NUND: Non-Uniform Node Distribution in Cluster-based Wireless Sensor Networks

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Abstract

Cluster-based wireless sensor network (WSN) can significantly reduce the energy consumption by data aggregation and has been widely used in WSN applications. However, due to the intrinsic many-to-one traffic pattern in WSN, the network lifetime is generally deteriorated by the unbalanced energy consumption in a cluster-based WSN. Therefore, energy efficiency and network lifetime improvement are two crucial and challenging issues in cluster-based WSNs. In this paper, we propose a Non-Uniform Node Distribution (NUND) scheme to improve the energy efficiency and network lifetime in cluster-based WSNs. Specifically, we first propose an analytic model to analyze the energy consumption and the network lifetime of the cluster-based WSNs. Based on the analysis results, we propose a node distribution algorithm to maximize the network lifetime with a fixed number of sensor nodes in cluster-based WSNs. Extensive simulations demonstrate that the theoretical analysis results determined by the proposed analytic model are consistent with the simulation results, and the NUND can significantly improve the energy efficiency and network lifetime.

Keywords: Wireless sensor networks, network lifetime, non-uniform node distribution and energy consumption

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1. Introduction

Wireless sensor network (WSN) has emerged as a promising technology to monitor environment and collect information in both military and civilian operations [1]. A typical WSN consists of a large number of resource-limited sensor nodes that sense targeted area periodically and deliver the sensed data to the sink via a multihop transmission. Since the sensor nodes are battery-powered and difficult to be recharged, energy efficiency is a crucial issue in WSNs [2].

Clustering is an effective mechanism to improve the energy efficiency of WSNs [3]. The data aggregation at cluster heads greatly reduces the energy consumption for data forwarding. However, since the clusters close to the sink have to forward the aggregated data from the other clusters, they would exhaust their energy quickly and cause unbalanced energy consumption in the network. The unbalanced energy consumption finally leads to a premature death in the hotspot and deteriorates the network lifetime. Therefore, how to smooth the energy consumption of the hotspot is a critical issue to improve the network lifetime.

Recently, non-uniform node distribution has been proved as a feasible solution and attracted increasing attention in balancing the energy consumption of sensor nodes [4, 5, 6]. The basic idea of non-uniform node distribution is to add more nodes to the areas with heavier traffic to mitigate the unbalanced energy consumption. Wu et al. [5] propose a quantified non-uniform node distribution approach to mitigate the unbalanced energy consumption in a corona-based WSN. Ferng et. al. [6] propose three non-uniform node distribution strategies to achieve completely balanced energy consumption, the longest network lifetime and the fewest sensor nodes cost respectively in a corona-based WSN. Most of the existing works can smooth the unbalanced energy consumption of the network and improve the network lifetime. However, little attention has been paid to the node distribution study in cluster-based WSNs. Since the energy consumption and network lifetime are different between the hierarchical WSNs and flat WSNs, it is essential to investigate the non-uniform node distribution in cluster-based WSNs. In addition, most of the related works focus on balancing the energy consumption of the whole network and hence to maximize the network lifetime, which obviously requires a large number of sensor nodes and leads to a huge distribution cost.

In this paper, we propose a Non-Uniform Node Distribution (NUND) scheme to improve the energy efficiency and network lifetime in cluster-based WSNs under a fixed number of sensor nodes. The main contributions are concluded as follows.

(1) We propose an analytic model to analyze the energy consumption and network lifetime in cluster-based WSNs. The proposed analytic model considers the energy consumption not only for data gathering, but also for clustering.

(2) We propose a non-uniform node distribution algorithm to maximize the network lifetime with a fixed number of sensor nodes. The fully balanced energy consumption is also discussed in NUND as a special case, which is the sensor nodes are enough to smooth the nodal energy consumption in the whole network.

(3) Extensive simulations demonstrate that our analytic model can accurately estimate the energy consumption and network lifetime of cluster-based WSNs and the proposed NUND scheme can significantly improve the energy efficiency and network lifetime with a fixed distribution cost.

The reminder of this paper is organized as follows. Section 2 reviews the related works. Section 3 describes the system model and design goals. Section 4 analyzes the energy consumption and network lifetime of cluster-based WSNs. The proposed NUND scheme is detailed in Section 5. Section 6 shows the comparison between theoretical analysis and simulation results and evaluates the effectiveness of the NUND. Finally, we conclude the paper in Section 7.

2. Related Work

There has been plenty of related works on studying node distribution in WSNs [4, 5, 6, 7, 8, 9, 10]. We can briefly divide the existing works into two categories according to the different concerns. The one is the coverage-focused scheme, which focus on ensuring the network coverage and connectivity [7, 8, 9]. The other is the performance-focused scheme, which aim to improve the network performance (e.g., energy efficiency, network lifetime) after meeting the coverage and connectivity requirements [4, 5, 6, 10]. In this paper, we concentrate on the latter and review the existing works in this section.

Olariu et. al. [10] first prove that the unbalanced energy consumption and energy hole problem is inevitable when the sensor nodes are distributed uniformly in the network and report data constantly. However, they discuss the energy hole problem in the WSNs with non-uniform node distribution in [4] and conclude that balanced energy consumption is possible when the data rates can be adjusted. Based on their analysis conclusions, Wu et al. [5] propose a quantified non-uniform node distribution approach to mitigate the unbalanced energy consumption in a corona-based WSN. They claim that the unbalanced energy consumption is unavoidable in a circular multihop sensor network with non-uniform node distribution and constant data reporting. Afterwards, a following work is done by Ferng et. al. [6]. They prove the feasibility of balanced energy consumption with a switch scheduling on the sensor node. And they propose three non-uniform node distribution schemes to achieve completely balanced energy consumption, the longest network lifetime and the fewest sensor nodes cost respectively. In [11], Chang et al. present a distance-based and a density-based node distribution scheme, to balance energy consumption and improve network lifetime. The former scheme is to control the node deployment distance and use power control mechanism to balance the energy consumption. And the latter is to adjust the density of sensor nodes which are switched between active and sleep modes in each zone.

Besides the schemes focusing on balancing the energy consumption of the network, a few related works try to improve other network performances (e.g., data capacity) with the non-uniform node distribution. Lian et al. [12] propose a non-uniform node distribution scheme to increase the data capability of WSNs. Sensor nodes in their scheme work in two modes: active mode and sleep mode. They propose a routing algorithm by dynamically changing the mode of the sensor nodes to save energy and a node distribution scheme to determine the node densities in different areas of the network. A power-aware non-uniform node distribution scheme is presented in [13] to address the sink-routing hole problem and ensure a long-term connectivity in WSNs. They derive out a node distribution function based on the hop counts to the sink.

Most of the existing node distribution schemes can mitigate, even eliminate, the unbalanced energy consumption or improve the network performance in WSNs. However, little attention has been paid to the node distribution study in cluster-based WSNs. Clustering is proved as an efficient way to gather information in WSNs [5, 14, 15, 16], since the data aggregation at cluster heads can filter the redundant sensed data and significantly reduce the energy consumption of data forwarding. One the other hand, the energy consumption characteristics and the network lifetime are different in the hierarchical WSNs by the change of the data collection mechanism [16, 17, 23]. Therefore, it is essential to study how to distribute sensor nodes to smooth the unbalanced energy consumption in cluster-based WSNs [24, 25]. Several existing works have investigated the energy consumption and network lifetime in cluster-based WSNs, which provide a basis for studying the node distribution schemes. Lee et al. [14] derive the upper bound on the network lifetime in cluster-based networks and investigate the effects of the number of clusters and spatial correlation on the network lifetime bound. Liu et al. [5] also investigate the lifetime time of cluster-based networks, and propose a routing protocol to improve the network FNDT based on unequal cluster radii.

In this paper, we propose an analytic model to estimate the energy consumption of sensor nodes and the network lifetime in cluster-based WSNs. Different from the existing works, we aim to propose a non-uniform node distribution scheme based on our analysis results to maximize the network lifetime with a fixed number of sensor nodes.

3. System Model and Design Goals

3.1 Network Model

Consider the cluster-based WSN model that is also used in [5]. n homogeneous sensor nodes are deployed in a circular region of radius R and a static sink (or base station) situated at the center. The sensor nodes autonomously form a number of clusters with a uniform clustering algorithm [5, 18, 19], such as EADC [15] where each cell head (CH) broadcasts clustering messages with the same transmission range. Therefore, each cluster will has a uniform cluster radius, denoted by r. When a sensor node is elected as a cluster head, it broadcasts clustering message to the neighboring nodes. And the sensor node chooses the nearest cluster head as its cluster head and send a joining message to the cluster head. All the sensor nodes periodically sense the monitored area and transmit the sensed data to the sink. The data transmission in each period consists of two procedures, intra-cluster data aggregation and inter-cluster data transmission. In intra-cluster data aggregation, each cluster member (CM) transmits its sensed data to the cluster head with a TDMA manner. Afterwards, the CH sends the aggregated data to the sink via a geographic greedy routing among the CHs during the inter-cluster data transmission. Geographic greedy routing is scalable for large WSNs, because it requires only local information for making forwarding decisions. This assumption has been widely adopted in analyzing multi-hop wireless sensor and ad-hoc networks. In addition, the inter-cluster transmission is based on a collision-free MAC protocol without data loss just as the assumptions in [4, 5, 6, 10, 11]. The sensor nodes can be switched between active mode and sleep mode by a simple switching mechanism.

3.2 Energy Consumption Model

According to the typical energy consumption model [20, 22], the energy consumption for transmitting sees Eq.(1) and the energy consumption for receiving is represented in Eq.(2).

$$\begin{cases} E_t(l) = lE_{elec} + l\varepsilon_{fs} d^2, & \text{if } d \le d_0 \\ E_t(l) = lE_{elec} + l\varepsilon_{amp} d^4, & \text{if } d > d_0 \end{cases} \tag{1}$$

$$E_r(l) = lE_{elec} \tag{2}$$

Here, E_{elec} is the transmitting circuit loss. Both the free space (d^2 power loss) and the multi-path fading (d^4 power loss) channel models are used in the model, depending on the distance between the transmitter and the receiver. ε_{fs} and ε_{amp} are respectively the energy required for power amplification in the two models. l denotes the bits of the data sent or received by a sensor node. The above parameter settings are shown in **Table 1**, which is adopted from [3].

Table 1. Network Parameters

Parameter	Value
Threshold distance (d_0)	87 m
E_{elec}	50 nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{amp}	0.0013 pJ/bit/m^4

3.3 Design Goals

The objective of NUND is to distribute a fixed number of sensor nodes to maximize the network lifetime in cluster-based WSNs. Since coverage ratio is the primary requirement of WSNs, we should uniformly deploy the sensor nodes to meet the coverage requirement according to the existing node deployment schemes [7, 8, 9]. Therefore, the objective of NUND changes to distribute the rest sensor nodes to maximize the network lifetime. To be clearer, we first define the following terms.

Definition 1. *Required node density is the minimum node density to meet the required coverage ratio of the monitored area.*

Definition 2. *Since the deployed sensor nodes should meet the required coverage ratio, in this paper, network lifetime is defined as the duration from the time the network begins to work to the time when the density of alive nodes in an area is lower than the required node density. Since the sensor nodes periodically send sensed data to the sink, the network lifetime can be measured by the number of data periods (rounds).*

Definition 3. *Distribution efficiency is defined as the ratio between the number of distributed sensor nodes and the network lifetime.*

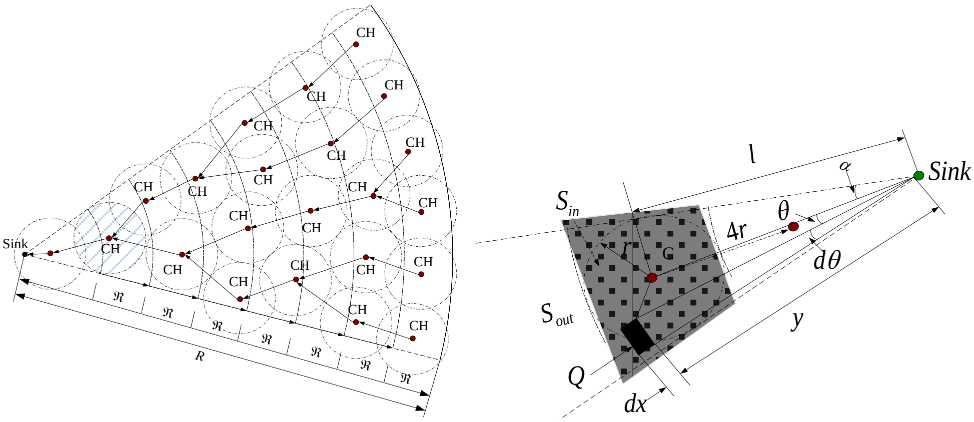
With the definitions above, we specifically conclude our design goals as follows.

(1) *Accurately estimate the energy consumption and network lifetime.* Since NUND aims to distribute the rest sensor nodes to maximize the network lifetime after meeting the required node density, we should first accurately estimate the energy consumption and network lifetime in cluster-based WSNs when the node is uniformly distributed with the required node density. Then, we can distribute the rest sensor nodes to mitigate the unbalanced energy consumption and improve the network lifetime.

(2) *Maximize the distribution efficiency.* Since the distribution cost is an important factor in WSN applications, NUND should maximize the network lifetime with a fixed number of sensor nodes, which also means maximizing the distribution efficiency.

4. Analysis on Energy Consumption and Network Lifetime

In this section, we propose an analytic model to analyze the energy consumption and network lifetime in cluster-based WSNs where the sensor nodes are uniformly deployed with the required node density. The data gathering model in cluster-based WSNs is shown in **Fig. 1(a)**. The monitored area of a cluster is described as the shadow area. Without loss of generality, we analyze the energy consumption of a cluster c where the distance between the cluster head C_l and the sink is $l = hr + x$, and the angle of the fan-shaped shadow region is 2α. The analytic model is shown as **Fig. 1(b).** Denote ρ as the required node density and r as the cluster radius. According to the law of cosines, we have $\alpha = \arccos(1 - r^2/2l^2)$. To mitigate the overlap impact of neighbouring clusters, we consider the nodes in the fan-shaped shadow region are the cluster members in the cluster c. And the area of the shadow region is $4\alpha lr$, therefore, there are $n = 4\alpha lr\rho$ nodes in the cluster c.



(a) **(b)**

Fig. 1. The Analytic Model for Cluster-based WSNs

Since the data transmission in cluster-based WSNs consists of two procedures according to our network model, our analysis focuses on analyzing the nodal energy consumption in each procedure and determining the network lifetime based on the energy consumption characteristics. In most of existing works, the energy consumption only consists of the energy consumption in sensed data transmitting and receiving. In our analytic model, we consider the energy consumption for clustering and cluster head re-election. We detail our analysis with the following lemmas and theorems.

Lemma 1. *Denote the cluster radius as r and the required node density as ρ. Suppose that each clustering message takes λ_1 bits, and the joining message takes λ_2 bits. The distance between the cluster head C_l and the sink is l. Then if E_c^{ch} and E_c^{cms} denote the energy consumption of CH and CMs for clustering respectively, we have*

$$\begin{cases} E_c^{ch} = (E_{elec} + \varepsilon_k r^\alpha)\lambda_1 + (n-1)E_{elec}\lambda_2 \\ E_c^{cms} = 2\lambda_2 lr\rho\alpha(E_{elec} + 2\varepsilon_{fs} l^2 + r^2) - 2\lambda_2 l\rho\varepsilon_{fs}\sin\alpha(2l^2 r + \frac{2}{3}r^2) + 2\lambda_1 lr\rho\alpha E_{elec} \end{cases} \quad (3)$$

where $\varepsilon_k = \varepsilon_{fs}$ and $\alpha = 2$, if $r \le d_0$; otherwise, $\varepsilon_k = \varepsilon_{amp}$ and $\alpha = 4$.

Proof. According to the clustering process described in Sec. 3, the CH consumes energy in broadcasting the clustering message to cluster members and receiving the joining messages from them. Therefore, with the energy consumption model, we have if $r \le d_0$, $E_c^{ch} = (E_{elec} + \varepsilon_{fs} r^2)\lambda_1 + (n-1)E_{elec}\lambda_2$; otherwise, $E_c^{ch} = (E_{elec} + \varepsilon_{amp} r^4)\lambda_1 + (n-1)E_{elec}\lambda_2$.

Denote a small region of the cluster c as Q shown as **Fig. 1(b)**. The distance between Q and the sink is $y\,|\,\{l-r \le y \le l+r\}$, and the width of Q is dy. Denote the angle between Q and the sink as $d\theta$. Therefore, we can determine the number of nodes in Q is $y \times d\theta \times dy \times \rho$. Since Q is a very small region, we consider all the nodes in Q have the same distance to the cluster head. Therefore, we can calculate the distance between Q and the cluster head is - $L^2 = l^2 + y^2 - 2ly\cos\theta$.

Since all the nodes in Q consume energy in receiving the clustering message and sending the jointing messages to the cluster head, the energy consumption in Q can be calculated as

$$\lambda_2\{y\rho E_{elec} \cdot d\theta \cdot dy + y\rho\varepsilon_{fs} L^2 \cdot d\theta \cdot dy\} + \lambda_1 y\rho E_{elec} \cdot d\theta \cdot dy .$$

Therefore, if we make integrals over the cluster c, we have the total energy consumption of all cluster members for clustering is

$$\begin{aligned} E_c^{cms} &= \int_{l-r}^{l+r}\int_0^{\alpha} \left\{\lambda_2\{y\rho E_{elec} + y\rho\varepsilon_{fs}(l^2 + y^2 - 2ly\cos\theta)\} + \lambda_1 y\rho E_{elec}\right\} \cdot d\theta \cdot dy \\ &= 2\lambda_2 lr\rho\alpha(E_{elec} + 2\varepsilon_{fs} l^2 + r^2) - 2\lambda_2 l\rho\varepsilon_{fs}\sin\alpha(2l^2 r + \frac{2}{3}r^2) + 2\lambda_1 lr\rho\alpha E_{elec} \end{aligned} .$$

[End]

Lemma 1 shows the energy consumption of the CH and CMs for clustering respectively. In a data period, the cluster members send the sensed data to the cluster head with a TDMA manner in this intra-cluster data aggregation process. The CH first broadcasts the time slot message to CMs, and then, each CM transmits the sensed data to the CH in its allocated time slot. Therefore, we calculate the energy consumption for intra-cluster data aggregation in a data period as follows.

Lemma 2. *Denote the time slot message takes δ bits, and each CM sends τ bits of sensed data to the CH in its time slot. Then, in a data period, the energy consumption of CH E_a^{ch} and CMs E_a^{cms} during the intra-cluster data aggregation are*

$$\begin{cases} E_a^{ch} = (E_{elec} + \varepsilon_k r^{\alpha})\delta + (n-1)E_{elec}\tau \\ E_a^{cms} = 2lr\tau\rho\alpha(E_{elec} + 2\varepsilon_{fs} l^2 + r^2) - 2l\tau\rho\varepsilon_{fs}\sin\alpha \cdot (2l^2 r + \frac{2}{3}r^2) + 2lr\delta\rho\alpha E_{elec} \end{cases} \quad (4)$$

where $\varepsilon_k = \varepsilon_{fs}$ and $\alpha = 2$, if $r \le d_0$; otherwise, $\varepsilon_k = \varepsilon_{amp}$ and $\alpha = 4$.

Proof. In the intra-cluster data aggregation, CH first broadcasts a time slot message to the CMs. After receiving the message, the CMs send τ bits data to the CH within their allocated time slots. Thus, the energy consumption of CH for intra-cluster data aggregation in a data period is

$$\begin{cases} E_a^{ch} = (E_{elec} + \varepsilon_{fs} r^2)\delta + (n-1)E_{elec}\tau, & \text{if } r \le d_0 \\ E_a^{ch} = (E_{elec} + \varepsilon_{amp} r^4)\delta + (n-1)E_{elec}\tau, & \text{if } r > d_0 \end{cases}$$

Similar to the proof of **Lemma 1**, we can calculate the energy consumption of CMs for intra-cluster data aggregation is

$$E_a^{cms} = \int_{l-r}^{l+r}\int_0^{\alpha}\left\{\tau\{y\rho E_{elec} + y\rho\varepsilon_{fs}(l^2 + y^2 - 2ly\cos\theta)\} + y\delta\rho E_{elec}\right\}\cdot d\theta\cdot dy$$

$$= 2lr\tau\rho\alpha(E_{elec} + 2\varepsilon_{fs}l^2 + r^2) - 2l\tau\rho\varepsilon_{fs}\sin\alpha\cdot(2l^2r + \frac{2}{3}r^2) + 2lr\delta\rho\alpha E_{elec}.$$

[End]

Lemma 3. *Denote the aggregation rate of the intra-cluster data is* ϕ. *We have, in a data period, the energy consumption of the CH in the inter-cluster data transmission* E_t^{ch} *is*

$$\begin{cases} E_t^{ch} = \phi\tau\rho\alpha(R^2 - (l-r)^2)(E_{elec} + \varepsilon_{k1}l^{\alpha 1}) + \phi\tau\rho\alpha(R^2 - (l+r)^2)E_{elec}, & \text{if } l \le 2r \\ E_t^{ch} = \phi\tau\rho\alpha(R^2 - (l-r)^2)(E_{elec} + \varepsilon_{k2}(2r)^{\alpha 2}) + \phi\tau\rho\alpha(R^2 - (l+r)^2)E_{elec}, & \text{if } l > 2r \end{cases} \quad (5)$$

where $\varepsilon_{k1} = \varepsilon_{fs}$ *and* $\alpha = 2$, *if* $l \le d_0$; $\varepsilon_{k1} = \varepsilon_{amp}$ *and* $\alpha = 4$, *if* $l > d_0$; $\varepsilon_{k2} = \varepsilon_{fs}$ *and* $\alpha = 2$, *if* $2r \le d_0$; $\varepsilon_k = \varepsilon_{amp}$ *and* $\alpha = 4$, *if* $2r > d_0$.

Proof. The energy consumption of CH in the inter-cluster data transmission consists of two parts, the energy consumption for sending its intra-cluster aggregated data and the energy consumption for receiving and forwarding the aggregated data from the upstream CHs. As shown in **Fig. 1**, the upstream area of the cluster can be calculated as

$$\frac{2\alpha}{2\pi}\pi R^2 - \frac{2\alpha}{2\pi}\pi(l+r)^2 = \alpha(R^2 - (l+r)^2).$$

Therefore, the data amount received by the CH in a data period is $D_r^{ch} = \phi\tau\rho\alpha(R^2 - (l+r)^2)$. Since the data amount sent by the CH includes its own data and the data from the upstream CHs, the data amount sent by the CH in a data period is $D_t^{ch} = \phi\tau\rho\alpha(R^2 - (l-r)^2)$.

In the inter-cluster data transmission, the CH communicates with the sink directly if the distance to the sink l is no greater than $2r$. Therefore, we have

$$E_t^{ch} = \phi\tau\rho\alpha(R^2 - (l-r)^2)(E_{elec} + \varepsilon_{k1}l^{\alpha 1}) + \phi\tau\rho\alpha(R^2 - (l+r)^2)E_{elec}, \quad \text{if } l \le 2r$$

where $\varepsilon_{k1} = \varepsilon_{fs}$ and $\alpha = 2$, if $l \le d_0$; otherwise, $\varepsilon_{k1} = \varepsilon_{amp}$ and $\alpha = 4$.

If the distance between the CH and the sink is larger than $2r$, it forwards the data to the next CH. Since the distance between two CHs is $2r$, the energy consumption of the CH in inter-cluster transmission is

$$E_t^{ch} = \phi\tau\rho\alpha(R^2 - (l-r)^2)(E_{elec} + \varepsilon_{k2}(2r)^{\alpha 2}) + \phi\tau\rho\alpha(R^2 - (l+r)^2)E_{elec}, \quad \text{if } l > 2r$$

where $\varepsilon_{k2} = \varepsilon_{fs}$ and $\alpha = 2$, if $2r \le d_0$; otherwise, $\varepsilon_{k2} = \varepsilon_{amp}$ and $\alpha = 4$.

[End]

Theorem 1. *If the CHs are re-elected every* η *data periods, the average energy consumption* E_l^{avg} *of the node whose distance to the sink is* l *is*

$$E_l^{avg} = \left((E_a^{ch} + E_t^{ch}) + (n-1)E_a^{cms}/n\right)/n + \frac{1}{\eta n}E_c^{ch} + (n-1)\frac{E_c^{cms}}{n\cdot\eta n} \quad (6)$$

Proof. When the node acts as a CM, the energy consumption for intra-cluster data aggregation in a data period is E_a^{cms}/n, and the energy consumption for clustering is E_c^{cms}/n.

When the node acts as the CH, the energy consumption for intra-cluster data aggregation and inter-cluster data transmission in a data period is $E_a^{ch}+E_t^{ch}$, and the energy consumed for clustering is E_c^{ch}/n. According to our network model, each sensor node have the same probability to be elected as the cluster head, therefore each node would act as CH for η rounds and as CM for $(n-1)\eta$ rounds within $n\eta$ rounds. The average energy consumption of each node in a data period can be derived as the average of the energy consumption of being CH and CM as follows.

$$\begin{aligned} E_l^{avg} &= \frac{\eta(E_a^{ch}+E_t^{ch})+E_c^{ch}}{\eta n}+\left((n-1)\eta E_\alpha^{cms}+(n-1)\frac{E_c^{cms}}{n}\right)\Big/\eta n \\ &= \left((E_a^{ch}+E_t^{ch})+(n-1)E_a^{cms}/n\right)\Big/n+\frac{1}{\eta n}E_c^{ch}+(n-1)\frac{E_c^{cms}}{n\cdot\eta n} \end{aligned} .$$

[End]

Theorem 2. *Denote the initial energy of the sensor nodes is* E_0. *Therefore, the network lifetime is* $LT=E_0\big/\max(E_l^{avg})\big|\, l\in(0,R]$.

Proof. Since the network is uniformly deployed with required node density, the network lifetime is the time when the first sensor node dies. And the first dead sensor node of the network should be the node with the largest average energy consumption. Therefore, the network lifetime depends on the lifetime of the node with the heaviest energy consumption. Since the largest energy consumption is $\max(E_l^{avg})\big|\, l\in(0,R]$, we can easily get $LT=E_0\big/\max(E_l^{avg})\big|\, l\in(0,R]$.

[End]

5. The Proposed NUND Scheme

5.1 The Non-Uniform Node Distribution Algorithm

In this section, we describe the NUND scheme in detail. According to the design goals in Sec. 3, the objective of NUND is to maximize the distribution efficiency. To be more specific, for a network with network radius R and required node density ρ, the objective of NUND is to distribute the n ($n>\rho\pi R^2$) sensor nodes to maximize the network lifetime.

First of all, we should uniformly deploy $n_{\min}=\rho\pi R^2$ nodes to meet the minimum deployment requirements of the network. Denote $m=n-n_{\min}$, the problem changes to deploy the m nodes to maximize the network lifetime. In the previous section, we have analyzed the energy consumption and network lifetime in cluster-based WSNs where the nodes are uniformly distributed with the required node density ρ. Based on the analysis results, we detail the NUND scheme with the following theorems.

Theorem 3. *If we require the network lifetime is* T, *the maximum nodal energy consumption of the network in a data period should be* $E_T=E_0/T$, *and the node density function is*

$$\begin{cases} \rho_l = \rho, & \text{if } E_l^{avg} \le E_T \\ \rho_l = (E_l^{avg} / E_T) \cdot \rho, & \text{if } E_l^{avg} > E_T \end{cases} \tag{7}$$

Proof. Since the network lifetime is determined by the maximum nodal energy consumption, if the required network lifetime is T, the maximum nodal energy consumption in a data period should be $E_T = E_0 / T$. Therefore, if there are sensor nodes whose energy consumption in a data period is larger than E_T, we should distribute more nodes in this area to mitigate the nodal energy consumption. Since the distributed nodes are assumed to share the energy consumption equally [4, 5, 6], the distributed node density in this area should be $(E_l^{avg} / E_T) \cdot \rho$. However, the node density in the regions where the energy consumption of the sensor nodes are not larger than E_T can stay the same, since their lifetime of these nodes are larger than T.

[End]

Theorem 4. *If the required network lifetime is T, the number of sensor nodes that should be deployed is at least* $m_T = \left\lceil \int_0^R \rho_l \pi R^2 \right\rceil$.

Proof. According to the node density function in Theorem 3, the number of sensor nodes should be $m_T = \left\lceil \int_0^R \rho_l \pi R^2 \right\rceil$. Here, the symbol $\lceil \; \rceil$ is to ensure the number of sensor nodes is an integer.

[End]

According to **Theorem 3**, **Fig. 2** shows the nodal energy consumption per round in different regions of the network, where $R = 400m$, $r = 70m$ and $\rho = 0.00198$. If the required network lifetime is T, we should ensure the maximal energy consumption of the network is below $E_T = E_0 / T$. According to **Theorem 4**, **Fig. 2** shows the number of added nodes under the different E_T after meeting the required node density. The shadow area indicates the region where needs to deploy additional nodes. It is shown that a smaller E_T indicates a larger number of sensor nodes, while a smaller E_T also indicates a longer network lifetime. And **Fig. 3** shows the node density in different areas of the network under different E_T.

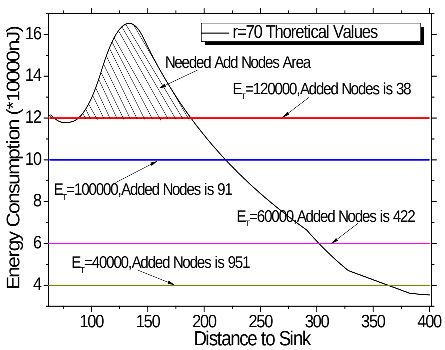


Fig. 2. The number of added nodes under various E_T

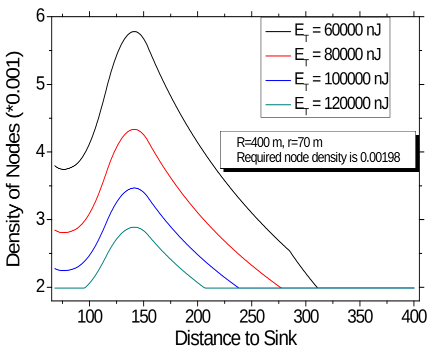


Fig. 3. Node density under various E_T

The two theorems above prove the number of sensor nodes is required to achieve a specific network lifetime. Given a fixed number of sensor nodes m, the optimal network lifetime can be achieved is proven in the following theorem.

Theorem 5. *If the number of sensor nodes is* m *(* $m \geq \rho\pi R^2$ *), the optimal network lifetime is* T_m *which makes* $m = \left\lceil \int_0^R \rho_l \pi R^2 \right\rceil$*, where*

$$\begin{cases} \rho_l = \rho, & \text{if } E_l^{avg} \leq E_0 / T_m \\ \rho_l = (T_m \cdot E_l^{avg} / E_0) \cdot \rho, & \text{if } E_l^{avg} > E_0 / T_m \end{cases}. \tag{8}$$

Proof. Given a fixed number of sensor nodes m, we should first uniformly distribute $\rho\pi R^2$ nodes to meet the coverage requirement. Denote T_m is the optimal network lifetime after we distribute the m sensor nodes. According to **Theorem 3**, we can calculate the node density of the network is

$$\begin{cases} \rho_l = \rho, & \text{if } E_l^{avg} \leq E_0 / T_m \\ \rho_l = (T_m \cdot E_l^{avg} / E_0) \cdot \rho, & \text{if } E_l^{avg} > E_0 / T_m \end{cases}.$$

And **Theorem 4** shows that the number of sensor nodes required to achieve the node density ρ_l is $\left\lceil \int_0^R \rho_l \pi R^2 \right\rceil$. Therefore, let $m = \left\lceil \int_0^R \rho_l \pi R^2 \right\rceil$, we can calculate the optimal network lifetime T_m.

[End]

According to **Theorem 5**, for a given number of sensor nodes m, we can always distribute them to achieve the optimal network lifetime. **Algorithm 1** illustrates how to obtain the maximal network lifetime T_m under a fixed number of sensor nodes m.

Algorithm 1. Determine the optimal network lifetime under a fixed number of sensor nodes

Input: Network radius R, the required node density ρ, cluster radius r, the number of sensor nodes m and other network parameters.
Output: The optimal network lifetime T_m.

1). Calculate the nodal energy consumption per round E_l^{avg} in different regions of the network according to **Theorem 1**; 2). $T_{pre} = E_0 / \min(E_l^{avg})$, $T_{last} = E_0 / \max(E_l^{avg})$; 3). According to **Theorem 3** and **4**, calculate the number of added nodes m_{pre} and m_{last} when the maximum lifetime is T_{pre} and T_{last} respectively. 4). If $m_{pre} \geq m$, then $T_m = T_{pre}$ and go to step 7); else if $m_{last} \leq m$, then $T_m = T_{last}$ and go to step 7); Otherwise, go to 5); 5). $T_{mid} = \left\lceil \frac{T_{pre} + T_{last}}{2} \right\rceil$, and calculate the number of sensor nodes m_{mid} required to achieve the network lifetime T_{mid} according to **Theorem 2**; 6). If $m_{mid} > m$, then $T_{last} = T_{mid}$ and go back to 5); If $m_{mid} < m$, then $T_{pre} = T_{mid}$ and go back to 5); Otherwise, $T_m = T_{mid}$ and go to step 7); 7). Return the maximum network lifetime T_m.

Based on **Algorithm 1**, we can determine the optimal network lifetime with a fixed number of sensor nodes. However, we find the cluster radius has a significant impact on the average energy consumption of sensor nodes and the network lifetime, according to **Theorem 1** and **2**. Therefore, if the number of sensor nodes m is fixed, we can still improve the network lifetime by determining the optimal cluster radius. Algorithm 2 illustrates how to choose the optimal cluster radius r_o under a fixed number of sensor nodes m.

Algorithm 2. Determine the optimal cluster radius under a fixed number of sensor nodes

Input: Network radius R, the required node density ρ, cluster radius r, the number of sensor nodes m and other network parameters.
Output: The optimal cluster radius r_o.
1). $LT_m = 0$; 2). For each r_j *do* 3). Determine the maximal network lifetime LT_j when the cluster radius is r_j and the number of sensor nodes is m according to **Algorithm 1**. 4). If $LT_m < LT_j$, then $LT_m = LT_j$ and $r_o = r_j$; 5). End for; 6). Return r_o.

Based on the two algorithms above, we detail the non-uniform node distribution algorithm as follows.

Algorithm 3. Non-Uniform Node Distribution Algorithm

Input: Network radius R, the required node density ρ, cluster radius r, the number of sensor nodes m and other network parameters.
Output: The optimal cluster radius r_o, the optimal network lifetime T_m, and the node density function ρ_l of the network.
1). Determine the optimal cluster radius r_o according to **Algorithm 2**; 2). Calculate the optimal network lifetime T_m with the cluster radius r_o according to **Algorithm 1**; 3). Calculate the node density function ρ_l with the cluster radius r_o and the required network lifetime T_m according to **Theorem 3**. 4). Return r_o, T_m, ρ_l.

5.2 A Special Case of the NUND scheme

In the previous subsection, we detail the non-uniform node distribution scheme. If we have enough sensor nodes (i.e., m is large enough), a balanced energy consumption of the whole network can be achieved. In this subsection, we discuss the fully balanced energy consumption of the network as a special case of the proposed NUND scheme.

Theorem 6. *To achieve balanced energy consumption, the node density function of the network* ρ_l^{all} *should be*

$$\rho_l^{all} = \frac{E_l^{avg}}{\min(E_l^{avg}) \big| l \in \{l_{\min}, R\}} \cdot \rho . \tag{9}$$

Proof. To balance the energy consumption of the network, the average energy consumption in all the areas of the network should be reduced to $\min(E_l^{avg}) \big| l \in \{l_{\min}, R\}$. Therefore, we can increase the node density of the areas whose energy consumption is higher than $\min(E_l^{avg}) \big| l \in \{l_{\min}, R\}$. Since $\min(E_l^{avg}) \big| l \in \{l_{\min}, R\}$ is the minimum nodal energy consumption of the network, we have the density function ρ_l^{all} should be

$$\rho_l^{all} = \frac{E_l^{avg}}{\min(E_l^{avg}) \big| l \in \{l_{\min}, R\}} \cdot \rho .$$

[End]

Theorem 7. *To achieve balanced energy consumption, the number of sensor nodes required to be distributed is at least*

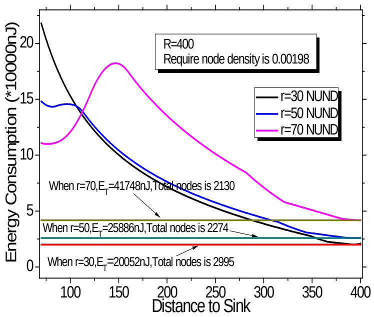
$$m_{all} = \left\lceil \int_0^R \frac{E_l^{avg}}{\min(E_l^{avg}) \big| l \in \{l_{\min}, R\}} \cdot \rho \pi R^2 \right\rceil . \tag{10}$$

Proof. According to **Theorem 4**, if we require a node density of ρ_l, the number of sensor nodes should be $m = \left\lceil \int_0^R \rho_l \pi R^2 \right\rceil$. Therefore, if the required node density is ρ_l^{all}, we have

$$m_{all} = \left[\int_0^R \rho_l^{all} \pi R^2 \right].$$

[End]

Fig. 4 shows the comparison of network lifetime and the number of sensor nodes that should be deployed to achieve fully balanced energy consumption under different cluster radii. It is shown that balanced energy consumption means setting the minimum energy consumption of the network as the energy line E_T . Compared to **Fig. 2** where E_T is a variant value, **Fig. 4** is just a special case of the NUND scheme. It is also can be seen from **Fig. 4** that the energy consumption is different under different cluster radii, so the energy line E_T and the number of required sensor nodes are different to achieve a fully balanced energy consumption. The distribution efficiency will be maximized when the cluster radius r is 50m. **Fig. 5** shows the node densities in different areas of network when achieving balanced energy consumption under different cluster radii.



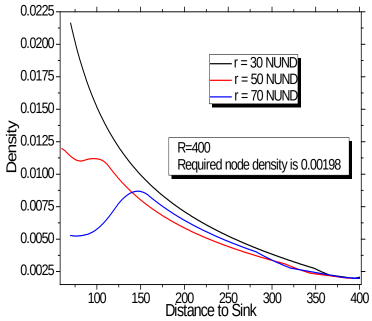


Fig. 4. Required sensor nodes under different cluster radii to achieve balanced energy consumption
Fig. 5. Node densities in different areas under different cluster radii to achieve balanced energy

6. Simulation Evaluation

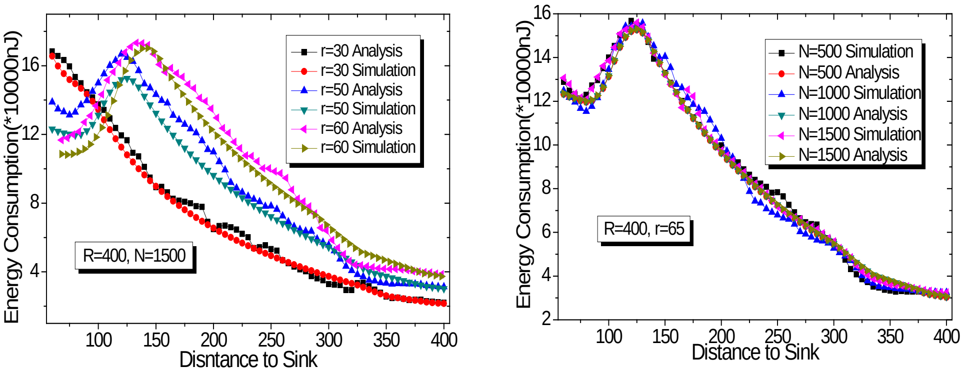
We evaluate the proposed NUND scheme in OMNET++. We setup a simulation where CHs encapsulate every 100 bits of gathering data into a packet and then send the data packets to the sink during the inter-cluster transmission. If there are no special explanations for parameters, all the simulation parameters are adopted from **Table 1** and **Table 2**. We compare the proposed NUND scheme with the Uniform Node Distribution (UND) scheme.

Table 2. Network Parameters for Simulations

Parameter	Value
Aggregation rate ϕ	75%
Network Radius R	400 m
Required Node Density ρ	0.00198
Length of the *Clustering* packet	10 bits
Length of the *Joining* packet	20 bits
Length of the *Timeslot* packet	50 bits
Length of the *Data* packet	100 bits

6.1 Energy Consumption Evaluation

In this subsection, we evaluate our theoretical analysis on the energy consumption of the cluster-based WSN. **Fig. 6(a)** shows the average energy consumption per round under various cluster radius, where the network radius $R = 400m$ and the number of sensor nodes $N = 1500$. **Fig. 6(b)** shows the average energy consumption per round under different node densities. It is shown that our theoretical analysis is consistent with the simulation results. And it can be seen from Fig. 10 that the average energy consumption is not impacted by the increment of the node density when the sensor nodes are distributed uniformly.



(a) **(b)**

Fig. 6. (a) Energy consumption per round under different cluster radii; **(b)** Energy consumption per round under different node densities.

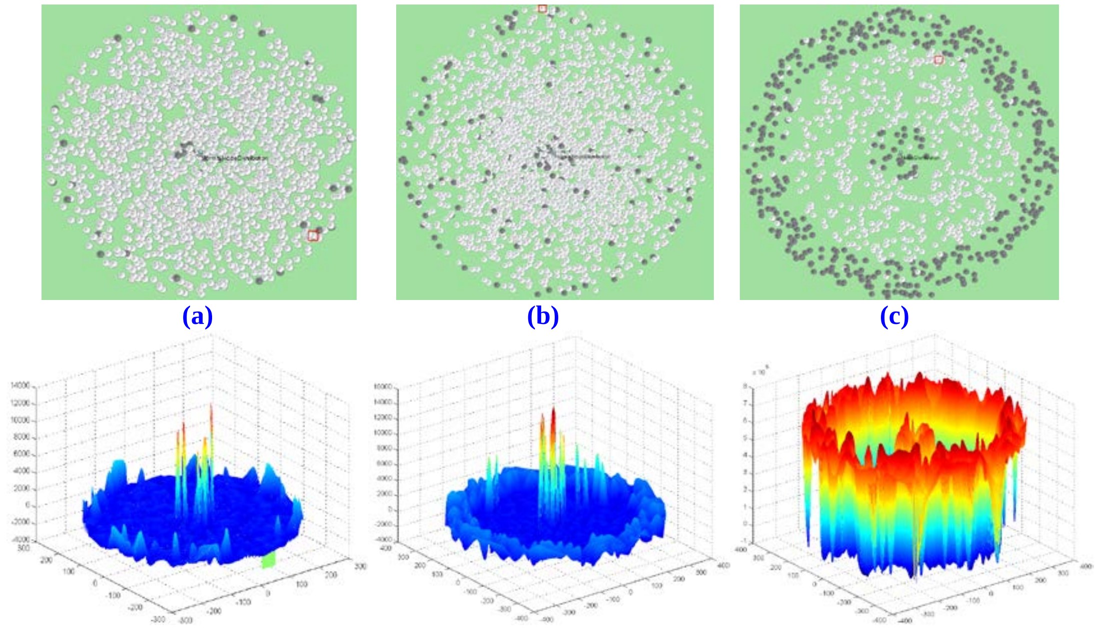
6.2 Balanced Energy Consumption of NUND

Since the balanced energy consumption of the network is a special case of NUND, we evaluate the idea network lifetime and energy efficiency of NUND in this subsection. According to **Theorem 3**, the average energy consumption in different areas of the network should be reduced to $E_T = \min(E_l^{avg})$, then we can get the optimal lifetime $T_m = E_0 / \min(E_l^{avg})$.

6.2.1 Energy Consumption

We compare the nodal energy consumption of NUND and UND. The experiment data of this section is generated as follows. Distribute the sensor nodes according to these two deployment strategies, and then record the energy consumption until the sink cannot receive any data.

Fig. 7(a) and **Fig. 7(b)** show the status of each sensor node in NUND when the network dies under $R = 300m$ and $R = 400m$ respectively. **Fig. 7(c)** shows the status of each sensor node in UND when the network dies. In the three figures, the white nodes are the dead nodes and the black ones are those still alive. Correspondingly, **Fig. 7(d)**, **Fig. 7(e)** and **Fig. 7(f)** show the residual energy of each node when the network dies. From **Fig. 7(c) and 7(f)**, it can be easily seen that there is a huge amount of energy left in UND, since the energy consumption of the hotspot is greatly larger than the other regions. Reversely, **Fig. 7(d)** and **7(e)** show that the residual energy in NUND is approximately zero, which indicates the perfect energy efficiency of NUND.



(a) (b) (c)

(d) (e) (f)

Fig. 7. When the network dies, **(a)** Nodal status in NUND (R=300m, r=80m); **(b)** Nodal status in NUND (R=400m, r=80m); **(c)** Nodal status in UND (R=400m, r=80m); **(d)** Nodal residual energy in NUND (R=300m, r=80m); **(e)** Nodal residual energy in NUND (R=400m, r=80m); **(f)** Nodal residual energy in UND (R=400m, r=80m).

6.2.2 Network lifetime and residual energy

Fig. 8(a) shows the number of data packets received by the sink in different data periods. It is shown that the number of data packets received by the sink stays stable during a long time and plummet to zero only after several data periods. **Fig. 8(b)** shows the total energy consumption of all the sensor nodes in different data periods. Similar with **Fig. 8(a)**, the energy consumption experiences minor fluctuations during a long time and plummet to zero after several data period. It indicates all sensor nodes completely exhaust their energy simultaneously. **Fig. 8(c)** shows the number of dead nodes in different data periods. **Fig. 8(d)** shows the number of dead nodes in different data periods under UND. It can be seen that sensor nodes die gradually until the network dies. Therefore, it can be seen from **Fig. 10** that the energy consumption of all the sensor nodes is balanced in NUND, which leads to a perfect energy efficiency. While the sensor nodes gradually die in NUD causing poor network efficiency.

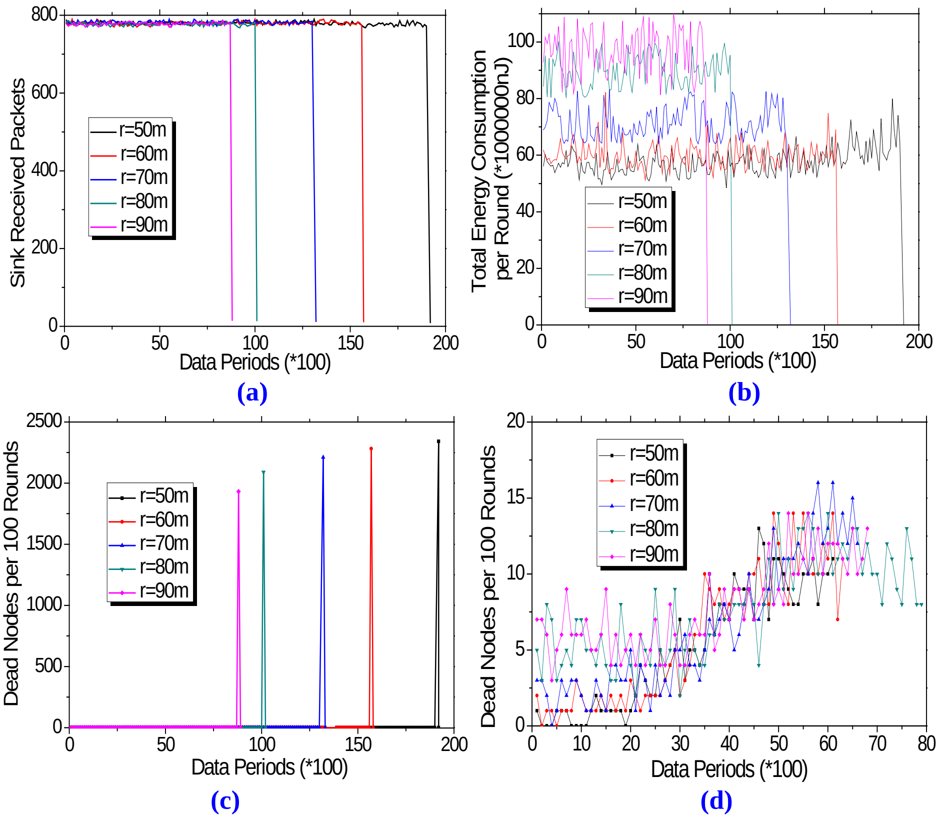


Fig. 8. (a) Data packets received by the sink in different data periods (NUND); **(b)** Total energy consumption of the network in different data periods (NUND); **(c)** Dead nodes in different data periods (NUND); **(d)** Dead nodes in different data periods (UND).

Fig. 9(a) shows the comparison of the number of sensor nodes required to achieve the balanced energy consumption under different cluster radii and network radii. As shown in the figure, the number of required sensor nodes grows linearly with the increase of network radius when the cluster radius is fixed. However, when the network radius is fixed, the number of required sensor nodes decreases with the increasing cluster radius. This is because the cluster radius directly impacts the average energy consumption of the sensor nodes. Meanwhile, if we aim to balance the energy consumption to achieve a longer network lifetime, the number of required sensor nodes would be larger. However, we still can find the optimal cluster radius to maximize the distribution efficiency.

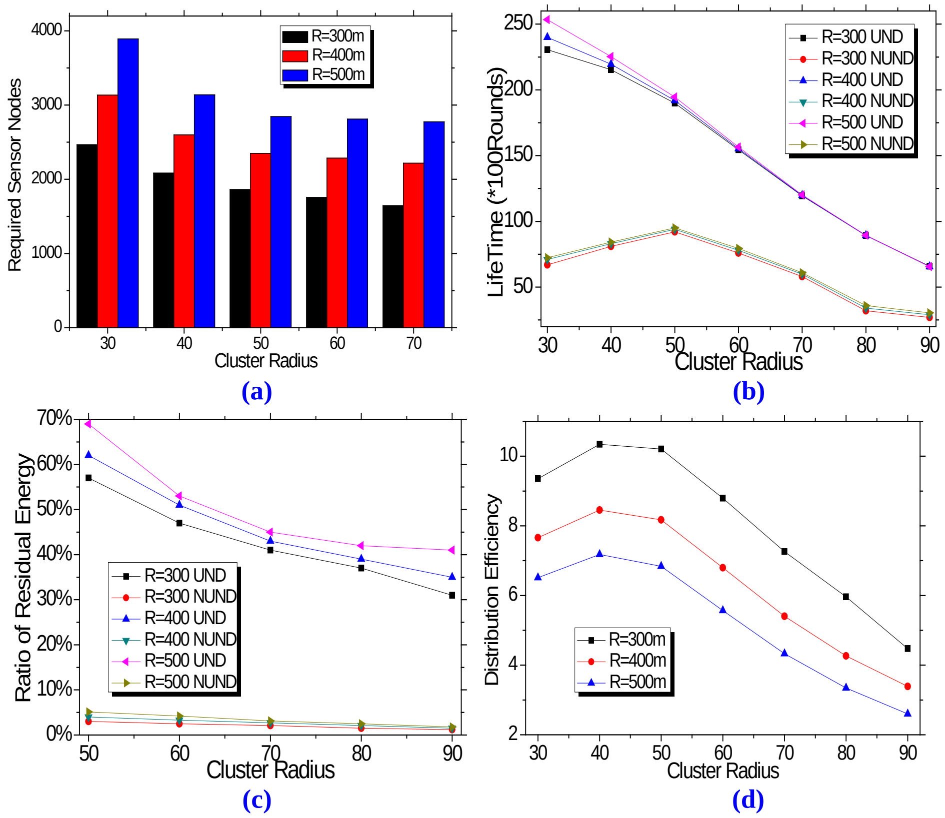


Fig. 9. **(a)** Required sensor nodes for balanced energy consumption (NUND); **(b)** Network Lifetime under different cluster radii (NUND); **(c)** Residual energy ratio under different cluster radii (NUND); **(d)** Distribution efficiency under different cluster radii (NUND).

Fig. 9(b) and 9(c) shows the network lifetime and residual energy comparison in NUND and UND under different cluster radii. It can be seen from **Fig. 9(b)**, the network lifetime in NUND is obviously longer than in UND, and under some cluster radii, the improvement ratio is nearly 100%. **Fig. 9(c)** shows that, the residual energy ratio decrease with the increasing cluster radius both in NUND and UND, but the residual energy ratio in NUND is much less than in UND. This is because, in our network model, the transmission range of inter-cluster communication rises with the increasing cluster radius, which directly impacts the residual energy ratio of the network. A larger cluster radius causes fewer nodes isolated in the network, and a lower residual energy ratio of the network.

Fig. 9(d) shows the network efficiency of NUND under different cluster radii. It is shown that a smaller network would achieve higher network efficiency when the cluster radius is fixed. But when the network radius is a fixed number, the network efficiency increases first and then decreases. The peak value is achieved at between 40m and 50m. Therefore, it also indicates that we can find the optimal cluster radius to achieve the highest network efficiency.

6.2.3 The impact of the required node density on network performance

In this subsection, we aim to evaluate the impact of the required node density on the network performance. **Fig. 10(a)** shows the comparison of data packets received by the sink under different node density. Obviously, if the required node density were larger, the number of data packets received by the sink would become larger since the number of sensor nodes is increased. **Fig. 10(b)** shows the nodal average energy consumption comparison under different required node densities. It is shown that the average energy consumption stays stable when the node density increases. Since the network lifetime depends on the average energy consumption, it indicates the network lifetime would not be impacted by the increment of the node density when the nodes are uniformly distributed in the network.

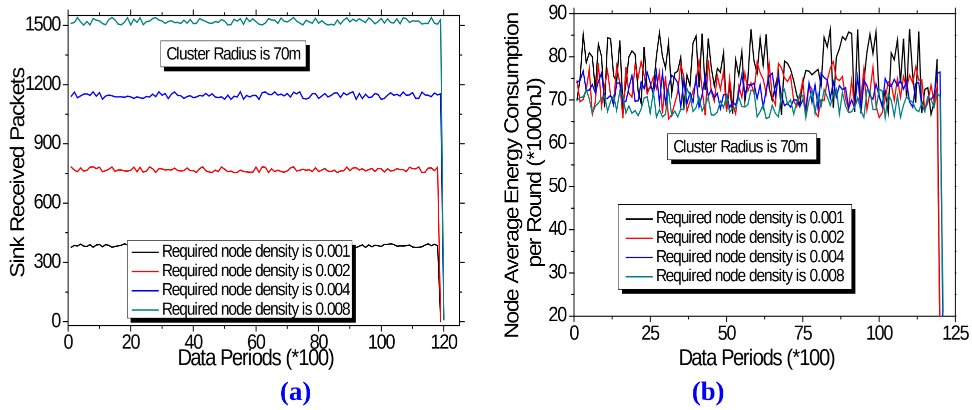


Fig. 10. (a) Data packets received by the sink in different data periods (NUND); **(b)** Average energy consumption in different data periods (NUND).

6.3 NUND with Limited Sensor Nodes

In this section, we evaluate the performance of the NUND with a fixed number of sensor nodes. According to **Theorem 5**, for m sensor nodes, we can always obtain the optimal network lifetime T_m in NUND strategy. And, for any network lifetime T, the maximum nodal energy consumption in a data period should be $E_T = E_0 / T$, which is also called *energy line*. Therefore, the simulations in this section are based on different energy consumption lines to analyze the performance of NUND.

Fig. 11(a) shows the node densities of different areas in the network under different energy lines. It is shown that when the number of sensor nodes is limited, the sensor nodes should be first distributed to the areas with highest average energy consumption, which is also called as hotspot. And the node density increases with the decline of the energy line. **Fig. 11(b)** shows the network lifetime comparison under different energy lines. Since the lower energy line means the larger number of sensor nodes, it can be seen from the figure that the network lifetime increases with the decreasing energy lines.

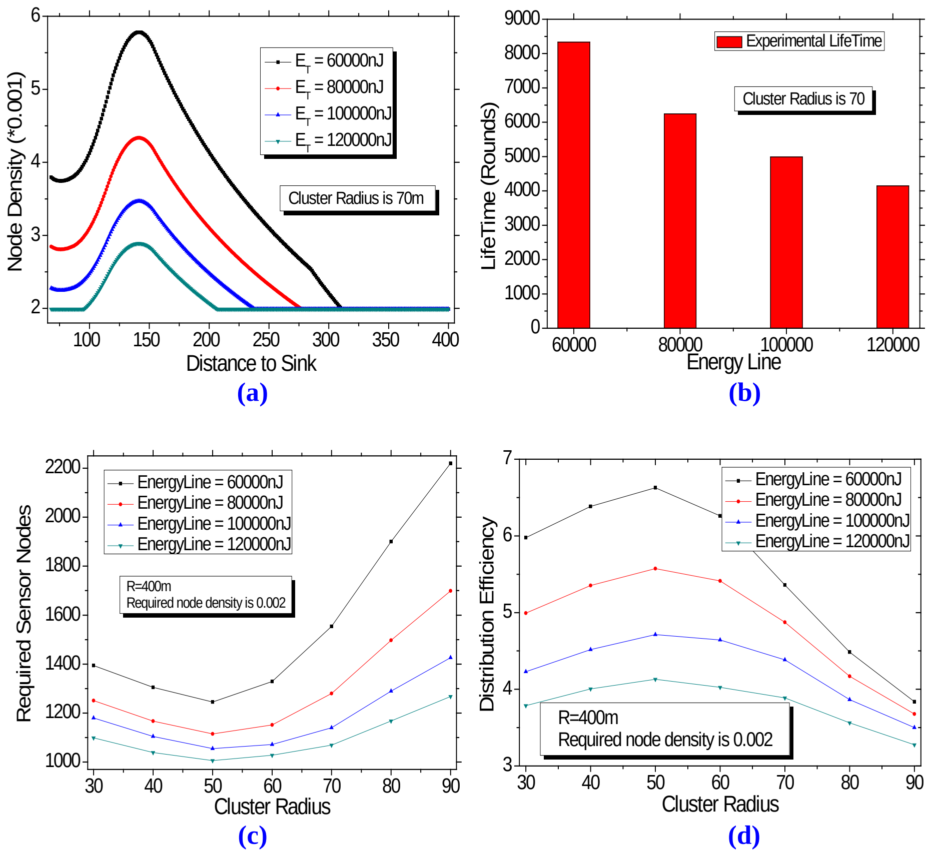


Fig. 11. (a) Node density under different energy lines; **(b)** Network lifetime under different energy lines; **(c)** Required sensor nodes under different energy lines and cluster radii; **(d)** Distribution efficiency under different energy lines and cluster radii.

Fig. 11(c) shows the required sensor nodes comparison under different energy lines in NUND. It is shown that the number of required sensor nodes increases with the decreasing energy line when the cluster radius is fixed. However, if the energy line is fixed, the number of required sensor nodes increases first and then decreases. The peak value is achieved when the cluster radius is 50m. **Fig. 11(d)** shows the distribution efficiency comparison under different energy lines and cluster radii. Similar with the **Fig. 11(c)**, the optimal network efficiency is achieved at the cluster radius of 50m, when the energy line is fixed. Meanwhile, the distribution efficiency increases with the decline of the energy line. It indicates that the more sensor nodes would lead to better distribution efficiency before we achieve balanced energy consumption in the network, while the distribution efficiency can be maximized by choosing the optimal cluster radius.

7. Conclusion

In this paper, we have proposed a Non-Uniform Node Distribution (NUND) scheme to improve the energy efficiency and network lifetime under a fixed number of sensor nodes in cluster-based WSNs. To identify the hotspot of the network, we propose an analytic model to analyze the energy consumption and network lifetime of the cluster-based WSNs. Since the analysis results show the cluster radius causes a significant impact on the network lifetime, we present an algorithm to determine the optimal cluster radius. Further, we propose a non-uniform node distribution algorithm to distribute the fixed number of sensor nodes to maximize the network lifetime. Extensive simulations demonstrate the proposed analytic model can accurately predict the energy consumption and network lifetime, and the NUND significantly improve the energy efficiency and network lifetime. In our future work, we will focus on the node distribution in energy harvesting WSNs. Since sensor nodes are supplied by the stochastic renewable energy, the node distribution will be complicated due to the change of the energy consumption characteristics.

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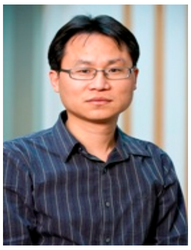

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