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An Optimal Trade-off Power Saving Scheme between Coverage and Connection Problem for WSNs

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Abstract. It is well known that connectivity and coverage are the important elements in the Wireless sensor networks (WSNs). In order to make a complete WSNs, scholars have begun to study how to use connected sensors to cover the designate area, but their proposed methods focused on 2D ideal plane or 3D full space, however, the actual terrain is rugged and uneven. It means that their proposed method may not suitable for a real environment. In addition, most of studies only consider single target that many researchers separated the connectivity problem and coverage problem. However, those two problems have very close relationship, so they must be considered in a same time, otherwise, the results may fall into a local optimum. For instance, several researches presented that use of transmission range adjustment to reduce redundant coverage so that they miss many chance to pass the message by shortest path since the many neighbors cannot be covered when coverage is decreased. Therefore, we use Spline function to shape the irregular FoI (Field of Interest) as well as use feature of convex hull of Spline function to ensure the full coverage and then design a shorter transmission path algorithm according to the coverage pattern to reduce network latency and energy consumption. The simulation results show that the proposed method indeed taking into account coverage and connection problem so that it certainty suitable for real WSNs environment.

Keywords: coverage problem, path planning, Spline function, wireless sensor network

1 Introduction

Wireless sensor network (WSN) is a promising technology for human's life that peoples have been widely used them in health care, war, resource exploration, environment detection and dynamic events monitor and so on [12]. In the past few decades, topic of WSNs is focus on the coverage problem. The

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scenario of those problems usually set in the 2D plane [1]. It means that the height is not be considered. However, the real environment is a 3D space. In this view point, many schemes from 2D may causing the misjudgment in coverage hole in 3D environment. Many researchers began to study the 3D space coverage. Watfa and Commuri found that using 2D method in 3D space may encounters the coverage holes as well as discussing the importance about the 3D space coverage, thus they start to study for coverage holes avoidance for 3D environment [3].

Huang, Tseng and Lo considered impact of height [2]. It represents that the sensors can be freely deployed in entire 3D space rather than a 2D plane only. It means the coverage hole may be found when we look down at deployment situation of the sensors. Many studies found a relationship between coverage overlapping phenomena and the network density in a 3D full space that the sensors must be deployed on an entity only. It means that the sensors cannot deploy in everywhere of 3D space, but deploying on a 3D surface [4]. In this research must overcome the definition of complex terrain. In order to precisely define a rolling and irregular terrain, some scholars used Spline function as a tool to paint the shape of topography [11]. The Spline function has a feature of convex hole which can ensure any sensors can be covered. Therefore, this method is also suitable for defining the underwater environment [12].

In general, coverage is a major way to ensure the basic functions of WSN, because purpose of the sensors is to perceive the surrounding environment. A well-defined terrain causes the coverage mechanism can work successfully. However, only sensing is not enough, it also has ability to exchange the data so that collected information will become the useful Information. It means that connection problem is a topic which must be concerned. The optimization of node placement is considered that ensures all of sensors are directly or indirectly connected with each others [5]. Due to the WSN has a power consumption issue, many scholars considered the remaining power to find out the connected coverage then the network lifetime can be extend [6]. In order to achieve the more energy efficient WSN, the adjustable transmission radius also be proposed. This method can decreases unnecessary transmission range in a acceptable coverage ratio. However, the connectable neighbors become fewer when the coverage is not enough to cover the more sensors. In simple terms, any sensor may have at least neighbor to help message transmission, but this link may not a best one. It means the found path may has more transmission costs which include time, power and so on.

In this paper, we use NURBS (Non-Uniform Rational B-Spline, NURBS) depicts a more realistic terrain surface, and use of convex hull features of NURBS to ensure full coverage for entire FoI. As well as the adjustable transmission radius is regards as the coverage basic for energy efficiency. Finally, we will take account into coverage and connect problem to design a better algorithm called STP, which plans the faster transmission path to obtain minimal network latency as well as the overlapped region will not be increased.

The rest of the paper is organized as follows. Section II discusses some related works and Spline function. In section III, we introduce our used network model, coverage model and connection model. Our proposed Shorter Transmission Path Algorithm is described in section IV. In Section V, simulation results are presented. Finally, conclusions and future works from this research are discussed in section VI.

2 Related Works

2.1 3D Space Coverage

Recently, the 3D space WSN has became one of hottest topic. They considered to height is an important metric in coverage issue. The purpose is to gets more accurate location information to avoid the coverage holes. Jiang, Zhang, Tan and Wang proved that the connectivity of 3D k-covered is much higher than the degree of sensing coverage *k* [8]. Therefore, we can found that there are more link options in the 3D space. However, several researches always deal the coverage and connectivity problems separately only. Actually, a real WSN environment must to take account into coverage problem and connection problem. Because by our observation, higher coverage lets connectivity becomes high, but the sensors must spend more power consumption. Relatively, connectivity will be less when the coverage is decreased. In other words, the coverage range is limited by battery so that many researches try to decrease the non-essential sensing radius to reduce the power consumption. In this way, some sensors lost the best opportunity to transfer. Therefore, we know that they have a trade-off relationship according to above descriptions.

2.2 Spline Function

The Spline function has three common types, which are Bézier curve, B-Spline curve and Non-Uniform Rational B-Spline (NURBS) curve respectively. The Bézier curve is earliest proposed one that has been widely used in the computer graphics field that the curve can become smooth. The advantage of Spline is that each curve has many control points that c can be graphically displayed as well as intuitively deal with the each curve. The main principle is to utilize linear interpolation makes numerical approximate to the targets via use of control points to influence the degree of linear interpolation. Spline function has the characteristics of the convex hull, it ensures that the entire curve will be included in a convex hull that shown in Fig. 1. The fundamental equation of Bézier curve [9] is

$$C(u)\sum_{i=0}^{n} P_i f_i(u) \text{ ， } 0 \le u \le 1 \tag{1}$$

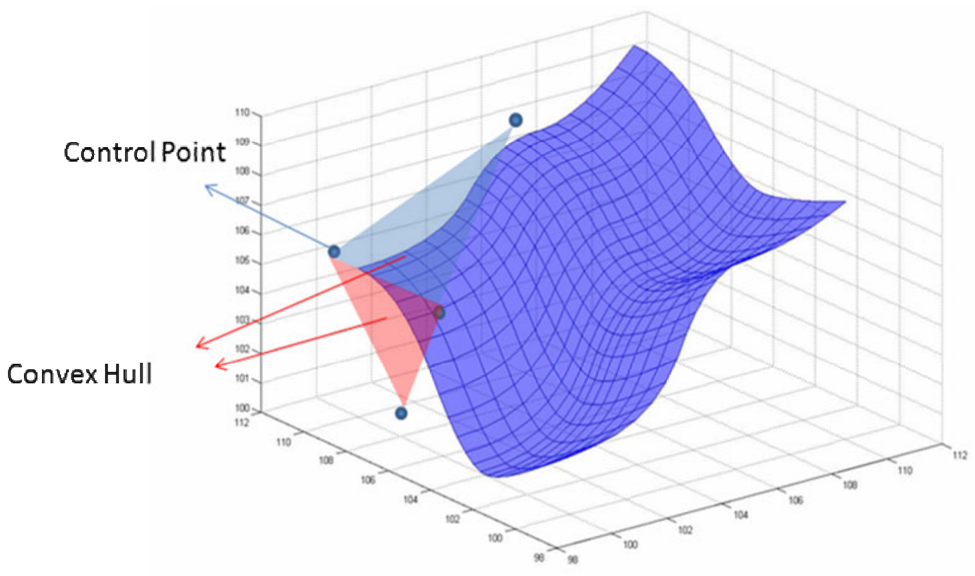

Fig. 1. Example of convex hull of spline surface

Where P_i is control points which control the direction u of the basis function f_i. The disadvantage of Bézier curve is that when a control point has been changed, the whole curve will also be changed. It means that Bézier cannot elastically control the local curve. In order to solve this drawback of the Bézier curve, the B-Spline curve is proposed in a piecewise polynomial function that is shown in the following formula [7]:

$$C(u)\sum_{i=0}^{n} P_i N_{i,k}(u) \text{ ， } t_0 \le u \le t_{n+k} \tag{2}$$

To make the curve has higher ability to accurately depict the more complex topography, NURBS has been proposed that this is an effective method for local control the curve. A weight $w_{i,j}$ is added to determine the effect degree of each control point for the target curve [7]. The weight values of each control point are difference. It means that any control points has not same range of impact so that NURBS can control every details in local.

$$C(u,v\sum_{i=0}^{n}\sum_{j=0}^{m} W_{i,j} P_{i,j} N_{i,k}(u) M_{j,l}(v) \tag{3}$$

For this reason, the Spline function will able to handle the uneven terrain. Brief comparison of these three functions can know the NURBS not only has the advantages of Bezier and B-spline, but also enabling local control flexibility. In this research, we utilize the NURBS to formulate the complex surfaces of FoI. The comparisons of three functions are listed in Table 1.

Table 1. Comparison of Bézier, B-Spline and NURBS

	Local control	Flexibility	Convex hull
Bézier	No	Low	Low
B-Spline	Yes	Medium	Medium
NURBS	Yes	High	High

2.3 Efficient Power Conservation Mechanism (EPC)

Tseng, Cho, Chou and Chao proposed EPC algorithm for coverage problems, which use of an adjustable radius to dynamically change the sensing radius of each sensor to achieve minimum energy consumption with high coverage ratio [11]. However, it has disadvantage that the hop count may increasing. It made more redundant energy consumption and too large latency in the transmission process. The reason is that authors did not consider the path selection. Therefore, the proposed method considered the connectivity issues, which try to find a trade-off between coverage and connectivity.

3 System Model

3.1 Network Model

A WSN with area size *A* is modeled by graph *G= (V,E)*, where $V=\{V_1,V_2,...,V_n\}$ are the set of sensor nodes in the network, and $E=\{E_1,E_2,...,E_n\}$ are the set of transmission range. These sensor nodes are deployed on a FoI *F*, which is composed of a set of surfaces. The set of surface is defined $S:F=\{S_1,S_2,...,S_n\}$, $\cup_{i=1}^{k} S_i = S, S_i \cap^{i\neq j} S_j = \phi$. Since each sensor's covered range may be overlapped. The overlap area will cause unnecessary power consumption. We define the redundant region as *O*= $G-S$, which can determines whether FoI is covered that shown in follows:

$$O=\begin{cases}\geq 1, \textit{if the sensor able to cover the FOL.}\\ <0, \textit{if the sensor able to cover the FOL.}\end{cases}$$

Because the coverage problem must also take into account the energy efficiency, and to ensure without coverage holes, so our goal is $Minimize(|O|)$, and must meet $(G\cup S)-G=\phi$.

3.2 Coverage Model

We can know that the blocks of surface can be expressed as $C_{block}(u,v)=W_{i,j}P_{i,j}N_{i,k}(u)\ M_{j,i}(v)$ according the NURBS definition. And Spline function has the convex hull feature that it can ensure full coverage. We can use the relationship between control points and sensors to achieve such expectation. The position of control point can be found via the following equation:

$$\sum_{i=0}^{n}\sum_{j=0}^{m}P_{i,j}=\frac{C(u,v)}{\sum_{i=0}^{n}\sum_{j=0}^{m}N_{i,k}(u)M_{j,l}(v)} \tag{4}$$

Assume that $v=(x_v,y_v,z_v)$ is a sensor node and $p=(x_p,y_p,z_p)$ is a control point. The distance *d* can be found by their coordinates easier, and then using the following formula to determine the relationship between the sensor and the control points:

$$d-r=\begin{cases}\geq 0,\ p \textit{ is not covered any sensor}\\ \leq 0,\ p \textit{ is covered by and sensor}\end{cases}$$

3.3 Connection Model

Each sensors has own transmission radius r_i. We have to firstly confirm whether two nodes within the transmission range, hence we assume that $v=(x_v, y_v, z_v)$ and $p=(x_p, y_p, z_p)$ are two different sensors, then to calculate the distance *d* and making a judgment according to their radius:

$$d=\begin{cases} > r, \textit{The senosrs cannot connect with each other} \\ \leq 0, \textit{The senosrs can connect with each other} \end{cases}$$

When the distance $d \leq r$ represents they are placed within transmission range, and two nodes can communicate with each other and vice versa.

4 Proposed Method

4.1 Variable Radius

Our methods based on the variable radius [11]. As long as a sensor's sensing range covered the other sensors, it represents that these sensors are able to connect with each other. In this way, we do not need to expand the sensing radius of sensor with maximum length. We can use the following formula to calculate the needed radius length of sensors. Assuming that $Senosr_1=(x_1, y_1, z_1)$ and $Senosr_2=(x_2, y_2, z_2)$ are two different sensor nodes, and then calculating the distance *d* which must to make a judgment with the radius:

$$d=\sqrt{(x_1-x_2)^2+(y_1-y_2)^2+(z_1-z_2)^2} \tag{5}$$

Where r_1 is the radius of the $Sensor\ r_1$, r_2 is the radius of the $Sensor\ r_2$, and *d is* the distance between these two sensors.

The r_1 must be greater than or equal *d* to be able to ensure that the $Sensor\ r_1$ and $Sensor\ r_2$ can be connected with each other. Here we just need to make sure r_1 greater than or equal *d*, because as long as a sensor node can be touch to center of another sensor node, they have a way to transmit data.

4.2 Shorter Transmission Path algorithm (STP)

In order to keep high coverage rate and then found the better path for transmission, we propose STP (Shorter Transmission Path Algorithm) algorithm to looking for a shorter transmission path without coverage hole after radius of each sensor has changed in an epoch. Firstly, we calculate distance *d* between initial $Senosr\ r_1=(x_1, y_1, z_{1nsor\ that\ vsize\ of\ the\ radius,})$ and $Senosr\ r_2=(x_2, y_2, z_{2nsor\ that\ vsize\ of\ the\ radius,2})$ which must be $Sensor_1$'s neighbor, and then calculate the distance *D* between neighboring nodes and sink. Second, we select a neighbor node which has the minimal *d* + *D*. This step will be repeated execution until the data is delivered to the receiver so far. In this way, it will greatly reduce the transmission delay, because we planned the shortest path so that the data will be transmitted with fewer hops. The distance *D* calculations are as follows:

$$r_1 \geq d, \textit{The Sensor } r_1 \textit{ can Connection to Sensor}_2$$

Where r_1 is the radius of the $Sensor\ r_1$, r_2 is the radius of the $Sensor\ r_2$, and *d is* the distance between these two sensors.

The r_1 must be greater than or equal *d* to be able to ensure that the $Sensor\ r_1$ and $Sensor\ r_2$ can be connected with each other. Here we just need to make sure r_1 greater than or equal *d*, because as long as a sensor node can be touch to center of another sensor node, they have a way to transmit data.

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$$D_i = \sqrt{(x_n - x_i)^2 + (y_n - y_i)^2 + (z_n - z_i)^2} \quad \textbf{(6)}$$

Where

$$D_i = \begin{cases} \leq \sqrt{(D_{i-1})^2 + (x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \\ > \sqrt{(D_{i-1})^2 + (x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \end{cases}$$

If $D_i \leq \sqrt{(D_{i-1})^2 + (x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$ represents that the sender search for a correct direction without redundant paths. Otherwise, found neighbor nodes farther away from the sender than the current node. We try not to select this node, unless there are not other nodes in the sensing range. Then we have actual examples to illustrate the state of STP operations.

Fig. 2 shows that the sensor nodes randomly deployed in the FoI. We assume that the heights are same. (8, 8) is a sink node, and the maximum sensing radius of each node as 2 unit length. (0, 0) is an initial node. In the first epoch, there are three nodes (1, 3) (2, 1) (2, 2) are the neighbors of (1, 1), and then we let (1, 1) as a candidate node because it has shortest path. We extend the acceptable sensing radius to covered the neighbors of (1, 1) thus find out the candidate node for next hop. Next we calculate the distance value of each neighbor node according to eq. 6. We can see that STP chooses nodes that based on the shortest path and our main concept which is referring from [11]. The authors proposed a method which adjusts the length of the radius to reduce redundant coverage so that the low transmission delay with high coverage ratio will be achieved. Fig. 3 shows that original method has largest coverage because each sensor releases the maximal transmission radius. Although it has best coverage and connectivity, it must spend very huge consumed power. EPC adjusted the radius according to the remaining power of sensors so that the coverage may be smaller than original method and the connection chance will become a bit less, even the found path may has very long distance that is shown in Fig. 4. In Fig. 5, STP provides a path suggestion to EPC then runs the sensing range adjustment. In general, the coverage only decreases a little bit but the message can be delivered with the faster paths. Notice that STP us a preliminary before EPC is running. In simple terms, STP not only enhances the connectivity of EPC, but also keeps the advance of high coverage ratio and lower power consumption. The pseudo code of STP is shown in follows:

Pseudocode of Shorter Transmission Path Algorithm.

```
{Run the following at each node u}
begin
  1. Extend radius that causing it exactly equal to distance d between
     itself and the corresponding sensor.

  2. Find a neighbor which has more two-hop neighbors and has smaller
     D to reach destination.
```

3. Let a neighbor as candidate path node if it has smallest $d+D$.

4. Create a complete path then call the EPC as well as provide corresponding d_i+D_i as a suggestion of radius r_i.

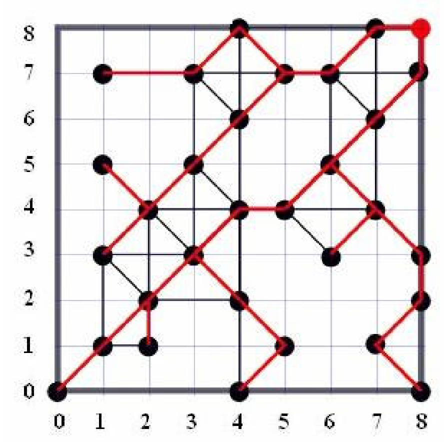

Fig. 2. Path selection of STP

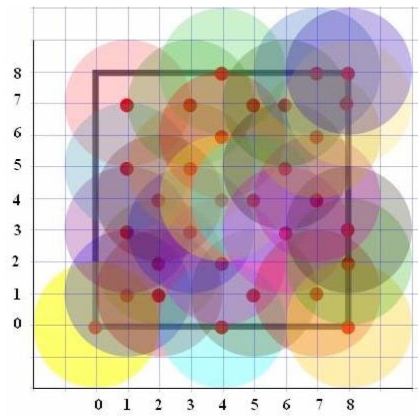

Fig. 3. Coverage and connectivity of original method

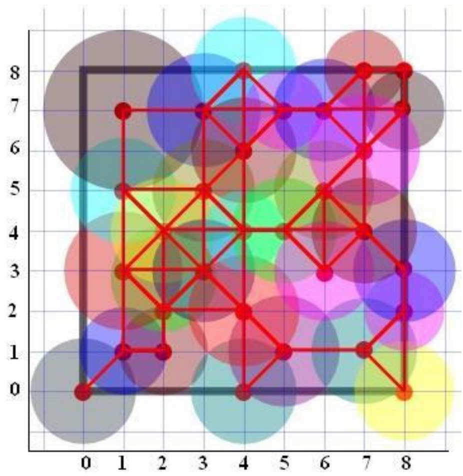

Fig. 4. Coverage and connectivity of EPC

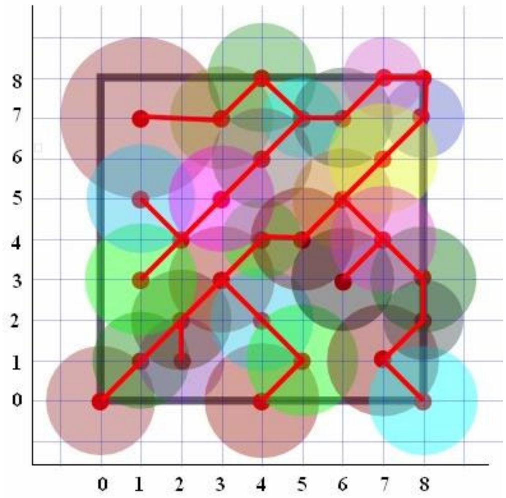

Fig. 5. Coverage and connectivity of STP

5 Simulation

5.1 Simulation Setting

The simulation is performed by utilizing MATLAB (see http://www.mathworks.com/). We deployed the sensor nodes in a 800×800m^2 network, and we simulated the sensor nodes from 100 to 1000. The energy consumption of a sensor by transmitting, receiving and transmitting amplifier is 0.0144 mJ, 0.00576 mJ and 0.0288nJ/m^2 respectively [10]. The time delay for transmitting is 0.4 ms.

5.2 Simulation Results

We compare our proposed STP algorithm, Original policy and EPC algorithm with coverage rate and average hop count. The reason is that coverage is a most important metric for ensuring the basic function of WSN can be run. And hop count represents the estimation of distance, because we think that network speed should be same in common case, therefore the hop count can regards as a relative distance between destination and source. Fig. 6 shows that coverage ratio of STP is slightly lower than the EPC. Because STP will consider the shorter path as a suggestion for adjustment of size of coverage. In order to reduce more power consumption, STP will try to recommended EPC use larger coverage to find out the overall shorter path as much as possible. However, the gap of coverage only at most 7% so that this result is still acceptable. Fig. 7 shows that the average hop count. We can see that EPC has most hop counts to complete the transmission, because transmission range is too small will leads the path must had a big circle around to be able to deliver the message to destination. An important reason is EPC let each sensor may has at most only one neighbor to help the message forwarding so that the path could not take the most efficient transmission path. Notice that original method has best path efficiency is because that they open the radius intemperately, hence all of sensors will obtain most chance to forward the message. Of course, it will consume the most power. In summary, STP will achieve a fair situation for taking into account coverage and connectivity problem in the same time.

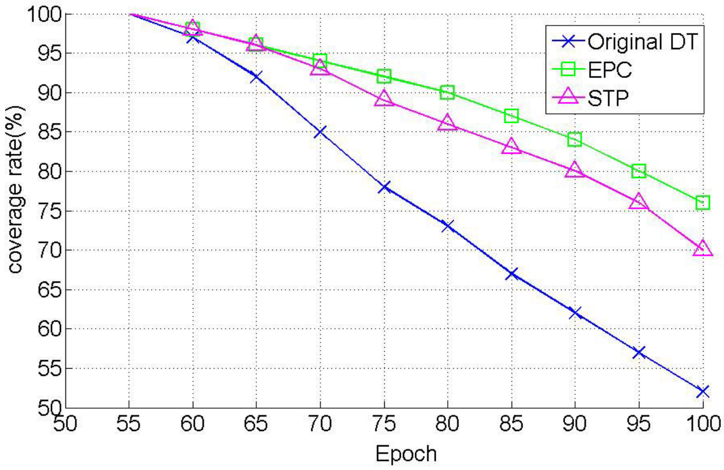

Fig. 6. Evaluation results of coverage rate

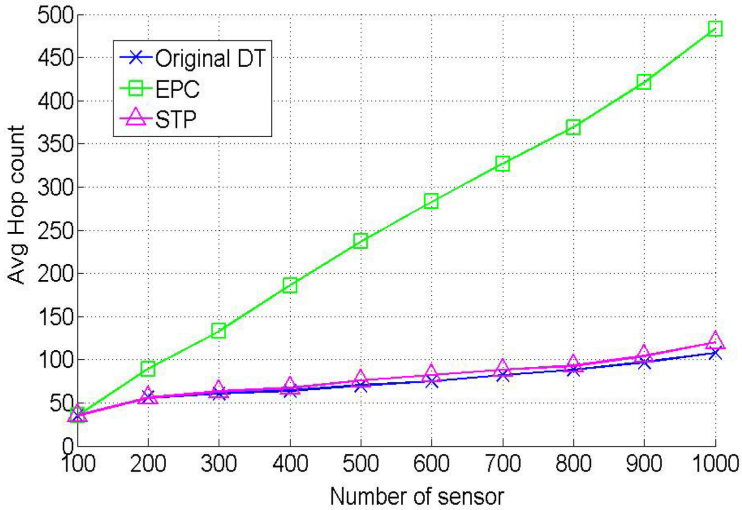

Fig. 7. Evaluation results of average hop count

6 Conclusion

No matter in which topic directions of WSN, the energy efficiency is an essential issue to be discussed necessarily. The reason is that life of the sensors must depend on the battery power. There are several studies have been proposed for issues of coverage, connectivity and so on to make a giant effort. However, most of works did not take into account the relationship between coverage and connection problem. In this paper, we follow the terrain definition way of EPC thus solving the drawbacks of EPC. We still use the adjustable radius to find out a coverage area which has not more redundant overlapping area. Importantly, the decision of length of sensor raduis is made by our proposed STP algorithm. Therefore, Use of STP can reduce more energy consumption since many distant paths will not be selected. The simulation results show that our proposed STP algorithm is more efficient than EPC and the original policy because the coverage and connectivity are considered in the same time.

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References

[1] S. Kumar, T.H. Lai, A. Arora, Barrier coverage with wireless sensors, in: Proc. 11th ACM Annual International Conference on Mobile Computing and Networking, 2005.

[2] C.-F. Huang, Y.-C. Tseng, L.-C. Lo, The coverage problem in three-dimensional wireless sensor networks, in: Proc. IEEE Global Telecommunications Conference, 2004.

[3] M.K. Watfa, S. Commuri, A coverage algorithm in 3d wireless sensor networks, in: Proc. 1st International Symposium on Wireless Pervasive Computing, 2006.

[4] H.M. Ammari, S.K. Das, Critical density for coverage and connectivity in three-dimensional wireless sensor networks using vontinuum percolation, IEEE Transactions on Parallel and Distributed Systems 20(6)(2009) 872-885.

[5] K. Kar, S. Banerjee, Node placement for connected coverage in sensor networks, in: Proc. WiOpt 2003: Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks, 2003.

[6] H. Gupta, Z. Zhou, S.R. Das, Q. Gu, Connected sensor cover: self-organization of sensor networks for efficient query execution, in: Proc. IEEE/ACM Transactions on Networking, 2006.

[7] H.M. Ammari, S.K. Das, A study of k-coverage and measures of connectivity in 3D wireless sensor networks, in: Proc. IEEE Transactions on Computers (TC), 2009.

[8] H. Jiang, S. Zhang, G. Tan, C. Wang, CABET: Connectivity based boundary extraction of large-scale 3D sensor networks, in: Proc. 30th Annual IEEE International Conference on Computer Communications IEEE (INFOCOM 2011), 2011.

[9] H. Zhou, H. Wu, S. Xia, M. Jin, N. Din, A distributed triangulation algorithm for wireless sensor networks on 2D and 3D surface, in: Proc. 30th Annual IEEE International Conference on Computer Communications IEEE, 2011.

[10] W. Liang, B. Chen, J.X. Yu, Response time constrained top-k query simulation in sensor networks, in: Proc. 14th IEEE International Conference on Parallel and Distributed Systems (ICPADS ’08), 2008.

[11] F.-H. Tseng, H.-H. Cho, L.-D. Chou, H.-C. Chao, Efficient power conservation mechanism in Spline function defined WSN terrain, IEEE Sensors Journal 14(3)(2014) 853-864.

[12] H.-H. Cho, C.-Y. Chen, T. K. Shih, H.-C. Chao, Survey on underwater delay/disruption tolerant wireless sensor network routing, IET Wireless Sensor Systems 4(3)(2014) 112-121.

[13] H.-H. Cho, T.K. Shih, H.-C. Chao, A robust coverage scheme for UWSNs using the Spline function, IEEE Sensors Journal PP(99)(2015) 1.