Research of RDF Algorithm for Wireless Sensor Network Heterogeneous Node Deployment

Abstract—The relation between the density of a randomly distributed wireless sensor network node and the node’s energy consumption is discussed, and the result shows that the way to extend the network lifetime is to deploy sink nodes in the field with a larger density of sensor nodes. Furthermore, the RDF algorithm a simple, effective and highly efficient strategy for deploying sink nodes, is proposed in this paper based on simulation results. The said algorithm determines the sink node location by giving reference for a large density of sensor nodes. Additionally, the sink node deployment can be efficiently achieved through dividing the region of network and the sink node communication range. Lastly, through simulation verification, the RDF algorithm deployment strategy is further proved valid and effective from the perspective of network lifetime and message delivery rate.

Index Terms—RDF algorithm, wireless sensor network, heterogeneous node deployment.

I. INTRODUCTION

As the heterogeneous node of a wireless sensor network has higher energy, larger quantities of resources and stronger processing capacity, its deployment in a wireless sensor network greatly exerts an influence on the data forwarding and energy consumption of the entire network. Presently, there are a number of researches of heterogeneous node deployment in wireless sensor networks. Reference [1] proposes the GEP-MSN algorithm which is a strategy for deploying multi-sink nodes in a lattice structure, and through applying this algorithm, the network lifetime can be extended, and the related response time can be shortened. However, the network senses under those research are not practical and can only be applied for theoretical analysis. Reference [2] puts forward two algorithms; one is a global algorithm deploying sink nodes on the basis of global information, and another one is a 1hop algorithm based on neighboring node information. Through applying both of these, the network lifetime can be extended.

The two algorithms proposed by reference [3] both need to acquire information from other nodes in the network, and accordingly a massive information interaction is required. As a result, extra overhead is brought to the network, which increases the energy consumption of the network. References [4] and [5] clarifies that the process of moving a sink node allows a node to remain in conformity with the energy consumption status and distribution status so as to extend the network lifetime. These pertinent research projects meet the requirement of moving sink nodes. Hereof reference [6] puts forward the DCHD, a heuristic algorithm with a capacity exceeding the greedy algorithm under the assumed simple structure where a sensor node merely surpasses one hop of a sink node. However, the said algorithm is too simple to further illustrate the energy conserving strategy due to the one hop distance. Based on this background, a more efficient and more convenient algorithm deploying heterogeneous nodes is proposed in this paper on the basis of a heterogeneous node deployment strategy.

II. THEORETICAL ANALYSIS OF ENERGY CONSUMPTION AND NODE DENSITY OF SENSOR NETWORK

As the wireless sensor network is distributed unevenly, the energy consumption of a node is accordingly uneven. Perillo [7] et al. concluded two occurrences of energy holes in the wireless sensor network. One case was where all the sensor nodes of the network directly transferred the collected sensor data to the sink node through the one hop process. However, as energy consumption is influenced by transmission distance, a node at a far distance from the sink node will firstly exhaust its energy[8]. As a result, the field monitored by said node will develop an energy hole. Another case was where the sensor node of the network transferred the data to the sink node through the multi-hop process. In this case, the node close to the sink node had to both transfer the independently collected data and help other nodes transfer data to the sink node. Because of this, it must consume more energy and be bound to die earlier than other nodes. The field monitored by the said node will develop an energy hole when these nodes exhaust their energy[9].

As the energy consumption of sensor node is influenced by the transmission distance, different density distributions nodes in the network will lead to different distances between a sensor node and a sink node and among sensor nodes, and accordingly the energy consumption are also different[10]. While nodes in the network transfer data information through a multi-hop process, more energy will be consumed by sensor nodes close to sink nodes. Thus, deploying a larger density of sensor nodes around sink nodes should prevent an energy hole from occurring while the network is deployed. If the distribution and density of sensor nodes are confirmed and settled, sink nodes will be deployed in the field with a larger density of sensor nodes while deploying sink nodes in network. In the coming pages, the relationship between node density and energy consumption is demonstrated and illustrated through theoretical analysis.

The energy consumption of sensor nodes mainly originates from the process of spare nodes (perception data), data transmitting and data receiving. The energy
consumption of three said processes can be expressed through the following formulas:

\[ P_{\text{sense}} = \alpha \cdot b \]  
\[ P_{\text{Tx}} = (\beta_1 + \beta_2 \cdot d^\gamma) \cdot b \]  
\[ P_{\text{Rx}} = \gamma_1 \cdot b \]  

Among the above formulas, \( b \) refers to the rate of data generation of a single sensor node; \( \beta_1 \) refers to the energy consumed by the node’s transmission circuit; \( \beta_2 \) refers to the energy consumed by the power amplifier; \( r \) refers to the transmission distance between two sensor nodes; \( n \) refers to the path loss coefficient. As the transmission distance \( r \) is less than the threshold value of \( d_0 \), the power amplifier will consume the energy through adapting the free space model, thus setting the path loss coefficient \( n \) as 2. If the transmission distance is larger than the threshold of \( d_0 \), the power amplifier will consume the energy through the multipath attenuation model setting \( n \) value as 4. As \( \beta_2 \) values are different in different models, the specific value standard should conform with the data provided by reference [11]. The following analysis is based on the analysis of reference [12] for the relation between node density and energy consumption of unevenly distributed sensor nodes in the network.

### III. ENERGY-LOAD OF NODE IN NETWORK

#### A. Energy-load of a Node in an Evenly Distributed Network

We assume the following data in an evenly distributed wireless sensor network. All the sensor nodes are assumed to be evenly distributed in the circular region with the radius of \( R \); sink nodes are located in the center of a circle; the communication radius of sensor nodes is set as \( r \); the nodes are deployed with \( b \) bit in every data collection process, as shown in Figure 1. Firstly, the data size loaded circularly with a diameter of \( ds(m) \) and with a distance of \( x(m) \) between sink nodes is analyzed. As the nodes in the network are transmitting data by the multi-hop method, the data size loaded in circular region consists of two parts; the data size generated by nodes within the circular region and the data size generated by external nodes transmitted by the circle. The \( ds \) hereof is relatively low and approaches zero[14].

Assuming that the external nodes are also located in many circular regions with diameters of \( ds(m) \), if the number of external circles refers to \( n \), the formula of \( n \) can be acquired conforming to the mentioned assumption as \( n = \frac{\pi \cdot R \cdot x}{\pi \cdot r} \). Accordingly, the data size transmitted by the circle should be the overall data size generated by external nodes forming \( n \) circles[15]. Thus, the data size required to be transmitted by the circle can be expressed as:

\[ k_1(x) = \rho \cdot \pi \sum_{j=1}^{n} (2x + j \cdot r) \cdot d_1 + d_2 \]  

The data size generated by internal nodes can be expressed as:

\[ k_2(x) = \rho \cdot \pi \sum_{j=1}^{n} (2x \cdot d_1 + d_2) \]  

With reference to the above formulas, the data loaded by a single node of sink nodes with \( x \) distance between nodes can be expressed as:

\[ k(x) = \lim_{d \to 0} \rho \cdot \pi \cdot \sum_{j=1}^{n} (2x + j \cdot r) \cdot d_1 + d_2 \]  

\[ = \rho \cdot \pi \sum_{j=1}^{n} (2x + j \cdot r) \cdot d_1 + d_2 \]  

\[ = \frac{(n-1)(x+rf \cdot n)b}{2x} \]  

The energy-load of every node can be further illustrated according to the energy consumption model mentioned above, and it can be discussed in two situations according to the different communication radiuses[16].

1. When \( r \leq d_0 \), the power amplifier will consume the energy through adapting the free space model, setting path loss coefficient \( n \) as 2. Here, the energy consumption of every single node can be obtained by:

\[ E_x = P_{\text{Rx}} + P_{\text{Rx}} + P_{\text{sense}} = \left\{ \begin{array}{ll}
\frac{k(x)\left(\beta_1 + \gamma_1 + \beta_2 \cdot x^\gamma\right)}{2} - \frac{\gamma_1 + \beta_2 \cdot x^\gamma}{2} + a_b \cdot x & \text{if } x \leq r \\\n k(x)\left(\beta_1 + \gamma_1 + \beta_2 \cdot x^\gamma\right) - \frac{\gamma_1 + \beta_2 \cdot x^\gamma}{2} + a_b \cdot x & \text{if } x > r \end{array} \right. \]  

2. When \( r > d_0 \), the power amplifier will consume the energy through the multipath attenuation model, setting \( n \) value as 4[17]. Here, the energy consumption of each node can be obtained by:

\[ E_x = P_{\text{Rx}} + P_{\text{Rx}} + P_{\text{sense}} = \left\{ \begin{array}{ll}
\frac{k(x)\left(\beta_1 + \gamma_1 + \beta_2 \cdot x^\gamma\right)}{2} - \frac{\gamma_1 + \beta_2 \cdot x^\gamma}{2} + a_b \cdot x & \text{if } x \leq r \\
 k(x)\left(\beta_1 + \gamma_1 + \beta_2 \cdot x^\gamma\right) - \frac{\gamma_1 + \beta_2 \cdot x^\gamma}{2} + a_b \cdot x & \text{if } x > r \end{array} \right. \]  

#### B. Energy-load of a Node in an Unevenly Distributed Network

When sensor nodes are unevenly distributed in a wireless network, the situation of one sink node must be considered. We assume that the density of all nodes in the distance of \( x(m) \) from the sink node is \( \rho \cdot x \). The energy consumption of each sensor node is balanced and can be illustrated as follows:

We assume that only sensor nodes are deployed on the edge of the entire circular monitoring field as \( x = R \) and with a density of \( \rho \)[18]. The node density of each specific deployment in the circular monitoring field is calculated in the following formulas (9) and (10). The value of \( q \) is derived from formula (6). Integrating formulas (4) and (5), this paper acquires the following:

1. When \( r < d_0 \):
nodes for transmitting the data in an approximately even manner[21]. This paper applies the RDF algorithm from the perspective of quadrants to resolve this question. In other words, while a multi-circle with Max (ns) occurs in different quadrants, the grid corresponding to a circle of quadrant with Min (ns) will be selected as the optimal grid, which makes sure that the locations selected are in different quadrants, and accordingly the key nodes can more evenly share the responsibility of normal sensor nodes for transmitting the data[22].

Taking the factor into consideration that after multi-sink nodes are deployed in the network, the network lifetime of Voronoi cell composed of each sink node might be respectively different due to different densities around the sink node and different number of the key node [23]. To reduce the difference, the average key nodes number, s-n, is used to refer to the number the of key node. According to formula (6), this paper determines the network lifetime after selecting a heterogeneous node location through the following formula:

\[ L = \frac{E_i}{P} = \frac{E_i}{\varepsilon_i + \lambda_{n_s} / \lambda_i - n_s / n_s (\varepsilon_i + \varepsilon_{n_s}) + \varepsilon_i} \] (11)

The network lifetime calculated through the RDF algorithm can be acquired by formula (9).

The network lifetime of 1 to 5 sink nodes deployed through applying the RDF algorithm is shown in Figure 3. Sink nodes are deployed as shown in Figure 2, and accordingly the parameters are as follow: 
\[ E_i=100J, \varepsilon_i=0.2J, \varepsilon_{n_s}=0.2J, \lambda_{n_s}=0.5J; \] the key nodes corresponding to sink node are 6,5,5,4 and 4 respectively; the average key node numbers are 6,6,5,5 and 5.
C. Performance Simulation

To prove and verify the effectiveness of the RDF algorithm, this paper conducts an simulation under the NS2 circumstance. The simulation is designed in the 1200x1200m rectangular region with 81 sensor nodes randomly distributed conforming to the poisson distribution model. In the simulation, the number of sink nodes changes from 1 to 9, and the sink node location in every scene is deployed through applying the RDF algorithm. The case of nine sink nodes deployment is displayed in Figure 4.

![Figure 4. Nine sink node distribution in the random network scenarios](image)

In this scene, the network lifetime and message delivery rate under different node numbers are simulated, and network lifetimes and message delivery rates deployed through different algorithms are compared.

D. Analysis of Simulation Result

The result of comparison between the theoretical network lifetime value and the simulated network lifetime value under the random distribution network structure is displayed in Figure 5. In the figure, the dotted line refers to the theoretical value, and the solid line refers to the simulated value, and one can see that the theoretical value approaches the simulated value. The network lifetime increases as the sink nodes number increases, but the overall increasing trend is slow, which indicates that the network lifetime can be greatly extended with only a few sink nodes deployed in the network. On the contrary, when too many sink nodes are deployed, the network lifetime is extended at an increasingly low rate. The simulated value being relatively lower than the theoretical value is mainly because other factors leading to energy consumption of a node occur in the actual simulation environment, such as conflicts and interference from neighbor nodes.

The message delivery rate drew great importance in examining the lifetime of a network. The message delivery rate with 1 to 9 sink nodes deployed is displayed in Figure 6, which shows that the more sink nodes deployed in the network, the longer the message delivery rate, ultimately reducing to 0, which means the network lifetime is longer. When the number of sink nodes turns to 7,8 and 9, there is no obvious change in message delivery rate, which demonstrates that the network lifetime will not be influenced by the number of sink nodes reaching more than 7. However, under this condition, the cost of network is increasing, which is the reason why RLC reaches the maximum value when the number of sink nodes is 7. According to the figure, when the number of sink nodes is 4 or 5, the message delivery rate falls dramatically and then recovers back to the relatively higher rate. This is because after the successive death of key nodes, the network gets separated, and the connectivity of the network reduces. Then, the connectivity of network gradually increases and the message delivery rate recovers to normal standards as the separated nodes pick up new sink nodes to join.

The comparison among message delivery rates of sink nodes acquired through applying the RDF algorithm, recursive algorithm and random distribution is displayed in Figure 7. The figure shows that the message delivery rates of sink nodes acquired through applying the RDF algorithm and recursive algorithm are relatively similar, which demonstrates that the two algorithms exert a relatively equal influence on extending the lifetime of the network. However, due to its relative ease the RDF algorithm can better meet the requirement of practical application. The performance of the random distribution strategy for deploying sink nodes does not justify its application in practice due to its results being deficient compared to the previously mentioned algorithms. According to the figure, the RDF algorithm curve falls later than the recursive algorithm curve, which indicates that the RDF algorithm is not likely to cause the network to be separated or reduce its connectivity. Additionally, the rate of the RDF algorithm recovering the connectivity back to a normal standard is faster than the recursive algorithm’s. Considering all the information mentioned
above, this paper determines that the heterogeneous nodes are better deployed through applying the RDF algorithm.

The comparison among network lifetimes using the three different deployment strategies is illustrated in Figure 7. Being similar to the result for the message delivery rate, the network lifetime results using the RDF algorithm and recursive algorithm are approximately similar, and the random distribution curve result is far less than the said algorithms’. As shown in Figures 7, the RDF algorithm and recursive algorithm exert relatively equal influence on extending the lifetime of the network. However, due to its relative ease the RDF algorithm can better meet the requirement of practical applications.

V. CONCLUSION

The relationship between the density of randomly distributed wireless sensor network node and the node’s energy consumption is discussed, and the result is acquired that the way to extend the network lifetime is to deploy sink nodes in the field with larger density of sensor nodes. Furthermore, the RDF algorithm is a simple, effective and highly efficient strategy for deploying sink nodes, is proposed in this paper based on simulation results. The said algorithm determines the sink node location by giving reference for a large density of sensor nodes. Additionally, the sink node deployment can be efficiently achieved through dividing the region of network and the sink node communication range. Lastly, through simulation verification, the RDF algorithm deployment strategy is further proved valid and effective from the perspective of network lifetime and message delivery rate.

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