A Scale-Free Network Model for Wireless Sensor Networks in 3D Terrain

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Abstract. The building strategy of network topology in 3D space is important technology for wireless sensor networks (WSNs). It is often more complex to assess the detection area of sensor node in 3D terrain. The research on topological modeling method, which can withstand a certain amount of node failures and maintain work properly, has become the focus in recent years. In this paper, a 3D terrain with multi-peaks is defined by Gaussian distribution and a new scale-free wireless sensor network topology is modeled in 3D terrain. According to the improved growth and preferential attachment criteria in complex network theory and considering the limited communication radius and energy of sensor nodes, this model is tolerant against random attacks and apply to WSNs in 3D terrain.

Keywords: Scale-free networks · Wireless sensor networks · 3D terrain

1 Introduction

Wireless sensor networks (WSNs) [1,2] are special networks for sensing environment and collecting information. They consist of large scale sensor nodes. Sensor nodes can collaborate monitoring, sensing and collecting environment information, which cover the geographic region, and send data to sink nodes through multi-hop. The target area of the real-world application in the WSNs is often 3-dimensional (3D) [3,4] and always has complex terrain and changeful climate, such as mountains, canyon, desert and underwater [5] etc. In recent years, with the harsh application environment and large application scale, the modeling for large-scale wireless sensor network topologies in 3D space has been brought into focus.

Complex networks [6,7] widely exist in the real world, such as global transportation networks, cooperation networks, social networks etc. As an interdisciplinary field, complex networks have attracted much attention. Small world networks [8] and scale-free networks [9,10] are classic models in complex network theory. The small world model has two characteristics for wireless network, which are smaller average path length and higher clustering coefficient. It is generally used in the modeling of heterogeneous network topologies [11]. Scale-free model is generally used in modeling homogeneous network topologies [12].

J. Wan et al. (Eds.): Industrial IoT 2016, LNICST 173, pp. 201–210, 2016.
DOI: 10.1007/978-3-319-44350-8_20

The node degree in scale-free networks follows power-law distribution. The majority of nodes have low degree. When random attack happened, the low degree nodes have a higher probability of being attacked, the network topology will not lost too many edges. Scale-free model compared with small world model is more strongly tolerant against random attacks [13]. Thus, how to construct the scale-free network topologies in wireless sensor networks is a urgent problem, which needs to be resolved.

In this paper, we reduce the actual 3D terrain to inerratic and continuous curved surface. we consider the limitation of communication radius in WSNs, the requirement of energy balance in distributed systems [14] and the maximum degree of nodes in topology firstly. Then, we design a modeling strategy of scale-free network topology in WSNs, which based on the BA model [9] and perceived probability. The theoretical model and analytical method conform to relevant restrictions of WSNs in 3D terrain.

The rest of this paper is organized as follows. A summary of related works is presented in Sect. 2. Section 3 describes a modeling strategy of scale-free network topologies for WSNs in 3D terrain. Section 4 describes the algorithm design in detail. We present the simulations in order to show the performance of modeling algorithm in Sect. 5. Finally, Sect. 6 summarizes the main results and discusses further works of the proposed schemes.

2 Related Works

Degree is an important factor for each node. The definition of degree k_i is the number of edges connected with node i. The dynamic changes exist in majority of networks. Nodes outside continuously join these networks and nodes inside possibly fail at the same time. Many networks have demonstrated that new joined node hopes to connect with "important" node. Thus, the new connection is not completely random (i.e. the connection probability is related to the degree of each node). In order to explore the mechanism of power-law distribution, Barabasi and Albert proposed the famous scale-free network evolution model [9]. They thought a lot of existing models did not take two important criteria into account of networks:

□ Growth: There are new nodes continuously joined, and network size is growing.
□ Preferential attachment: The new joined node tends to connect with node which has higher degree. This phenomenon is also known as the "Matthew Effect".

The two criteria reflect power-law distribution of network connectivity in traditional scale-free networks, such as Internet, social networks, transportation networks, etc. But limited by the harsh application conditions of distributed systems, the preferential attachment property of BA model cannot be simulate directly. Hence, many researchers focus on the application of scale-free network topologies in wireless sensor network. Liu et al. [15] proposed a complex network model based on heterogeneous network used in sensor networks. This model has both small world and scale-free properties. Du et al. [16] studied on the shortest path feature of scale-free network and designed a transportation system which is more efficient. Zheng et al. [17,18] also designed two robustness scale-free network topologies, LGEM (linear growth evolution model) and AGEM (accelerated growth evolution model). They paid attention to actual situation such as increasing or removing nodes, reconstruction edges. Jian et al. [19] proposed a new scale-free model with energy-aware based on BA model, named EABA (energy-aware Barabasi-Albert). They presented the tunable coefficients to balance the connectivity and energy consumption of sensor network topology. These references take both energy balance and transmission performance into account. It will increase data overhead during the modeling process. They also not considering the influence of 3D terrain. Thus, we need to find a tradeoff solution between scale-free property and modeling overhead in 3D space.

3 Scale-Free Model for WSNs in 3D Terrain

In order to simulate the application scenarios of WSNs in real world more visually, we simplify the terrain as regular and continuous curved surface. We assume that the surface topography in 3D terrain is regular. All sensor nodes are deployed within the area of $L * W\ m^2$ and the terrain is divided into $L * W$ grid points. We adopt the multi-peaks graph which is satisfied with Gaussian distribution to simulate the application scenarios and consider the entire surface is nonlinear and continuous.

$$Height(x, y) = max_{\{n=1,2...N_{peak}\}} K * normcdf(peak(n), 0, 1) \tag{1}$$

$$peak(n) = \sqrt{\rho * ((x - x(n))^2 + (y - y(n))^2)^{\frac{-\eta}{2}}} \tag{2}$$

Equation (1) describes the height value of gird point (x, y) on the 3D terrain which is composed of multi-peak value functions. The max value of overlap part will be selected. N_{peak} is the number of peaks in 3D space. The function $normcdf(a, b, c)$ describes the Gaussian feature distribution, also known as Gaussian integral. It consists of *norm* Normal distribution and *cdf* probability distribution. Equation (2) describes the cumulative distribution of grid point (x, y). ρ and η are peak coefficient. $(x(n), y(n))$ is the coordinate of nth peak.

We consider the height of each peak in the range of 10 to 20 and build the 3D terrain according to ρ, η, N_{peak} and different coordinate of peaks. As can be seen in Fig. 1, $(x, y, Height(x, y))$ is the coordinate of each grid point, $x \subseteq \{1, 2, \cdots, W\}$, $y \subseteq \{1, 2, \cdots, L\}$. There are $L * W$ data points in the 3D hill terrain.

Each node in wireless sensor network topology has its own communication range, so it only possesses and uses local information in the wireless sensor networks. As a result, the new joined node maybe has not sufficient neighbors to connect. In this case, preferential attachment property cannot work. In order to solve this problem, we focus on the following two criteria during the modeling process of scale-free wireless sensor network topologies.

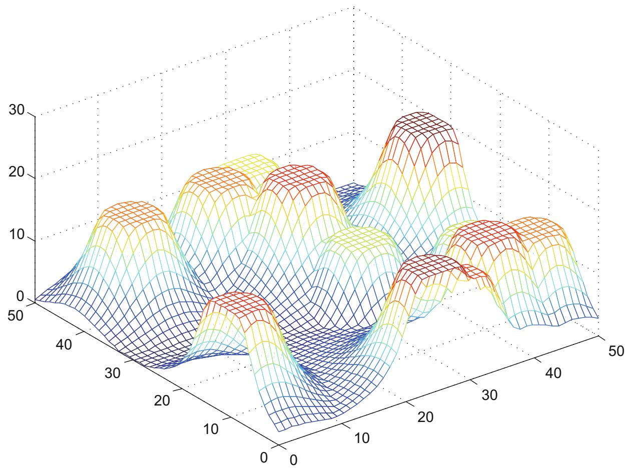


Fig. 1. The 3D terrain for scale-free networks in WSNs.

- ☐ Preferential attachment property is limited in the range of communication radius. Two nodes can be directly connected without the limitation of their location in Internet or other traditional scale-free networks. But in wireless sensor networks, any two sensor nodes communicate with each other through multi-hop.
- ☐ We control the maximum degree of nodes to prevent excessive energy consumption. In case of there are some nodes with too high degree in wireless sensor networks, they will forward and deal with a large amount of data and their energy is consumed quickly. This is a very negative phenomenon. If there is no enough energy to support, the entire wireless sensor network will soon collapse. Therefore, the maximum degree of node must be limited.

From what has been mentioned above, we consider two aspects of improvement based on the constructing criteria of BA model. Firstly, each new joined node must have sufficient neighbor nodes in its communication range. Hence, we put all the new joined nodes into the wireless sensor network topology, instead of one by one. But the nodes need asynchronously calculation during the process of adding edges. Meanwhile, neighbor nodes cannot perform the algorithm at the same time.

The perceived probability of the deployed sensor nodes is determined by the application regions of the sensor network. In Boolean perception model, the detection range of the node is in a sphere where the node is the center and the detection range is the radius. If a point falls within the radius of the sphere, the detection probability is 1, otherwise it is 0. However, the monitoring ability of each sensor node is affected by terrain, noise, signal attenuation etc. in real 3D application regions. So we use Eq. (3) to reflect the monitoring ability of nodes.

$$P_{ij} = \begin{cases} 1\Big/\alpha e^{\frac{\beta D_{ij}}{r}}, & (D_{ij} \le r), \\ 0, & (D_{ij} > r). \end{cases} \tag{3}$$

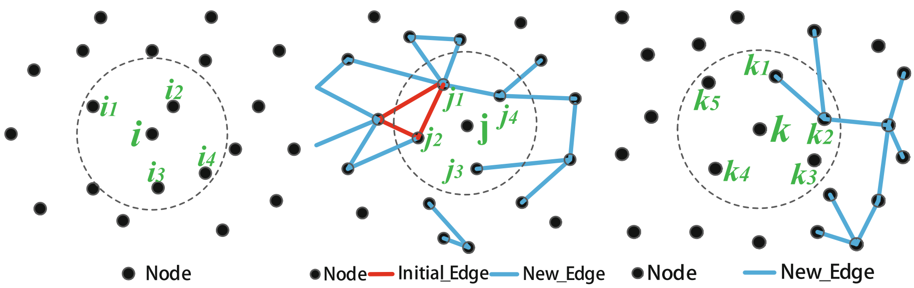
P_{ij} is the perceived probability of grid point j by sensor node i. α, β are adjusted according to the physical properties of the sensor. r is the radius of the individual sensor node. D_{ij} is the Euclidean distance between sensor node i and grid point j. The bigger D_{ij} is, the lower perceived probability of grid point is. Then, we can further calculate the perceived probability P_j of each grid point j according to the number and distance of sensor nodes in Eq. (4).

$$P_j = 1 - \prod_{i=1}^{N_l} (1 - P_{ij}) \tag{4}$$

N_l is the number of sensor nodes in the perceived range of grid point j. Because the grid points are always detected by more than one sensor node and the detections of all nodes is independent, the probability of one point is accomplished by all sensor nodes that can detect it together. During the following process, only when the perceived probability of sensor node is greater than 0.9, it can be connected.

Then, we assume that all the neighbors in the communication range of a new joined node is the local-world of the new joined node. But the neighbors which already connected with the new joined node or reached the maximum degree do not belong to the local-world of the new joined node. The new joined node tends to connect with higher degree node. We define the connection probability $\prod_{Local}(i)$ for a neighbor node i in Eq. (5).

$$\prod\nolimits_{Local}(i) = \frac{d_i}{\sum_{i=1}^{n} d_i} \tag{5}$$



(a) (b) (c)

Fig. 2. The adding connection process of new joined nodes.

Wherein, d_i is the degree of node i, and n is the total number of neighbors for the new joined node. Figure 2 describes the specific situation of connection probability during the preferential attachment process. We use the vertical projection in 2D space to explain this process more clearly. At the beginning stage, we choose 3 nodes as the initial wireless sensor network. The edges between the 3 nodes are represented by the solid red lines. The solid blue lines represent the edges, which are added during the modeling process. We assume that the perceived probability of sensor nodes in the communication range of i, j and k are all greater than 0.9. In Fig. 2a, the four neighbors in the local-world of node i are all isolated. So, when node i broadcasts the request of adding edges, it chooses m neighbors to establish connection in equal probability. However, the four neighbors in the local-world of node j have different degrees, which are 6, 3, 3 and 1 in Fig. 2b. The connection probabilities can be calculated from Eq. (5), which are 0.46154, 0.23077, 0.23077 and 0.07692. Then, it chooses m neighbors to establish connection by roulette method. In Fig. 2c, There are not only isolated nodes, but also connected nodes in the local-world of node k. The connected nodes, k_1 and k_2, whose degrees are 3 and 1, will be prior considered by node k. Node k determines the connection scheme by the value of m, whose threshold is equal to the number of connected nodes. As shown in Fig. 2c, the threshold of m is 2. If $m > 2$, in addition to establish connection with nodes k_1 and k_2, it chooses $m - 2$ neighbors to establish connection in equal probability. If $m = 2$, node k establishes connection with nodes k_1 and k_2 directly without calculation. If $m < 2$, it calculates the connection probabilities of nodes k_1 and k_2, which are 0.25 and 0.75, then uses roulette method to choose the neighbor.

4 Algorithm Design

This algorithm describes the modeling process of scale-free network topology in wireless sensor networks. The variables used in the algorithm are as follows.

- □ *N_0*: the number of nodes in initial wireless sensor network topology.
- □ *N*: the total number of nodes in scale-free wireless sensor network topology. *N* contains the nodes in *N_0*.
- □ *V*: the set of all nodes in scale-free wireless sensor network topology.
- □ *V_0*: the set of nodes in initial wireless sensor network topology.
- □ *V_i*: the set of nodes in the communication range of node i but not connected with it and have not reached the maximum degree.
- □ r: the communication radius of each node.
- □ *P_i*: the perceived probability of node i.
- □ m: the number of adding edges for each new joined node.
- □ *Lst_i*: list of the neighbor nodes, which connected with node i.

```
program BANetworkbuild (Lst_i)
   var
     N, V, r, P_i, m
   begin
   V_in = initial N_0 nodes();
   repeat
     broadcastStartPacket(v_i);
```

```
      V_i=receiveDisconnectNeighborDegree();
      if the degree of nodes in V_i are all zero && P_i>0.9
        equal connection possibility;
      else if P_i>0.9
        repeat for all v_j in V_i do
          calculating connection possibility by degree;
        until all v_j in V_i are selected
      use Roulette method select m nodes in V_i base on
      connection possibility;
      Lst_i = Modify neighbor list of v_i;
      broadcastEndPacket(Lst_i);
    until all v_i in {V-V_in} are selected
end.
```

This algorithm works as follows. At the beginning, a new joined node i sends an adding connection request to all neighbors. Then, it receives the degree information of nodes which in the local-world of node i. During the adding connection process of node i, the other neighbor nodes cannot execute at the same time. Next, node i calculates connection probability of each neighbors based on feedback information. If the degree of each neighbor node is zero, node i connects with them in equal probability. In other case, node i calculates connection probability according to the degree of neighbor nodes. Then we describe the process of establishing m edges between node i and its neighbors by roulette method. At last, the neighbor list Lst_i is updated and broadcasted to all neighbor nodes.

5 Simulation Results

We evaluate the scale-free properties of our proposed model in Matlab. Total nodes based on homogeneous networks are randomly deployed in a 3D sensor field of $50 * 50\ m^2$. The number of peaks is set to 12 and their heights are in the range of 10 to 20. Considering each node must have sufficient neighbors during the modeling process, the communication radius r is set to 15 m after many simulations and analysis. The number of nodes in initial wireless sensor network topology N_0 is set to 3 and the maximum degree of all nodes is set to 20.

Figure 3 shows the scale-free properties of network topologies with 100 nodes. All of the nodes are represented by the blue dots. The size of dot is used to distinguish different nodes degree. So bigger dot means higher degree. The black solid lines are used to represent the connection between nodes. In Fig. 3a, the probability parameters of deployed nodes α, β are set to 2 and 0.3. It shows the perceived probability of the deployed sensor nodes. The blue dots represent the projective position of nodes in xy plane. We can find that the majority parts of 3D terrain are achieved over 0.8 perceived probability. They can be monitored with high probability. But there are also some parts with sparse nodes have lower perceived probability. Figure 3b show the scale-free network topology without 3D terrain. Each node needs to add 2 edges during the modeling process and the

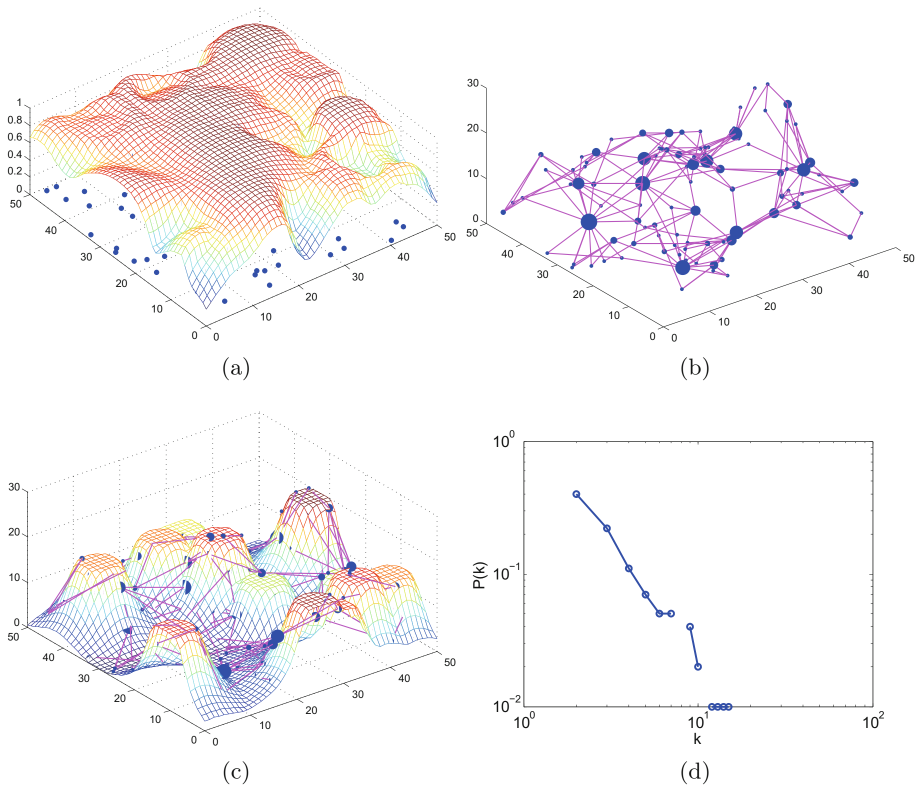


Fig. 3. Scale-free properties of wireless sensor network topologies with 100 nodes in 3D terrain.

perceived probabilities of them are all over 0.9. The majority nodes have low degree. But there are also few nodes with high degree, they have more edges. Nodes degree completely accords with power-law distribution. It proofs that the wireless sensor network topology, which is modeled by the proposed strategy, maintains good scale-free property. In Fig. 3c, we put the completed scale-free network topology in the 3D terrain. The peaks hid some nodes from view. But the location and connection of all nodes keep the same with Fig. 3b. And Fig. 3d shows the degree distribution. It follows the power-law distribution.

6 Conclusion

After fully considering the requirements of wireless sensor networks in practical application, this paper builds a network model with scale-free property based on developed growth and preferential attachment criteria for homogeneous wireless sensor network in 3D terrain. The simulation results show that the scale-free wireless sensor network topology according to our modeling strategy keeps obvious scale-free property.

We will further focus on the application of complex network theory in sensor networks of Internet of Things (IoTs). Combining with the advantages of scale-free model and small world model, we will explore the robust optimization strategy of sensor networks for distributed IoTs in the future work.

Acknowledgments. This work is partially supported by Natural Science Foundation of P.R. China (Grant Nos. 61572106 and 61202443), and the Fundamental Research Funds for the Central Universities.

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