HIGH: A Hexagon-based Intelligent Grouping Approach in Wireless Sensor Networks

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***Abstract*—In a random deployment or uniform deployment strategy, sensor nodes are scattered randomly or uniformly in the sensing field, respectively. Hence, the coverage ratio cannot be guaranteed. The coverage ratio of uniform deployment, in general, is larger than that of the random deployment strategy. However, a random deployment or uniform deployment strategy may cause unbalanced traffic pattern in wireless sensor networks (WSNs). Therefore, cluster heads (CHs) around the sink have larger loads than those farther away from the sink. That is, CHs close to the sink exhaust their energy earlier. In order to overcome the above problem, we propose a Hexagon-based Intelligent Grouping approacH in WSNs (called HIGH). The coverage, energy consumption and data routing issues are well investigated and taken into consideration in the proposed HIGH scheme. The simulation results validate our theoretical analysis and show that the proposed HIGH scheme achieves a satisfactory coverage ratio, balances the energy consumption among sensor nodes, and extends network lifetime significantly.**

***Index Terms*—Wireless sensor networks, Cluster Head, Energy efficiency, Coverage Ratio.**

I. INTRODUCTION

A wireless sensor network (WSN) consists of a large number of connected sensor nodes capable of sensing, computing, processing, and storing sensed data. These sensor nodes gather environmental data, collaborate with each other and send the measured data via wireless communications to the sink. Hence, WSNs are greatly important in cyber-physical system for observing the physical world at a low cost. These useful features permit WSNs to be used in a wide range of applications [1-6], such as environmental monitoring, battlefield surveillance, weather monitoring forecasting, biological detection, home appliance and inventory tracking.

Effective node deployment [7-10] is one of the crucial topics in WSNs. There are two node deployment strategies in WSNs, which are deterministic and random manners. Even if the random deployment method is preferable in several applications, the coverage ratio cannot be guaranteed. Therefore, a deterministic deployment strategy is investigated in this work. A proper node deployment strategy has proven to be an important way to reduce overhead in terms of routing and data fusion. Moreover, it is well recognized that a proper node deployment strategy can reduce the energy consumption and prolong the network lifetime of WSNs.

There are two different types of WSNs, called homogeneous or heterogeneous sensor networks, which provide the same or different communication capabilities, respectively. Although several works discuss heterogeneous WSNs, a lot of recent research takes node deployment strategies in homogeneous WSNs into account because of their less complex nature. Therefore, this paper studies homogeneous WSNs.

In WSNs, the critical challenge is energy efficiency due to the fact that sensor nodes have limited battery and non-rechargeable energy resources. In a multi-hop WSN, the sensor nodes close to the sink tend to consume a lot of energy and use up their energy earlier. This is because these sensor nodes must forward the relay traffic for a large number of sensor nodes, which are is known as the hotspots. Sensor nodes in the hotspots run out of batteries much faster than other sensor nodes because of their higher energy dissipation rate. This phenomenon is referred to as the energy-hole problem [11]. Thus, how to effectively balance the energy consumption among sensor nodes, minimize energy consumption and maximize the network lifetime of the entire system become the central concerns when designing protocols for WSNs.

To this end, this paper proposes a novel node deployment strategy, Hexagon-based Intelligent Grouping approacH (called "HIGH") for WSNs, which provides a more accurate and realistic reading of the node density in each group based on the energy consumption among CHs. More specifically, the proposed HIGH scheme provides detailed numerical calculations for the node density in each group to guarantee that all the sensor nodes use up their energy almost at the same time, which extends the network lifetime greatly. The contributions of this work are as follows.

(1) Adopt the hexagon-based intelligent grouping approach in WSNs.

A hexagon-based WSN can be used in many applications and provides several advantages. Deploying sensor nodes in a hexagon-based WSN maximizes the additional sensing area, while deploying randomly sensor nodes cannot guarantee the maximal additional sensing area.

(2) Pre-calculate the node density appropriately in each group according to the energy consumption among CHs.

We calculate the node density in each group to alleviate the "energy hole problem" in WSNs. The proposed HIGH scheme prevents the overloading of CHs around the sink. That is, relay load is uniformly allocated to CHs in each group so that the CHs near the sink do not use up their energy far earlier than others. This important finding provides the criterion for deploying sensor nodes in hexagon-based WSNs.

(3) Adopt multi-hop transmissions in inter-group routing.

The proposed HIGH scheme adopts multi-hop transmission in inter-group routing. We also propose the load balancing approach so that the relay load delivered from CHs in layer H_i is equally shared by CHs in layer H_{i-1}.

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In this way, the network lifetime can be effectively extended.

The rest of the paper is organized as follows. In Section II, we discuss related work in the area of the clustering and node deployment strategy in WSNs. The network model and relevant assumptions are proposed in Section III. Section IV analyzes energy consumption among CHs in each layer. According to the analysis results, Section V describes the proposed HIGH in detail. The performance evaluation of the proposed HIGH scheme is discussed in Section VI. Finally, the conclusion is presented in Section VII.

II. Related Work

The positions of sensor nodes have a critical impact on the effectiveness of the WSN. Therefore, a significant amount of research has studied the node deployment issue in WSNs. The choice of deployment strategy highly depends on the type of sensors application. In general, there are two types of deployment categories (e.g., random deployment and deterministic deployment) in WSNs. Random deployment is used in inaccessible areas (e.g., volcanoes or seismic zones), where sensor nodes are dropped from a helicopter. On the other hand, deterministic deployment is preferable in accessible areas (e.g., target tracking or urban monitoring), where sensors are placed by hand at selected spots prior to network operation.

Random deployment is one of the most important deployment methods in WSNs. Random deployment enables fast installation of a large number of sensor nodes in locations difficult to access, which is important for many infrastructure-less cyber physical systems (CPS). That is, deploying sensor nodes randomly is the only possible solution. This is especially true for harsh environments (e.g., a battlefield or a disaster area). Won et al. [12] provided a characterization of random deployment in detail and proposed a novel radio model that effectively captures its distinctive characteristics. Moreover, they introduced a prototype sensor package that can be utilized to alleviate the impact of random deployment. Khajeh et al. [13] proposed a novel algorithm for constructing a connected k-dominating set (kCDS), which takes node density into consideration in adjusting the number of paths. Simulation results show higher performance compared to other schemes in terms of packet delivery rate, packet delay, and area coverage. Kulkarni et al. [14] presented a novel node deployment technique called Quasi Random Deployment (QRD), to improve energy efficiency, increase coverage, and prolong the network lifetime. The random deployment pattern of wireless sensor nodes is analyzed as well in this study. Balister and Kumar [15] addressed the effects of placement errors and random failures on density when sensors are deployed randomly versus deterministically. They have provided a comprehensive comparison to help a practitioner decide the lowest-cost deployment strategy in real life. Tsai [16] studied the impact of shadowing and non-shadowing effects on sensing coverage for randomly distributed WSNs. Their proposed model can well reflect the shadowing and non-shadowing phenomenon of sensing signals in realistic environments.

There is a lot of related research on the deterministic deployment for WSNs. Senouci et al. [17] first addressed the topic of handling uncertainty and information fusion to deploy sensor nodes in an efficient manner (called EBDA). Then, they presented an uncertainty-aware deployment strategy to determine the locations and minimum number of sensor nodes for the purpose of achieving full area coverage. He et al. [18] investigated deterministic sensor deployment for barrier coverage in WSNs. They first showed the sub-optimality of line-based deployment when the length of the shortest line segment is greater than that of the shortest path. They also proposed two novel schemes to achieve optimal or close-to-optimal sensor deployment when the deployment curve is distance continuous or not, respectively. Numerical results are obtained to validate the conclusions. Eftekhari et al. [19] introduced two multi-round deployment strategies (e.g., complete and partial deployment) and analyzed the barrier coverage problem with multi-round sensor deployment. They also find the optimal node density in each round that minimizes the total expected cost of deployment. Yoom and Kim [20] introduced the maximum coverage sensor deployment problem (MCSDP) in WSNs and analyzed the properties of the problem and its solution space, trying to find best sensor deployments using novel genetic algorithms. Chen et al. [21] investigated the theoretical aspects of the non-uniform deployment scheme and addressed the energy hole problem in WSNs. They also proved that completely balanced energy depletion of all nodes is unachievable because of the many-to-one traffic pattern in WSNs. Our prior work (called ACT) [22] proposed a cluster-based routing scheme in rectangle topology. ACT aims to alleviate the energy hole problem by calculating the cluster radius to balance the energy dissipation among each CH. ACT inspired us to propose a new cluster-based routing protocol in hexagon-based WSNs.

III. Preliminaries

We consider a hexagon model with a static sink located at the center of the sensing area. A hexagon model is further considered by partitioning the sensing area into layers. The ith layer is denoted as H_i, with each layer having the same length (x). A layer H_i is further divided into group ($H_{i,j}$), where i represents the ith layer and j denotes the order of the group, as shown in Fig. 1. Without loss of generality, let us label the center of the $H_{1,1}$ in the hexagonal coordinate system. Then, all other groups (e.g., $H_{1,2}$, $H_{1,3}$, $H_{1,4}$, $H_{1,5}$, and $H_{1,6}$) are located around $H_{1,1}$ clockwise. Consequently, we can determine the location of all groups in layer one in a hexagonal coordinate system. Let C_i indicate the number of divided sub-groups in $H_{i,j}$: it can be derived as follows.

$$C_i = \begin{cases} 6, & if\ i = 1 \\ 6 \times (i-1), & if\ i \geq 2 \end{cases} \tag{1}$$

More specifically, we divided the sensing area into groups of 6, 6 and 12 in layer H_1, H_2, H_3, respectively. As for the area of $Group_{i,j}$, it can be derived as follows.

$$Group_{i,j} = \begin{cases} \frac{\sqrt{3}}{4} \times x^2, & if\ i = 1 \\ 6 \times \frac{\sqrt{3}}{4} \times x^2, & if\ i \geq 2 \end{cases} \tag{2}$$

, where x is the length of the hexagon.

In the case of x = 40 *meter* and k = 3, the area of $Group_{i,j}$ can be calculated as follows.

$$Group_{1,j} = \frac{\sqrt{3}}{4} \times (40)^2 = 400\sqrt{3}, \qquad \forall j = 1...6 \tag{3a}$$

$$Group_{2,j} = 6 \times \frac{\sqrt{3}}{4} \times (40)^2 = 2400\sqrt{3}, \quad \forall j = 1...6 \tag{3b}$$

$$Group_{3,j} = 6 \times \frac{\sqrt{3}}{4} \times (40)^2 = 2400\sqrt{3}, \quad \forall j = 1...12 \tag{3c}$$

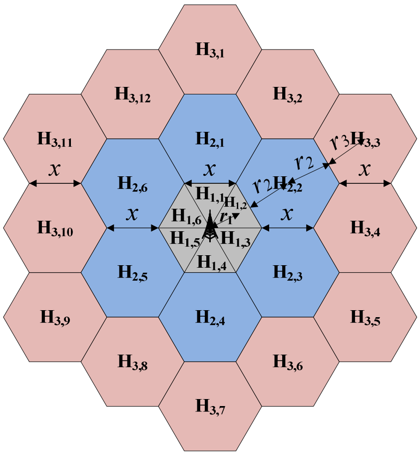

Figure 1. An example of three layers in the hexagon model

According to the radio energy consumption model in [23], the consumed energy for transmitting *DU* data unit over a distance *d* is *DU* × (E_{elec} + E_{amp}×d^{α}), where E_{elec} is the energy consumed in a sensor node for transmitting 1 bit of sensed data, E_{amp} is the amplifier energy (e.g., multi-path model), *d* denotes the transmission distance, and *α* refers to the path loss exponent (e.g., *α* = 4). Note that varied energy dissipation models can be used in the following derivations. In other words, the proposed HIGH scheme can be practical for various models. We use the radio energy dissipation model as an example because it is a representative model in WSNs.

IV. Analysis of Energy Consumption

Each sub-group is assumed to have selected a sensor node to be a cluster head (CH), as mentioned later in Section IV. Assume that each sensor node is generated and transmits one unit of data traffic per round to the sink via its CH using multi-hop communications. Let $H_{i,j}$ and D_i be the CH belonging to $Group_{i,j}$ and the density of the sensor nodes in each H_i, respectively.

In the hexagon model, each CH in outermost $Group_{k,j}$ only handles the sensed data from its group member nodes (e.g., $Group_{k,j} \times d_k$). Furthermore, each CH in $Group_{k-1,j}$ not only copes with the data transmitted by its own group member nodes, but also relays data from $Group_{k,j}$ (e.g., $Group_{k\text{-}1,j} \times D_{k\text{-}1} + Group_{k,j} \times D_k \times \frac{C_k}{C_{k-1}}$, where C_k is the number of sub-groups in $Group_{k,j}$). For the purpose of simplicity in calculations, we assume that the transmission distance is measured between the centers of two adjacent groups (e.g., ($r_k + r_{k\text{-}1}$) in layer H_k, ($r_{k\text{-}1} + r_{k\text{-}2}$) in layer $H_{k\text{-}1}$ and so on). The distance between each CH in the innermost layer (H_1) and the sink is r_1. Finally, the total energy consumption of each CH in layer H_i, $\forall i = 1...k$, can be derived as follows.

$$\begin{aligned}
E_k &= [Group_{k,j} \times D_k] \times [\mathrm{E}_{elec} + \mathrm{E}_{amp} \times (r_k + r_{k-1})^{\alpha}] \\
E_{k-1} &= [Group_{k-1,j} \times D_{k-1} + Group_{k,j} \times D_k \times \frac{C_k}{C_{k-1}}] \\
&\quad \times [\mathrm{E}_{elec} + \mathrm{E}_{amp} \times (r_{k-1} + r_{k-2})^{\alpha}] \\
E_{k-2} &= [Group_{k-2,j} \times D_{k-2} + Group_{k-1,j} \times D_{k-1} \times \frac{C_{k-1}}{C_{k-2}} + \\
&\quad Group_{k,j} \times D_k \times \frac{C_k}{C_{k-2}}] \times \\
&\quad [\mathrm{E}_{elec} + \mathrm{E}_{amp} \times (r_{k-2} + r_{k-3})^{\alpha}] \\
&\ldots \\
E_1 &= [Group_{1,j} + \sum_{i=2}^{k} Group_{i,j} \times D_i \times \frac{C_i}{C_1}] \times \\
&\quad [\mathrm{E}_{elec} + \mathrm{E}_{amp} \times (r_1)^{\alpha}]
\end{aligned} \tag{4}$$

V. The Proposed High Scheme

The proposed HIGH scheme consists of four phases, namely, the group division phase, deployment phase, CH selection phase, and routing phase.

A. *Group division phase*

- Determining the number of layers (*K*) in network topology

Clustering (e.g., grouping) is an effective technique for utilizing the energy of sensor nodes and extending the network lifetime for WSNs. First of all, the sink divides the network topology into *K*-layers. In the hexagon model, the length of each $Group_{i,j}$ is set to *x*. Sub-groups closest to the sink are put in the $H_{1,j}$, $\forall j = 1...6$. Sub-groups located farthest from the sink are put in the $H_{k,j}$, $\forall j$. Note that the parameter (*K*) is adjustable in the proposed HIGH scheme, as shown in Fig. 1.

B. *Deployment phase*

There are two deployment strategies in WSNs, which are deterministic and random. The deployment strategy is one of the critical topics in improving target detection and tracking accuracy in WSNs. Sensor nodes can be deployed usefully in a predetermined hexagonal area to achieve full coverage by adopting the proposed HIGH scheme.

- Calculating the node density in each group

We assume that sensor nodes are deployed *a priori* in each $Group_{i,j}$ based on the following conditions and constraints.

$$\frac{[Group_{1,j} \times D_1] \times \varepsilon_1}{E_1} \cong \frac{[Group_{2,j} \times D_2] \times \varepsilon_2}{E_2} \cong \ldots \cong \frac{[Group_{k-1,j} \times D_{k-1}] \times \varepsilon_{k-1}}{E_{k-1}} \cong \frac{[Group_{k,j} \times D_k] \times \varepsilon_k}{E_k} \tag{5a}$$

$$\sum_{i=1}^{k} C_i \times [Group_{i,j} \times D_i] = TN_{ALL} \tag{5b}$$

$$\text{subject to: } Group_{i,j} \times D_i \geq 1, \forall i = 1...k \tag{5c}$$

, where ε_i is the initial energy of a sensor node in layer H_i, E_i is the total energy consumption of each CH in layer H_i (as mentioned above in Section IV), and TN_{ALL} is the total number of sensor nodes. The ratio of D_1, D_2, …, D_k can be obtained from (5a). From (5a) and (5b), we can calculate how many sensor nodes should be deployed in each group. From Constraint (5c), the coverage requirement can be guaranteed. That is, each sub-group can be completely covered by at least one sensor node for the purpose of monitoring the whole sensing area.

- A numerical example for $K = 3$

We consider a numerical example of a 3-layer hexagon model with x = 40 *meter*, ε_1 and ε_2 are 1 joule and an adjustable ε_3 (e.g., 0.6). We pre-deployed 96 sensor nodes in the sensing field. The ratio of d_1, d_2 and d_3 can be obtained based on (6a). The obtained ratio can be put in (6b) to calculate the number of sensor nodes in each group to achieve approximately balanced energy consumption.

$$\frac{[\frac{\sqrt{3}}{4}\times 40^2\times D_1]\times 1}{E_1} \cong \frac{[6\times\frac{\sqrt{3}}{4}\times 40^2\times D_2]\times 1}{E_2} \cong \frac{[6\times\frac{\sqrt{3}}{4}\times 40^2\times D_3]\times 0.6}{E_3} \quad (6a)$$

$$6\times\frac{\sqrt{3}}{4}\times 40^2\times D_1 + 6\times\frac{\sqrt{3}}{4}\times 40^2\times D_2 + 12\times\frac{\sqrt{3}}{4}\times 40^2\times D_3 = 96 \quad (6b)$$

$$\text{subject to: } Group_{i,j}\times D_i \geq 1, \forall i = 1\ldots 3 \quad (6c)$$

Here, we utilize Wolfram Mathematica to calculate the above equations. We obtain $D_1 \approx 0.00872954$, $D_2 \approx 0.00143645$ and $D_3 \approx 0.000478816$. Therefore, we have $G_{1\text{-total}} = 36$, $G_{2\text{-total}} = 36$ and $G_{3\text{-total}} = 24$, where $G_{i\text{-total}}$ denotes the total number of sensor nodes in all $Group_{i,j}$. This example can be extended easily in any K-level hexagon model.

C. *CH selection phase*

- Selecting the CH in each sub-group

The most important part of the clustering scheme is the CH selection. Each sensor node first broadcasts the information within radius R. The information includes its current location information (e.g., $Group_{2,3}$) and its residual energy. Each $Group_{i,j}$ selects the ideal location (the most central location) to serve as an initial CH, as shown in Fig. 2. The selected CH in each sub-group broadcasts the CH message (CH_Msg) to member nodes that it will be a CH. If a sensor node receives multiple CH_Msgs, a sensor node only joins its $Group_{i,j}$. If a sensor node does not serve as a CH and does not receive any CH_Msg, it may send a find message (Find_Msg) to seek the closest group to join.

- CH rotation within the sub-group

Rotating the role of CH within each sub-group is needed in order not to use up the energy of CHs early. Several traditional clustering methods reselect CHs in each round in order to share the loads among all sensor nodes. However, frequent rotation of CHs increases considerable overheads because all of the cluster members have to be notified about the changes. To avoid such a scenario, in this phase we define the threshold of CH power as TH_e. When the residual energy of the original CH is below a threshold TH_e, CH rotation is triggered. Meanwhile, a new CH broadcasts the Change_Msg to notify its cluster members.

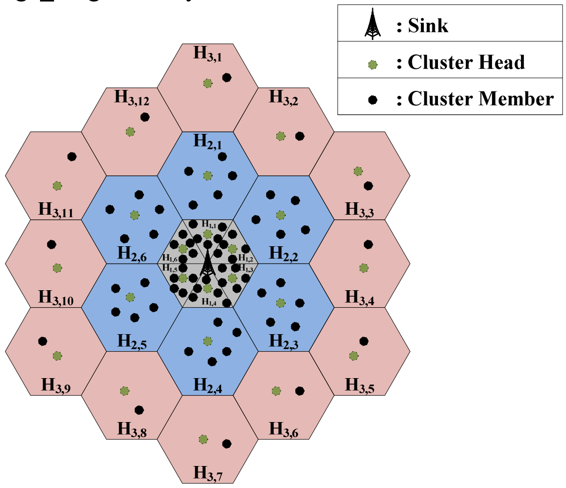

Figure 2. An illustration of the initially selected CH in each subgroup

D. *Routing phase*

The routing phase consists of intra-group routing and inter-group routing.

- Intra-group routing

We implemented the MST [24] in intra-group routing to reduce the transmission distance between member nodes and CHs. Consider a WSN with high density of sensor nodes, in which the transmitted data may take a long time before reaching its CH. To overcome the above problem, a hop count *HC* is assigned. When sensor nodes proceed to forwarding data, the value of *HC* is decreased by one. Once the value of *HC* is equal to zero and the data has not yet reached the targeted CH, the sensor node holding the data will directly transmit data to the CH. This can avoid time-consuming routing between sensor nodes and the CH, with the goal of enabling time-sensitive applications of WSNs.

- Inter-group routing

As mentioned in [23], we know that the energy consumption in a radio transmission is proportional to the α-th power of transmission distance (e.g., $\alpha = 4$). It is well known that if a CH transmits data to the sink directly, it may consume a lot of energy. Therefore, we utilize multi-hop transmissions in inter-group routing. The following specifies how to get the relay load of inter-group routing in order to balance energy among CHs.

According to (1), the relay load (RL_i) of a CH in layer H_i from CHs in layer H_{i+1} can be derived as follows.

$$RL_{i+1\to i} = \frac{C_{i+1}}{C_i}\times DS_{i+1} = \begin{cases} 1 & , if\ i = 1 \\ \frac{i}{i-1} & , if\ i \geq 2 \end{cases} \quad (7)$$

, where DS_i is the data size in $Group_{i,j}$.

For example, six and twelve sub-groups are in layer H_2 and H_3 (e.g., $C_2 = 6$ and $C_3 = 12$), respectively. Hence, each CH in layer H_2 copes with relay load of $\frac{12}{6}\times RL_{3\to 2}$ from CHs in layer H_3. It also indicates that the relay load delivered from CHs in layer H_3 is equally shared by CHs in layer H_2.

VI. Performance Evaluation

We evaluate the performance metrics of the proposed

HIGH scheme, the EBDA scheme [17], the Uniform scheme, and the Random scheme. The simulation is performed in MATLAB. Every simulation result shown is the average result of 1000 independent experiments. Note that the Random scheme and the Uniform scheme adopt the same group division phase and routing phase as compared to the HIGH scheme, except for the deployment phase. The Random scheme scatters sensor nodes randomly, while the Uniform scheme distributes sensor nodes uniformly in the sensing field. To evaluate the performance of the proposed HIGH scheme, several performance metrics have been used, which are described as follows.

(1) coverage ratio;

(2) network lifetime;

(3) the number of sensor nodes still alive over rounds.

The definition of the network lifetime is the time elapsing until the first sensor node uses up its energy, and is measured in 'rounds'. We defined a 'round' as the sensor node transmitting the sensed data via targeted CH to the sink. In addition, all the parameters are given as follows. E_{elec} = 50 nJ/bit; ε_{amp} = 0.0013 pJ/bit/m^4; the path loss exponent is 4; we divide the network topology into 3-layers (e.g., K = 3); the length of the hexagon is 40 meters (e.g., x = 40); the sensed radius of each sensor node is 20 meters; initial energy of each sensor node is 1 joule, except for the sensor nodes in the outermost sub-groups (e.g., $\varepsilon_1 = \varepsilon_2 = 1$ and $\varepsilon_3 = 0.6$ joule); in each round, sensor nodes transmit 800 bits of data to the sink via multi-hop communications.

A. *Coverage ratio*

We first evaluate the coverage ratio with the varying number of sensor nodes (e.g., TN_{ALL} = 96, 150, and 200) in a hexagon-based WSN. In scenario 1, the covered range of each sensor node is 20 meters (i.e., Rs = 20 m). In scenario 2, the covered range of each sensor node is 30 meters (i.e., Rs = 30 m).

As shown in Fig. 3 (e.g., scenario 1), one can see that the coverage ratio of the HIGH is over 95 percent. This is due to the fact that we appropriately utilize the deployment strategy (as mentioned in 5a-5c). It makes sense that the coverage ratio has a tendency to rise as the sensor nodes increase. Moreover, the EBDA scheme only needs 96 sensor nodes to get the full coverage ratio, while the HIGH scheme needs 150 sensor nodes. In all cases, the EBDA scheme needs fewer sensor nodes than the HIGH scheme, the Random scheme and the Uniform scheme to get the full coverage ratio.

As for the Uniform scheme and Random scheme, the node deployment strategy is to scatter sensor nodes uniformly and randomly, respectively. Hence, the coverage ratio of the Uniform scheme and Random scheme is lower than the HIGH scheme and EBDA scheme.

Next, we consider the case in scenario 2. As shown in Fig. 4, the EBDA scheme needs fewer sensor nodes than the HIGH scheme, the Random scheme and the Uniform scheme to obtain the full coverage ratio. Furthermore, it can be observed that the HIGH scheme, the Random scheme and the Uniform scheme have a slightly larger coverage ratio compared to scenario 1. This is due to the fact that scenario 2 sets a larger covered range of each sensor node.

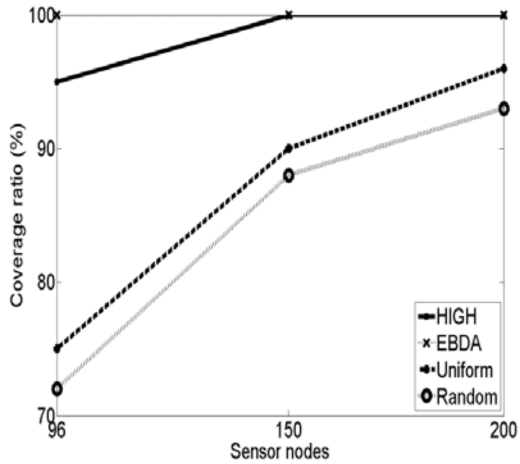

Figure 3. The coverage ratio comparison between the HIGH scheme, EBDA scheme, Uniform scheme, and Random scheme with Rs = 20 meters

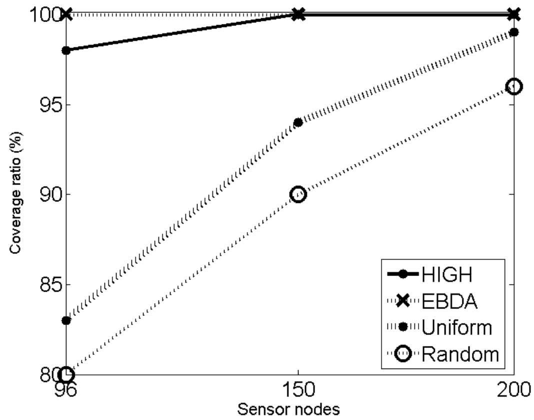

Figure 4. The coverage ratio comparison between the HIGH scheme, EBDA scheme, Uniform scheme, and Random scheme with Rs = 30 meters

B. *Network lifetime*

Table I compares the proposed HIGH scheme with the EBDA scheme, Uniform scheme, and Random scheme. By comparison, we can clearly observe that the HIGH scheme exceeds the EBDA, Uniform, and Random scheme in terms of the network lifetime in both sparse and dense scenarios. This phenomenon indicates that the HIGH scheme takes the node density in each group into account to alleviate the energy hole problem. The HIGH scheme achieves the extension of the network lifetime by about 25 percent compared to the EBDA scheme, 252 percent compared to the Uniform scheme, and 224 percent compared to the Random scheme when the deployed sensor nodes are 96. The same trends hold for TN_{ALL} at 150 and 200.

TABLE I. COMPARISON WITH OTHER SCHEMES

Schemes \ Sensor nodes	96	150	200
HIGH	9380	8819	8357
EBDA	7482	6806	6318
Uniform	2662	2367	2205
Random	2894	2603	2411

C. *The number of sensor nodes still alive*

Fig. 5 compares the number of sensor nodes still alive over rounds. The HIGH scheme performs far better than the

EBDA, Uniform and Random schemes. This phenomenon indicates that the HIGH scheme computes the appropriate node density in each group for the purpose of balancing the energy consumption of CHs. Furthermore, the network lifetime of the HIGH scheme has a more rapid decline than in the EBDA, Uniform and Random scheme; this is due to the fact that the HIGH scheme allocates relay traffic equally.

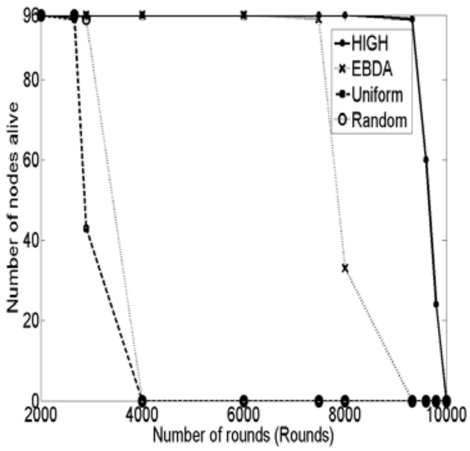

Figure 5. Comparison of the number of sensor nodes still alive over rounds in all schemes

VII. Conclusion

Energy efficiency is the key component in WSNs. In hexagon-based multi-hop WSNs, CHs around the sink have more relay traffic than those CHs farther away from the sink. To avoid the “energy hole problem”, we propose “Hexagon-based Intelligent Grouping approacH in WSNs” (called HIGH). That is, in order to let each sensor node exhaust its energy at approximately the same time, we calculate how many sensor nodes should be deployed in each group based on the relay traffic of each CH. The proposed HIGH performs better in comparison to the EBDA, Uniform and Random schemes with respect to performance metrics such as the coverage ratio, the network lifetime, and the number of sensor nodes still alive over rounds. Moreover, the simulation results demonstrated that the proposed HIGH scheme alleviates the unbalanced relay traffic (e.g., energy hole problem) significantly.

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