Minimize Residual Energy of the 3-D Underwater Sensor Networks with Non-uniform Node Distribution to Prolong the Network Lifetime

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Abstract. Underwater sensor networks (UWSNs) have caused widespread concern of academia due to their wide range of applications. Efficient energy depletion and avoiding energy holes are the important issues. In this paper, we study on the theoretical aspects of the non-uniform node distribution strategy in the 3-D underwater environment, which aim to mitigate the energy holes and balance energy depletion of nodes in the 3-D underwater sensor networks. Based on extensive analysis and theoretical proofs, the absolute balanced energy depletion in the whole underwater sensor networks is not achievable, while the maximized balanced energy depletion except for the nodes in the outermost *AGR* (Annular Globular Region) is possible. Furthermore, we propose a non-uniform distribution routing algorithm based the minimum energy consumption called MEC to address the energy hole problems and prolong the network lifetime. Extensive simulations show that the network achieves a high energy efficiency, less than 5% of total initial energy is wasted and the network lifetime is prolonged more than 400% compared with the uniform node distribution strategy.

Keywords: Underwater sensor networks · Energy holes
Minimize residual energy · Non-uniform node distribution
Load balancing

1 Introduction

As the application extension of the traditional terrestrial wireless sensor networks, the underwater sensor networks (UWSNs) enable application for underwater data collection, ocean sampling and assisted navigation. Due to the complicated underwater environment and node energy constraint, it is difficult to obtain a perfect deployment strategy which ensures high energy efficiency, long network lifetime, strong connectivity and low costs of whole networks.

In the UWSNs, energy constraint is a big challenge. The traffic scheme is many-to-one, and the nodes nearer to the sink will forward more data than

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the nodes far away from the sink. Therefore, the nodes near to the sink will consume more energy, even die because of using up their initial energy. At the same time, an energy hole occurs around the sink. Many existing works focus on planar networks [1–4], while those deployment schemes and algorithms are very difficult to directly apply to 3-D underwater situations [5–8]. Intuitively, the 3-D networks are more suitable for real-life situations.

Olariu et al. [4] first prove that the energy hole is unavoidable under some situations in traditional circular terrestrial region WSNs. In a circular area, Wu et al. [1,2] prove completely balanced energy consumption among all nodes is impossible. Akbar et al. [5] use a mobile sink node i.e., AUV, in each sub rectangular cuboid region. Although they can achieve energy efficiency and avoid energy hole in some cases, however, the AUVs will spend much extra money and deplete much energy on controlling the moving trajectory.

In this paper, we explore the energy hole problem by means of theoretical analysis and mathematical models in the UWSNs with the non-uniform node distribution strategy. Firstly, we divide the spherical region into different annular globular regions ($AGRs$, as shown in Fig. 1). Secondly, we analyze and prove that the absolute balanced energy depletion (ABED) is not achievable among all nodes which are equipped the same initial energy. Then, the maximum balanced energy depletion (MBED) is possible among all nodes with non-uniform deployment in the UWSNs through theoretical analysis. Finally, we carry out extensive simulations to evaluate the performance of the proposed non-uniform distribution strategy and the proposed routing algorithm.

The main contributions of this paper can be summarized as follows. We theoretically prove that the absolute balanced energy depletion in the whole UWSN is not achievable, while the maximized balanced energy depletion except for the nodes in the outermost AGR_K is possible. The proposed the non-uniform node distribution strategy of the 3-D UWSNs can achieve high energy efficiency and prolong the network lifetime. We carry out extensive simulation experiments to evaluate the performance of the proposed schema. The simulation results show that the proposed schema achieve a high energy efficiency and less than 5% of total initial energy is wasted. Moreover, the network lifetime can be prolonged more than 400% compared with the uniform node distribution strategy.

The remainder of this paper is organized as follows. In Sect. 2, related work will be presented. Assumptions and network models will be introduced in Sect. 3. Theoretical analysis and the proposed routing algorithm are illustrated in Sect. 4. Section 5 presents the simulation results of the proposed non-uniform node distribution strategy. Finally, we conclude this paper in Sect. 6.

2 Related Work

Pal et al. [10] propose a centralized cluster head selection scheme based on genetic algorithm. The proposed scheme aims at selecting an optimal cluster head in different clusters according to their residual energy and taking trade-off of inter- and intra-cluster communication distance into account. Different from [9], the proposed scheme in [10] takes trade-off of inter- and intra-cluster communication distance into account for optimizing cluster heads instead of just considering the Eulerian distance between each nodes like in [9]. Therefore, they can achieve better balanced energy depletion in the WSNs. The proposed method in [11] addresses the energy depletion problem via introducing various states of a node such as sleep, idle, start-up and busy for conserving energy as much as possible. They utilize a randomized N-policy queuing model to derive the probabilities of various states, not similar to [12], in which the switch of different states just depends on a fixed time threshold, i.e., when a specific time is used up, the state of the node will change immediately.

Wang et al. [13] take node mobility and density of water into account and proposed EGRCs scheme that can select optimal cluster heads considering residual energy and locations of sensor nodes. The proposed algorithm also decides the next-hop by combining residual energy, locations and end-to-end delay.

Khan et al. [14] utilize an AUV as a mobile sink to collect data from cluster heads and propose a distributed data-gathering scheme. The proposed scheme can control the topological changes in a small range. Hence, it can avoid energy hole phenomenon and balance energy depletion to some extent. Chen et al. [12] propose a mobile geocast routing to tackle the energy unbalanced problem in the underwater environment by introducing the sleep/active modes, thus the proposed protocol minimizes the energy depletion of the sensor nodes.

3 Assumptions, Definitions and Network Model

We assume that all nodes are distributed in a spherical region with spherical center O and radius R. The unique special relay node (SRN) is located at the center of the spherical region, which is shown in Figs. 1 and 2. All sensors have an unique ID number used to identify them and its transmission radius is $r(r \ll R)$. Note that we ignore the size of nodes. We divide the spherical region into K adjacent annular globular regions ($AGRs$) with the same width of $\frac{R}{K}$, where K is the number of $AGRs$. We denote the $i-th$ annular globular region as AGR_i and nodes are uniformly deployed in AGR_i with the density $\rho_i(\rho_{i-1} \neq \rho_i, 2 \leq i \leq K)$. As shown in Fig. 1, the darker AGR shows a higher node density. The upper radius R_U and lower radius R_L are $\frac{R}{K}i$ and $\frac{R}{K}(i+1)$, respectively. We assume that each node sends data at a certain rate H which means a sensor node generates and sends H bits of data per unit time. We assume that ε energy will be depleted when a node transmits or receives a bit of data. Similar to [1,2], we assume that there is no data aggregation at any forwarding nodes and the initial energy of each node is E_{init}. Due to the need to forward data collected by other nodes to the sink on surface of the water, we assume the SRN has no energy limitation. Furthermore, we assume that a node consumes different energy when sending and receiving a bit of data. For simplicity, e_t and e_r units of energy will be depleted respectively when sending and receiving a bit of data. We assume that e_t, e_r are constant and satisfy the limitation $e_t > e_r > 0$.

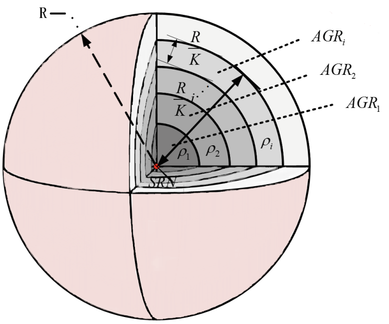


Fig. 1. A spherical region consisting with multiple annular globular regions ($AGRs$).

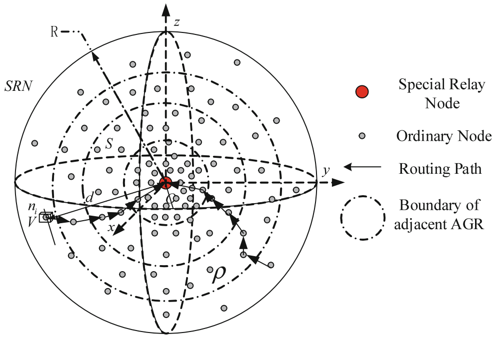


Fig. 2. Network model in a spherical region with non-uniform node distribution strategy.

4 Theoretical Analysis and Routing Strategy of Non-uniform Node Distribution

A. The Energy Depletion Model of Non-uniform Node Distribution

We define the load of node n as $load_n$ which presents the energy that node n consumes because of sending and receiving data. The average load of node n is $\overline{load_n}$ which presents an average load over both a time period and a subset of nodes within the transmission range of n. Obviously, the $\overline{load_n}$ is distance-variant.

Motivated by [3], we discuss the energy load of a node. Given a node n_i that is at distance d from the SRN, as shown in Fig. 1. The geographic average load taken by this node is in proportion to $\frac{V_1\rho_i+V_2\rho^*}{V_1\rho_i}$.

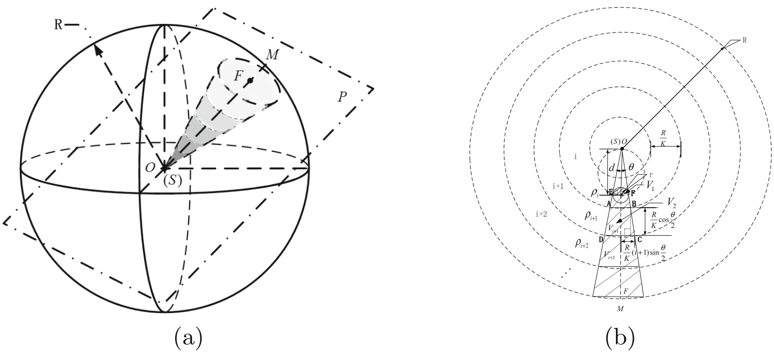


Fig. 3. Non-uniform node distribution in a spherical region. (b) is sectional view of (a) by plane P.

Intuitively, all the traffic routing from both region V_1 and V_2 have to through nodes in region V_1 shown in Fig. 3(b). The average energy that a node in region V_2 consumes to forward the data to the SRN can be calculated as the intensity pressure:

$$\overline{load}_{in_i} = \frac{V_1\rho_i + V_2\rho^*}{V_1\rho_i} H\varepsilon \tag{1}$$

where $V_1\rho_i = \frac{1}{2} \cdot \frac{4}{3}\pi r^3 \rho_i = \frac{2}{3}\pi r^3 \rho_i$, $V_2 = V_{i+1} + V_{i+2} + \cdots + V_K + V_{ABFE}$, $\rho^* = \{\rho_j\}, j = i+1, \ldots, K$. For the sake of simplicity, we approximately regard the region V_i as a circular truncated cone. The simple calculation process of $\overline{load}_{in_i}$ as follows, when $d > r$:

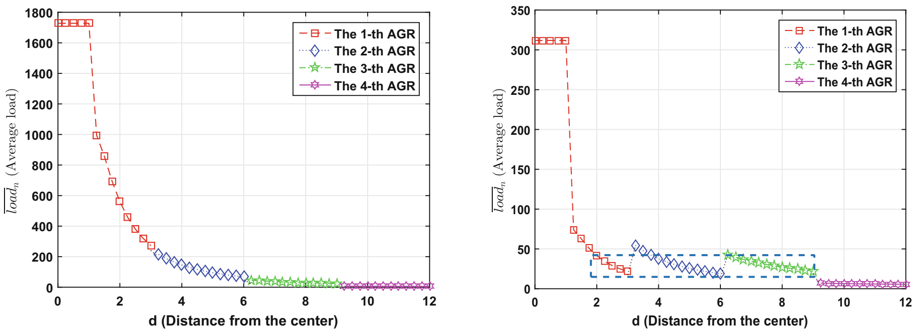
$$\begin{aligned} V_2\rho^* \approx \tfrac{1}{3}\pi \tfrac{R}{K} cos\tfrac{\theta}{2}\Big((\tfrac{R}{K})^2 sin^2\tfrac{\theta}{2} \cdot \textstyle\sum_{j=i+1}^{K} [(j-1)^2 + j^2 + (j-1)j]\rho_j \\ +[(\tfrac{R}{K} isin\tfrac{\theta}{2})^2 + r^2 + \tfrac{R}{K} irsin\tfrac{\theta}{2}]\rho_i \Big) \end{aligned} \tag{2}$$

Applying Eq. (2), the Eq. (1) can be rewritten as:

$$\overline{load}_{in_i} \approx \begin{cases} \frac{\frac{R}{K} cos\frac{\theta}{2}((\frac{R}{K})^2 sin^2\frac{\theta}{2} \cdot \sum_{j=i+1}^{K}[(j-1)^2+j^2+(j-1)j]\rho_j + [(\frac{R}{K} isin\frac{\theta}{2})^2 + r^2 + \frac{R}{K} irsin\frac{\theta}{2}]\rho_i) H\varepsilon}{2r^3\rho_i} + 1, & d > r, \\ (\frac{R}{K})^3 \cdot \sum_{i=1}^{K}[i^3 - (i-1)^3]\rho_i H\varepsilon, & d \le r \end{cases} \tag{3}$$

where $\theta = 2arcsin(r/d)$. Figure 4(a) presents the average load of a sensor node. With the distance increasing between the node and the SRN, the average of load of a node decreases sharply. It illustrates that the nodes near to the SRN will use up their initial energy quickly.

Figure 4(b) illustrates that the load of nodes in the outermost AGR_K is never equal to the load of nodes in the inner $AGRs$, even though there are different densities in different $AGRs$. However, we can observe that there exist different



(a) (b)

Fig. 4. (a) Load distribution with a stationary SRN at the place of the center of sphere. We assume $R = 12$, $K = 4$, $r = 1$, $H = 1$, $\varepsilon = 1$ and $\rho_1 = \rho_2 = \rho_3 = \rho_4$; (b) Except for $\rho_1 \neq \rho_2 \neq \rho_3 \neq \rho_4$, the other parameters are same to (a).

densities in inner $AGRs$ except for the outermost AGR_K that make their load balanced (see the dotted area in Fig. 4(b)). In other words, the ABED is not achievable and the MBED is possible.

B. Energy Depletion Analysis of Non-uniform Node Distribution

Let N_i present the number of nodes in the AGR_i and E_i present the energy consumed per unit time by the nodes in the AGR_i. $H[e_t + (bw)^2]$ presents the consumed energy per unit time with the distance bw, where b is coefficient of energy depletion; w is the width of two adjacent $AGRs$. The parameters K, e_t and e_r are defined in Sect. 3.

According to the above assumptions, the energy of the outermost AGR_K consumed per unit time can be computed as:

$$E_K = N_K H[e_t + (bw)^2]$$

Note that the nodes in the outermost only need to forward data collected by themselves. The nodes in other $AGRs$ have to forward both the data generated by themselves and the data generated by nodes near to them. The energy consumed in the AGR_i can be computed as:

$$E_i = H\big(\sum_{j=i+1}^{K} N_j(e_t + (bw)^2 + e_r) + N_i[e_t + (bw)^2]\big) \tag{4}$$

Thus, we can merge E_i as follows:

$$E_i = \begin{cases} N_K H[e_t + (bw)^2], & i = K, \\ H\Big(\sum_{j=i+1}^{K} N_j(e_t + (bw)^2 + e_r) + N_i[e_t + (bw)^2]\Big), & 1 \le i \le K-1 \end{cases} \tag{5}$$

C. Impossibility of the Absolute Balanced Energy Depletion

Intuitionally, the network lifetime and the energy efficiency are maximized when all nodes in the network use up their initial energy simultaneously. It can be formalized as follows:

$$\frac{N_1 E_{init}}{E_1} = \frac{N_2 E_{init}}{E_2} = \cdots = \frac{N_{K-1} E_{init}}{E_{K-1}} = \frac{N_K E_{init}}{E_K} \tag{6}$$

Claim 1: *An absolute balanced energy depletion is impossible.*

Proof. Similar to [3,6], we use rebuttal to prove. Suppose $\frac{N_{K-1}E_{init}}{E_{K-1}} = \frac{N_K E_{init}}{E_K}$ holds. Combining Eq. (5), we can get the following formula:

$$\begin{aligned} & N_{K-1} E_{init} N_K H[e_t + (bw)^2] \\ & = N_K E_{init} H\Big(\sum_{j=i+1}^{K} N_j[e_t + (bw)^2 + e_r] + N_{K-1}[e_t + (bw)^2]\Big) \end{aligned} \tag{7}$$

After simplifying Eq. (7), we can get the following equation:

$$N_K[e_t + (bw)^2 + e_r] = 0 \tag{8}$$

Obviously, the Eq. (8) is impossible, i.e., the assumption is impossible, thus the Eq. (6) is impossible. The ABED is never achieved. □

D. The Maximized Balanced Energy Depletion

In the last part, we have proved the impossibility of ABED, but except for nodes in the outermost AGR_K, there exists a maximized balanced energy depletion in other $AGRs$, in which nodes can use up their initial energy at the same time.

Claim 2: *The Maximized Balanced Energy Depletion is achievable, i.e., the system can achieve a maximum energy efficiency among all AGRs except for the outermost AGR_K.*

Proof. Suppose the following equation holds.

$$\frac{N_i E_{init}}{E_i} = \frac{N_{i+1} E_{init}}{E_i}, 1 \leq i \leq K-2 \tag{9}$$

Combining Eq. (5) and after simplification and basic transformations, we can rewrite Eq. (9) as:

$$\frac{N_i}{N_{i+1}} = \frac{\sum_{j=i+1}^{K} N_j}{\sum_{j=i+2}^{K} N_j}, 1 \leq i \leq K-2 \tag{10}$$

We denote N as the total number of nodes in the whole network, i.e., $N = \sum_{j=1}^{K} N_j$. By *Equal Ratios Theorem*, we get the following equation:

$$\frac{N_i}{N_{i+1}} = \frac{N_{i-1}}{N_i}, 2 \leq i \leq K-2 \tag{11}$$

Thus, if we satisfy the Eq. (11), the Eq. (9) can hold. In other words, if we make $\frac{N_i}{N_{i+1}} = q, 1 \leq i \leq K-2$ satisfied, the Maximized Balanced Energy Depletion is achieved. Where q is a proportional constant. □

E. Routing Strategy With Non-uniform Node Distribution

In this part, we introduce the non-uniform distribution routing algorithm called MEC (Minimum Energy Consumption). Different from [1,2], the proposed MEC not only considers the distance between two nodes but also considers the all neighbor nodes near to the node, which can allow each node to make full use of their initial energy.

The proposed MEC is based on the previous sections. Before the all nodes are deployed, we first calculate the coordinate of each node according to the proportional constant q and ensure that any node has at least q relay nodes in its upstream AGR. Thus, we can derive a set of upstream neighbor nodes (upList) and a set of neighbor nodes (neiList). To reduce energy consumption, a node should select one optimal relay node in upList or neiList according to the maximum residual energy and the distance between them. The pseudo-code of the proposed routing algorithm is presented in Algorithm 1.

Algorithm 1. Routing strategy with non-uniform node distribution

The function of the proposed algorithm: Data are forwarded by node i
Input: Net: consists of many nodes marked with unique ID
N = Net[i] // N represents the i-th node in the Net
if IsNotEmpty(N.upList) **then**
  K = SelectNextNodeWithMinConsumedEnergy (N, N.upList)
else if IsNotEmpty(N.neiList) **then**
  K = SelectNextNodeWithMinConsumedEnergy (N, N.neiList)
else
  DiscardMsg
end if
SendDataTo(K)
UpdateResidualEnergy (N, K)
UpdateNetWork (Net)

5 Simulations Evaluation

In this Section, we evaluate the performance of the non-uniform node distribution with the proposed routing algorithm. We assume a perfect MAC layer to ensure wireless channel communication, as in [2,15,16]. The experimental parameters are listed in Table 1. Note that all the simulation results of our simulation experiments are averaged over 1000 independent runs.

Table 1. Experimental parameters

Parameter	Value
Initial energy of each node (E_{init})	500 units
System constant (e_t)	7.510^3 unit
Receiving energy cost (e_r)	510^3 unit
Energy depletion coefficient (b)	1
Unit time	60 s
The amount of data sent per second (H)	10 units
Proportional constant (q)	2, 3
Transmission range (r)	1, 2
Radius of the spherical region R	5–12

A. Residual Energy of Each Node

We deploy 2000 nodes in a spherical region with a radius 8. The transmission range of each node is 2, and the proportional constant is 3. There are 50, 150, 450, 1350 nodes in AGR_4, AGR_3, AGR_2 and AGR_1 respectively. Figure 5 shows the residual energy of each node when the network lifetime ends. Nodes with a smaller ID numbers means near to the SRN while those with large ID number belong to the outer AGR_4. The four fragments of lines are not straight lines but have tiny fluctuations.

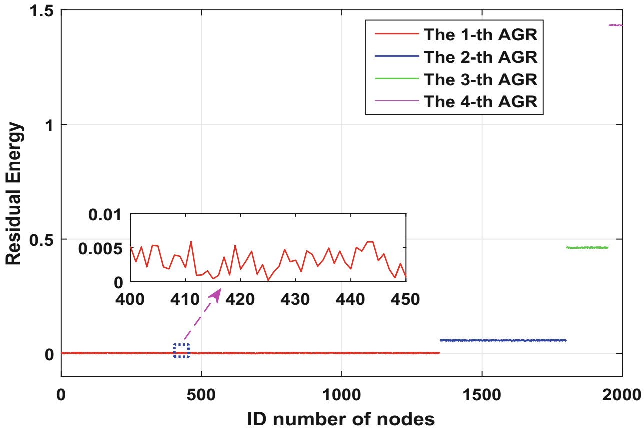


Fig. 5. Residual energy of each node when the network lifetime ends, where $N = 2000$, $q = 3$ and $K = 4$.

We notice that the nodes near to the SRN nearly use up their initial energy while the nodes in outermost AGR_K have much residual energy. This phenomenon is in line with our previous analysis. The reason for this phenomenon is that the nodes near to the SRN need to transmit both the data collected by themselves and the data forwarded by nodes in downstream, which makes their energy burn up quickly. Whereas, the nodes in the outermost AGR_K only need to transmit the data collected by themselves.

B. Residual Energy Ratio

When the network lifetime ends, the residual energy can be computed as:

$$E_{res} = \sum_{i=1}^{K} \sum_{j=1}^{N_i} (E_{init} - E_{ij}) \tag{12}$$

where E_{init} presents the initial energy of each node, and E_{ij} donates the $j - th$ node in the $i - th\ AGR$. The total number of the network is given as:

$$N = \frac{N_K(q^K - 1)}{q - 1}, q > 1 \tag{13}$$

Thus, the residual energy ratio is

$$\lambda = \frac{E_{res}}{NE_{init}} = \frac{(q-1)\sum_{i=1}^{K}\sum_{j=1}^{N_i}(E_{init} - E_{ij})}{N_K E_{init}(q^K - 1)} \tag{14}$$

As shown in Fig. 6, the residual energy ratio decreases rapidly when the radius is less than 6, but there is slow change when the radius exceeds 7. With the growth of the network radius, the tendency of residual energy ratios in different proportional constants can match well, even though the differences are relatively large at the beginning. We explain the differences in two aspects. On the one hand, when the radius is same, the number of nodes in the network with $q = 3$ are more than the nodes in the network with $q = 2$. The larger the number of nodes is, the better the connectivity is in the network. When a node nearly uses up its initial energy, its neighbor node with high residual energy will replace it. On the other hand, when the radius is more than 7, the total number of nodes in network are too enough so that small residual energy is divided by a large total energy to get a relatively small value. Thus, the tendency of residual energy ratios in different proportional constants can match well when the radius is more than 7. Nonetheless, the ratios of residual energy are all below 1.4%, even with a small proportional constant achieving higher energy efficiency.

Note that the simulation experiments above are carried out under the condition of $w = r$, i.e., the width of AGR is equal to the transmission range of a node. The next simulation, we relax this constraint. Figure 7 illustrates the residual energy ratio under different widths of AGR and different proportional constants. We obverse that the ratios of residual energy decrease greatly at the beginning but decrease slowly (for example, $K = 3$, $q = 3$; $K = 4$, $q = 3$) or increase slowly (for example, $K = 3$, $q = 2$) when the radius of network exceeds a threshold. Comparing with Fig. 6, under the premise of same radius, the residual energy ratios in Fig. 6 are all less than those in Fig. 7. Thus, we can draw the conclusion that the best strategy is to design all the $AGRs$ to be of the same width and the best width of AGR is equal to r. We explain why the residual energy ratios will increase slowly when the radius of network exceeds a threshold under the premise of $K = 3$, $q = 2$. On the one hand, when the radius exceeds a threshold (9 or 10), the volume of the outermost AGR_K becomes larger and larger with the radius increasing. On the other hand, the number of nodes in the outermost AGR_K is fixed, and the connectivity of the outermost AGR_K begins to decrease. Those eventually leads to an increase in residual energy ratio.

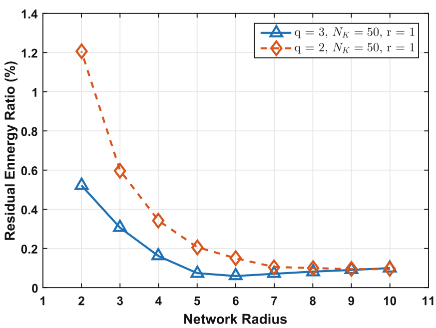


Fig. 6. Residual energy ratio with different radius and proportional constants, where $N_K = 50$ and $r = 1$.

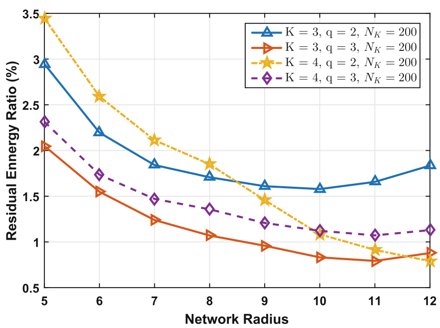


Fig. 7. Residual energy ratio under different widths of AGR, where $K = 3, 4$, $q = 2, 3$, $N_K = 200$ and $r = 1$.

C. Comparison with Uniform Node Distribution

In this part, we perform simulations to compare the proposed strategy with the uniform node distribution strategy in the two aspects: (1) the residual energy ratios and (2) the network lifetime. *Uniform Node Distribution*, where nodes are deployed at any place with equal probability, and different from non-uniform node distribution strategy, the number of nodes in each AGR is linearly related to the volume of the AGR. Figure 8 shows the simulation results of different node distribution strategies. We observe that the residual energy ratios of network with uniform node distribution are greatly higher than that of network with non-uniform node distribution. The residual energy ratios remain related stable when the radius exceeds a threshold (7, approximately) and increase greatly at the beginning with the uniform node distribution strategy. While the network with non-uniform node distribution strategy performs well. This also illustrates the effectiveness of the proposed node distribution strategy.

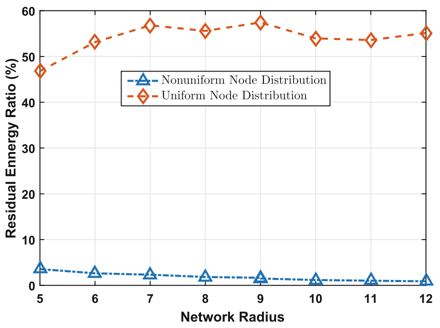


Fig. 8. Residual energy ratios of different node distribution, where $K = 4, q = 2, r = 1, N_K = 200$ under non-uniform node distribution; and $r = 1$ under uniform node distribution.

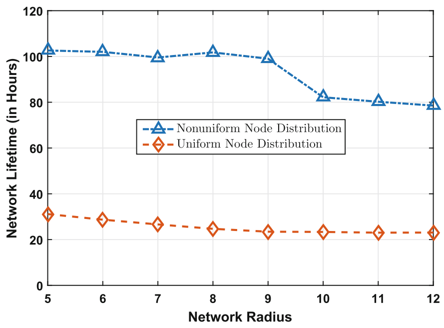


Fig. 9. Network lifetime of different node distributions, where $K = 4, q = 2, r = 1, N_K = 200$ under non-uniform node distribution simulations; and $r = 1$ under uniform node distribution.

Figure 9 shows the network lifetime (the duration till the death of the first node in the whole network) using the two strategies: (1) the uniform node distribution and (2) the non-uniform node distribution. We obverse that the network lifetime of the network with non-uniform node distribution are more than four times greater than those of the network with uniform node distribution. There is a downward trend when the radius is greater than 9. We explain this phenomenon as follows. On the one hand, with the increasing of the radius exceeding a threshold, the number of nodes in the network is more and more (exceed a threshold), and the load in the innermost AGR is greater and greater, thus, the nodes in the innermost AGR use up their energy relatively fast. On the other hand, when the radius exceeds a threshold, the number of relay nodes around a node is very close to $q(q = 3)$, and the number of optional relay nodes for a node is reduced and its load increases, thus, those nodes will die early.

6 Conclusions

In this paper, we propose a non-uniform node distribution strategy to address the energy hole issue in the 3-D underwater sensor networks consisting of a static SRN and other ordinary sensor nodes. We also propose a new routing algorithm that the distance between two adjacent nodes is considered in the non-uniform node distribution strategy. In our extensive simulations, the network achieves a high energy efficiency, less than 5% of total initial energy is wasted and the network lifetime is prolonged more than 400% compared with the uniform node distribution strategy.

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