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Energy Balanced Routing Strategy in Wireless Sensor Networks

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***Abstract*—In order to tackle the energy hole problem of sensor networks, the non-uniform node deployment strategy was presented recently. For achieving the expected performance of this deployment method, nodes need to transmit data to the sink node through selecting a node in the adjacent inner-region decided by the deployment strategy. Since nodes near the outer-boundary of a region will be covered by more nodes, the random selection method will cause the unbalanced energy consumption problem. In this paper, this issue is rigorously studied and a region constrained selection scheme is proposed based on the analytical result. Numerical and simulation results show that region constrained scheme can achieve acceptable performance improvements over random scheme.**

***Index Terms*—Sensor networks, non-uniform deployment, routing protocols, lifetime, stochastic geometry.**

I. Introduction

Recent advances in processor, memory and radio technology have made it possible for the deployment of large scale sensor networks where thousands of small sensing nodes capable of sensing, communicating and computing are used to monitor the physical world. A typical static sensor network consists of a large number of static sensing nodes and one or more static data collection nodes called sinks. Under this network structure the sensor nodes transmit sensed data to sinks in a traversal-multicast manner through multi-hop paths, which leads to heavier data transmissions for the nodes near the sink. This problem is known as the energy hole problem for the sensor network[1]. In order to tackle this problem, some strategies have been proposed[2], [3], which are based on the non-uniform distribution of the sensor nodes in the sensing field. The fundamental idea of this mechanism is to divide the sensing field into multiple regions and put more nodes in the regions close to the sink node to balance the energy consumption. Since the data transmission is in a region-by-region manner, the specific routing scheme should be designed to achieve the balanced energy consumption.

The most straightforward method is to select the next hop of certain node randomly among its neighbours. However this method will lead to spatially unbalanced energy consumption if the width of each region is large. In this scenario, the nodes near the outter-boundary of one region will be covered by more nodes than those near the inner-boundary. Consequently, the sensors, covered by more nodes, will be selected with higher probability. This difference of the selection probability is the reason for the spatially unbalanced energy consumption problem. The residual energy information can be used to balance the energy consumption of the network. But since a special equipment[4] is needed to obtain the residual energy information of the sensor node, the complexity and cost of the system will be increased. Thus a routing mechanism is needed to tackle the spatially unbalanced energy consumption problem for the system without the energy information device.

In this paper the issues discussed above will be dealt with. The major contributions of this paper are as follows: 1) The analytical model for the spatially unbalanced energy consumption for random node selection scheme is proposed; 2) The region constrained mechanism is provided.

The paper is organized as follows. Section II provides the network model, fundamental assumptions and notations for this paper. In the following section III, the mathematical model for the spatially unbalanced energy consumption issue is proposed, based on which the region constraint strategy is given in section IV. The experimental results are provided in section V. In section VI the existing works related to this article are discussed and in section VII the conclusions of this paper are drawn.

II. System Model

A. Network Model

The desired sensing field is assumed to be a circle region with radius r_D, i.e. the area of the network is πr_D^2, with the sink node being located at the centre of the network. Sensing nodes of the network are assumed to be homogenous with communication range r_t, so that one node can communicate with any other node within the circular area of πr_t^2 centred at the node. Within the distance of r_t from the sink node, nodes can communicate directly with the sink node. Out of this region nodes transmit data to the sink node through multi-hop path. It is also assumed that each node generates a data unit of l bits in the period of τ seconds to the sink node. Since this paper mainly focuses on the large scale sensor network, the radius of the network is assumed to be far larger than the transmission range ($r_D \gg r_t$). The sink node is assumed to be a super node without energy constraint. In this paper, it is also supposed that an ideal MAC protocol is used, so that the collision can be tackled and overhearing can be avoided[5].

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The network is divided into several circular regions with the same centre of the sink node. Except for the first region, the widths of all the other regions are the same with the value of r'_t ($r'_t \leq r_t$), which can ensure the communication between two nodes in adjacent regions. The first region is composed of the nodes that can communicate with the sink directly. Hence it has the width of r_t. Sensors in other regions need to transmit data through multi-hop routes in a region by region fashion, which only allows a node to select relay node in the adjacent inner region. This postulate is proposed to ensure that the network lifetime can be lengthened through non-uniform node deployment scheme. For the purpose of the analysis in this paper, each region is further divided into several sub-regions with width δ. Fig. 1 shows the network division model used in this paper, where $\Xi(3, i)$ represents the ith sub-region of region 3.

Nodes in the network are assumed to be deployed non-uniformly in different regions and scheduled by a proper scheduling scheme, so that the density of working nodes can be maintained to be a constant value λ_n to fulfil the application's coverage requirement[6]. This assumption implies that the distribution of the nodes follows the Poisson distribution. It is also practical to suppose that each node knows its own position. In addition a sensor also knows the information of the positions of all the nodes within its transmission range through some information exchanging stage. Since the focus of this paper is on the energy balance of the routing scheme, only energy consumed by the data transmission is considered in this article.

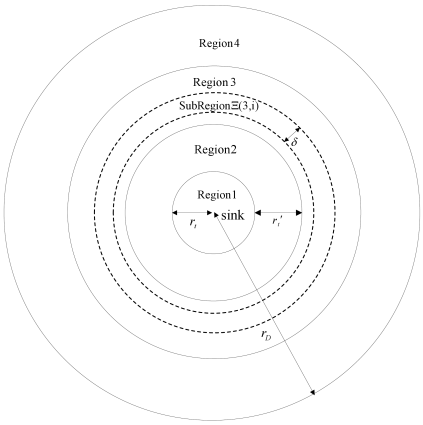

Fig. 1. The division of the network

B. Notations

The notations commonly used for the analysis of the paper are listed in Table I. Others will be explained when they first appear in the paper.

TABLE I
NOTATIONS

Notations	Definations
$\Xi(i,k)$	The sub-region k of region i.
δ	The width of a sub-region
λ_n	The density of active nodes in the network
N	The total number of nodes in the network
l	The amount of data that generated by a node in each cycle
G	The total number of regions in the sensing area
r_t	The transmission range of a sensor node
r'_t	The width of region $i(2 \leq i \leq G)$ of the network
M_i	The total number of sub-regions for the region i
$\delta_{l(i)}$	The width of the last sub-region of region i

III. Random Selection Scheme

The fundamental strategy of selecting the relay node is to randomly select one neighbour node in the adjacent inner region. In this section, the balance of the energy usage of this node selection strategy will be analysed.

A. Node Selection Probability

In order to evaluate the performance of the random selection scheme, the first step is to calculate the probability for a node in the sub-region $\Xi(i+1, m)$ to choose a certain node in the sub-region $\Xi(i, k)$, which is denoted as $\rho_{(i+1,m,k)}$.

Suppose that a node in sub-region $\Xi(i+1, m)$ can cover totally $\Phi_{(i+1,m)}$ nodes in region i and in sub-region $\Xi(i, k)$, the node has $\phi_{(i+1,m,k)}$ sensors in the contact range. The probability, $\rho_{(i+1,m,k)}$, can be calculated by

$$\rho_{(i+1,m,k)} = \frac{\phi_{(i+1,m,k)}}{\Phi_{(i+1,m)}} \tag{1}$$

In accordance with the Poisson distribution of sensor nodes, the value of $\Phi_{(i+1,m)}$ and $\phi_{(i+1,m,k)}$ can be derived as

$$\Phi_{(i+1,m)} = \lambda_n \Omega_{(i+1,m)} \tag{2}$$

$$\phi_{(i+1,m,k)} = \lambda_n \Omega_{(i+1,m,k)} \tag{3}$$

where $\Omega_{(i+1,k)}$is the area covered in region i by a node in $\Xi(i+1, k)$, and $\Omega_{(i+1,k,m)}$ represents the area covered in $\Xi(i, m)$ by a node in $\Xi(i+1, k)$. Also the area Ω can be obtained by a function of the distance r between the node and the sink node, expressed as below

$$\Omega = g(r) \tag{4}$$

If δ is small enough, it is practical to estimate the value of Ω for any node in $\Xi(i+1, m)$ according to the expectation of minimum value of r, $E(min(r))$, as

$$\Omega = g(E(min(r))) \tag{5}$$

We denote $F_r(x)$ as the cumulative distribution function of $min(r)$ and also define the following notations:
$x_{\delta(i,j)}$ - the distance between a node in $\Xi(i, j)$ and the inner boundary of $\Xi(i, j)$.
$r_{(i,j)}$ - the radius of the inner boundary of $\Xi(i, j)$.
$A_{(i,j)}$ - the area of $\Xi(i, j)$.
$\Phi(A)$ - the total number of nodes in area A.
$A_{(i,j)}(x)$ - the area, which is formed by the inner boundary of $\Xi(i, j)$ and the circle with the radius $(r_{(i,j)} + x)$ centred at

the sink node.
According to the Poisson distribution of sensor nodes, the following relation holds[7]

$$F_r(x) = 1 - e^{-\lambda_n A_{(i+1,m)}(x - r_{(i+1,m)})} + e^{-\lambda_n A_{(i+1,m)}} \quad (6)$$

Denote $r'_{(i+1,m)}$ as the distance between a node in $\Xi(i+1,m)$ and the sink node. Thus $E(min(r'_{(i+1,m)}))$ can be calculated as

$$E(min(r'_{(i+1,m)})) = \int_{r_{(i+1,m)}}^{r_{(i+1,m)}+upper_{(i+1,m)}} \varphi(r)dr \quad (7)$$

where $\varphi(r) = 2r^2\lambda_n\pi \cdot e^{-\lambda_n\pi(r^2 - r^2_{(i+1,m)})}$ and

$$upper_{(i,j)} = \begin{cases} \delta & \text{if } 1 \le j \le M_i - 1 \\ \delta_{l(i)} & \text{if } j = M_i \end{cases} \quad (8)$$

Exploiting the value of $E(min(r'_{(i+1,m)}))$, the probability $\rho_{(i+1,m,k)}$ can be calculated as

$$\rho_{(i+1,m,k)} = \frac{g_{(i+1,m,k)}(E(min(r'_{(i+1,m)})))}{g_{(i+1,m)}(E(min(r'_{(i+1,m)})))} \quad (9)$$

where $g_{(i+1,m)}$ is the function for $\Omega_{(i+1,m)}$, and $g_{(i+1,m,k)}$ is the function for $\Omega_{(i+1,m,k)}$.

B. Sub-Region Selection Probability

Based on the node selection probability derived in previous section, the probability for a certain number of the nodes to choose sensors in a certain sub-region will be obtained in this section.

Suppose that all the nodes in $\Xi(i,j)$ have $\eta_{(i,j,k)}$ nodes within the communication range in $\Xi(i+1,k)$. Let random variable, $m_{(i,j,k)}$, represent the number of nodes in $\Xi(i+1,k)$ to choose nodes in $\Xi(i,j)$. Thus, $m_{(i,j,k)}$ is considered as a binomial random variable with parameters $(\eta_{(i,j,k)}, \rho_{(i+1,k,j)})$. The probability for $m_{(i,j,k)}$ to be m is given by

$$P_r(m_{(i,j,k)} = m) = \binom{\eta_{(i,j,k)}}{m} \rho^m_{(i+1,k,j)} \cdot (1 - \rho_{(i+1,k,j)})^{\varsigma} \quad (10)$$

where $\varsigma = \eta_{(i,j,k)} - m$. In order to fully achieve this probability, the parameter $\eta_{(i,j,k)}$ needs to be estimated.

The estimation of this value needs the support of following result presented in [8]: If the probability for a point being in one circle is a constant value p, the expectation value for the total area of κ circles intersecting the plane domain with area B can be calculated as

$$E(X) = B(1 - (1-p)^{\kappa}) \quad (11)$$

Let $X_{(i,j,k)}$ represent the area of the region that formed by the intersection of the circle with radius r_t, centred at some node in $\Xi(i,j)$, and sub-region $\Xi(i+1,k)$. Also denote the probability for a point locating in $X_{(i,j,k)}$ as $p_{(i,j,k)}$. It can be derived as

$$p_{(i,j,k)} = \frac{X_{(i,j,k)}}{A_{(i+1,k)}} \quad (12)$$

$X_{(i,j,k)}$ can be expressed as following function

$$X_{(i,j,k)} = f_{\delta(i,j,k)}(x_{\delta(i,j)}) \quad (13)$$

where $x_{\delta(i,j)}$ is the distance between the node and the inner-boundary of $\Xi(i,j)$. When the value of δ is small enough, it can be estimated through the expectation of the maximum value of $x_{\delta(i,j)}$, $E(max(x_{\delta(i,j)}))$.

Denote $F(x)$ as the cumulative distribution function of $max(x_{\delta(i,j)})$. It can be given by

$$F(x) = (1 - e^{-\lambda_n A_{(i,j)}(x)}) \cdot e^{-\lambda_n(A_{(i,j)} - A_{(i,j)}(x))} \quad (14)$$

Hence $E(max(x_{\delta(i,j)}))$ can be calculated as

$$E(max(x_{\delta(i,j)})) = \int_0^{upper_{(i,j)}} xe^{\alpha(x)} \cdot (2x + \lambda_n\pi)dx \quad (15)$$

where $\alpha(x) = -\lambda_n\pi(2r_{(i,j)} \cdot (upper_{(i,j)} - x) + upper^2_{(i,j)} - x^2)$. Leveraging this result, the value of $p_{(i,j,k)}$ can be estimated by

$$p_{(i,j,k)} = \frac{f_{\delta(i,j,k)}(E(max(x_{\delta(i,j)})))}{A_{(i+1,k)}} \quad (16)$$

Let $\kappa_{(i,j)}$ represent the number of nodes in $\Xi(i,j)$. According to Poisson distribution of the sensor nodes, $\kappa_{(i,j)}$ can be calculated as

$$\kappa_{(i,j)} = \lambda_n A_{(i,j)} \quad (17)$$

Denote $A_{(i,j,k)}$ as the total area formed by the intersections of the transmission regions of all the nodes in $\Xi(i,j)$ and the sub-region $\Xi(i+1,k)$. Based on (11), $A_{(i,j,k)}$ can be derived as

$$A_{(i,j,k)} = A_{(i+1,k)} \cdot (1 - (1 - p_{(i,j,k)})^{\kappa_{(i,j)}}) \quad (18)$$

Exploiting this estimation, the value of the number of nodes in $\Xi(i+1,j)$, which can choose the nodes in $\Xi(i,k)$ as data relay nodes, $\eta_{(i,j,k)}$, can be calculated as

$$\eta_{(i,j,k)} = \lambda_n \cdot A_{(i,j,k)} \quad (19)$$

C. Estimated Sub-Region Data Amount

Using the results obtained in the previous sections, the expected data transmission amount of each sub-region in each region will be derived in this section.

In accordance with the binomial distribution of $m_{(i,j,k)}$, the expectation of this random variable can be derived as

$$E(m_{(i,j,k)}) = \eta_{(i,j,k)} \cdot \rho_{(i+1,k,j)} \quad (20)$$

Let $m_{(i,j)}$ be the number of nodes that select nodes in $\Xi(i,j)$ as relay nodes. The expectation of $m_{(i,j)}$ can be obtained as

$$E(m_{(i,j)}) = \sum_{k=1}^{\Delta_{(i,j)}} E(m_{(i,j,k)}) \quad (21)$$

where $\Delta_{(i,j)}$ stands for the largest sub-region number in region $i+1$ that can use the nodes in $\Xi(i,j)$ as data relay nodes. Through this result, the value of the total data amount, $D_{(i,j)}$, and the average data amount, $d_{(i,j)}$, for the nodes in $\Xi(i,j)$ to transmit, can be derived as below.

For the region G-1, these values can be obtained as

$$D_{(G-1,i)} = l(E(m_{(G-1,i)}) + \lambda_n \cdot A_{(G-1,i)}) \tag{22}$$

$$d_{(G-1,i)} = l(\frac{E(m_{(G-1,i)})}{\lambda_n A_{(G-1,i)}} + 1) \tag{23}$$

For region i with $(G-2) \leq i \leq 1$, the calculation is given by

$$D_{(i,j)} = \sum_{k=1}^{\Delta_{(i,j)}} d_{(i+1,k)} \cdot E(m_{(i,j,k)}) + l\lambda_n A_{(i,j)} \tag{24}$$

$$d_{(i,j)} = \frac{D_{(i,j)}}{\lambda_n A_{(i,j)}} \tag{25}$$

D. Routing Balance Ratio

In this section, a measure is proposed to evaluate the degree of unbalanced energy consumptions of the sub-regions in each region.

The ideally balanced data transmission amount for each node of region i in the network, represented by ds_i, can be calculated as

$$ds_i = \frac{D_{all(i)}}{\lambda_n A_i} \tag{26}$$

where A_i is the area of region i and $D_{all(i)}$ represents the total amount of data for the nodes in region i to transmit. $D_{all(i)}$ can be derived as

$$D_{all(i)} = \sum_{j=1}^{M_i} D_{(i,j)} \tag{27}$$

where $D_{(i,j)}$can be evaluated by (22) or (24). The *routing balance ratio* for $\Xi(i,j)$ can then be defined as

$$\Psi_{(i,j)} = \frac{d_{(i,j)}}{ds_i} \tag{28}$$

It is noted that the energy consumption of the sub-region $\Xi(i,j)$ is more balanced, if the value of $\Psi_{(i,j)}$ is closer to 1. The value larger than 1 indicates that certain part of the network is overused. While a value smaller than 1 implies that the workflow for the corresponding sub-region is lower than its capacity.

IV. Region Constraint Selection Scheme

Through the numerical results of the analytical model and simulation results presented in section V, it indicates that the random selection scheme suffers seriously from the spatially unbalanced energy consumption. In this section, the region constraint scheme is proposed to tackle this problem.

A. Scheme Description

The proposed region constraint node selection scheme restricts the relay nodes selection area of certain node. In order to achieve this goal, the parameter S, which is leveraged to control the node selection region, is illustrated in Fig. 2 and defined as

Definition 1: S is the length of a sub-segment, of the segment determined by the sink node and certain sensor node,

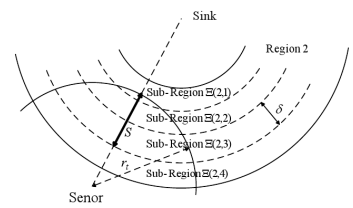

Fig. 2. The definition of S

starting at the point with the distance of r_t to this sensor node on the segment, following the direction to this node.

With this region constraint parameter, the selection area of a node can be restricted. The sub-regions, in which the sensors can be selected by this node, are those covered by this sub-segment with the length of S, in the next inner-region of the region the node belongs to. This scheme allows the nodes to select relay nodes randomly among the sensors in this controlled selection area. As a result, through the usage of a proper value of S, the energy usage for nodes in different sub-regions can be balanced.

B. The Modification of Node Selection Probability

Since the further limited node selection area leads to the change of the number of sensors that have the potential to be selected by certain node(i.e. the value of $\Phi_{(i,k)}$), the calculation of the node selection probability, $\rho_{(i+1,m,k)}$, needs to be modified to analyse this scheme.

Define $g_{c(i+1,m)}(r'_{(i+1,m)})$ as the function for calculating the value of $\Phi_{(i+1,m)}$ of the region constraint node selection scheme. Also let $A_{outer}(r',r)$ be the function of the area formed by the intersection of the coverage area of the node with distance r' to the sink node, and the circle with radius r centred at sink node. Leveraging the function $A_{outer}(r',r)$, $g_{c(i+1,m)}(r'_{(i+1,m)})$ can be calculated. The node selection probability for the region constraint node selection scheme, $\rho_{c(i+1,m,k)}$, can be calculated as

$$\rho_{c(i+1,m,k)} = \frac{g_{(i+1,m,k)}(E(min(r'_{(i+1,m)})))}{g_{c(i+1,m)}(E(min(r'_{(i+1,m)})))} \tag{29}$$

With this result, the probability for m nodes to choose nodes in $\Xi(i,k)$ presented by (10) can be modified to the following formula for this scheme.

$$P_r(m_{(i,k,j)} = m) = \begin{pmatrix} \eta_{(i,k,j)} \\ m \end{pmatrix} \rho^m_{c(i+1,j,k)} \cdot (1-\rho_{c(i+1,j,k)})^{\varsigma} \tag{30}$$

where $\varsigma = \eta_{(i,k,j)} - m$.

C. The Modification of Estimated Sub-region Data Amount

Since the selection region constraint parameter limits the node selection area, it is necessary to modify equations (21) and (24), in order to estimate the expectation of the value of $m_{(i,j)}$ for this scheme.

Denote $\zeta_{(i,j)}$ as the start value of the summation in (21) and (24). This value is the first sub-region number, in which the

sensors can select the nodes in $\Xi(i,j)$ as relay node. Exploiting this notation, the (21) and (24) can be re-written as

$$E(m_{(i,j)}) = \sum_{k=\zeta_{(i,j)}}^{\Delta_{(i,j)}} E(m_{(i,j,k)}) \tag{31}$$

$$D_{(i,j)} = \sum_{k=\zeta_{(i,j)}}^{\Delta_{(i,j)}} d_{(i+1,k)} \cdot E(m_{(i,j,k)}) + l\lambda_n A_{(i,j)} \tag{32}$$

The modification of the model can be used to analyse the node selection region constraint scheme. According to (30), the equation (20) can be modified as

$$E(m_{(i,j,k)}) = \eta_{(i,j,k)} \cdot \rho_{c(i+1,k,j)} \tag{33}$$

D. The Applying of the Scheme

Once the network parameters are specified by the application, the optimum value of S can be obtained through the calculation of the mathematical model presented above, as shown in section V-C, and configured into the operating system of the sensor nodes. Since the position information of the neighbouring nodes is able to be gathered through an initialisation process, a sensor node can simply use the information to determine whether a node is a candidate next hop, by checking whether it is in the region constrained by S internally, without the necessity of adjusting the transmission range.

V. Experimental Results

In this section, both the numerical results and the simulation results will be presented. Through the results of the routing balance ratio, the problem of the spatially unbalanced energy consumption for the random node selection scheme will be demonstrated. Then the results of this measure for the region constrained mechanism will show its improvement to this issue. At the end of this section, the performances of the two node selection strategies mentioned in this paper will be evaluated and compared through simulations.

Simulations are issued by the Java based network simulator J-SIM[9][10][11], on which some necessary modifications have been made. The numerical results are obtained through MATLAB.

A. Parameter Settings

In order to establish the experiments, proper parameters for both the sensor nodes and the network should be exploited. In this section the parameter settings of the experiments will be explained.

1) Sensor Node Parameters: As the experiments need to evaluate the energy consumption of each node, proper model for energy consumption for the radio transceiver must be applied. In this paper the model used is as follows[12]

$$e_{tx} = e_{elec} + e_{amp} d^{\beta} \tag{34}$$

In the equation above, the e_{elec} is the energy consumed for activating the circuit of radio transceiver and the e_{amp} is for the transceiver amplifier to communicate. The d is the transmission distance, which is set to r_t in this paper. For the experiments, the hardware parameters for each sensor node are selected similar to the Motes[13][14]. Table II lists the settings for all the hardware parameters used in the experiments, in which the e_{ini} is the initial amount of power supply for each sensor node.

TABLE II
Sensor Node Parameter Settings

Parameter Name	Value
e_{ini}	$2J$
e_{elec}	$5.0 \times 10^{-11} J/bit$
e_{amp}	$1.0 \times 10^{-11} J/bit$
β	2
r_t	$40m$

2) Network Parameters: In addition to the configurations of the nodes, the settings of the network parameters should also be allocated. In Table III the values of these settings used in this paper are listed.

TABLE III
Network Parameter Settings

Parameter Name	Value
r'_t	$30m$
G	7
l	$640bits$

The region width, r'_t, is set to $30m$, so that each node in one region can communicate with at least one node in the adjacent inner-region. Still this value is close enough to the transmission range, so that the number of hops for the data transmission can be decreased.

In order to analyse the performance of the mechanism, the value of the parameter δ needs to be correctly chosen. In this paper δ is chosen to fulfil the requirement $\lambda_n A_{(1,1)} \geq 1$. In Table IV the values of δ for the three network densities used in the experiments of this paper are listed.

TABLE IV
The Value of δ

Network Density (λ_n)	δ
0.1	$2m$
0.04	$6m$

B. Routing Balance Ratio for Random Scheme

In Fig. 3 and 4 the routing balance ratios for each sub-region of three regions, according to two network density values are presented. These results indicate that with random node selection mechanism the spatially unbalanced energy consumption is serious. From the curves, it can be noticed that the sensors in the sub-regions further from the inner-boundary of the region need to consume more energy than those in the inner-sub-regions.

The corresponding simulation results for the network density values, 0.1 and 0.04 are provided from Fig. 5 to Fig. 6.

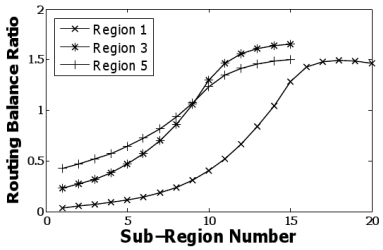

Fig. 3. Routing Balance Ratio($\lambda_n = 0.1$)

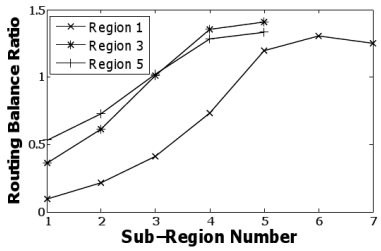

Fig. 4. Routing Balance Ratio($\lambda_n = 0.04$)

Each value of the simulation results is the average of the results of 1000 runs. The figures prove that simulated system performs the same spatially unbalanced energy consumption characteristic, as predicted by the mathematical model proposed in previous sections. In addition it is also clear that the distortions between the simulation results and the numerical results are acceptable. This proves the accuracy of the mathematical model for random node selection mechanism presented in this paper.

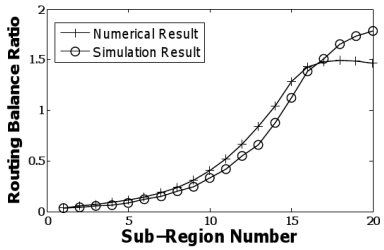

Fig. 5. Routing Balance Ratio(Region 1, $\lambda_n = 0.1$)

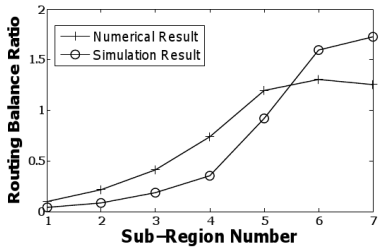

Fig. 6. Routing Balance Ratio(Region 1, $\lambda_n = 0.04$)

C. Routing Balance Ratio for Region Constraint Scheme

In this section the results of routing balance ratio for the region constraint node selection scheme are presented. As mentioned in section IV, the value of the parameter S is crucial for the performance of this mechanism. Thus in the first part of this section, the problem of how to find the proper S is discussed. In the second part, the results of routing balance ratio are provided based on the chosen values of S.

1) The Setting of S: The value of S can be determined by the results of the mathematical model, with different configurations of this parameter. Since the maximum number of the routing balance ratio is important for the system, the proper setting of S is selected as the value, which leads to the lowest routing balance ratio.

In Fig. 7 and 8 the maximum routing balance ratio of different region, under various values of S, for the two values of network density are provided respectively. Through these results the proper values for S can be clearly determined. The values used in this paper are given in Table V.

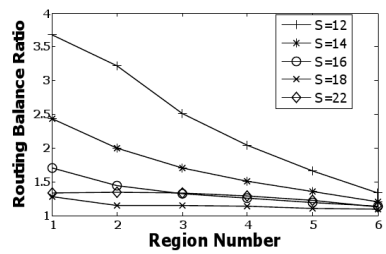

Fig. 7. Maximum Routing Balance Ratio($\lambda_n = 0.1$)

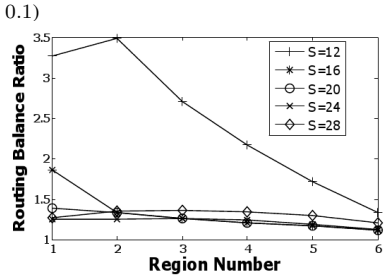

Fig. 8. Maximum Routing Balance Ratio($\lambda_n = 0.04$)

TABLE V
THE VALUE OF S

Network Density (λ_n)	S
0.1	$18m$
0.04	$24m$

2) Results of Routing Balance Ratio: Fig. 9 and 10 provide the numerical results of the routing balance ratio, for the region constraint node selection scheme, according to the two network densities. These results of the analytical model indicate that through region constraint scheme, the maximum

values of the routing balance ratio decrease for all the conditions examined, comparing to the random scheme. This improvement is caused by forcing more data to be transmitted through the inner-sub-regions of a region. From the figures, it can be noticed that the curves are much flatter than those for the random scheme. In Fig. 11, the simulation result of routing

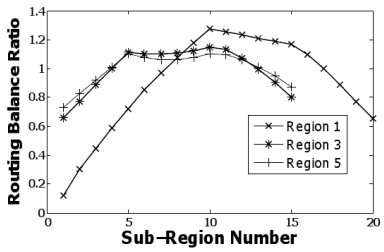

Fig. 9. Routing Balance Ratio($\lambda_n = 0.1$)

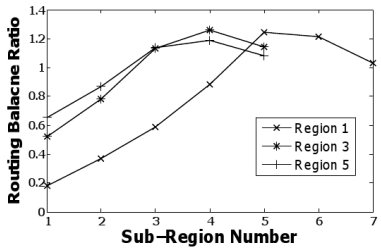

Fig. 10. Routing Balance Ratio($\lambda_n = 0.04$)

balance ratio for sub-region 1, according to network density 0.1 is provided along with the corresponding numerical result. Fig. 12 presents the corresponding result for the network density 0.04. These results prove the accuracy of the analytical model for the region constrained selection scheme. Fig. 13 and 14 present the simulation results for the maximum values of routing balance ratio for each region, obtained by random and region constraint scheme, according to the network density values of 0.1 and 0.04 respectively. These results imply that the energy usages for region constraint scheme are more balanced than the random node selection mechanism.

D. Performance

In this section, the simulation results for evaluating the performances of random selection scheme and region constraint strategy are presented. The definition of lifetime used in this section is the time, during which all the nodes are alive. This period of time is measured through the number of transmission cycles. As scheduled nodes can be regarded as working in groups, it is proper to evaluate only one group of nodes with density λ_n[6]. Based on the results in previous sections, the unbalanced energy consumption levels among sub-regions in region 1 for both random scheme and the region constraint scheme are high. Thus region 1 is the typical region for evaluating the performances of the two mechanisms.

Table VI presents the results of lifetime of the two schemes, obtained through simulation experiments, under the network

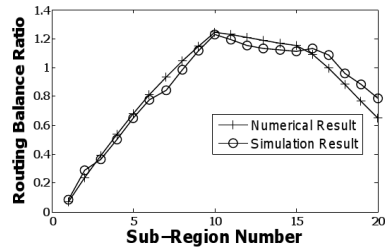

Fig. 11. Routing Balance Ratio(Region 1, $\lambda_n = 0.1$)

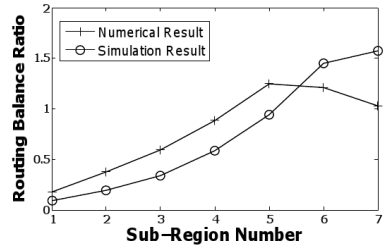

Fig. 12. Routing Balance Ratio(Region 1, $\lambda_n = 0.04$)

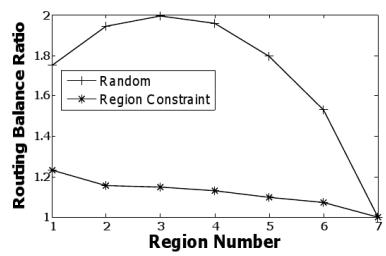

Fig. 13. Maximum Routing Balance Ratio($\lambda_n = 0.1$)

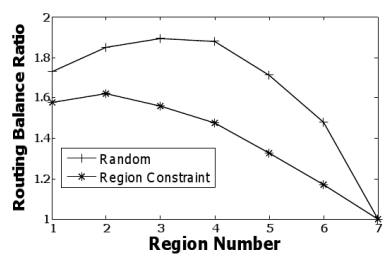

Fig. 14. Maximum Routing Balance Ratio($\lambda_n = 0.04$)

densities of 0.1 and 0.04. The results indicate that the region constraint node selection scheme highly prolongs the lifetime of region 1, in comparison to the random mechanism. The reason for the performance improvement under network density 0.04 to be not as dramatic is that for the sparse network, the spatial distribution of the nodes among regions will be more random. This randomness will affect the performance of the region constraint strategy.

TABLE VI
PERFORMANCE RESULT

Network Density	Random Scheme	Region Constraint Scheme
0.1	2030	3794
0.04	2274	2603

VI. RELATED WORKS

The problem of designing energy balanced routing scheme for wireless sensor networks is examined by [15], [16], [17], [18], [19], [20] and [21]. In [15] and [16], the strategy of using optimized multiple paths to balance the power usage of data transmission is considered. A parameterized spatial energy balancing routing strategy for wireless networks is proposed in [15], which spreads the data flow for each session in different transmitting paths. In [16] a basestation controlled mechanism is presented to adjust the traffic flow among different data relay routes. A different method of adjusting the transmission range to achieve the balanced energy usage is theoretically analysed in [17]. The mechanisms in [18] and [19] are based on Directed Diffusion[22]. In [18] an algorithm is provided to choose the optimal path in sensor networks for data transmission considering global energy balance and limited delivery delay. The authors of [19] designed the fuzzy next-hop selecting strategy to further balance the energy consumption of Directed Diffusion. The article [20] proposed a swarm intelligence based energy balance routing scheme, based on the neighbours' weight and residual energy. A strategy that trades off the energy consumption and the latency in accordance with the route length is proposed in [21]. All these works have not considered the issue of balancing the energy consumption for region-by-region routing, used in the non-uniform deployed sensor network. As far as we know, till now no work has rigorously examined the problem of spatially unbalanced energy consumption, for the non-uniform deployed sensor network.

VII. CONCLUSION

In this article, the problem of the spatially unbalanced energy consumption problem of the region-by-region routing scheme is examined.

The results of the analytical model and simulation experiments illustrate that the pure random node selection scheme suffers seriously from this problem. As a resolution, this paper provides the region constraint scheme without need of the energy information. Experimental results show that this scheme makes noticeable improvements of performance, in comparison to the random mechanism.

The issue of designing the node deployment strategy, in accordance with the analytical result of unbalanced energy consumption problem presented in this paper, will be examined in the future.

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