3MeSH for Full Sensing Coverage in a WSN without Location Awareness

Xiaoyun Li David K. Hunter
Electronic System Engineering Department, University of Essex, UK
xliw@essex.ac.uk dkhunter@essex.ac.uk

Abstract——We propose a Triangular Mesh Self-organizing self-Healing protocol (3MeSH), to maintain sensing coverage over an entire wireless sensor network. It partitions the area into hexagonal cells, without requiring location awareness information. 3MeSH can conserve energy significantly by electing as few active nodes as possible, while accommodating a high tolerance to node positioning. The self-healing algorithm can guarantee full coverage in hostile environments having high node failure rates. Simulation demonstrates that 3MeSH is scalable and robust for a variety of topologies and node densities.

1. Introduction

The purpose of a sensor network is to carry out sensing tasks, and send the sensed data periodically to at least one sink node. Applications include environmental monitoring, conferencing, battlefield operations, disaster relief and rescue operations, and police operations. They can be deployed in virtually any environment, even those that are inhospitable, or where it is difficult for humans to reach the sensor nodes.

The sensor coverage issue is fundamental to both power saving and data aggregation. As adjacent sensors may collect similar data, a subset of carefully selected sensors, covering the whole sensing area, can reduce data redundancy, and prolong both battery life and the lifetime of the network itself.

In this paper, a protocol named 3MeSH is proposed, which is based on a triangular grid topology. A self-organized network is set up to achieve full coverage while minimising the number of active nodes. Location awareness is not necessary, which is highly advantageous since it is generally impossible for micro-sensors to obtain location information. Distance estimation is performed via Received Signal Strength Indication (RSSI) in order to set up the network and implement self-healing in real time.

2. Related work

A Voronoi diagram (see section 3.1) is used to solve the full coverage problem in Reference 1. In order to estimate the distance between nodes and calculate the angles on triangles, a location awareness system such as GPS is needed. Every node needs the location information of all its neighbours to judge whether it is an active node or a redundant node. The algorithm is too complex for the simple processors and limited memory that are used within small sensor nodes. References 2-4 propose similar triangle grid algorithms, but they all require location awareness in every node.

As node failure can disrupt full coverage, self-healing must be implemented. GS3 [4] employs a self-healing algorithm using the triangle topology, but requires full location awareness over the whole network, and the algorithm is more complex than 3MeSH. SoRCA [5] also implements self-healing, but it partitions the working area into fixed hexagons, and considers each hexagon to be fully covered if there is one active node within the cell. Assuming the worst case, when three nodes fall at the edges of three adjacent hexagons (shaded in Figure 1), to guarantee full coverage, the sensing radius (R) should be twice the hexagonal radius, which is inefficient.

3. 3MeSH description

3.1 Theory of Voronoi diagrams

Given a set S of n nodes $s_1, s_2 \ldots s_n$ in the sensed area, a Voronoi diagram is defined as the subdivision of the area into n polygons, one for each node, where any point inside the polygon is closer to the node inside the polygon than to any other node. Two Voronoi polygons share a Voronoi edge, while three Voronoi polygons intersect at a Voronoi vertex. The vertex has equal distance to those three nodes belonging to the three adjacent polygons. In a Voronoi diagram, the area having nodes deployed as an equilateral triangle grid may be partitioned into hexagonal cells, with one node in the centre of each cell, as shown in figure 1.

Assuming that each node's sensing range is a disk with radius R, the nodes (deployed in an equilateral triangle grid with distance $\sqrt{3}$ R between adjacent nodes) can achieve full coverage in the whole working area, as shown in Figure 1. The non-cascaded coverage area for each active node is the area of the hexagonal cell $3\sqrt{3}\, R^2 / 2 \approx 2.6\, R^2$, which is larger than $2\, R^2$, the area of a square cell with square edges of length $\sqrt{2}\, R$. An equal sized polygon with more edges has a greater coverage area, tending to $3.14\, R^2$, but the triangular grid is the simplest topology which partitions the area into hexagonal cells automatically. The distance from one node to each of its adjacent neighbours is the same, and the minimum number of active nodes is:

Total Sensing Area / each nodal non-cascaded coverage area ≈ Total Sensing Area / 2.6 R^2

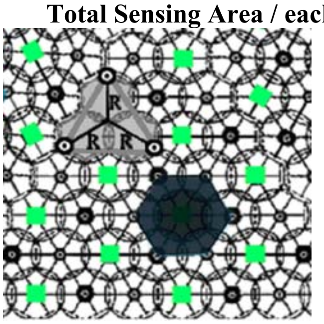


Figure 1. *Triangle Mesh active nodes*

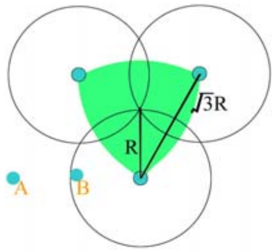


Figure 2. *Optimum Case.*

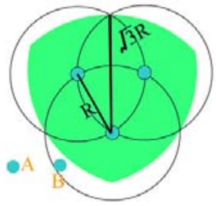


Figure 3. *Worst Case*

*(**A**: candidate active node **B**: Redundant node)*

3.2 3MeSH algorithm

Assuming that every sensor node has a uniform sensing disk of radius R, it can send sensor data to a sink, with the first hop being within a radio transmission range of $\sqrt{3}\,R$. If the network is connected, every node has at least one neighbour within its radio transmission range.

3.2.1 Active node election for full coverage

Firstly the sink broadcasts a message to trigger the active node election process, then any node between a distance of R to $\sqrt{3}\,R$ from the sink can be elected as an active node. Those further away (closer to $\sqrt{3}\,R$ from the sink) have a higher priority for election. To prevent multiple nodes being elected as active nodes simultaneously, the candidate node should register with the existing active node broadcasting the message.

Consider two adjacent active nodes; other nodes receiving messages from both take part in the election procedure. Such a candidate node sums the distances to each of the two active nodes. The node having the sum distance closest to $2\times\sqrt{3}\,R$ is elected as a third active node. A node falling within an active node's sensing area is regarded as being redundant. If the triangular mesh formed by active nodes is continuous, then the working area is fully covered and all redundant nodes are covered by three adjacent active nodes' radio transmission range, except at the boundary area, or if a blind hole without any live nodes exist, for example, the shadow hexagon shown in Figure 1.

3.2.2 Self-healing algorithm

When active node failure occurs, the adjacent redundant nodes detect it, and elect new active nodes to cover the un-sensed area. When the active nodes send data to the sink, each redundant node can overhear the signals from its three adjacent active nodes. If a redundant node receives fewer packets than expected, and does not lie within any active node's sensing area, then it start to elect itself as a new active node. The new active node election is finished when all redundant nodes are covered by active nodes' sensing ranges.

4. Practical considerations

4.1 Full coverage guarantee and blind hole detection

To guarantee full coverage in location awareness case with a Voronoi diagram, Reference 1 needs the location information of all neighbours for each node, in order to detect the blind hole and decide if it is redundant. References 4-5 require information on the positions of all nodes to guarantee full coverage. Without location information for the whole network or the neighbour nodes, how does 3MeSH guarantee full coverage? Sometimes, the nodal density is high enough to cover fully the working area within multiple overlays by different subset of nodes. In this case, 3MeSH can elect the active nodes efficiently to guarantee full coverage as shown in Figure 1, and there is no blind area inside the triangles formed by any three adjacent nodes within the least cascaded area (Figures 2, 3). After multiple nodal failures, or if the nodal density not high enough to form more than one overlay, it is difficult to detect a blind hole (shaded in Figure 1) and guarantee critical full coverage as the 3MeSH algorithm is too simple. However, 3MeSH can still elect active nodes efficiently to achieve near full coverage.

In the following simulation we consider that the working area is fully covered if all the nodes (both live and dead) are covered by the sensing ranges of active nodes. The result shows that 3MeSH can detect that the working area is not fully covered if the number of current active nodes is less than a threshold percentage (i.e. 90%) of the initial number when the nodal density is high.

4.2 Received Signal Strength Indication (RSSI) distance estimation error
In this paper we use Received Signal Strength Indication (RSSI) to estimate the distance between a radio transmitter and a receiver. Within the micro-sensor testbed in our department, we found that the accuracy when estimate the distance using RSSI is poor. In plane area without obstacles, the RSSI attenuation is proportional to distance squared, but this may increase to powers of 3 or 4 for indoor radio transmission, or if there are different kinds of obstacles. The RSSI value can change with time, due to variable background noise and other issues. Is it feasible to estimate distance using RSSI? As the 3MeSH triangle algorithm is distributed, it selects the new active node only considering its distance to two existing adjacent active nodes, so the estimation error and topology distortion do not accumulate. More software simulation, and test bed evaluation will be necessary to evaluate performance in an interfering and fading environment.

5. Simulation result

Simulation in OPNET was implemented, assuming RSSI attenuation increases with the square of distance. Nodes are evenly or unevenly deployed in a 200m×200m area as shown in Figure 4.

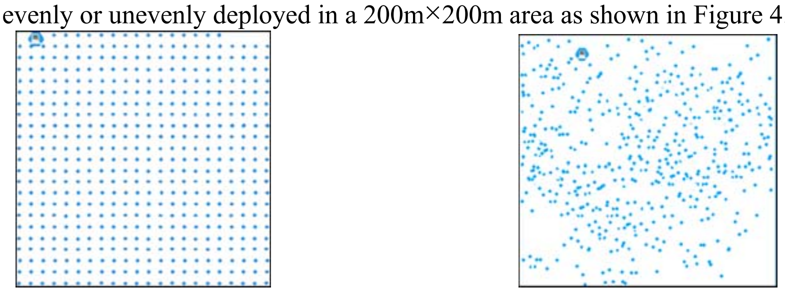
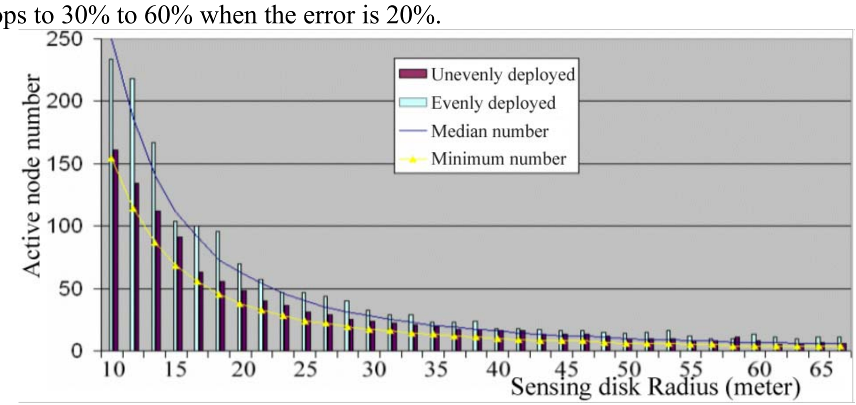


Figure 4. *500 nodes evenly (grid) deployed* *500 nodes unevenly deployed*

5.1 Comparing the number of active nodes in different cases with SoRCA [5]
Section 3.1 shows that the **minimum number of active nodes** = **Total Sensing Area/2.6 $\boldsymbol{R^2}$** for a hexagonal radius of R. As the hexagon radius is varied from R to $\sqrt{3}\,R/3$ in 3MeSH algorithm, the median radius of a hexagonal cell is $(R + \sqrt{3}\,R/3)/2 \approx 0.79R$, hence the median area of a hexagonal cell $\approx 1.6\,R^2$. Thus the **median number of active nodes** ≈ **Total Sensing Area/1.6 $\boldsymbol{R^2}$**. Figure 5 shows the minimum/median number of active nodes for full coverage, and the number of active nodes determined by simulation of the 3MeSH election algorithm, where the number in the evenly deployed case is slightly more than the median number, but in the unevenly deployed case it is less than the median.

In SoRCA [5], the hexagonal cell radius is $R/2$ to guarantee full coverage as described in section 2, hence the **minimum number of active nodes** ≈ **Total Sensing Area/2.6 $\boldsymbol{(R/2)^2}$,** which is 2.5 times as many as the median number in 3MeSH (**Total Sensing Area/1.6 $\boldsymbol{R^2}$**).

5.2 Evaluating the election efficiency using RSSI distance estimation
If the RSSI estimation for distance R is between R and $R–E\%R$, in the worst case the actual maximum sensing hexagonal radius is reduced to $R–E\%R$. Because the sensing coverage area for each node is proportional to the square of the sensing radius, the number of active nodes is inversely proportional to sensing radius squared. The simulation result shows (Figure 5) that the number of active nodes increased by 60% to 110% when the sensing radius drops by 30%, corresponding to an RSSI estimation error of 30%. The increase in number of active nodes drops to 30% to 60% when the error is 20%.



Working area: 200m × 200m
Total number of nodes: 500

Figure 5.

5.3 Self-healing performance
Assume each node has a maximum lifetime of 200 hours in active mode, and that the energy consumption in sleeping mode is negligible. We assume that the lifetime of an active node is uniformly distributed between 100 to 200 hours, with an average of 150 hours. An alternative

way of implementing self-healing for full coverage is elect **different overlays** of active nodes for full coverage, then switch to a new overlay of active nodes every 100 hours in the worst case, because nodal power after 100 hours may be exhausted, hence (100 × Number of overlays) is the minimum lifetime for full coverage, and (150 × Number of overlays) is the maximum lifetime in the optimum case when all the nodes have uniform lifetime of 150 hours.

Using the self-healing algorithm, each redundant node overhears neighbours to detect nodal failure every time an active node sends data. To simplify the simulation we assume active nodes send data every 20 hours, hence new active nodes are elected every 20 hours to cover nodal failure. The simulation for sensing radius 25m (Table 1) shows, in the grid deployed case, the self-healing lifetime for full coverage is slightly longer than the maximum lifetime in the different-overlays model. In the random deployed case, the lifetime using self-healing algorithm is 12~30% longer than the minimum lifetime of the different-overlays model.

Coverage for Sensing Radius=25m	Maximum Lifetime for full coverage (Hours)			
	Unevenly deployed case		Evenly (grid) deployed case	
	Self-Healing	diff-overlays min / max	Self-Healing	diff-overlays min / max
>98%	560	500 / 750	920	600 / 900
>90%	1180	900 / 1350	1380	900 / 1350

Table 1.*Self-healing performance Vs diff-overlays in accident failure free environment*

Hostile environments could make active nodes fail, and in this case, the active nodal lifetime would be unpredictable. If few nodes fail, the different-overlays model is inefficient. Alternatively, if all nodes are reset after any nodal failure and restart the active node election algorithm (see section 3.2.1), it could elect a new subset of active nodes close to the optimum case, although this is inefficient for frequent re-election. Simulation for a sensing radius of 10m to 40m (Table 2) shows that when the active nodal accident failure rate every 10 hours is 30%, the lifetime using self-healing algorithm is very close to that with re-election every 10 hours, both in unevenly and evenly deployed scenarios.

Sensing Radius	**Unevenly deployed case**				**Evenly (grid) deployed case**			
	Max lifetime (hrs)		Coverage area		Max lifetime (hrs)		Coverage area	
	S-Heal	re-elect	S-Heal	re-elect	S-Heal	re-elect	S-Heal	re-elect
10 m	30	30	>91.2%	>88.4%	30	30	>92.4%	>94.8%
20 m	90	90	>96.2%	>95.6%	130	120	>96.0%	>96.0%
30 m	220	210	>98.0%	>98.6%	270	300	>97.8%	>98.4%
40 m	360	360	>98.6%	>98.4%	560	600	>98.2%	>97.2%

Table 2.*Self-healing Vs Re-election per duty circle in hostile environment*
(Active node failure rate per 10 hours: 30%)

6. Conclusion

The 3MeSH algorithm is a distributed algorithm for full coverage, with minimum active sensor nodes, and without nodal location awareness information. It can also be applied to fault-tolerant cluster-based routing protocols. The simulation result shows, that 3MeSH can achieve high fault tolerance for full coverage sensing using RSSI distance estimation without location awareness, and excellent self-healing performance in both hostile environments having high node failure rate, and environments free of accidents and failures, compared to a re-election algorithm. Further research and simulation using our micro sensor test bed will be implemented in the near future to test the performance of 3MeSH in reality.

Reference

1. Bogdan Carbunar, Ananth Grama, Jan Vitek, Octavian Carbunar, Coverage Preserving Redundancy Elimination in Sensor Networks, IEEE SECON 2004, October 2004.
2. H. Zhang and J. C. Hou Maintaining Sensing Coverage and Connectivity in Large Sensor Networks. Technical report, UIUC, 2003.
3. Jie Wu, Shuhui Yang: Coverage Issue in Sensor Networks with Adjustable Ranges. ICPP Workshops 2004: 61-68
4. H. Zhang, A. Arora, "GS3: scalable self-configuration and self-healing in wireless networks", ACM Symposium on Principles of Distributed Computing 2002
5. X. Wang, T. Berger, "Self-Organizing Redundancy Cellular Architecture for Wireless Sensor Networks", (WCNC), New Orleans, LA, USA, March 2005