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Research Article

Energy Efficiency and QoS Enhancement for Wireless Sensor Networks with Applications to Long-Narrow Structures

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There is a class of special environments, such as roads, mines tunnels, rivers, bridges, and pipelines, whose geographical shapes are long-narrow for several hundred meters. Wireless sensor networks (WSN) can be applied to monitor these environments. Long-narrow structure makes the WSN face plenty of challenges, such as unbalanced energy consumption and data aggregation. This paper proposes a nonuniform symmetric cluster model (NUSCM) using reasonable coverage routing controlling. The NUSCM consists of two base stations, sensor node clusters (SNCs) and transmission node clusters (TNCs), which can make the sensor networks be scalable to cover various long-narrow structures. Hierarchical nodes spacing and routing strategy of NUSCM are addressed. Furthermore, we simulate the proposed NUSCM, in comparison with the nonuniform deployment with two base stations (NUD-TBS) and uniform deployment with two base stations (UD-TBS). Research results indicate that the NUSCM and NUD-TBS have the same energy efficiency, which are better than that of UD-TBS. Moreover, NUSCM is superior to the UD-TBS and NUD-TBS in the link communication load and network survivability.

1. Introduction

With the development of wireless sensor networks (WSN) [1], sensing, processing, communicating, and other tasks can be collaboratively completed by self-organizing network, which is formed through multihop in monitoring areas [2]. There is a kind of special monitoring environment with long-narrow structures, such as roads, mine underground tunnels, and pipelines [3]. WSN can be used to locate mobile target, for vehicles in the corridor, miners in the mine underground tunnel, and boats in the river [4]. These networks are fundamentally different from traditional wireless sensor networks, where sensor nodes are deployed along long and narrow geographic regions. Compared with conventional square network scenarios or circular network scenarios, the quality of service (QoS) for long-narrow structures has many challenges [5].

(1) Unbalanced energy consumption: an increase in data quantity will unbalance energy consumption along the length direction, which makes the sensor nodes have different lifetime.

(2) Weak network survivability: a failure of partial sensor nodes can result in the failure of the entire network in dusty, noisy, and humid environment.

(3) Long data delay: the perceived parameter is transmitted from the head to base station through multihop, which will cause long data delay.

For the limitation of nodes battery and computing power of WSN, long-narrow structures make the network face much more challenges, such as unbalanced energy consumption, weak network survivability, and long data delay. Under the situation of limited resource and challenges, coverage routing controlling is the key to improving the performance of network resource [6]. It has been regarded as an effective method to attain network optimization, which can be divided into determinate coverage and random coverage according to whether wireless nodes can identify their locations [7, 8]. As long-narrow structure is a kind of determinate environment, coverage routing can be designed based on monitoring requirements and topological structures [9]. A few scholars have done some researches on coverage routing controlling, which can be classified as uniform deployment, nonuniform deployment, probability deployment, cluster deployment, and more. Reviews on coverage routing controlling are as follows.

Qiao and Zeng [10] made sensor nodes with uniform deployment (UD) and base station with center deployment along length direction. The perceived parameters were transmitted to base station at the center, which can make the sensor nodes transmit data quantity with shorter routing path in comparison with base station at the tail. However, the UD would still lead to unbalanced energy consumption, especially energy black-hole effect problem near the base station. In order to deal with the unbalanced energy consumption along length direction, Wu and Chen [11] proposed a nonuniform deployment (NUD) that can achieve the suboptimal energy efficiency and make the network attain balanced energy consumption. Jawhar et al. [12] built a hierarchical addressing scheme (HAS) for long-narrow structures, which consists of basic sensor nodes (BSN), data relay nodes (DRN), and data discharge nodes (DDN). However, data quantity of the BSN presented draw-bridging effect, which made the lifetime of the BSN present antidraw bridging effect. Then energy black-hole effect came out. With respect to addressing bridging effect and energy black-hole effect, Jawhar et al. proposed two hypotheses: variable initial energy capacity of DRN nodes and variable distance between DRN nodes. Li et al. [13] proposed a method that sensor nodes were deployed nonuniformly along length direction, which prevented sensor nodes near base station from dying quickly. Nevertheless, the method is only suitable for these networks with shorter length. Noori and Ardakani [14] described the long-narrow structure about traffic condition monitoring. Owing to the irregular traffic load, the deployment of sensor nodes was random. Then authors confirmed that sensor nodes near base station were the bottleneck of entire network performance and gave a solution to enhance the performance. However, without considering energy consumption in different locations, the random deployment of sensor nodes resulted in uncertain connectivity of the network. Zimmerling et al. [15] put forward a local energy aware routing protocol of minimum energy relay routing (MERR) and adaptive MERR (AMERR) based on Poisson deployment model of nodes. These coverage routing protocols can be extended to general two-dimensional scenes. Liu and Shi [16] organized sensor nodes into a few clusters that can meet various requirements and then summarized some typical clustering routing protocols, which may be used in these WSN.

This paper designs an innovative architecture for the network and proposes a cluster model of sensor nodes with nonuniform deployment for long-narrow structure. Considering node deployment strategy and routing path, this paper deploys two base stations at the head and tail and nonuniformly deploys sensor node clusters and transmission node clusters. The model proposed in this paper will spread “hot zone” of the network to various sensor node clusters, shorten data transmission path, and reduce transmission latency.

2. Problems Analysis

2.1. Sensing Scene of WSN. Sensing scene is a kind of long-narrow structure, which can be expressed as narrow band structure. Without loss of generality, sensing scene enclosed by two thick solid lines is rectangle [17]. Figure 1 describes uniform deployment (UD) of sensor nodes in WSN. The sensor nodes are alternately deployed with the same spacing distance. As shown in Figure 1, every sensor node cannot directly communicate with the base station in long-narrow structures. Perceived parameters are transmitted to the base station through multihop. Then, there is the phenomenon of data aggregation at the base station, which can be described as black shadow. The increased data quantity along length direction can consume more energy along length direction and make sensor nodes die quickly at the base station.

Under UD model, the sensor nodes have different life time along length direction. In order to balance energy consumption, the nonuniform deployment (NUD) model is proposed as shown in Figure 2. The energy consumption not only relates to the amount of data, but also associates with the spacing distance among sensor nodes. The spacing distance can affect the energy consumption in transmitter circuit and receiver circuit. If the amount of data between two sensor nodes is the same, shorter spacing distance between two sensor nodes would reduce the energy consumption. Hence, the density of sensor nodes needs to increase when the amount of data increases along length direction.

Sensor nodes at different locations need to have different deployment density. Hence, the NUD model among sensor nodes is adopted, which can make the energy consumption balance. But the perceived data of sensor node SN_i needs to be transmitted from sensor node SN_i to SN_n along length direction. In the long-narrow structure, when a node runs out of energy, the node cannot receive perceived data from its neighboring node and forward the perceived data to its neighboring node, which make the network unconnected. The death of sensor nodes will make the network ineffective and unreliable. Commonly, the length of these structures is mainly thousands of meters. A long distance will make the network suffer from serious data aggregation, data transmission latency, and weak network survivability. A simple and effective way is to deploy base stations at the head and tail. Figure 3 describes uniform deployment with two base stations (UD-TBS) and nonuniform deployment with two base stations (NUD-TBS). The UD-TBS and NUD-TBS make the network transmit the perceived data in two directions, which partly eases the problems of data aggregation, data transmission latency, and weak network survivability.

2.2. An Innovative Architecture for WSN. To improve network performance, this paper proposes an innovative architecture called a nonuniform symmetric cluster model (NUSCM). The lowest layer consists of common sensor nodes which are used to perform the sensing tasks. The data gathered by the

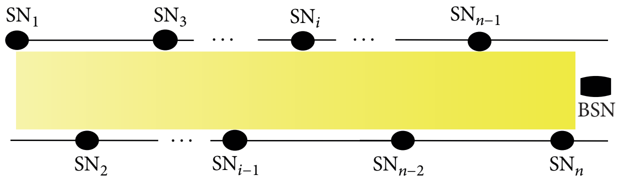

Figure 1: Sensing scene of uniform deployment.

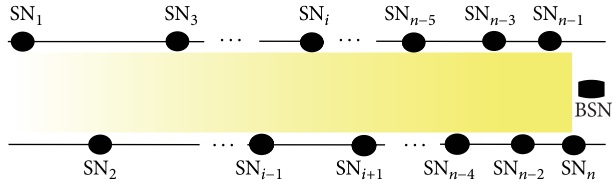

Figure 2: Sensing scene of nonuniform deployment.

common sensor nodes is transmitted to sensor node head by multihop. All common sensor nodes and sensor node head form a sensor node cluster (SNC). The SNC not only senses the parameters, but also transmits the perceived data. The second layer consists of transmission nodes which are served as forwarding the perceived data from the SNC to a base station node (BSN). All transmission sensor nodes are grouped into several transmission node clusters (TNCs). The TNC is in charge of transmitting the data from SNC to BSN.

The SNCs and TNCs are deployed on both sides of the network, respectively, whose spacing distance is calculated based on data quantity. There are m SNCs and m TNCs. Each of SNC and TNC is expressed as SNC_i and TNC_i. The BSNs with limitless energy are deployed at the head and tail, respectively. All SNCs, TNCs, and BSNs can form an innovative architecture.

Then, we propose the sensing model of NUSCM:

$$\mathrm{NUSCM} = \langle \mathrm{BSNs}, \mathrm{SNCs}, \mathrm{TNCs} \rangle, \tag{1}$$

where $\mathrm{BSNs} = \{\mathrm{BSN}_1, \mathrm{BSN}_2\}$ are base station nodes at the head and tail; $\mathrm{SNCs} = \{\mathrm{SNC}_1, \mathrm{SNC}_2, \ldots, \mathrm{SNC}_i, \ldots, \mathrm{SNC}_m\}$ are sensing node clusters of NUSCM, $i = \{1, 2, 3, \ldots, m\}$; every sensing node cluster SNC_i denotes the set of sensor nodes, $\mathrm{SNC}_i = \{\mathrm{SNC}_i^1, \mathrm{SNC}_i^2, \ldots, \mathrm{SNC}_i^j, \ldots, \mathrm{SNC}_i^{ns_i}\}$, $j = \{1, 2, 3, \ldots, ns_i\}$; $\mathrm{TNCs} = \{\mathrm{TNC}_1, \mathrm{TNC}_2, \ldots, \mathrm{TNC}_i, \ldots, \mathrm{TNC}_m\}$ are transmission node clusters of NUSCM, $i = \{1, 2, 3, \ldots, m\}$; every transmission node cluster TNC_i denotes the set of transmission nodes, $\mathrm{TNC}_i = \{\mathrm{TNC}_i^1, \mathrm{TNC}_i^2, \ldots, \mathrm{TNC}_i^j, \ldots, \mathrm{TNC}_i^{nt_i}\}$, $j = \{1, 2, 3, \ldots, nt_i\}$.

It is obvious that the NUSCM can be easily expanded by adding more SNCs and TNCs for long-narrow structure. In order to maximize NUSCM survival time and minimize deployment nodes, sensors nodes deployment and routing scheme are needed to be tackled [18].

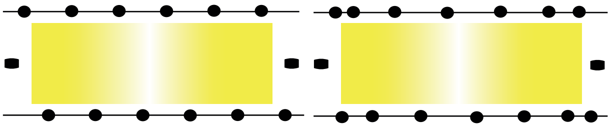

Figure 3: Sensing scene of uniform deployment and nonuniform deployment with two base stations.

3. Energy Efficiency and QoS Enhancement for NUSCM

3.1. Energy Model. Wireless communication consumes a lot of energy in WSN. This paper focuses on the related energy consumption of sensor nodes. Nodes energy consumption is mainly in the transmitter circuit and receiver circuit. Then it is given as follows [19]:

$$\begin{aligned} e_c(\mathrm{SN}_i) &= e_{\mathrm{trs}}(k_{\mathrm{trs}}) + e_{\mathrm{trs}}(k_{\mathrm{trs}}, d) + e_{\mathrm{rcv}}(k_{\mathrm{rcv}}) \\ &= Bk_{\mathrm{trs}}e_{\mathrm{elec}} + Bk_{\mathrm{trs}}d^{\alpha}\varepsilon_{\mathrm{amp}} + Bk_{\mathrm{rcv}}e_{\mathrm{elec}}, \end{aligned} \tag{2}$$

where $e_c(\mathrm{SN}_i)$ is the energy consumption; k_{trs} is data quantity by transmitter circuit; k_{rcv} is data quantity by receiver circuit; B is the bit contained in one data; e_{elec} is the energy consumption of transmitter and receiver circuit; $\varepsilon_{\mathrm{amp}}$ is energy efficiency of channel model; d is the distance between two nodes; α is path loss exponent; ξ is the ratio of e_{elec} and $\varepsilon_{\mathrm{amp}}$, $\xi = e_{\mathrm{elec}}/\varepsilon_{\mathrm{amp}}$.

The lifetime of wireless single node is described as

$$T(\mathrm{SN}_i) = \frac{e_{\mathrm{ini}} - e_{\mathrm{min}}}{e_c(B, d)} = \frac{e_{\mathrm{ini}} - e_{\mathrm{min}}}{Bk_{\mathrm{trs}}e_{\mathrm{elec}} + Bk_{\mathrm{trs}}d^2\varepsilon_{\mathrm{amp}} + Bk_{\mathrm{rcv}}e_{\mathrm{elec}}}, \tag{3}$$

where $T(\mathrm{SN}_i)$ is the lifetime of wireless node; e_{ini} is the initial energy of nodes; e_{min} is the minimum energy when nodes run out of energy.

Due to the limited energy and the different data quantity of the SNCs and TNCs, the lifetime of all nodes is not always the same. In order to prolong the lifetime of the network, the best situation is the one that all nodes of the SNCs and TNCs have the same survival time. So two constraints need to be satisfied:

$$\begin{aligned} T(\mathrm{SNC}_i) &= T(\mathrm{SN}_i^1) = T(\mathrm{SN}_i^2) = \cdots = T(\mathrm{SN}_i^j) \\ &= \cdots = T(\mathrm{SN}_i^{ns_i}), \end{aligned} \tag{4a}$$

$$\begin{aligned} T(\mathrm{TNC}_1) &= T(\mathrm{TNC}_2) = \cdots = T(\mathrm{TNC}_i) \\ &= \cdots = T(\mathrm{TNC}_m), \end{aligned} \tag{4b}$$

where $T(\mathrm{SNC}_i)$ means the lifetime of every SNC; $T(\mathrm{SN}_i^j)$ means the lifetime of every sensor node; $T(\mathrm{TNC}_i)$ means the lifetime of every TNC.

Equation (4a) means that the common sensor nodes of a SNC consume their energy at the same time. Equation (4b) illustrates that all transmission node clusters use up their energy at one time. In order to realize the best network performance of the NUSCM, the designed routing scheme and calculated node deployment are applied in the following section.

3.2. Nodes Deployment in a SNC. Figure 4 shows the routing scheme among SNC_i. The SNC_i consists of ns_i sensor nodes, which can be expressed as SN_i^j. The designed routing scheme of the SNC_i is proposed to eliminate defects of consuming uneven energy, which is due to data collection and aggregation at different locations. In this paper, each common sensor node is within range of only its neighboring node. Then every common sensor node senses the parameter and transmits it to sensor node head. In fact, common sensor nodes at the side of the cluster SNC_i transmit with the sensor node head $\mathrm{SN}_i^{(ns_i+1)/2}$. Then, the collected data at the sensor node head can be transmitted directly to the transmission node.

When the sensor node SN_i^j locates at the left of the cluster SNC_i, the collected data is transmitted from the common sensor node SN_i^1 to sensor node head $\mathrm{SN}_i^{(ns_i+1)/2}$. The sensor node SN_i^j receives $(j-1)$ B bits from its neighbor SN_i^{j-1}, and then SN_i^j needs to send j B bits to its neighbor SN_i^{j+1}.

From formula (3), we can obtain the lifetime of SN_i^j:

$$T\left(\mathrm{SN}_i^j\right)=\frac{e_{\mathrm{ini}}-e_{\mathrm{min}}}{j\left(Be_{\mathrm{elec}}+B\left(ds_i^j\right)^{\alpha}\varepsilon_{\mathrm{amp}}\right)+(j-1)\,Be_{\mathrm{elec}}},\qquad j<\frac{(ns_i+1)}{2}, \tag{5}$$

where i represents serial number of every cluster, $i=\{1,2,3,\ldots,m\}$; j represents serial number of nodes in a SNC_i, $j=\{1,2,\ldots,(ns_i-3)/2\}$; ds_i^j represents the distance between sensor nodes in a SNC_i.

Meanwhile, the lifetime of SN_i^{j+1} can be expressed as

$$T\left(\mathrm{SN}_i^{j+1}\right)=\frac{e_{\mathrm{ini}}-e_{\mathrm{min}}}{(j+1)\left(Be_{\mathrm{elec}}+B\left(ds_i^{j+1}\right)^{\alpha}\varepsilon_{\mathrm{amp}}\right)+(j)\,Be_{\mathrm{elec}}},\qquad j<\frac{(ns_i+1)}{2}. \tag{6}$$

We can obtain the lifetime of common sensor node. From formula (4a), we have $T(\mathrm{SN}_i^j)=T(\mathrm{SN}_i^{j+1})$:

$$\frac{e_{\mathrm{ini}}-e_{\mathrm{min}}}{j\left(Be_{\mathrm{elec}}+B\left(ds_i^j\right)^{\alpha}\varepsilon_{\mathrm{amp}}\right)+(j-1)\,Be_{\mathrm{elec}}}=\frac{e_{\mathrm{ini}}-e_{\mathrm{min}}}{(j+1)\left(Be_{\mathrm{elec}}+B\left(ds_i^{j+1}\right)^{\alpha}\varepsilon_{\mathrm{amp}}\right)+(j)\,Be_{\mathrm{elec}}},\qquad j<\frac{(ns_i+1)}{2}. \tag{7}$$

Then, formula (7) is simplified:

$$j\left(ds_i^j\right)^{\alpha}-(j+1)\left(ds_i^{j+1}\right)^{\alpha}=2\xi,\qquad j<\frac{(ns_i+1)}{2}. \tag{8}$$

Sensor nodes at different locations can receive and transmit different amounts of data. In order to make all nodes exhaust their energy, the effective method is to give different spacing distances among sensor nodes. Owing to the fact that the data quantity of common sensor nodes from sensor node SN_i^1 to sensor node $\mathrm{SN}_i^{(ns_i-1)/2}$ increases, the spacing distance among the nodes decreases.

As for the sensor node head $\mathrm{SN}_i^{(ns_i+1)/2}$, it need receive (ns_i-1) B bits from its neighbor $\mathrm{SN}_i^{(ns_i-1)/2}$ and $\mathrm{SN}_i^{(ns_i+3)/2}$ and then send ns_i B bits to the transmission node. So, the lifetime of sensor node head $\mathrm{SN}_i^{(ns_i+1)/2}$ can be expressed as

$$T\left(\mathrm{SN}_i^{(ns_i+1)/2}\right)=\frac{e_{\mathrm{ini}}-e_{\mathrm{min}}}{ns_i\left(Be_{\mathrm{elec}}+B\left(ds_i^{(ns_i+1)/2}\right)^{\alpha}\varepsilon_{\mathrm{amp}}\right)+(ns_i-1)\,Be_{\mathrm{elec}}},\qquad j=\frac{(ns_i+1)}{2}. \tag{9}$$

When the collected data is transmitted from the common sensor node $\mathrm{SN}_i^{ns_i}$ to the sensor node head $\mathrm{SN}_i^{(ns_i+1)/2}$, the data of the common sensor from the center to the right is decreasing. Following the process of formulas (5), (6), (7), and (8), the distance relationship of sensor node SN_i^j at the right of the cluster SNC_i can be obtained:

$$(ns_i-j+1)\left(ds_i^j\right)^{\alpha}-(ns_i-j)\left(ds_i^{j+1}\right)^{\alpha}=-2\xi,\qquad j>\frac{(ns_i+1)}{2}. \tag{10}$$

3.3. Nodes Deployment among the TNCs. Figure 5 shows that there are a set of TNCs, described as $\{\mathrm{TNC}_1,\mathrm{TNC}_2,\ldots,\mathrm{TNC}_m\}$. The TNCs on the left of the network receive data from every sensor node cluster and forward the data to the BSN_1 through its neighboring cluster. The TNCs on the right of the network communicate with the BSN_2.

The routing scheme among the TNCs is described as

$$\begin{aligned}&\mathrm{BSN}_1\longleftarrow\mathrm{TNC}_1\longleftarrow\mathrm{TNC}_2\cdots\longleftarrow\mathrm{TNC}_{m/2-1}\\&\qquad\longleftarrow\mathrm{TNC}_{m/2},\quad i\le\frac{m}{2},\\&\mathrm{BSN}_2\longleftarrow\mathrm{TNC}_m\longleftarrow\mathrm{TNC}_{m-1}\cdots\longleftarrow\mathrm{TNC}_{m/2+2}\\&\qquad\longleftarrow\mathrm{TNC}_{m/2+1},\quad i\ge\frac{m}{2}+1.\end{aligned} \tag{11}$$

Based on the routing scheme among the TNCs, every TNC not only transmits the data from its corresponding SNC, but also loads the data from its neighboring TNC. So the data from the $\mathrm{TNC}_{m/2}$ to the TNC_1 increases, while the data from the $\mathrm{TNC}_{m/2+1}$ to the TNC_m increases too. The TNC nearby the BSN needs to transmit the largest amount of data.

When the data is transmitted from the $\mathrm{TNC}_{m/2}$ to the TNC_1, the TNC_i receives $(ns_{i+1}+ns_{i+2}+\cdots+ns_{m/2})$ B bits from

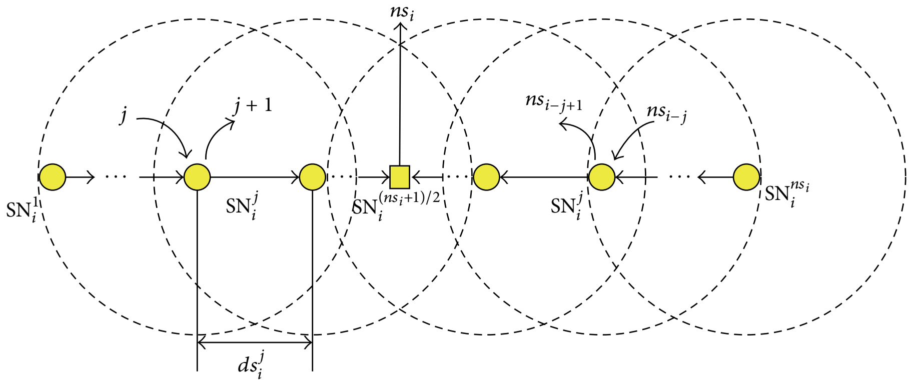

FIGURE 4: Routing scheme among the SNC$_i$.

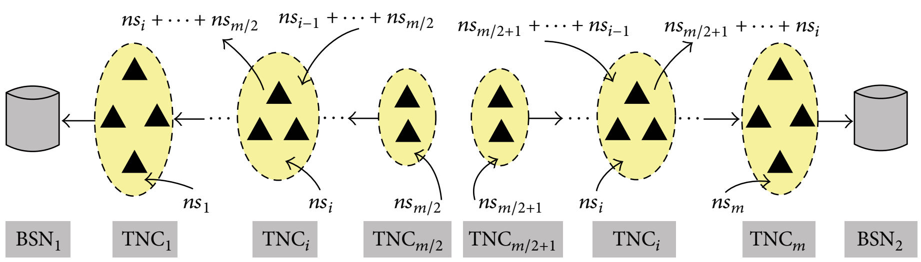

FIGURE 5: Routing scheme among the TNCs.

its neighbor TNC$_{i+1}$ and then sends $(ns_i + ns_{i+1} + \cdots + ns_{m/2})$ B bits to its neighbor TNC$_{i-1}$.

From formula (3), we can obtain the lifetime of TNC$_i$:

$$\begin{aligned} T(\text{TNC}_i) = {} & (e_{\text{ini}} - e_{\min}) \\ & \times \Big((ns_i + ns_{i+1} + \cdots + ns_{m/2}) \\ & \quad \times \left(Be_{\text{elec}} + B (dt_i)^{\alpha} \varepsilon_{\text{amp}} \right) \\ & \quad + (ns_{i+1} + ns_{i+2} + \cdots + ns_{m/2}) Be_{\text{elec}} \Big)^{-1}, \\ & \qquad i < \frac{m}{2}, \end{aligned} \tag{12}$$

where i represents serial number of every transmission node clusters, $i = \{1, 2, 3, \ldots, m/2\}$; dt_i represents the distance among transmission nodes.

Meanwhile, the lifetime of TNC$_{i+1}$ can be expressed:

$$\begin{aligned} T(\text{TNC}_{i+1}) = {} & (e_{\text{ini}} - e_{\min}) \\ & \times \Big((ns_{i+1} + \cdots + ns_{m/2}) \\ & \quad \times \left(Be_{\text{elec}} + B (dt_{i+1})^{\alpha} \varepsilon_{\text{amp}} \right) \\ & \quad + (ns_{i+2} + \cdots + ns_{m/2}) Be_{\text{elec}} \Big)^{-1}, \\ & \qquad i < \frac{m}{2}. \end{aligned} \tag{13}$$

We can obtain the lifetime of every transmission node cluster TNC$_i$. From formula (4b), we have $T(\text{TNC}_i) = T(\text{TNC}_{i+1})$:

$$\begin{aligned} & - (ns_i + ns_{i+1} + \cdots + ns_{m/2}) (dt_i)^{\alpha} \\ & + (ns_{i+1} + \cdots + ns_{m/2}) (dt_{i+1})^{\alpha} \\ & = (ns_{i+1} + ns_i) \xi, \quad i < \frac{m}{2}. \end{aligned} \tag{14}$$

As for the TNC$_{m/2}$, it only sends $ns_{m/2}$ B bits to the TNC$_{m/2-1}$ without receiving data from its neighbor nodes. So, the lifetime of TNC$_{m/2}$ can be expressed as

$$\begin{aligned} T(\text{TNC}_{m/2}) = {} & \frac{e_{\text{ini}} - e_{\min}}{ns_{m/2} \left(Be_{\text{elec}} + B (dt_{m/2})^{\alpha} \varepsilon_{\text{amp}} \right) + 0 Be_{\text{elec}}}, \\ & \qquad i = \frac{m}{2}. \end{aligned} \tag{15}$$

When the data is transmitted from the TNC$_{m/2+1}$ to the TNC$_m$, the TNC$_i$ receives $(ns_{m/2+1} + ns_{m/2+2} + \cdots + ns_{i-1})$ B bits from its neighbor TNC$_{i-1}$ and then sends $(ns_{m/2+1} + ns_{m/2+2} + \cdots + ns_i)$ B bits to its neighbor TNC$_{i+1}$. The relationship between the TNC$_i$ can be derived following the similarity step of formulas (12), (13), (14), and (15):

$$\begin{aligned}&\left(ns_{m/2+1} + ns_{m/2+2} + \cdots + ns_i\right)\left(dt_i\right)^{\alpha}\\&\quad - \left(ns_{m/2+1} + ns_{m/2+2} + \cdots + ns_{i+1}\right)\left(dt_{i+1}\right)^{\alpha}\\&\quad = \left(ns_i + ns_{i+1}\right)\xi, \quad i > \frac{m}{2} + 1.\end{aligned} \tag{16}$$

3.4. The Flow of NUSCM. Based on the above-mentioned equations and analysis, we can create an order of operations for the NUSCM. The flow of NUSCM is shown as follows.

Step 1. Set scene parameters, such as L, W, and more.

Step 2. Deploy two base stations of BSN$_1$ and BSN$_2$.

Step 3. Route the scheme and nodes deployment of SNCs.

Step 3.1. Obtain the number of SNCs in the NUSCM.

Step 3.2. Design the routing scheme of every SNC.

Step 3.3. Obtain the nodes number of every SNC, $ns = \{ns_1, ns_2, \ldots, ns_i, \ldots, ns_m\}$.

Step 3.4. Calculate sensor nodes spacing ds_i^j based on energy balance.

Step 4. Route the scheme and nodes deployment of TNCs.

Step 4.1. Obtain the number of TNCs in the NUSCM.

Step 4.2. Design the routing scheme of every TNC.

Step 4.3. Obtain the nodes number of every TNC, $nt = \{nt_1, nt_2, \ldots, nt_i, \ldots, nt_m\}$.

Step 4.4. Calculate transmission nodes spacing dt_i based on energy balance.

Step 5. Coverage routing controlling is the end.

4. Research Results and Analysis

Energy efficiency and QoS enhancement for NUSCM are two main research works, and simulation is conducted to verify the performance. Before performing the evaluation, several announcements should be clarified. The length is about 1000 m, and the width is 2 m; we adopt Zigbee nodes with 2.4 GHz band; all nodes are supplied by two batteries with 2 × 1.5 V voltage and 3000 mAh, so the initial energy is 15.12 MJ, which is set to be 100 J in order to shorten the experimental time; ds_i^1 is 32 m, $e_{\min}$ is 5 J, and B is 64 bits; the processing time from one node to its neighboring node is 20 ms. The remaining experimental parameters are of default values.

4.1. Quality of Service (QoS) [20]

Definition 1 (lifetime). The time when the first node begins to die is described as the lifetime of the networks.

Definition 2 (link communication load). The data quantity transmitted by every sensor node is called link communication load.

Definition 3 (network survivability). The influence of invalid node on network is called network survivability.

Definition 4 (data delay). The time for the perceived data to be transmitted from its location to base station is described as data delay.

4.2. Different Network Performance under Different Network Structure. Spacing distances of sensor nodes and transmission nodes are needed to be obtained, which can realize energy balance of networks. Different lengths of long-narrow structure need different numbers of SNCs and TNCs. For a certain length, various numbers of nodes in every SNC and TNC also affect network performance. Hence, supposing that the length is 1000 m, four SNCs and TNCs are able to cover and connect in the whole length direction. Every SNC and TNC can contain different numbers of nodes, which may form different network structures. Then we try to research the different network performance with different network structures:

(a) structure$_1$ = $\{ns_1 = 7, ns_2 = 15, ns_3 = 15, ns_4 = 7; nt_1 = 6, nt_2 = 16, nt_3 = 16, nt_4 = 6\}$;

(b) structure$_2$ = $\{ns_1 = 11, ns_2 = 11, ns_3 = 11, ns_4 = 11; nt_1 = 9, nt_2 = 15, nt_3 = 15, nt_4 = 9\}$;

(c) structure$_3$ = $\{ns_1 = 15, ns_2 = 7, ns_3 = 7, ns_4 = 15; nt_1 = 12, nt_2 = 16, nt_3 = 16, nt_4 = 12\}$.

The number of sensor nodes in a SNC will directly affect the number of transmission nodes in a TNC, which will affect the network performance, such as link communication load and data delay. Hence, the next part is to research the relationship between the network performance and structure parameters.

4.2.1. Link Communication Load. As shown in Figure 6, the number of sensor nodes with three network structures is 44, while the numbers of transmission nodes are 44, 48, and 56, respectively. If the sensor node cluster near base station contains more nodes, the corresponding transmission node cluster will contain more nodes. Average link communication loads are 0.67 kbits, 0.62 kbits, and 0.60 kbits with structure$_1$, structure$_2$, and structure$_3$, respectively. As the number of adopted nodes varies from 88 and 92 to 100, the average link communication load reduces. Moreover, the link communication load has the same value in every TNC. The link communication load presents opposite trend in every SNC and then reduces multibridging effect in NUSCM.

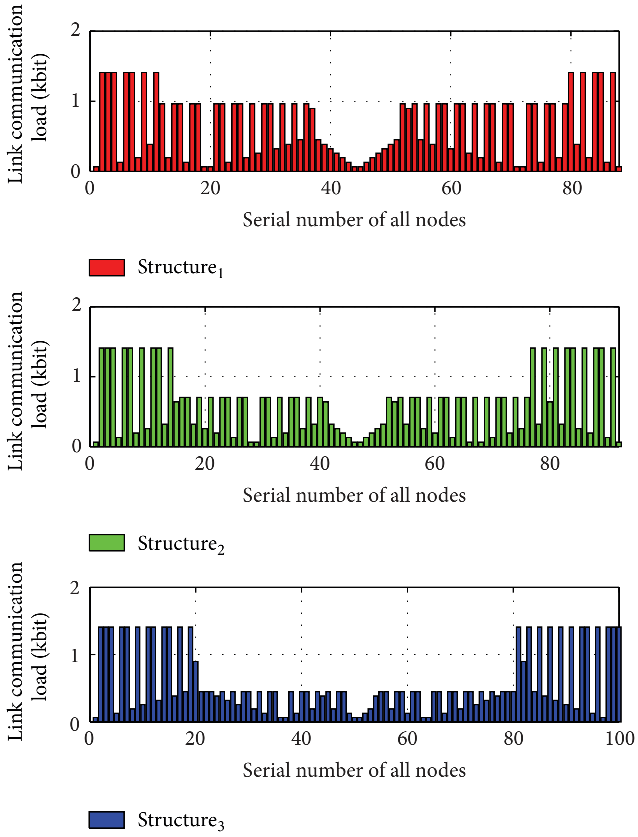

FIGURE 6: Link communication load with three network structures.

4.2.2. *Data Delay.* Figure 7 outlines data delay transmitted from their locations to the base station. The average data delay is 0.41 s, 0.38 s, and 0.42 s with structure$_1$, structure$_2$, and structure$_3$, respectively. In common, the sensor nodes near the base station have short data delay no matter which network structure is selected. But the smaller number of sensor nodes in a SNC will lead to shorter data delay when the structure$_3$ is adopted. This is due to the fact that the smaller the SNC near the base station is, the smaller the corresponding TNC is and then the fewer the hops from the location of sensor nodes to the base station are needed. Owing to coverage routing scheme among the TNCs, the perceived data of sensor nodes will be transmitted through the corresponding TNC. The sensor nodes near the base station will have lower data delay than the sensor nodes farther away from the base station.

We can choose network structure parameters to meet extensive application for WSN. If all sensor nodes need to have the shortest data delay, structure$_2$ can be adopted. If sensor nodes near the base station need to have lower data delay, structure$_1$ can be adopted. However, structure$_3$ is forbidden.

4.3. *Network Performance.* We have researched the network performance under different network structures. Meanwhile, structure$_2$ = $\{ns_1 = 11, ns_2 = 11, ns_3 = 11, ns_4 = 11; nt_1 = 9, nt_2 = 15, nt_3 = 15, nt_4 = 9\}$ has been adopted. Next, we

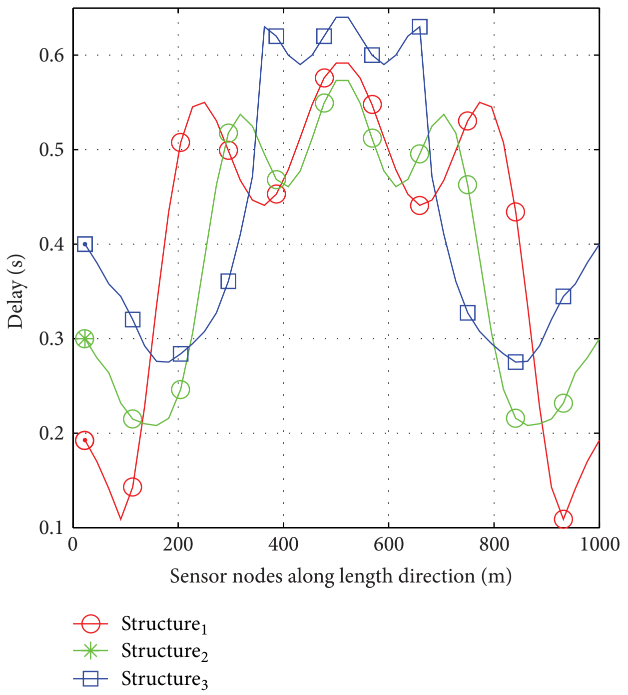

FIGURE 7: Data delay with three network structures.

research nonuniform symmetric cluster model (NUSCM), nonuniform deployment with two base stations (NUD-TBS), and uniform deployment with two base stations (UD-TBS).

4.3.1. *Lifetime.* From Figure 8, we can conclude that the lifetime of NUSCM is the same as that of NUD-TBS, but longer than that of UD-TBS. When the network begins to die, UD-TBS still has half-energy about 3.48 k J, while NUD-TBS and NUSCM almost exhaust their energy. The results demonstrate that the NUD-TBS and NUSCM have better energy efficiency than UD-TBS. Spacing distances of UD-TBS are equal without considering link communication load along length direction, which will cause nodes near the base station to die quickly. However based on energy model, nodes spacing of the NUSCM and NUD-TBS can be adjusted according to the data quantity and most nodes have died when the network begins to die.

4.3.2. *Link Communication Load.* As shown in Figure 9, link communication load of the UD-TBS and NUD-TBS will increase when the sensor nodes data is transmitted from the center to the sides. But the NUSCM can keep it within a certain range. The average link communication load of the UD-TBS, NUD-TBS, and NUSCM is 1.12 kbits, 0.99 kbits, and 0.62 kbits, respectively. That is to say, NUD-TBS and UD-TBS transmit perceived parameters to sensor nodes, which will form “hot spot” zone at two base stations. NUSCM can balance network communication task. All nodes of NUSCM can send their perceived parameters to the base stations with fewer hops.

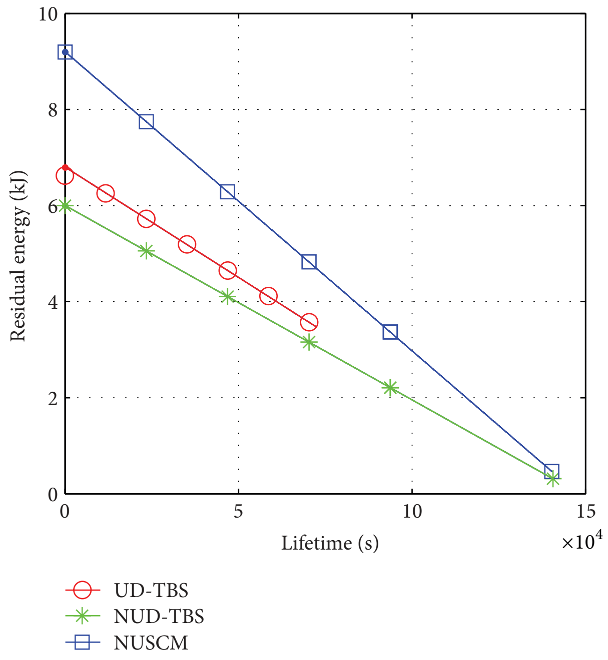

Figure 8: Lifetime.

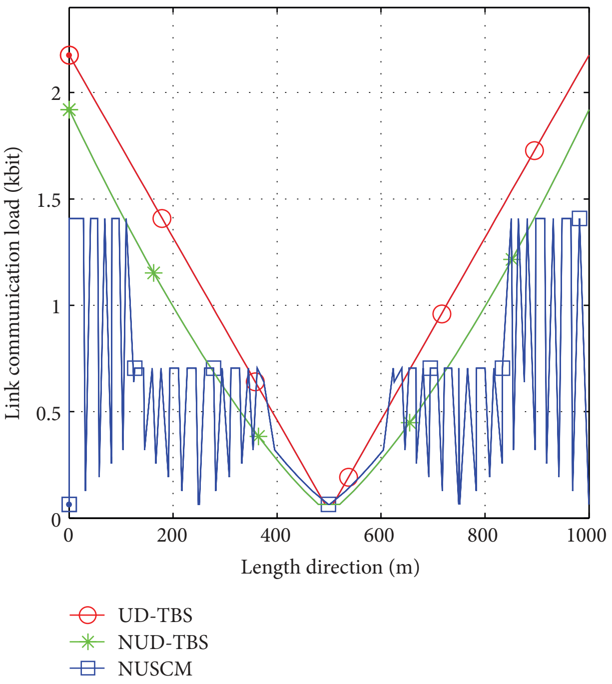

Figure 9: Link communication load.

4.3.3. Network Survivability. In a common network, a failure of partial sensor nodes can result in the failure of the entire network, especially when sensor nodes near base station die. Figure 10 shows the network survivability when parts of the network are disabled. Network survivability of the UD-TBS, NUD-TBS, and NUSCM is 0.71, 0.75, and 0.81, respectively. The network survivability decreases when disabled sensor nodes are near the base station. Sensor nodes failure will divide the whole network into three parts with UD-TBS and NUD-TBS. If the failure occurs at the left part of the network, the first part is from the left base station to the failure node and the second part is from the failure node to the center, while the third part is from the center to the right base station with UD-TBS and NUD-TBS. The first and third parts are all effective. Hence, network survivability is weakest when these nodes near the base station die with UD-TBS and NUD-TBS. Disabled nodes along length direction only cause the failure of partial SNC and TNC, which will make other networks still alive with NUSCM.

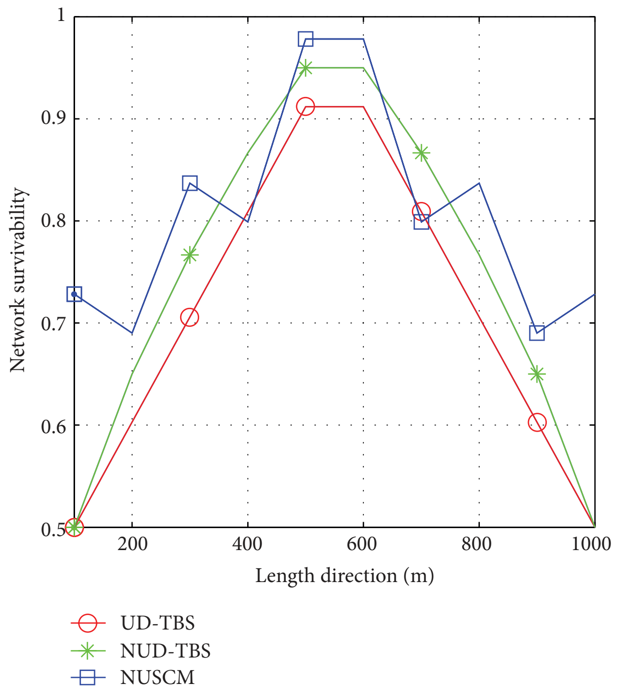

Figure 10: Network survivability.

4.3.4. Data Delay. From Figure 11, we can conclude that data delay of the NUD-TBS and UD-TBS reduces from the center to the sides along length direction, but that of NUSCM keeps within a certain range. The average data delay of the NUD-TBS, UD-TBS, and NUSCM is 0.35 s, 0.31 s, and 0.38 s, respectively. This is due to the fact that data delay is related to the distance from sensor nodes to base stations. With NUD-TBS and UD-TBS, perceived parameters are transmitted to the base stations through one hop to another, which can shorten the routing path. However, perceived parameters are transmitted not only by their neighbor sensor nodes, but also by the corresponding transmission nodes. Then they are forwarded to the base stations. Hence, more hops from sensor nodes to base stations will lengthen routing path so as to increase the data delay.

5. Conclusions

Aiming at special topological structures of long-narrow scenes, this paper proposes a nonuniform symmetric cluster

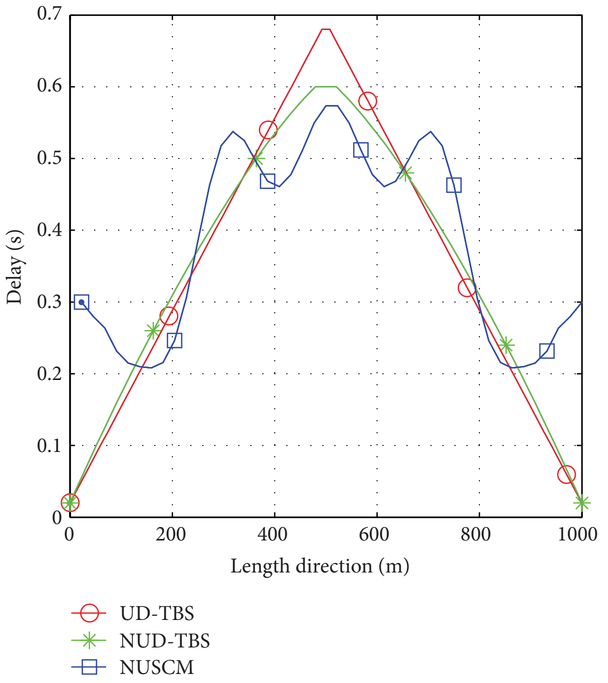

Figure 11: Data delay.

model (NUSCM) firstly and then compares it with UD-TBS and NUD-TBS models. The results indicate that the lifetimes of NUSCM and NUD-TBS are longer than UD-TBS. Moreover the perceived parameters transmitted by sensor nodes are balanced with NUSCM, which makes link average communication load reduce by 44.6% and 33% and network survivability grow by 12.5% and 7.4% in comparison with UD-TBS and NUD-TBS, respectively. Therefore, it is concluded that the proposed NUSCM can effectively improve energy efficiency and enhance QoS performance in long-narrow structures.

Given the method of coverage and routing, we will carry out our work from two aspects. On one hand, an accurate energy consumption model is required in the practical applications. On the other hand, we will prolong network lifetime using the sleep and activation strategy of sensor nodes.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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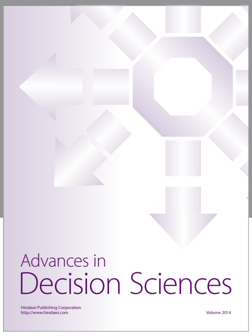
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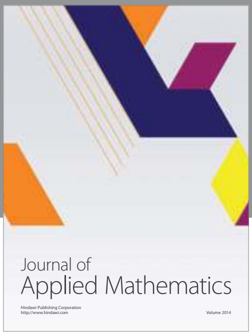
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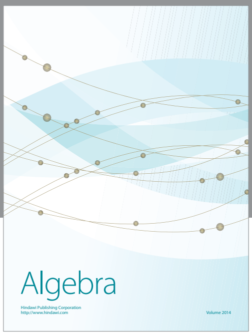
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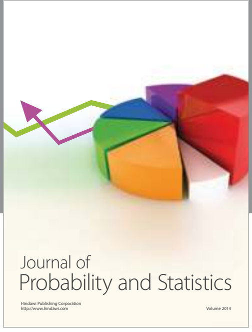
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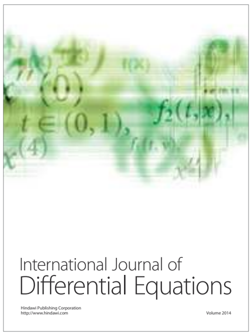
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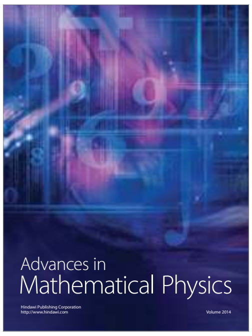
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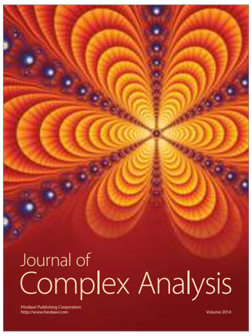
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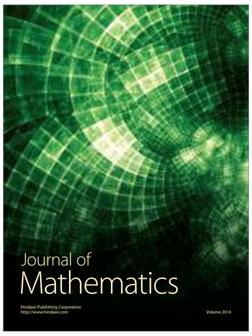
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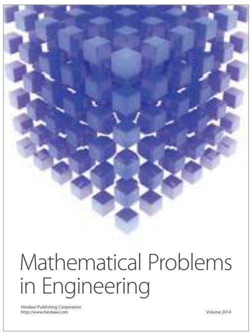
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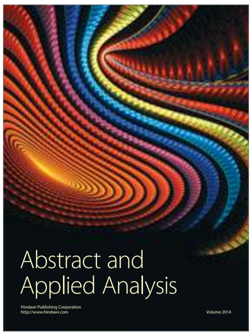
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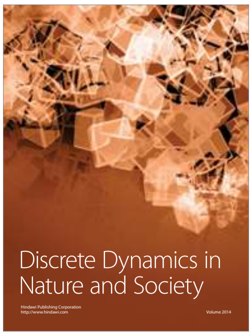
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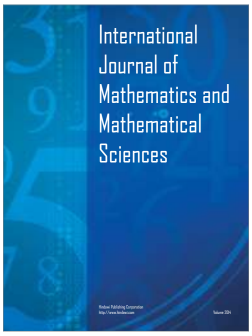
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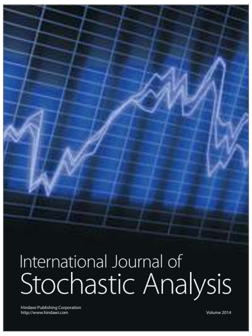
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