An Energy-Efficient and Distributed Cooperation Mechanism For k-Coverage Hole Detection And Healing in WSNs

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***Abstract*—In this paper, we devise a distributed method for this problem, namely Distributed VOronoi based Cooperation scheme (DVOC), where nodes cooperate in hole detection and recovery. In previous Voronoi based schemes, each node only monitors its own critical points. Such methods are inefficient for k-coverage because the critical points are far away from their generating nodes in k-order Voronoi diagram, causing high cost for transmission and computing. As a solution, DVOC enables nodes to monitor others' critical points around themselves by building local Voronoi diagrams (LVDs). Further, DVOC constrains the movement of every node to avoid generating new holes. If a node cannot reach its destination due to the constraint, its hole healing responsibility will fall to other cooperating nodes. The experimental results from the real world testbed demonstrate that DVOC outperforms the previous schemes.**

***Keywords*-k-coverage; Voronoi diagram; hole detection;**

I. Introduction

Among numerous challenges confronted in designing protocols for WSNs, the coverage problem, especially the k-coverage problem, stands out as one of the most critical issues in this area. A target field is termed k-covered ($k \geq 1$) if every point in the target field is in the sensing ranges of at least k nodes. A k-coverage hole is a continuous area in the target field comprised of points that are covered by at most $k-1$ sensors. The problem of k-coverage is motivated by robustness concerns as well as protocol requirements. Previous schemes [1], [2] for k-coverage hole detection generate a high time complexity in a large-scale WSN with a large number of nodes. Also, their centralized method makes them not feasible in large-scale WSNs because it burdens the central node while sensor nodes have limited energy and computation capacity, thus easily generating bottlenecks.

Hence, our work aims to solve the formidable challenge: how can k-coverage holes be efficiently detected and healed in a distributed manner? Accordingly, we propose a Distributed VOronoi based Cooperation scheme (DVOC) based on mathematical models for k-coverage in WSNs. In DVOC, nodes cooperate in hole detection and recovery by node movement, which significantly saves energy by reducing message transmission and avoiding generating new holes during node movement. In DVOC, each node builds *local k-order VD (LVD)* that enables it to find its nearby critical point's generating nodes and check if the generating nodes cover this critical points. Thus, nodes cooperate in monitoring each other's critical points and informing the generating nodes of uncovered critical points. We have proven that DVOC never misses any holes if the accuracy of the LVD is guaranteed, and it alleviates the transmission burden for each node significantly. Further, in order to avoid generating new holes during node movement, we mathematically identify the safe area of each node, where the node should be located to avoid new hole generated. In summary, compared with previous schemes, DVOC costs less for both transmission and mechanical movement.

II. The Design of DVOC

In this part, we will give the detail design of DVOC. Rather than relying on one central node to collect the location information of all nodes in the WSN and then build the k-order VD, DVOC distributes this workload among the nodes by letting each node collect location information and build its own k-order VD in order to build the k-order VD. In particular, we observe that nodes' partial k-order VDs always overlap with each other. In other words, each critical point is known by several nodes rather than only one node. Thus, multiple nodes checking the same critical point leads to duplicated checking and unnecessary energy cost. Therefore, simply extending the distributed 1-order VD construction method to a k-order VD construction method still leads to a high energy cost, especially when k is large. It is crucial to find an energy-efficient method to reduce the probing cost for high accuracy. To this end, we propose a k-coverage checking method based on *local k-order VD (LVD)*.

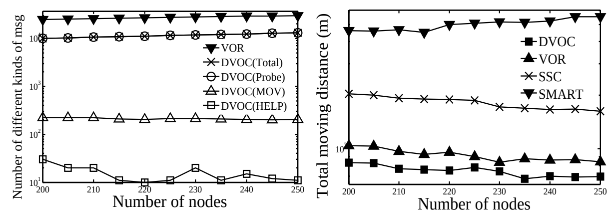
LVD designates the node s_i closest to a critical point of another node s_j to conduct the accuracy checking and k-coverage checking on this point. Thus, LVD shrinks the range where s_i needs to collect location information, hence reducing GPSR probing distances and the number of probed nodes of each node. It also avoids unnecessary probing cost due to the overlapping. A challenge in LVD is how to distribute the set of all critical points in the target field to sensors so that each critical point is only assigned to one sensor that is closest to itself. We notice that a point s_i's 1-order Voronoi cell is mutually exclusive to any 1-order Voronoi cell of other node's location. We then define LVD as the intersection of s_i's 1-order Voronoi cell and the k-order VD. Then, the local k-order VD of each node must be mutually exclusive.

Further, in order to avoid generating new holes during node movement, we mathematically identify the safe area of each node, where the node should be located to avoid new hole generated. If a node cannot reach its destination due to the constraint, its hole healing responsibility falls to another kth generating node. Hence, DVOC can avoid oscillating movement with its cooperation mechanism, it converges more rapidly than previous movement schemes.

III. Performance Evaluation

In this section, we present the experimental results of DVOC in comparison with typical VORonoi-based algorithm (VOR) [3], [4]. Also, we compare DVOC with the other two typical movement-assist schemes for full coverage in WSNs: Scan-based Movement-Assisted Sensor Deployment (SMART) [5] and Sea Surface Coverage (SSC) [6] on GENI Orbit testbed [7], [8]. The testbed uses a large two-dimensional grid of 400 802.11 radio nodes, which can be dynamically interconnected into specified topologies. Since GENI-Orbit testbed has limited number of nodes (less than 400 nodes), here we only take the 2-coverage as an example for the k-coverage. The target field is a $400\text{m} \times 400\text{m}$ area. The number of sensors was varied from 200 to 250. We measured the following metrics: 1) *number of messages* and 2) *total moving distance*.

Fig. 1 (a) shows the total number of messages costs between DVOC and VOR measured by the total number of probes and messages, respectively, when the sensing range was set to 50m and the transmission range was set to 70m. From the figure, we find that DVOC is significantly superior to VOR. The total number of messages in VOR is about 2 (range from 1.936 to 2.176) times of that of DVOC. The reason why DVOC has higher efficiency than VOR in terms of transmission cost is that DVOC uses a cooperation mechanism based on a local k-order VD, which requires less location information than the partial k-order VD used in VOR. Admittedly, DVOC still makes nodes communicate with each other after the VD is built, but such communication cost is very small compared with the cost



(a) Total number of messages (b) Total moving distance

Figure 1. Experimental results.

for probing location information.

Fig. 1 (b) shows the *total moving distance* versus the number of nodes in different schemes. From the figure, we find that DVOC has the shortest *total moving distance*. On average, the *total moving distances* of VOR, SMART, and SSC are respectively 1.23, 2.45 and 6.65 times as long as that of DVOC when the sensing range is 45m, and are respectively 1.25, 2.08 and 8.65 times as large as that of DVOC when the sensing range is 50m. It is because that DVOC is a cooperation based algorithm where each node needs to calculate whether it will move out of its *safe area* when informed to recover holes. If the destination is outside of its safe area, the node stops moving and asks for partners' help in covering the hole.

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