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Fault-tolerant Method for Detecting Coverage Holes of Wireless Sensor Networks

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Abstrak

Cakupan adalah salah satu masalah mendasar dalam jaringan sensor nirkabel (WSNs) karena merupakan ukuran penting dari Quality of Service (QoS) untuk aplikasi jaringan. Namun, karena pengembangan yang acak, pembuangan daya, intrusi dan serangan node lain yang jahat, lubang cakupan sering muncul dan merusak jaringan. Untuk mengatasi masalah ini, disajikan algoritma desentralisasi koordinat bebas dan toleransi kegagalan untuk mendeteksi lubang cakupan, yang dapat dijalankan pada node tunggal. Ini hanya membutuhkan konektivitas informasi dikumpulkan dari satu hop tetangga dari node berjalan. Selama proses deteksi, penyederhanaan masalah komplek secara maksimal dari lokal area diperlukan untuk menentukan apakah node pada batas lubang atau tidak. Setelah informasi dari sensor di sekitar lubang cakupan diproses oleh base station, maka ukuran lubang cakupan akan diperoleh. Hasil simulasi menunjukkan toleransi kesalahan pada metode yang diusulkan. Akurasi deteksi, deteksi kesalahan dan deteksi-tidak terjawab dibandingkan dengan beberapa metode terkait yang ada saat ini. Hasil penelitian juga menunjukkan bahwa metode yang diusulkan adalah efektif, kuat, dan sangat cocok untuk jaringan skala besar.

Kata kunci: *jaringan sensor nirkabel, lubang cakupan, maximal simplical complex, sensor statis*

Abstract

Coverage is one of the fundamental problems in wireless sensor networks (WSNs) since it is an important measure of Quality of Service (QoS) for the network's applications. However, due to random development, power exhausting, intrusion and attacking of other malice nodes, coverage holes often appear and undermine the networks. In order to solve this problem, we present a decentralized, coordinate-free, and fault-tolerant algorithm for detecting coverage holes, which can be run on a single node. It only needs the connectivity information gathered from one-hop neighbors of the running node. During the detection process, maximal simplicial complex of the local area is required to determine whether the node is at the boundary of a hole or not. After the information of sensors around the coverage hole will be processed by the base station, and the size of coverage holes will be obtained. Simulation results show the fault tolerance of the proposed method. Meanwhile the detection accuracy, error-detection and missed-detection are compared with some related methods reported recently. The results also show that our method is effective, robust, and especially suitable for large scale networks.

Keywords: *coverage holes, maximal simplicial complex, static sensors, wireless sensor networks*

1. Introduction

Wireless sensor networks can be used in many fields,from landslide monitoring [1] to multimedia application such as wireless visual sensor networks [2]. In wireless sensor networks, an efficient coverage can ensure the QoS and desired functionalities i.e, sensing and communication of the WSNs. Due to random deployment, power exhausting or intrusion, etc, different kinds of holes will appear in such networks, which may produce geographically correlation problem in that area, such as coverage holes, routing holes, jamming holes, sink/black holes and worm holes [3], etc. In this paper, we focus on detecting coverage holes, since detection is the fundamental technical problem before how to repair.

The related researches on coverage detection in WSNs were classified into two types: using the location or not. There are 4 types of detection methods with accurate location information: energy conservation, virtual forces, graph theory and balanced coverage. Energy-conservation based method [4-6] propose a node replacement and reclamation strategy (NRR), in which a mobile robot or human labor called mobile repairman (MR) traverses the sensor

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network periodically, reclaims nodes with low or no power supply, replaces them with fully-charged one, and brings the reclaimed nodes back to an energy station for recharging. The second type methods are based on virtual forces. Virtual forces based algorithms or protocols [7-9] employed mobile sensors as the assistants, which moved from densely covered areas to sparsely covered areas to achieve balanced coverage. Thirdly, the graph theory based methods [10-12] use to determine the accuracy size and position. For example, Wang et al. [11] use Voronoi diagrams to discover the existence of coverage holes once all the sensors have been initially deployed in the target area. Three distributed self-deployment algorithms of Vector based (VEC), Voronoi based (VOR) and Minimax algorithm were also proposed for the moving sensors to get the optimal position. Finally, the methods based on energy conservation [12], [13] try to get the balance of coverage of WSNs. Wu[12] proposed a method named SMART, which divides the network into grid and guides the moving sensor from the dense grid to the sparse one. To acquire the accuracy location, expensive devices should be equipped which increase the cost of the network.

Methods without location are often centralized [14-16], in which a base station finds the coverage hole by using all the location of all nodes. Ghrist [14] introduced a novel idea of using the mathematical field of homology. Kanno el al. [15] proposed two methods, divide-and-conquer strategy and triangle collapsing algorithm, which determine the location and the number of the coverage holes in different ways. The divide-and-conquer strategy divides the complex into sub-complexes and computes the number of holes by computing 1st betti-number of each sub-complex, then decides whether to divide the sub-complex or not. Chintakunta et al.[16] also presented a method based on divide-and-conquer strategy, in which they computed the laplacian-matrix instead of 1st betti-number to determine the number of coverage holes. The computing complexity of Chintakunta’s algorithm is less than Ref [15]. The two divide-and-conquer strategy based methods are both based on the simplicial complex [17], in which the overview of the entire networks is required. So they are centralized. It is unfortunately that the centralized algorithms will become more time-consuming, when the number of sensor nodes becomes larger.

Some decentralized methods are proposed, such as Refs [18-22], in which the accuracy coordinate location information is also not needed. 3-Mesh [20] is a typical distributed algorithm that elects nodes for full coverage efficiently, and detect holes either caused by faults of static nodes or by mobility of mobile nodes. However, most decentralized methods mentioned above [18-20] are low efficient and very time-consuming since they determine the fault node one by one, and the sensors run the detection algorithm in turn. Until now, it is a difficult question to find a decentralized method without location information for large scale networks. It is also too expensive to equip each sensor with a motion base and a GPS device by using location information. To avoid this dilemma, we focus on large scale static networks. We detect the coverage holes by the co-operation of static nodes and using the mobile nodes supported by the static nodes to repair the detected holes. In this paper, we propose a distributed detection method with fault tolerance, in which GPS based location information is not required. The remainder of this paper is organized as follows: Section 2 provides some preliminaries for the work; Section 3 describes our work in detail including the procedure of our algorithm. Experimental study is presented in Section 4 to evaluate the performance of our algorithm. Finally, Section 5 concludes this paper and discusses about further research.

2. Preliminaries

2.1. Network Model

(i) Each sensor knows its neighbors and their connectivity. Furthermore, the maximal communication range RC is twice of the maximal sensing range RS.

(ii) We assume that the network is usable when there is only a small part of blind area in some time slot. It was proved that the uncompleted coverage is acceptable [23] in practice when the maximal coverage is over 90%. So it is unnecessary to keep the whole monitored area covered by the sensor networks.

(iii) A sensor is called a hole-boundary-node if it is located in the boundary of a coverage hole. And we take each hole-boundary-node as a vertex of an irregular polygon which is the boundary of the coverage hole.

2.2. Maximal Simplicial Complex

Defination 1 (Simplicial Complex) [24]. Given a set of vertex V, a k-simplex is an unordered subset $\{S_0, S_1\ldots, S_i, \ldots, S_k\}$ where $S_i \in V$ and $i \neq j$ for all $S_i \neq S_j$, where the region of this k-simplex consist of all (k−1)-simplex of the set $\{S_0, S_1\ldots, S_{i-1}, S_{i+1}\ldots, S_k\}$ for $0 \le i \le k$. A simplicial complex G is defined as a finite collection of simplices that satisfies the following two conditions:

(i) For any simplex $\rho_i \in G$, the region of ρ_i also belongs to graph G for each i.

(ii) For any two k-simplices $\rho_i, \rho_j \in G$, if $\rho_i \cap \rho_j \neq \Phi$, then a common region ρ_k will be obtained, that is to say, $\rho_i \cap \rho_j = \rho_k$ and $\rho_k \in G$.

For example, in Figure 1, (a), (b), (c) (d) are 0-simplex, 1-simplex, 2-simplex, 3-simplex respectively. But (e) and (f) are examples for non- simplex. Simplicial complex is an extension of the concept of k-simplices. It may be taken as the collections of the attached simplices.

Graph theory was often employed in solving the problems of coverage holes detection for the similarities between communication network's topology and graph. Muhammad and Egerstedt [17] have recently proposed a simplicial complex based method to eliminate the edges of the crossing pair in the communication networks, and the structure of the topological holes is still maintained. Simplicial complexes can simplify the communication network efficiently. Figure 2(a) shows a typical network communication graph, which is non-planar and very complicated. Figure 2(b) gives the maximal simplicial complex sub-graph of Figure 2(a). Obviously, the simplicial complex is more concise and keeps the key information of the coverage. So we think the entire communication graph is not needed in analyzing the coverage. The maximal simplicial complex sub-graph not only simplifies the communication networks but also makes it planar. A plane graph reduces the dimension of the data structures of the networks and is helpful for further processing. Based on this dimension reduction, we can use Euler formula instead of time-consuming method for calculating higher dimension homology graph.

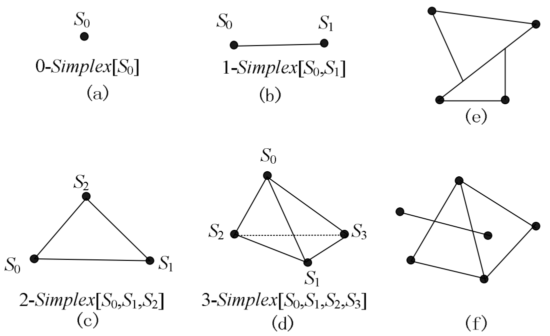
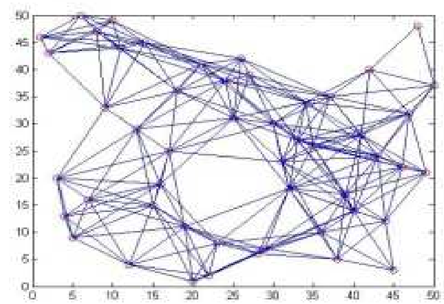
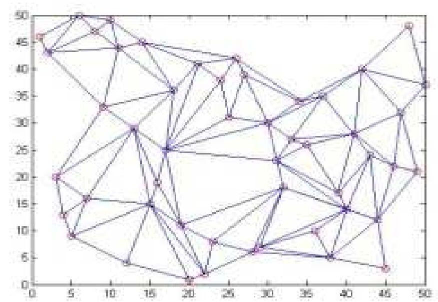


Figure 1. k-simplex and non-examples of simplicial complexes



(a) Network Topology Graph



(b) maximal simplicial complex sub-graph

Figure 2. The communication Network and its maximal simplicial complex

Defination 2 (Neighbors). For a node S_i, $N(S)$ is the set of its neighbors, the definition can described as following:

$$N(S)=\{S_i \in V' \mid d(S,S_i) \le R_C, S \ne S_i\}\ \ i=1,2,3\ldots \quad (1)$$

where *V'* is the set of nodes in WSNs, and $d(S, S_i)$ is the euclidean distance between those two nodes.

Definition 3 (Maximal Simplicial Complex Sub-Graph of a Node). The communication graph of a node consists of its neighbors and itself based on the communication distance. And the maximal simplicial complex sub-graph of a sensor is a graph eliminated the cross edges from the communication graph.

Definition 4. (Counter Vertex) A vertex which shares a triangle with an adjacent edge is called a counter vertex of that edge. As shown in Figure 3(a), S_3, S_7 are two counter vertexes of adjacent edge S_1S.

In the following, we firstly give some theorem which will support our coverage hole detection algorithm.

Theorem 1 [25]. If each pair of sensors of ΔSS_iS_j can communicate when R_C is twice of R_S, the coverage degree C inside the triangle is:

$$C \ \ge \ \frac{\pi}{2\sqrt{3}} C_{\Delta SS_iS_j} \quad (2)$$

And in this case, the coverage will be not less than 90%.

Theorem 2 In sub-graph, if inequality (3) is content, S_i and S_j will lie on two sides of adjacent edge SS_k respectively.

$$C_{\Delta SS_iS_j} + C_{\Delta SS_iS_k} + C_{\Delta S_iS_jS_k} > C_{\Delta SS_kS_j} \quad (3)$$

where $C_{\Delta SS_iS_j}$ is the area of triangle ΔSS_iS_j. S_i and S_j are two counter vertexes of edge SS_k.

Proof: We assume that if S_i, S_j lie on the two sides of the line SS_k. Hence, SS_k is a diagonal of $SS_iS_kS_j$ and the graph is isomorphic to (a) (b) (c) as shown in Figure 4. In (a), it is obvious:

$$C_{\Delta SS_iS_j} + C_{\Delta SS_iS_k} + C_{\Delta S_iS_jS_k} > C_{\Delta SOS_j} + C_{\Delta S_jOS_k} = C_{\Delta SS_kS_j} \quad (4)$$

Because $C_{\Delta S_iS_jS_k} > C_{\Delta SS_kS_j}$, we can get inequation (3) in (b), which is similar in (c). In a sub-graph, (e) cannot happen, since there are no cross edges. If S_i and S_j are at the same side as shown in (d), we will get $C_{\Delta SS_iS_j} + C_{\Delta SS_iS_k} + C_{\Delta S_iS_jS_k} = C_{\Delta SS_kS_j}$.

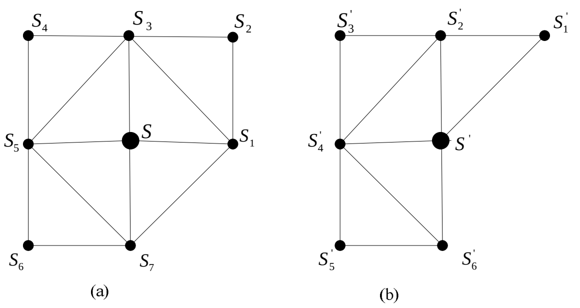


Figure 3. (a) non hole-boundary-node S , (b) hole-boundary-node S

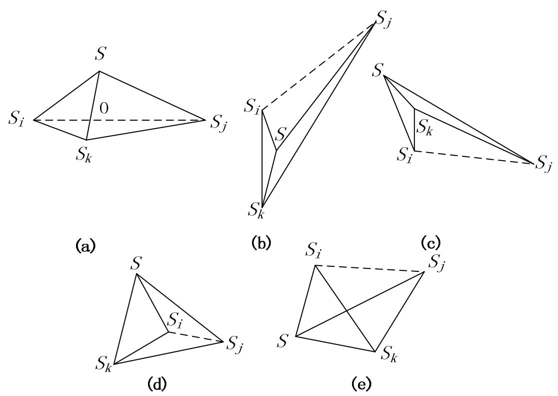


Figure 4. S_i, S_j two counter vertexes of SS_k

Theorem 3 In a sub-graph of a sensor, if every adjacent edge has two counter vertexes which lie two side of this edge, and then the area around the node is covered and it is a non hole-boundary-node.

Proof: In Figure 3 (a), it shows a sub-graph of S. and its adjacent edge SS_1 is diagonal of quadrangle $SS_3S_1S_7$, meaning S_3 and S_7 lie two side of SS_1. Based on the theorem 1, coverage within $\triangle S_1SS_3$ and $\triangle S_1SS_7$ is not less than 90%. So coverage within quadrangle is not less than 90%. Similarly, the other three adjacent edges, SS_3, SS_5 and SS_7 also meet this condition. The area around the node S, labeled as A, is covered and the coverage of A is not less than 90%, so node S is a non hole-boundary-node. Figure 3(b) shows sub-graph of S', because there are no appropriate quadrangles embrace adjacent edges $S'S_1'$ and $S'S_6'$, and then the part of its boundary is not fully covered. So it is a hole boundary node.

3. Description of Algorithm

In this section, we describe the algorithm about each sensor node how to determine whether it is a hole-boundary-node or not. As we know, if all the area around a node is covered by the node itself and its neighbors, it will not be a hole–boundary-node. But in Ref [23], the authors mention that it is available for the WSNs in some practical environment, when the coverage is not below 90%. Hence we assume that a sensor is a non-hole-boundary node, when the coverage around it is up to 90%.

To do this, we use maximal simplicial complex sub-graph defined in defination3. According theorem3, we can get that whether a sensor is a boundary node or not by verifying it's each adjacent edge. Thus, verifying the existence of two counter vertexes which lie different side of an adjacent edge is a key for our algorithm. Based on theorem3, we describe the method of verification process of two counter vertexes in section 3.1. Furthermore, in sention 3.2, the pseudo code is given which is the algorithm that every sensor should execute.

3.1. Verification Process of Adjacent Edge

Choosing a sensor S, SS_k is a adjacent edge of S, and S_i, S_j are two counter vertexes of SS_k to be verified. We get the angles $\angle S_i SS_k$, $\angle S_k SS_j$, $\angle S_i SS_j$, marked as α, β, γ, and length SS_i, SS_k, SS_j, marked as a, b, c. Using these parameters, we can get whether the condition can be satisfied in theorem3.

Algorithm1: verification process of adjacent edge.

(i) Calculate the area f_1 of ΔSS_iS_j, $f_1=\frac{1}{2}\times a\times c\times \sin\gamma$;

(ii) Calculate the area f_2 of ΔSS_iS_k, $f_2=\frac{1}{2}\times a\times b\times \sin\alpha$;

(iii) Calculate the area f_2 of ΔSS_jS_k, $f_3=\frac{1}{2}\times b\times c\times \sin\beta$;

(iv) Calculate the length f_4 of S_iS_j, $f_4=\sqrt{a^2+c^2-2ac\cos\gamma}$;

(v) Calculate the length f_5 of S_iS_k, $f_5=\sqrt{a^2+b^2-2ab\cos\alpha}$;

(vi) Calculate the length f_6 of S_jS_k, $f_6=\sqrt{b^2+c^2-2bc\cos\beta}$;

(vii) Calculate the angle f7 of ∠SjSiSk,

(viii) $f_7=\arccos\left\{\frac{(f_6)^2-(f_4)^2-(f_5)^2}{2\times f_4\times f_5}\right\}$;

(ix) Calculate the area f_8 of $\Delta S_iS_jS_k$, $f_8=\frac{1}{2}\times f_4\times f_5\times \sin f_7$;

(x) If $f_1+f_2+f_8 > f_3$ return d=1; else return d=0;

The output of the algorithm 1 is d=0 or d=1, where S_i, S_j are two counter vertexes lying at two side of SS_k with d=1; S_i, S_j are two counter vertexes lying at same side of SS_k with d=0.

If there are two vertexes lying at the different side of a adjacent edge, we can know that the coverage of two side 2-simplex of this quadrangle is more than 90% based on theorem1. If there are not two vertexes with this feature of SS_k, coverage of one side around it will be less than 90%. Therefore this area is a part of the coverage hole, and the sensor S is a hole-boundary-node. Meanwhile, the other point S_k of the adjacent of SS_k is also a hole boundary node, because above condition can also be contend in the maximal simplicial complex of S_m. For example, in Figure 3(b), adjacent edges $S'S'_1$, $S'S'_4$ do not have such vertexes to satisfy the condition of theorem3, so S', S'_1, S'_4 are three hole boundary points.

3.2. The Detection Algorithm

The distributed coverage holes detection algorithm is applicable on large-scale WSNs. With limited available location information, our algorithm can effectively detect coverage holes. Below we present a pseudo-code for DCDA.

Algorithm 2: *Distributed coverage hole detection algorithm*

```
(i)       Find all sensor nodes N(S) within the communication radius of S;
(ii)      Obtain the communication graph with N(S) and target sensor node S;
(iii)     Eliminate cross edges form communication graph G to get the maximal simplicial complex sub-
          graph H;
(iv)      Set D stores all the adjacent edges in H;
(v)       tap=0; L=length(D)
(vi)      WHILE  length(D)>0
(vii)     Select a adjacent edge e, and its vertexes is S, Sk;
(viii)    Obtain the set Vex(e); d=0;
(ix)      Select two counter vertexes Si, Sj∈Vex(e) randomly;
(x)       WHILE Exist the counter vertex which do not have be verified.
(xi)      Input S, Sk, Si, Sj, and run algorithm1;
(xii)     IF d==1
(xiii)    continue;
(xiv)     ELSE IF d==0
(xv)      Select two new counter vertexes Sm, Sn∈Vex(e);
(xvi)     END
(xvii)    END
(xviii)   IF d==1
(xix)     tap=tap+1;
(xx)      Delete edge e form set D;
(xxi)     ELSE IF d==0
(xxii)    Sensor S and Sk are two hole boundary nodes
(xxiii)   Delete edge e form set D;
(xxiv)    S stores the ID of Sk;
(xxv)     END
(xxvi)    END
(xxvii)   IF tap==L
(xxviii)  S is not the hole boundary node;
(xxix)    END
```

The output of algorithm 2 is the value of Sensor S and its neighbors are hole-boundary nodes or not. In step11, we determine the adjacent edge e whether has two vertexes lying two side of it based on theorem2. And the basic idea is based on the theorem3 which can judge the executing sensor is a sensor network or not.

In the end, a base station collects the information from the sensor nodes and connects every hole boundary node to identify coverage holes within the WSNs. Note that the base station or the network gateway needs to collect only node IDs of the hole boundary nodes. Comparing with the distribute method in Ref [18], our method can easily get the irregular polygon, while their method should use extra communication expenditure to get the same polygon. If there are m sensors bound to the coverage hole, and each of them has m_0 neighbors evenly. The energy which is used to broadcast and receive one bit are *Es*, *Er*, respectively. The total energy used to broadcast and receive is E, and $E= E_s+m_0\times E_r$. Thus, the method in Ref [18] will use at least $m\times(E_s+m_0\times E_r)$ to get the polygon.

4. Simulation Result

To simulate the algorithm, we build a node-by-node detection algorithm using MATLAB. First, in order to improve the robustness of our scheme, we propose a threshold-type policy in which a hole is reported by the network if and only if the number of nodes who report that they border a hole is greater than a threshold. Second, we do other simulation for further evaluation of the effectiveness of our approach comparing with the method DAC mentioned in Ref [16].

4.1. Fault Tolerance

In practice, there may be errors in the distance measurements, which in turn lead to errors in coverage holes detection. We demonstrate how to make our scheme more robust to errors in this. Two types of errors in coverage holes detection: (a) false alarm and (b) misdetection. A false alarm is the error that there is actually no hole, but a hole is reported by the network. A misdetection is the error that there is actually a hole, but it is not reported by the network.

We deploy appropriate sensors randomly in a field 120×120 meters^2, so as to ensure that the probability that there is a coverage holes is roughly 0.5. We assume the evaluated distance between adjacent nodes S and S' is given by:

$$Eval\_Dist_{s,s'} = d_{s,s'}(1+X\times Error\_Index) \quad (5)$$

Where, $d_{u,v}$ is the actual distance between the nodes, X~$N(0,1)$is a normal random variable and *Error_Index* is a simulation parameter that controls the variance of the distance measurement errors.

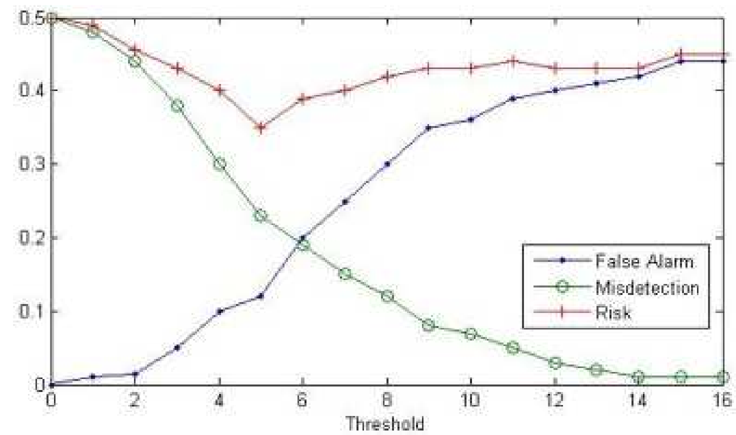


Figure 5. False alarm probability, misdetection probability with Error_Index = 2%

In Figure 5, the risk is minimized at a certain 4 threshold value, which is the optimal threshold. So, the risk can be reduced with a threshold-type policy if the threshold is chosen judiciously.

4.2. Simulation and Comparison

The detection accuracy, error-detection and missed-detection are shown in this simulation and we take 12 iterations results of the DAC to do this work. n' is the number of real coverage holes which exist in the network. The number of coverage holes detected by detection algorithm is n. The detection number n can be divided into two parts. One is the false coverage holes n_0 which are detected by the detection algorithm but not exist in the network. The other n_1 is the number of the real coverage holes which are detected and also exist in the network. We can get the follow definition: Detection is n_1/n'; Accuracy is n_1/n; Error-detection is n_0/n; Missed-detection is $(n'-n_1)/n'$;

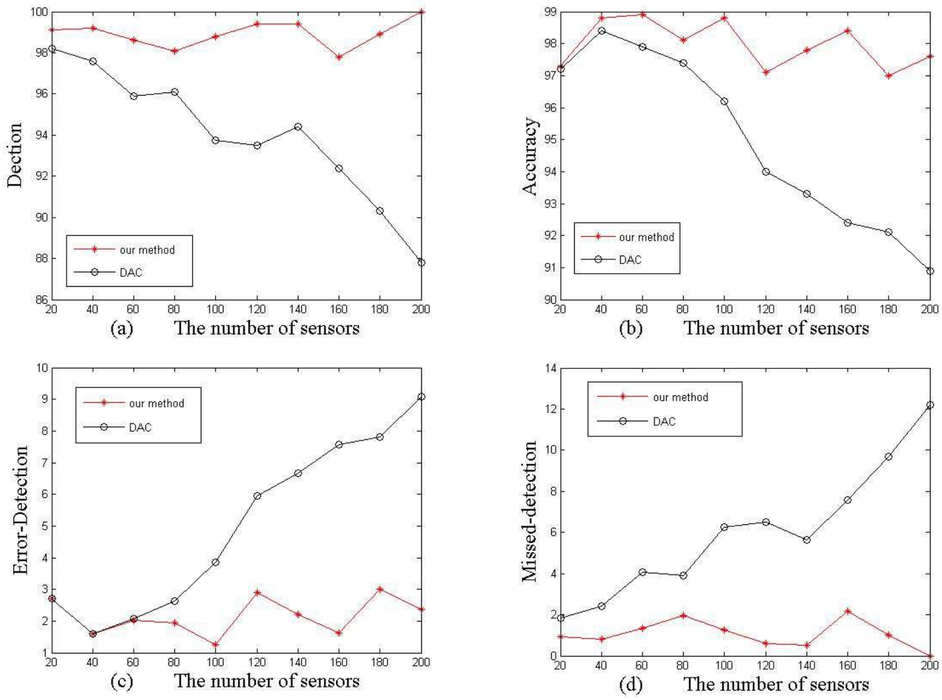


Figure 6. Comparison with related work

In Figure 6, there is no big gap between our method and DAC when the network is not complicated. But as the network become complicated and the number of sensor nodes becomes significantly large, DAC performance decreases drastically. Compared to 93.99% detection and 94.98% accuracy of DAC, our method can get 98.93% and 97.98%, respectively. Meanwhile, in Figure 6 (c) (d), we can see the error-detection and missed-detection become higher than our method. So we can get the conclusion that our method is better than DAC mentioned in Ref [16].

5. Conclusions

To solve the problem of coverage holes due to energy exhausting and random deployment, the paper proposed a solution for distributed coverage holes detection in coordinate-free wireless sensor networks using model of maximal simplicial complex sub-graph. The distributed coverage holes detection algorithm is running at each individual node to determine whether it is a boundary node, and then the position and size of the coverage holes can be obtain by node cooperation. Our future work will be focused on the patching algorithm to repair the holes after locating the position of the holes by implementing our algorithm.

Acknowledgments

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