topology control algorithm can effectively balance the ECR of MLC and EAC. Compared with MLC-R, MLC-E takes steady EAC during the whole lifetime, which proves that our topology control algorithm can effectively resolve problems generated by unexpected and unbalanced energy consumption.

6.2. Lifetime. The main goal of coverage model is to prolong the lifetime under the premise of maintaining network required coverage ratio. We plot a group of comparative experiments among NNDS [6], HNDS [9], and our model. NNDS is a homogeneous node deployment model; HNDS is a heterogeneous deployment model. The experiments adopt five-layer network structure in two experiment scenarios, that is, Ideal Model and Realistic Model.

![Figure 4: ECR of RNs in different layer.](image)

Figure 5: Influence on ECR by topology control algorithm.

Figure 6 shows the lifetime of three deployment models under Ideal Model simulation scenario. The different layers’ lifetimes in NNDS are different to each other. However, the lifetimes of different layers are fairly constant in our model and HNDS, which proves that the heterogeneous deployment can balance energy consumption among different layers. The lifetime of our model is longer than HNDS, which proves that the topology control algorithm based on area energy consumption ratio can dynamically balance area energy consumption and prolong the network lifetime.

Figure 7 shows the lifetime of three deployment models under Realistic Model simulation scenario. The different
layers’ lifetimes in NNDS are also different to each other and are shorter than corresponding values in Figure 6, because there are some uncertain factors that affect node energy consumption in this scenario and NNDS does not take effective approach to balance unexpected energy consumption. The different layers’ lifetimes in HNDS take slight changes; on the contrary, the different layers’ lifetimes in our model are the same, owing to topology control algorithm based on area energy consumption to dynamically balance the energy consumption of each cell.

Figure 8 shows the residual energy of each layer at the end of network lifetime under Realistic Model simulation scenario. Compared with HNDS and NNDS, there are less residual energies in our model and approximated residual energies in each layer. The residual energies are slightly increasing with the layer number increasing in HNDS and are severely increasing in NNDS.

7. Conclusion

After we deeply analyzed the related factors of WSNs energy consumption and network lifetime, a heterogeneous node deployment model based on area topology control was proposed in this paper. In order to improve network lifetime, this coverage model adopted heterogeneous node deployment to balance area energy consumption ratio and adopted topology control based on area energy consumption ratio to maintain dynamic equilibrium energy consumption. The experimental results show that our model has achieved the goal to keep same ECR in various areas of WSNs with the premise that sensing coverage and connected coverage meet certain requirements. Compared with similar heterogeneous deployment model, our model was easier to implement deployment program and further prolong the lifetime of WSNs; in particular it had more advantages in reducing dependence on accuracy of deployment, balancing dynamic energy consumption, and improving lifetime in poor network environment, which benefited from topology optimization based on area energy consumption ratio. The further work is to further research on the collaboration among heterogeneous nodes to improve resource utilization.

Notations and Descriptions

$\beta_1, \beta_2, \alpha$: Parameters of energy consumption formula for transmitting $L$-bits data over a distance $R_c$.
\[ \beta_3: \text{ Parameter of energy consumption formula for receiving } L \text{-bits data from distance } R_c \]

\[ \beta_4: \text{ Parameter of energy consumption formula for sensing } L \text{-bits data around distance } R_s \]

\[ \frac{E_0}{e_0}: \text{ The initial energy of SN and RN, respectively} \]

\[ \frac{R_c}{R_s}: \text{ The radius of node communication and sense, respectively} \]

\[ \frac{e_{\text{tra}}}{e_{\text{rec}}}: \text{ The energy consumption to transmit and receive } L \text{-bits data over a distance } R_c, \text{ respectively} \]

\[ e_{\text{sen}}: \text{ The energy consumption for SN to sense } L \text{-bits data around distance } R_s \]

\[ \frac{e_s}{e_r}: \text{ Energy consumption of a SN/RN for } L \text{-bits data in a } q(t) \]

\[ N: \text{ The total number of network layers} \]

\[ ECR_s/ECR_r: \text{ Energy consumption ratio of SNs and RNs, respectively.} \]

**Conflict of Interests**

The authors declare that there is no conflict of interests regarding the publication of this paper.

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