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Obstacle-Avoiding Connectivity Restoration Based on Quadrilateral Steiner Tree in Disjoint Wireless Sensor Networks

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ABSTRACT In the harsh environment, wireless sensor networks can suffer from a significant damage that causes many nodes/links to fail simultaneously and the network to get splitted into multiple disjoint partitions. In such case, linking the separated partitions by placing the least number of relay nodes and obstacle-avoiding to re-establish a strongly connected network topology is necessary to maintain the functional operations of wireless sensor network. However, the problem of finding the minimum count and the position of relay nodes is NP-hard hence heuristics methods are preferred. In this paper, we present a novel Obstacle-Avoiding Connectivity Restoration based on Quadrilateral Steiner Tree (OACRQST) algorithm to address this problem. First, the appropriate quadrilaterals are selected to connect the separated partitions and the Steiner nodes of these quadrilaterals are found. Then the disjoint islands are connected with the triangle Steiner tree or minimum spanning tree method, which are not connected by these selected quadrilaterals. Finally, relay nodes are placed to the appropriate position according to the edges of Steiner tree to restore network connectivity. However, if the found position is in the area of the obstacle, the relay node will be placed at the position of the bordering that nearest to the found position. If the network still is not connected, the relay nodes will be placed at the appropriate position according to the bordering of the obstacle starting from the node placed at the position of the bordering nearest to the found position exploring the left rule. Extensive simulation experiments demonstrate the beneficial aspects of the resulting topology with respect to number of relaying nodes, degree of connectivity and fault resilience.

INDEX TERMS Wireless sensor network, connectivity recovery, quadrilateral Steiner tree.

I. INTRODUCTION

Recently, wireless sensor network has been used almost in anywhere, especially in harsh environment, such as, search-and-rescue, battlefield reconnaissance, underwater monitor, and so on. Due to the dry battery power and the harsh environment, sensors may easily stop working. However, the network connectivity is very important in WSN, especially search-and-rescue, battlefield reconnaissance and so on. The damage of the network may cause inestimable loss. Thus, it is very important to restore network connectivity when the network is not connected.

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When the network was damaged in a large-scale, the most critical problem is how to re-deploy or move the least nodes to the critical position to restore network connectivity. Of course, this problem has been demonstrated to be the NP-hard. Hence, almost all of the literatures about solving this problem are based on heuristic algorithm to find the arrangement position, in which the most common method is the Steiner minimum tree (SMT) algorithm. This algorithm will degenerate into the minimum spanning tree algorithm (MST_1tRNp) [1], [2] in many cases, it first uses the classical Prim or Kusual algorithm to search the MST, and then deploys relay nodes in corresponding position according the length of each edge and the communication radius of the relay node. Recently, many researchers have proposed some approximate algorithms to deploy the relay nodes, such as Spider-web model, CORP algorithm [3], [4] and FeSTA [5]. FeSTA is based on steinerizing appropriate triangles. First, FeSTA finds the best triangles and forms islands of segments by establishing intra-triangle connectivity. Then, disjoint islands of segments are federated. Finally, the steinerized edges are optimized. The run time complexity of Algorithm 1 is $O(n^4)$ where n is the number of terminals..FeSTA outperforms contemporary heuristics in the literature in terms of the average node degree, average path length and network coverage. However, in some practical environment, obstacle may be exist in the damaged area, so in this paper, we also considering the obstacle-avoiding when deploying relay nodes.

In this paper, a novel Obstacle-Avoiding Connectivity Restoration based on Quadrilateral Steiner Tree (OACRQST) algorithm on the basis of our previous study of quadrilateral Steiner tree algorithm [15] is proposed. It assumes each separate partition as one point. Firstly, list all quadrilaterals which may be connected to each partition. Secondly, find the quadrilaterals which comply solving the quadrilateral Steiner points in ascending order. Thirdly, find out the corresponding Steiner points and connect the four partitions via deployed relay nodes. And then, explore the same method to look for other quadrilaterals connecting the four partitions. Finally, the partitions will be not connected with the quadrangle Steiner tree, therefore, employ Steiner triangular approximation algorithm (FeSTA) or the minimum spanning tree algorithm (MST_1TRNP) to deploy relay node to the corresponding position to realize the entire network connectivity. If the found position is in the area of the obstacle, the relay node will be placed to the position of the bordering that nearest to the found position. If the network still is not connected, the relay nodes will be placed at the appropriate position according to the bordering of the obstacle started from the above node exploring the left rule.

II. RELATED WORK

Two categories of approaches have been pursued in the literature for network connectivity recovery in WSNs. In the first category, additional nodes are populated to the position of the failure node or the failure area. The second category is moving the original node to realize the connectivity recovery. Nodes are not needed to be redeployed in the second method, but the node mobile is required. Abbasi *et al.* [7] proposed Movement-Assisted Connectivity Restoration, which consider simply connected and biconnected algorithm. Firstly, it detect actor failure and initialization the recovery process. Then decide which node as the mobile node and where to move and at last is the node relocation. Wang et al. [6] analyzed the proposed algorithm, and pointed out some defects of the theory, presenting a centralized algorithm to realize K-connectivity recovery network. Akram and Dağdeviren [24] also proposed an algorithm named TAPU for k -connectivity restoration that guarantees the optimal movement cost. This algorithm improves the time and space complexities of the previous approach (MCCR) in both best and worst cases. Almasaeid and Kamal [26] presented a centralized solution that utilizes the amount of intersection between communication ranges of existing sensor nodes to reduce the total number of additional nodes needed to repair k-connectivity in a k-disconnected network.

Mi and Yang [8] have proposed a connectivity restoration method, which is restore the network connectivity through the local information of k-hop neighbors. Mohamed Younis *et al.* [9] present a distributed algorithm for Recovery through Inward Motion(RIM), which is restore the network connectivity after the node failure through moving the neighbors of the lost node. Imran *et al.* [10] present DCR, which can detect the partition and tolerate the actor failure. The two algorithms are all hybrid in the sense that they consists of two parts, i.e. proactive and reactive, and all designates backup nodes with an ordered criteria. The difference from the previous literature is that this paper employs mixed localized detection recovery algorithm, and selects backups only with the information of 1-hop-neighbours.

The approach of moving nodes usually started from a single node failure, and then expanded to the failure of multiple nodes. When the failure of a single or a small number of nodes occurs, moving node method is very effective, but using this method, people need to move too many nodes in a large-scale of nodes failure. It may also result in considerable energy loss, which shortens the life cycle of the node and is not conducive to extend the life of the network.

There are no special requirements to node to deploy the new relay nodes to realize connectivity, therefore, we use the deployed new relay nodes to realize connectivity restoration. However, this problem is NP-hard and hence heuristics methods are preferred.

Lee and Younis [11] proposed method DORMS, which through constructing Steiner tree in failure region to reduce the number of relay nodes. They also present a method to restore the network through establishing a bi-connected inter-partition topology [20]. Senel and Younis [12] proposed an algorithm CIST, which thorough locating all nodes on the segment boundary to restore the network. Senel *et al.* [3] also presented an Spider-web relay node deployment strategy, First, identify the boundary segments. After that, choose a representative node from each segment; connect that node and the center node, and then form a straight line. Then sort in descending order according to the Euclidean distance between two points, arrangement of the relay node in the order from the largest one, employ the left and right connected method to connect the segments, until all of them are connected. Lee and Younis [4] proposed CORP algorithm, which is based on deploying additional nodes to move closer to the center to connect the segments. In [13], the author proposed EQAR algorithm, which considers the QoS requirements. Uwitonze *et al.* [19] proposed a heuristic algorithm RPSNC, which considers the Space Information Flow. Al-Turjman *et al.* [25] proposed two schemes for relay node placement in federating WSNs: Connectivity-Based Placement (CBP) and Connectivity-Based Placement with

Delay-constraint (CBP-D).CBP maximizes the connectivity of the network without any delay considerations, while CBP-D maximizes the network connectivity with an upper bound on the maximum delay. Xiaoding *et al.* [21] proposed a distributed restoration algorithm based on optimal relay node placement. They also brought forward a practical method in Literature [22], which is a hybrid recovery strategy based on random terrain, taking both realistic terrain influences and quantitative limitations of relay devices into consideration.

Lloyd and Xue [1] presented minimum spanning tree algorithm(MST_1tRNP),which first uses the classical Prim or Kusual algorithm to search the MST, and then deploys relay nodes in corresponding position according the length of each edge and the communication radius of the relay node. Senel and Younis [5] proposed FeSTA algorithm which is based on nding the best triangles to connect the islands of segments until the whole network is complete connected.

In practical environment, the obstacle is exist in the network, thus recently, some obstacle-avoiding algorithms have been proposed. In Literature [16], the author proposes ORRD algorithm, which can obstacle-avoiding when replay nodes through robot moving to realize the network connected. Literature [17] proposes a Steiner-point based algorithm, which is focused on the usage of Steiner points instead of the handling of obstacles. Senturk and Akkaya [18] presents an connectivity restoration algorithm in disjoint MSNs, which considers the realistic terrains when avoiding obstacles. Wang *et al.* [23] presents a novel connectivity restoration strategy —proposed-Obstacle-Avoid connectivity restoration strategy, based on Straight Skeletons (OASS), which employs both the polygon based representative selection with the presence of obstacles and the straight skeleton based SMT establishment.

In this paper the obstacle is considered when deploy new relay nodes, and OACRQST is based on our previous research of QTA [15] algorithm. Though compared with the QTA, triangular Steiner tree, and the MST algorithm, OACRQST further reduces the number of required relay node, and improves the average node degree of the recovery connectivity network.

III. SYSTEM MODEL

We assumed that a set of sensors are deployed in an area of harsh environment to monitor, such as in forest, battlefield, desert, mountain and so on. Of course, in the monitor area may be exist obstacle. The nodes are stationary, and the sensing radius and communication radius is fixed. Sensor nodes can communicate with each other in their communication radius, the collected data will be transmitted to the base station finally.

In the general environment, the sensor nodes may be failure because of the energy depletion, but in most cases, will lead to only a small number of node failures. If it is not affect the network connectivity, we can do nothing, otherwise, simply by detecting algorithm to find the corresponding failure nodes and then deploy some nodes. This paper focuses on the harsh environment, in addition to energy depletion failure, sensor network nodes may be emergence massive failure due to the influence of the external environment (such as bombs and other attacks),in this case will lead to the destruction of the entire network, Fig. 1 shows an scene.

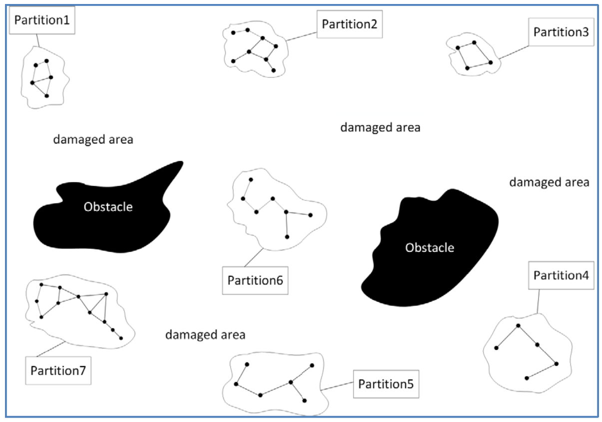

FIGURE 1. Scene of a damaged WSN.

In this case, deploying new nodes for achieving the network connectivity is needed, whether deployed the same sensor nodes or relay node, add nodes need some definite cost. Therefore, the primary goal of this paper is employ minimum nodes obstacle avoiding to achieve network connectivity. Here, all newly-deployed nodes are referred to as a relay node, given that these nodes are stationary and have the same communication radius R. The divided isolated sub network formed after the destruction of the sensor network is called partitions. In order to simplify the problem, this paper is to describe partition with the location of the point. Network connectivity problem is abstracted as graph connectivity issues, given n partitions, how to find a way to layout a certain number of relay node to connect the n partitions.

In order to reduce the algorithmic complexity of the proposed algorithm, we take the central location of the partition as the location of the corresponding partition. There are still some more complex methods, such as convex hull method, which determines the location of the partition through the boundary of each partition. The connection of a partition or different partitions will have different partition location. This method may reduce the relay node number in some cases, but the complexity of the algorithm and its implementation become very complicated. When deploying new relay nodes, we employ left rule to avoid the obstacle.

IV. OBSTACLE-AVOIDING CONNECTIVITY RESTORATION BASED ON QUADRILATERAL STEINER TREE ALGORITHM(OACRQST)

A. ALGORITHM BACKGROUND

This section gives an important theory about the Steiner tree and related glossary used in this article.

Steiner Points: Given n points in the plane, to seek a minimum tree connecting n points, we will need to find some middle points, based on these intermediate point with a given n points constituting the set of vertices constructed a minimum tree. These intermediate points are called Steiner points.

Triangular Steiner Points: One point must be found inside the triangle if the three angles of a triangle is less than 120°, and if the three angles of the point with the three vertices of the triangle are all 120°, then this point is the triangle Steiner point.

Degenerate triangle: If triangle has an interior angle greater than 120°, then it is called degenerate triangle.

Triangle Steiner points is determined by the method of respectively on the triangle arbitrarily both sides outward as an equilateral triangle, and then each equilateral triangle circumcircle, two circumcircles at the intersection point inside the triangle is a Steiner points. Diagram shown in Fig. 2 is constructed triangle Steiner point, where the F point is this triangle Steiner point, relevant certificates had been proven in the literature [14].

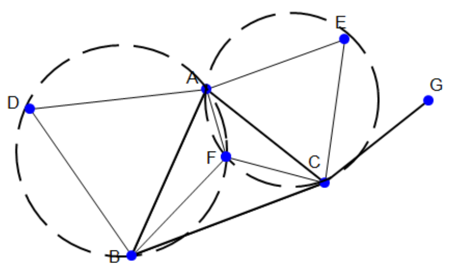

FIGURE 2. Determination of the triangle Steiner points.

Convex quadrilateral: No internal angles greater than 180°, the quadrangular any side extended to the two sides, and the other at each side at the same side of extension of the straight line obtained, this quadrilateral is called a convex quadrilateral.

Degenerate convex quadrilateral: Using triangles through three points of the quadrilateral to find the Steiner point with the method of Triangular Steiner Points, if this point and the two vertex angle greater than 120°,then the quadrilateral is the degenerate convex quadrilateral, as shown in Fig.2 above, if FCG >120°, quadrilateral ABCG is a degenerate quadrilateral.

Pollack Theorem: Let A, B, C, D are the four points, they construct a quadrilateral and the angle of intersection of the two diagonals is θ and $180° - \theta$ and suppose the two quadrilateral Steiner trees are exist. If $\theta \leq 90°$, the shorter tree should be located in the region of the angle of intersection of the two diagonal lines of θ.

In Fig. 3,we describe the detail process of Constructing quadrilateral Steiner point, firstly ensure that the quadrilateral is convex non-degenerate quadrilateral, according to Pollack Theorem to determine the shorter tree, that is, $\theta \leq 90°$ region, and then separately make equilateral triangles ADE and BCF according edges AD and BC in Figure 3, and connect the two

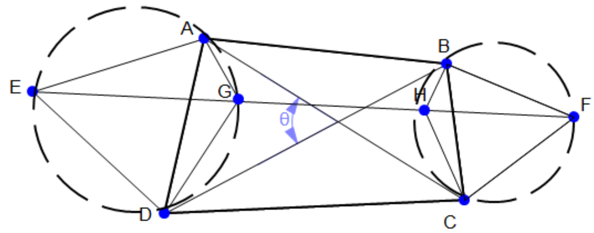

FIGURE 3. Determination of the quadrilateral Steiner points.

equilateral triangles of the other two vertices E and F, and finally do the circumcircle of the equilateral triangle ADE and BCF, intersects with the straight line EF, respectively G and H, then G and H is the Steiner point. Relevant certificates had been proven in the literature [14].

The following is the comparison and analysis of the triangle Steiner tree, quadrilateral Steiner tree and the minimum spanning tree three connection methods. In an actual scene, it is assumed that the entire network at a time is divided into four isolated partition, as shown in the Fig. 4 above, blue dots indicate sensor nodes, the red dot indicates the representatives of each partition node, black node represents the Steiner points found and the relay node deployed in the edge.

Fig. 4,5,6 respectively describe the corresponding triangle Steiner tree, quadrilateral Steiner tree, and the minimum spanning tree, in Fig. 4 of the S is triangular Steiner points, S1 and S2 in Fig. 5 is quadrilateral Steiner points. Suppose

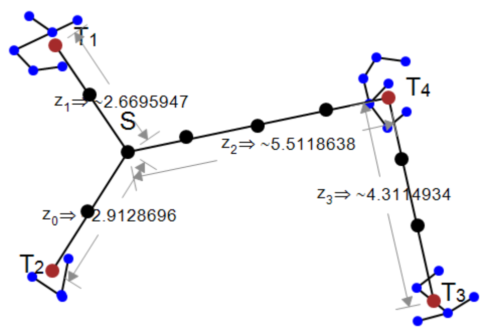

FIGURE 4. Connectivity recovery based on triangle Steiner tree.

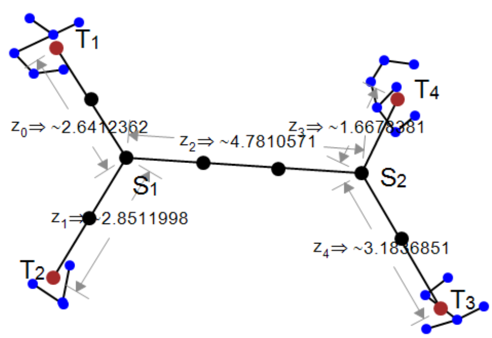

FIGURE 5. Connectivity recovery based on quadrilateral Steiner tree.

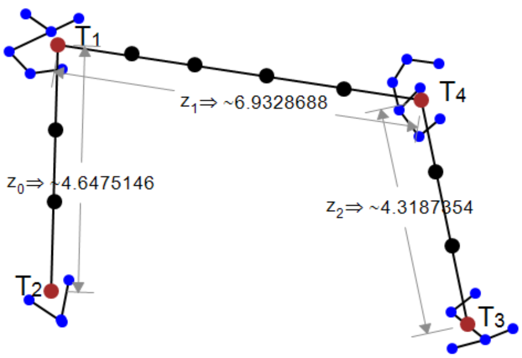

FIGURE 6. **Connectivity recovery based on MST.**

L is respectively represent the sum distance of the tree, and from Fig. 4,5,6 seen:

$$L\ Triangle\ Steiner\ tree = Z0 + Z1 + Z2 + Z3 = 15.39$$
$$L\ Quadrilateral\ Steiner\ tree = Z0 + Z1 + Z2 + Z3 + Z4 = 15.11$$
$$L\ Minimum\ Spanning\ tree = Z0 + Z1 + Z2 = 15.88$$

From above can be seen in the same topology, L Quadrilateral Steiner tree < L Triangle Steiner tree < L Minimum Spanning tree, Therefore, compared to the other two method, quadrilateral Steiner tree method layout less relay nodes along the edges. We assumed R represents the relay node communication radius, then total number nodes required Sum as follow:

$$Sum_{Triangle\ Steiner\ tree} = \left(\left\lceil\frac{|ST_1|}{R}\right\rceil - 1\right) + \left(\left\lceil\frac{|ST_2|}{R}\right\rceil - 1\right) + \left(\left\lceil\frac{|ST_{41}|}{R}\right\rceil - 1\right) + I + \left(\left\lceil\frac{|T_4T_3|}{R} - 1\right\rceil\right) = \left\lceil\frac{|ST_1|}{R}\right\rceil + \left\lceil\frac{|ST_2|}{R}\right\rceil + \left\lceil\frac{|ST_4|}{R}\right\rceil + \left\lceil\frac{|T_4T_3|}{R}\right\rceil - 3$$

$$Sum_{Quadrilateral\ Steiner\ tree} = \left(\left\lceil\frac{|S_1T_1|}{R}\right\rceil - 1\right) + \left(\left\lceil\frac{|S_1T_2|}{R}\right\rceil - 1\right) + \left(\left\lceil\frac{|S_2T_4|}{R}\right\rceil - 1\right) + \left(\left\lceil\frac{|S_2T_3|}{R}\right\rceil - 1\right) + \left(\left\lceil\frac{|S_1S_2|}{R} - 1\right\rceil\right) + 2 = \left\lceil\frac{|S_1T_1|}{R}\right\rceil + \left\lceil\frac{|S_1T_2|}{R}\right\rceil + \left\lceil\frac{|S_1T_4|}{R}\right\rceil + \left\lceil\frac{|S_1T_3|}{R}\right\rceil + \left\lceil\frac{|S_1S_2|}{R}\right\rceil - 3$$

$$Sum_{Minimum\ Spanning\ tree} = \left(\left\lceil\frac{T_2T_1}{R}\right\rceil - 1\right) + \left(\left\lceil\frac{T_1T_4}{R}\right\rceil - 1\right) + \left(\left\lceil\frac{T_4T_3}{R}\right\rceil - 1\right) = \left\lceil\frac{T_2T_1}{R}\right\rceil + \left\lceil\frac{T_1T_4}{R}\right\rceil + \left\lceil\frac{T_4T_3}{R}\right\rceil - 3$$

We assumed that the communication radius of relay node is 1.7, therefore according above three Formulas the number of the required node of the Fig. 4, 5 and Fig. 6 can be calculated as follow:

$$Sum_{Triangle\ Steiner\ tree} = 8$$
$$Sum_{Quadrilateral\ Steiner\ tree} = 7$$
$$Sum_{Minimum\ Spanning\ tree} = 8$$

The specific deployment above as shown in Fig. 4, 5, 6, which can be seen quadrilateral Steiner tree method required less relay nodes, according to the above diagram the relay node deployment, The Average node degree is calculated by the sum of all node degrees, being divided by the number of all nodes(including the deployment of the relay nodes and the original sensor nodes), it is easy to calculate the average node degree of Fig. 4,5,6 three topology,.therefore the three structures of all nodes average node degree is as follows:

$$Average\ Node\ Degree_{Triangle\ Steiner\ tree} = 1.86$$
$$Average\ Node\ Degree_{Quadrilateral\ Steiner\ tree} = 1.96$$
$$Average\ Node\ Degree_{Minimum\ Spanning\ tree} = 1.82$$

Form the above results, we can see that the highest average node is the Average Node Degree Quadrilateral Steiner tree, therefore, the quadrilateral Steiner tree method about network topology constructed is not only use less the number of relay nodes, but also the network robustness is very good.

B. MAIN IDEA OF OACRQST

The OACRQST algorithm proposed in this paper is a heuristic algorithm. First determine the quadrilateral composition of each partition can be connected, and then sort in ascending order according to the length of the quadrilateral perimeter, in order to determine the Steiner points of each quadrilateral, construct Steiner tree. Finally, along Steiner tree edge deploying relay nodes to achieve connectivity restoration of the entire network, if the found position is in the area of the obstacle, the relay node will be placed to the position of the bordering that nearest to the found position. If the network still can't connected, the relay nodes will be placed the appropriate position according to the bordering of the obstacle started from the above node exploring the left rule, concrete steps are as follows:

(1) Mark all partitions is not connected.

(2) Enumerate all partitions non-degenerate convex quadrilateral combination, and sort in ascending order according the calculated perimeter, finally store them in a list.

(3) Sequentially processing each quadrilateral front to back. If the four vertices of the quadrilateral only one or are not connected to the other partitions, according to Pollack Theorem to determine the shorter Steiner tree. Using the Quadrilateral Steiner tree constructor method find out the Steiner points, and then deploy relay nodes along the Steiner tree edges, moreover four vertex partition of quadrilateral marked as already connected, merge the four partitions and marked it as already connected; otherwise, no further treatment.

(4) After running (1), (2) and (3), Connection with quadrilateral Steiner tree partitions have been connected, the remaining partition is no longer available for quadrilateral Steiner tree connection, so enumerate all triangle combination which connected by all the remaining partition, and then put them into a new list, Finally, the triangle is sorted in ascending order in accordance with the perimeter. (5) Sequentially processing each triangle in the new list front to back. If the three vertices partition belonging to three different partitions, construct triangle Steiner tree, and then deploy relay nodes along the Steiner tree edges. Merge the three partitions and marked it as already connected.

(6) After the above operation, the number of partitions is not greater than 2. If the partition number is 1, the algorithm ends, if it is 2, then check all can be connected to the edge of the two partitions, find one of the shortest piece, deploy relay nodes in the corresponding position along the edge, Merge the two partitions, so that the entire network achieve connectivity.

(7) If the found position is in the area of the obstacle, the relay node will be placed to the position of the bordering that nearest to the found position. If the network still can't connected, the relay nodes will be placed the appropriate position according to the bordering of the obstacle started from the above node exploring the left rule.Now, we use figure 7 to explain how to use the left rule, V1 represents the found position which is in the area of the obstacle and V2 stands for the position of the bordering that is nearest to the found position. The left direction of V2 is the direction of the deploying nodes, which is seen the direction of the arrow in the following figure. And then deploying relay nodes along the bordering of the obstacle according the this direction, the accurate location of the deploying relay nodes can be calculated through the transmission radius and the position of the deployed relay nodes.

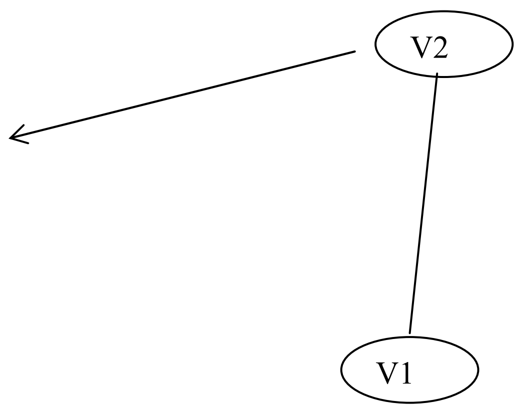

FIGURE 7. The explanation figure of the left rule.

C. ALGORITHM INSTANCE

We illustrate how OACRQST works with the following example. Let's assume there are 13 partitions in the entire network, namely {a,b,c,d,e,f,g,h,i,j,k,l,m},as shown in Fig. 8.After performing the OACRQST, the 13 partitions will be connected together so as to realize the network connectivity.

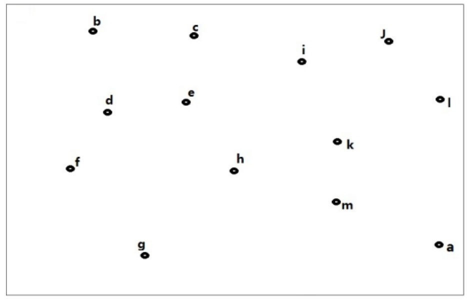

FIGURE 8. The original topology to be restored network.

In step 1,mark the a-m of 13 partitions which are not connected, and then run step 2,list all the non-degenerate convex quadrilateral and sort in ascending order according the perimeter, finally store them in a list.

In step 3, process each quadrilateral Sequentially front to back, assuming the smallest quadrilateral is bced, and in this quadrilateral the number of partitions is 0 (marked as connected), thus find out its Steiner points, and deploy relay nodes along the Steiner tree edges to connect the four partitions, finally merge the four partitions of a partition, as shown in Fig. 9.

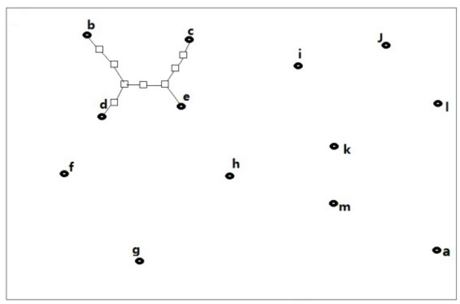

FIGURE 9. Deploy relay nodes to connect partition b,c,e and d.

Afterward, continually run step 3, then find out the second small quadrilateral, and we assume it is quadrilateral ijlk, in this quadrilateral the number of partitions is also 0, marked as connected, so deploy relay nodes along the Steiner tree edges to connect the four partitions, and merge the four partitions of a partition, shown in Fig. 10. Continually keep running step 3, and find out the third small quadrilateral efgh, in this quadrilateral the number of partitions is 1, marked as connected, so find out its Steiner points, deploy relay nodes along the Steiner tree edges to connect the four partitions, and merge f,g,h the three partitions to the first partition, shown in Fig. 11.

Continually carry out step 3, we discover that there is no quadrilateral meeting the condition, so move on to step 4, check the triangle combination of all partitions formed after the above series of operations. And instantly we discover triangle kma and triangle hmk meet the condition,

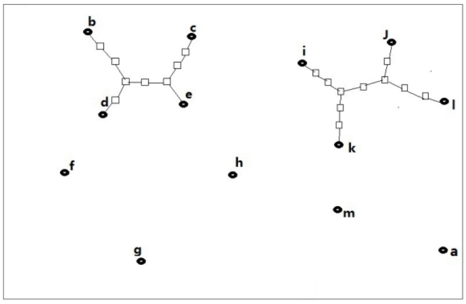

FIGURE 10. Deploy relay nodes to connect partition i,j,l and d.

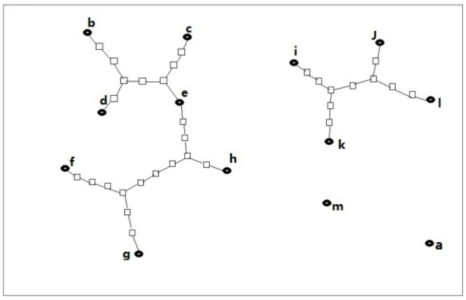

FIGURE 11. Deploy relay nodes to connect partition e,f,g and h.

so immediately go to perform step 5, construct triangle Steiner tree, deploy relay nodes along the edges, and merge the partitions m with the two partitions formed in front a partition, shown in Fig. 12.

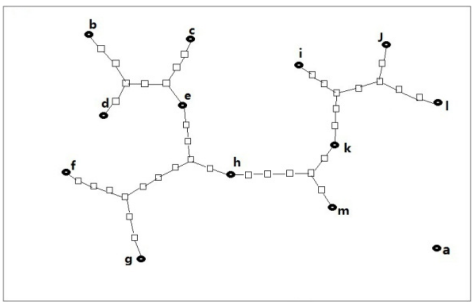

FIGURE 12. Deploy relay nodes with triangle Steiner tree method.

The above running 5 steps lead the network to become only two partitions, then execute step 6, as the number of partitions

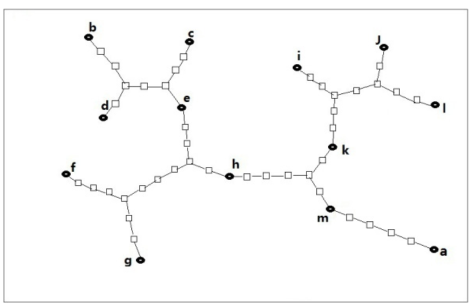

FIGURE 13. Deploy relay nodes with MST method.

is 2, so check all connected to the edges of the two partitions, find the shortest edge ma, then deploy relay nodes in the corresponding position along the edge, as a result, the two partitions are combined into one, making the entire network connectivity realized, as shown in Fig 13.

D. PSEUDO CODE OF OACRQST

The pseudo code of OACRQST as follows:

Pseudocode

```
Input: The network topology G(including the position of
each partition and the obstacles), Relay node's
communication radius R
Output: The number of the relay node to redeploy and the
position of each relay node

Procedure OACRQST (G, R)
for each partition p
        mark it as a disconnected partition
endfor
dealQuadrilateral(G)// Processing quadrilateral
dealTriangle(G)// Processing triangle
if no disconnected partition left // The network has only
one partition, network connectivity algorithm terminate
Else // The network has two disconnected partitions
    find the shortest edge (u, v), u in partition1 and v in
    partition2
    compute the length of edge (u, v) and deploy relay
nodes along the edge obstacle-avoiding with the step(7)
method of OACRQST algorithm
    merge partition1 and partition2
endif
```

In the Main algorithm OACRQST, firstly mark for each partition is not connected partition, then deploy relay nodes obstacle-avoiding in the corresponding position along the Steiner edge respectively according the quadrilateral Steiner tree and triangle Steiner tree method, and at the same time merge each partition, eventually, algorithm execution to the 7th row, the number of partitions in the entire network will not be more than two, if the number of partitions is one, and that the entire network has been connected, the algorithm terminates. Otherwise, perform line 10, find two shortest side of the two partitions, and then calculate the length of the relay nodes deployed along this edge, merge two partitions, and eventually the whole network connectivity.

In the processing of algorithm DealQuadrilateral, firstly enumerate all possible quadrilaterals. And then, perform the second row, judge for each quadrilateral. The third line is used for judging the quadrilateral whether a non-convex quadrilateral or degenerate quadrilateral, if it is, then remove it. The main idea of function Convex() to which determine whether the quadrilateral is a convex quadrilateral as follows: First starting from a certain point of the quadrilateral to connect two adjacent points i and i + 1, to obtain the straight line equation, and then the other two points of abscissa values are

Pseudocode

```
Procedure DealQuadrilateral (G)
list all quadrilaterals in list Q
for each q in Q
    if q is not convex or degenerated
      delete it from Q
    endif
endfor
sort Q by the perimeter in ascending order
for each q in Q in ascending order
   if the number of disconnected partitions that the vertexes
of q represent >= 3
      compute the Steiner Edge and deploy relay nodes
along the Steiner Edge obstacle-avoiding
      mark these 4 partitions being connected
   endif
endfor
```

substituted into the linear equation to obtain the coordinate value of a longitudinal, through compared the value obtained by above method with this point's vertical coordinate values, thereby to determine the point at which side of the straight line, and so can be judged to another point on which side of the straight line, if the two points are not in the same side of the straight line, then it is a concave quadrilateral, end the judgment directly; otherwise continue the judgment until the quadrilateral the four adjacent nodes are judged, all in a straight line on both sides of this quadrilateral is a convex quadrilateral. The main idea of function Degenerate() to which determine whether the quadrilateral is a degenerate quadrilateral as follows: Calling the Pollak theorem function to determine the Steiner points should be determined by which two edges, To these two edges, respectively, outwardly as equilateral triangle, and then obtained two points of the coordinate values of the two equilateral triangles outside. The linear equation can be obtained through the two points based on the above two coordinates; then determine the four vertices, respectively in which side of the straight line, if the three vertices in the same side as compared to the non-degenerate quadrilateral otherwise degenerate quadrilateral.

After screening the quadrilateral, perform line 7, Sort the quadrilateral which are satisfied the conditions in ascending order by perimeter, and then turn to take one of the quadrilateral, if the quadrilateral connected to four different partitions, implement the 10 rows at once, computing Steiner edge, seeking the corresponding Steiner points, and deploy relay nodes in the corresponding position along Steiner side, and then merge four partitions into a partition, so execution continues until all quadrilateral that satisfied the conditions are finished building. the main idea of the line 10 for which seek the quadrilateral Steiner points as follows: First, according to the Pollack Theorem judgment function, find the two sides required, thereby get the coordinates of the two endpoints of the two edges. Assume that two coordinates of one side is (x1, y1) and (x2, y2); first angle between the two points is obtained:

$$\tan\alpha = (y2 - y1)/(x2 - x1) \tag{1}$$

From above formula the angle α can be obtained as follows:

$$\alpha = \tan^{-1}((y2 - y1)/(x2 - x1)) \tag{2}$$

The distance L between two points can be calculated according to the two points coordinates:

$$L = \sqrt{(y2 - y1)^2 + (x2 - x1)^2} \tag{3}$$

Thus another point coordinates of the equilateral triangle is obtained:

$$\mathrm{x3} = \mathrm{x1} + \mathrm{L} * \cos(\alpha + 60^\circ) \tag{4}$$

$$\mathrm{y3} = \mathrm{y1} + \mathrm{L} * \cos(\alpha + 60^\circ) \tag{5}$$

With the same method the point coordinates of another equilateral triangle is obtained, and assumed the coordinates is (x4,y4), So the total number of nodes n that required layout in this quadrangle can be calculated:

$$n = \frac{\sqrt{(y4 - y3)^2 + (x4 - x3)^2}}{R} - 3 \tag{6}$$

According to the above two point's coordinates, it is possible to obtain this quadrilateral corresponding two Steiner point coordinates, the specific method as follows: Suppose one desires Steiner point coordinates (X6, Y6), first according to the equilateral triangles known coordinates, seeking its circumcircle center coordinates:

$$x5 = (x1 + x2 + x3)/3 \tag{7}$$

$$y5 = (y1 + y2 + y3)/3 \tag{8}$$

And then according to the methods of the above-obtained two sides outwardly as an equilateral triangle obtained two coordinates obtained on the slope of this linear:

$$(y4 - y3)/(x4 - x3) \tag{9}$$

And because Steiner point on this straight line therefore the following equation holds:

$$(y6 - y4)/(x6 - x4) = (y4 - y3)/(x4 - x3) \tag{10}$$

Further the distance of the center coordinates and this point is the radius of a circle, so the radius r of the circle is easily computable:

$$r = \sqrt{(y5 - y1)^2 + (x5 - x1)^2} \tag{11}$$

Also known that the following equation holds:

$$r = \sqrt{(y6 - y5)^2 + (x6 - x5)^2} \tag{12}$$

Simultaneous (10) (11) (12) can be obtained coordinates (x6, y6) value; And another Steiner point coordinates (X7, Y7) quadrilateral can be obtained by the same method, finally according seeking both Steiner point coordinates and four quadrilateral point value of the coordinate and the sensing radius R to obtain the coordinate position of the node to be arranged.

Simultaneous (10) (11) (12) can be obtained coordinates (x6, y6) value. And another Steiner point coordinates (X7, Y7) quadrilateral can be obtained by the same method, finally according seeking both Steiner point coordinates and four quadrilateral point value of the coordinate and the sensing radius R to obtain the coordinate position of the node to be arranged.

Pseudocode

```
    Procedure DealTriangle(G)
    list all triangles in list T
    sort T by the perimeter in ascending order
    for each t in T in ascending order
      if the number of disconnected partitions that the ver-
  texes of t represent >= 2
        compute the Steiner Edge and deploy relay nodes
  along the Steiner Edge obstacle-avoiding
        mark these 3 partitions being connected
    endif
  endfor
```

After above quadrilateral processing algorithm, part of the partition of the network has been connected. In the triangle processing of algorithms DealTriangle. First list all the triangles by perimeter ascending sort, and then sequentially take one of the triangle, and judged (line 4), if the corresponding triangle partition at least two are not connected, perform the fifth line at once, and calculated Steiner edge, find the corresponding Steiner points, deploying relay nodes along the Steiner edge in the corresponding position, and then merge the three partitions of a partition, so continue execution until the conditions are satisfied to all triangle when it completed. The main idea of the fifth line for which seek the triangle Steiner points as follows: the interior angles of a triangle is less than 120°, then a Steiner points in the triangle can be found, and makes the angles that formed by this point with the triangle's three points are all 120°, namely outwardly to the three sides of the triangle for an equilateral triangle, and then separately for corresponding circumcircle of the triangle, and the three circumcircle's intersection point inside the triangle is this triangle Steiner point. Known coordinates of the triangle of three dots is not difficult to obtain the coordinates of this point. If the internal angle of the triangle has a value greater than 120°, we will directly take two shorter sides of the triangle to achieve connectivity, i.e. using the minimum spanning tree method.

E. PERFORMANCE ANALYSIS

In this section we analyze the time complexity and convergence of the algorithm.

The run time complexity of Algorithm OACRQST is O(n^4logn) where n is the number of partitions.

Proof: Let m be the number of all quadrilaterals combined with the n partitions, therefore

$$m = \binom{n}{4} = O(n^4)$$

In the main algorithm OACRQST, the time complexity of line 2-4 is the number of partition, is a constant n. line 5 is quadrilateral processing algorithms, in this algorithm the time complexity of listing all quadrilateral is O(n^4), the time complexity of the function Convex() is a constant 4,and the time complexity of the function Degenerate () is also a constant 4,so the line 2-6 of the algorithm time complexity is O(4*n^4), line 7 sorted quadrilateral in ascending order, the time complexity of sorting algorithm is O(mlogm)=O(n^4logn), lines 8-14 in solving Steiner points the time complexity is also a constant, which is the required number of relay nodes of this quadrilateral obtained, each implementation is also a constant, so the time complexity is a constant multiple of n^4. Main algorithm executed line 6 triangles processing algorithms, this algorithm is similar with quadrilateral whose time complexity is a constant multiple of n^3, then the main algorithm execution to 10 rows, find the shorter sides not need to compare the number of more than a constant multiple of n^2, so the entire time complexity of the algorithm is O(n^4logn). Although the complexity of our algorithm is higher than that of the algorithm proposed in literature [23], considering the complexity of the straight skeleton based on connectivity restoration is only O(nlogn), the algorithm OACRQST deploys fewer relay nodes and the average degree of nodes is larger. And in the actual environment, the value of n is not very large, because n is the number of partitions, so our algorithm performance is effective in practical applications.

The algorithm OACRQST is convergence, algorithm OACRQST forms a Steiner tree connecting all partitions.

Proof: In the algorithm, First find the connection of quadrilateral Steiner tree, which will make the network to form a combined partition, then connected by triangle Steiner tree.when it is connected by the triangle Steiner tree, which is certain to connected three partitions together. eventually either is making the whole network to form a partition, i.e. to achieve connectivity, either the entire network, leaving only two partitions, if two partitions are left, it will be processed in line 7 of the main algorithm, i.e. to find the connected two partitions shortest side deploying relay nodes along this edge, merge two partitions into a partition, thereby achieve the entire network connectivity, so the proposed algorithm is convergence.

V. PERFORMANCE EVALUATION AND ANALYSIS

We evaluate and analyze the proposed algorithm OACRQST through simulation, and compared with QTA (Quadrilateral steiner Tree Algorithm), FeSTA and MST_1tRNp algorithm.

A. EXPERIMENT SETUP AND PERFORMANCE METRICS

In the simulation, nodes of WSN are deployed in a rectangle area. The distance between two nodes is less than the communications radius R can direct communicate, the network is specified number of partition by simulating different topology. And some obstacle are deployed in the area randomly. The deployment area is 1500m × 1500m square, the communication radius of R is 100 m, the partition number is 9. In the simulation, the above parameters can be changed in order to research its impact on the performance of the algorithm.

Performance metric mainly include the number of the relay node, the average node connectivity degree and so on. Deploying the relay node is for the connectivity of the entire network, so using the least of the relay node is optimal. Average node degree is the average of each node connected to the number of other nodes, obviously, the larger the average node degree, the better the network robustness. Each execution of the simulation algorithm 100 times and averaged.

B. SIMULATION RESULTS

This section compares OACRQST with other three different baseline methods, namely QTA, FeSTA and MST_1tRNp, in terms of the numbers of relay nodes and the average node degree.

VI. NUMBERS OF RELAY NODE

Fig. 14 depicts the impact of the partition number of the deployment to the number of the relay nodes. As can be seen from the figure, the number of relay nodes of the four algorithms increases with the increasing partitions that is because more relay nodes required to connect the more partitions. It is also obvious that QTA requires less number of relay nodes than the algorithm FeSTA and MST_1tRNp. And this advantage will be more obvious with the increase of partition number. That is because the more number of partitions, the more quadrilateral Steiner tree is able to connect the number of partitions, thus reducing the required number of relay nodes. It is also can be seen from Fig. 14, OACRQST is always less than FeSTA and MST_1tRNp, but sometimes the number of relay nodes is more than QTA, that's because when deploy relay nodes in the damaged area, obstacles may be exist, so need deploy more relay nodes.

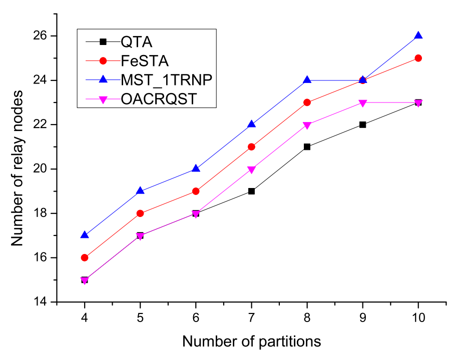

FIGURE 14. Comparison of the number of relay nodes with the partition increases.

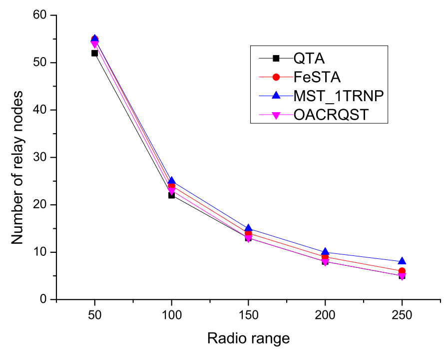

FIGURE 15. Comparison of the number of relay nodes with the Radio range increases(9 partitions).

Fig.15 depicts the impact of the changes of the communication radius to the number of relay nodes, when the number of partitions is 9. As can be seen from the figure, for all algorithms the number of relay nodes reduces with the increasing communication radius. This trend is in line with the actual situation, because with increase of communication radius, the connection path length is fixed, the number of relay nodes required will certainly reduce, so when the communication radius is 250m, the number of relay nodes required is only 5. From Fig. 14 we also can see the QTA algorithm required less number of relay nodes than the other three algorithms. Sometimes the number of relay nodes of OACRQST is more than QTA, the reason is the same as above. Of course, with increase of the communication radius this advantage is not obvious, this is because the increase of communication radius lead to reduce the length of the connected path, thus the advantage becomes not obvious.

Fig. 16 depicts the impact of the area size to the number of relay nodes, when the number of partitions is 9 and the communication radius is 100m. As can be seen from the figure, the number of relay nodes of the four algorithms increases with the increasing area size that is because the area increase will lead to the distance increases between the partitions. From Fig. 16 we also can see the QTA algorithm required less number of relay nodes than the other three algorithms. Sometimes the number of relay nodes of OACRQST

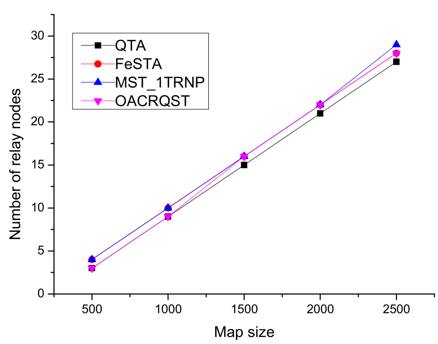

FIGURE 16. Comparison of the number of relay nodes with the area increases(9 partitions).

is more than QTA, the reason is the same as above. And this advantage will be more obvious with the increase of area. That is because with the region increases will cause the distance increase between partitions, The distance of QTA algorithm required is smaller than the other two methods, and this advantage will be more obvious with the increase of area.

From above three figures, sometimes OACRQST need more relay nodes than QTA, that is because the obstacle is considered in this paper, so the OACRQST proposed in this paper is more practical.

VII. AVERAGE NODE DEGREE

Fig. 17 depicts the impact of the area size to the average node degree, when the number of partitions is 9 and the communication radius is 100m. As can be seen from the figure, for all algorithms the average node degree of the four algorithms increases with the increasing area size that is because the area increase will lead to the number of relay nodes increases. From Fig. 17 we also can see the average node degree of the OACRQST algorithm is bigger than the other three algorithms, which indicate that the network robustness of QTA algorithm build is much better than the other two algorithms. This is because OACRQST algorithm arranged relay node in the connection inside of the four partitions quadrilateral, thus improving the connectivity of the node. Of course, with the increase of area, this advantage becomes smaller, due to with the area increases OACRQST algorithm required less number of nodes than the other two algorithms to deployment, therefore, so the advantages become smaller.

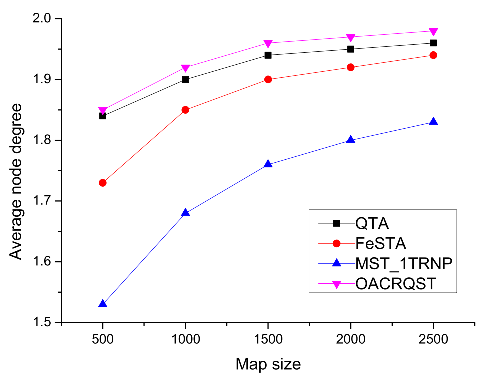

FIGURE 17. **Comparison of the average node degree with the area increases(9 partitions).**

Fig. 18 depicts the impact of the radio range to the average node degree, when the number of partitions is 9 and the communication radius is 100m. As can be seen from the figure, the average node degree of the four algorithms increase with the radio range increases due to the fact that the radio range increase will lead to the number of relay nodes decrease. OACRQST algorithm is better than the other algorithms, and this advantage is more obvious with the communication radius increases, which shows that OACRQST algorithm deployed node is more evenly distributed, and the robustness of the formation of network topology is better.

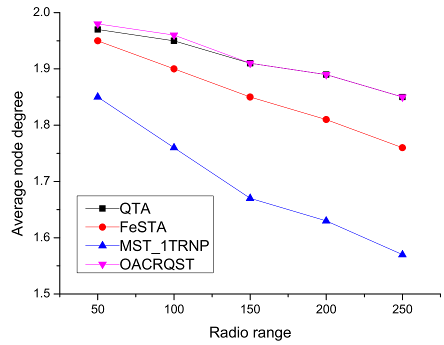

FIGURE 18. **Comparison of the average node degree with the radio range increases(9 partitions).**

Fig. 19 depicts the impact of the number of the partitions to the average node degree. As can be seen from the figure, for all algorithm of the average node degree increases with the partitions increases. And with the partitions increase the growth trend of OACRQST algorithm proposed in this paper shows increasing trend. This is because the more number of partition, the more number of partitions quadrilateral Steiner tree able to connect.

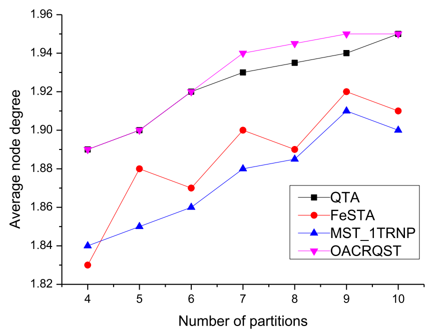

FIGURE 19. **Comparison of the average node degree with the partitions increases.**

The proposed algorithm OACRQST in this paper is superior to FeSTA and MST_1TRNP algorithms in terms of the numbers of relay nodes and the average node degree through a comparative analysis of the results of these experiments, and very close to QTA. It shows a great advantage in some respects, such as requirement for deployment of the relay node number on average is increased by 11.2%, the highest average node degree can be increased by about 10%, the lowest increase about 2%. In the literature [14] and later many papers have proved the quadrilateral the Steiner tree and the minimum spanning tree ratio is greater than or equal to $\sqrt{3}/2$, that is, in theory, the rate is increased no more than 13.4%.This problem is a NP problem, so the OACRQST algorithm proposed in this paper adopts a heuristic algorithm to get the approximate solution, and the approximate solution has been relatively close to the ideal value, therefore, the performance of the OACRQST algorithm is better. Although the number of relay nodes required of the OACRQST algorithm is less than the other algorithms, but the average node degree is also higher than the other algorithms, which show that the algorithm proposed by this paper recovery network has strong robustness and fault tolerance. At the same time, the obstacle also is considered in OACRQST algorithm proposed in this paper, it will be more practical.

VIII. CONCLUSION

The Obstacle-Avoiding Connectivity Restoration based on Quadrilateral Steiner Tree algorithm is a heuristic algorithm, which can deploy less relay nodes obstacle-avoiding to restore the connectivity of each partition in a severely damaged wireless sensor network. This algorithm is mainly adopts local optimum quadrilateral to construct Steiner tree, allowing the entire network to form a larger partition by this algorithm iteratively, Finally, the remaining partitions are connected by triangle Steiner tree method or the minimum spanning tree, and thereby use as little as possible relay nodes to restore the network connectivity.

In addition, we also carried out an assessment based on OACRQST, simulation results show that OACRQST algorithm is better than some other algorithm from the performance on the deployment of nodes, average node degree and so on, which further demonstrates the connectivity network constructed using this algorithm has better robustness.

As a future work we will consider extend OACRQST to achieve higher level of coverage and QoS requirements, further improve the robustness of the restored connectivity network, and also consider the applications to achieve network connectivity by node mobility scene.

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