Research Issues

• Protocols Design for Mobile WSNs
• Obstacle Handling Mechanisms in WSNs
• Data-Centric Storage Mechanisms in WSNs

Protocols Design for Mobile WSNs

• Coverage Hole Handling
• Localization
• Robot Deployment
Assumptions

- Every sensor is aware of its location information
- Locations of mobile sensors are known by every static sensor
Network Model

- Every static sensor constructs its Voronoi diagram.
- Sensor with hole in its Voronoi diagram will evaluate the price.

Price = \text{Max}\{ \text{the distance from sensor to each Voronoi Vertex-sensing range} \}
• Static sensors can locally obtain the hole information
• All mobile sensors broadcast their locations over WSN
• Static sensor that has hole sends a request to the closest mobile sensor

• Mobile sensors move to heal the hole
• Mobile sensors broadcast its location and hole information
Conclusion

- Use mobile sensor to handle the hole
- Advantage
  - Full coverage

Disadvantages

- Moving in a zig-zag path consumes much more energy
Disadvantages

- Several mobile sensors go to the same location of one hole

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Coverage Hole Handling: Paper 2

**Title:** Proxy-Based Sensor Deployment for Mobile Sensor Networks

**Authors:** G. Wang, G. Cao and T. La Porta

**From:** The 1st IEEE International Conference on Mobile Ad-hoc and Sensor Systems (MASS2004)
Assumptions

- Every sensor is aware of its location information
- Locations of mobile sensors are known by every static sensor
- Basic Idea: Mobile sensors logically move from small holes to large holes iteratively

- Static sensors can locally obtain the hole information
• Use proxy to logically move
• Proxy broadcasts location of a mobile sensor and hole information

Distance-based vs. Price-based

• Types of how static sensor to send messages to mobile sensors
  – Distance-based
    • Sensors bid the closest mobile sensors
  – Price-based
    • Sensors choose the lowest-price mobile sensors

\[
\overline{m_1B + m_2A} \quad \text{Better than} \quad \overline{m_1A + m_2B}
\]
Distance-based

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Price-based

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- Distance-based:
  - Points: A, B, C, D
  - Connections: A to B, B to C, C to D

- Price-based:
  - Points: A, B, C, D
  - Prices: A to B (25), B to C (86), D to C (10)
Conclusion

• Advantages
  – One-time movement
  – Multiple healing avoidance
  – Load balance

• Disadvantage
  – High complexity of Cooperative computing

Coverage Hole Handling : Paper 3

Title: Movement-Assisted Sensor Deployment
Authors: Guiling Wang, Guohong Cao, and Tom La Porta
From: INFOCOM 2004
Goals

• Given the target area, how to maximize
  – The sensor coverage with less time
  – Movement distance
  – Message complexity

Movement-assisted Sensor Deployment Protocols

• The VECtor-based Algorithm (VEC)
• The VORonoi-based Algorithm (VOR)
The VECtor-based Algorithm (VEC)

- $d_{ave}$ = the average distance between any two sensors of WSN
- $d(s_i, s_j)$ = the distance between sensor $s_i$ and sensor $s_j$
- $F_{ij} = (d_{ave} - d(s_i, s_j))/2$
The VECtor-based Algorithm (VEC)
The VECtor-based Algorithm (VEC)

(a) Round 0  (b) Round 1  (c) Round 2

Fig. 2. Snapshot of the execution of VEC

The VORonoi-based Algorithm (VOR)
VOR-Disadvantage

VOR-Disadvantage
Objective

- Maximize the coverage for a given number of sensors within a cluster in cluster-based DSNs
- Propose a Virtual force algorithm (VFA)
Virtual force algorithm (cont.)

– Attractive force

![Diagram showing attractive force between sensors S1 and S2]

– Repulsive force

![Diagram showing repulsive force between sensors S1 and S2]

Virtual force algorithm (cont.)

• The virtual force ideas
  – Each sensor behaves as a “source of force” for all other sensors

![Diagram showing positive and negative forces between multiple sensors]

S1
S2
S3
S4
F
F
X
Y
Virtual force algorithm (cont.)

- Virtual Force calculation in the VFA algo.
  - $\vec{F}_j$: the vector exerted on $S_i$ by another sensor $S_j$
  - Obstacles and areas of preferential coverage also have forces acting on $S_i$
    - $\vec{F}_i$: the total (attractive) force on $S_i$ due to preferential coverage areas
    - $\vec{F}_{ik}$: the total (repulsive) force on $S_i$ due to obstacles
  - The total force $\vec{F}$ on $S_i$

$$\vec{F}_i = \sum_{j \neq i} \vec{F}_j + \vec{F}_{ik} + \vec{F}_{it}$$

Conclusion

- The virtual force algorithm (VFA)
  - Uses a force-directed approach to improve the coverage after initial random deployment
  - Advantages
    - Negligible computation time
    - Flexibility
Coverage Hole Handling: Paper 5

**Title:** Energy Efficient Organization of Mobile Sensor Networks

**Authors:** Joengmin Hwang, David H.C. Du, and Ewa Kusmierek

**From:** IEEE ICPPW’04

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**Motivation**

- To increase lifetime of a sensor network
  - Organized the sensors into disjoint sets
  - Only one set is active at a time
  - The lifetime of the network increases proportionally to the number of disjoint sets
Objective

- To provide a complete coverage of the area for the longest amount of time
- To increase the number of disjoined sets by repositioning some of the sensors

Disjoint sets

We can organize the sensors into disjoint sets
Disjoint sets

Only one set is active at a time

Disjoint sets

Only one set is active at a time
Overview

Heuristic solution - Area identification

Target field – a field that is not covered by any sensors

The rectangle containing the target field is given by \((L_x, B_y)\) and \((R_x, T_y)\)
Heuristic solution - Area identification

Location boundary – if a sensor is placed within the boundary, it completely covers the target field

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Heuristic solution – Sensor and area selection

(area, sensor)
(area1, A)
(area2, A)
(area3, A)
(area4, A)

Movement Range
Heuristic solution – Sensor and area selection

Negative effect occurs

A New Target field is created

(area, sensor)
(area1, A)
(area2, A)
(area3, A)
(area4, A)
Heuristic solution – Sensor and area selection

The value of Objective function – a number of target fields that sensor the can cover from the given area

The value is 1

Heuristic solution – Sensor and area selection

• First, construct a set of (area, sensor) pairs
  – Sensor can be moved into the area
• Second, if the negative effect occurs, the pair cannot be selected for rearrangement
• Third, compute the value of the objective function
  – The pair with highest value is selected
Conclusion

- This paper presented efficient algorithm
  - Increase the number of the independent covered sets
- Future work
  - Distribute algorithm

Problems

- How to deal with a big hole that requires more than one mobile sensor?
- A big hole can be treated as an obstacle and how to minimize the impact of the obstacle on packet transmission?
- How to prevent the network from partition?
Coverage Hole Handling: Paper 6

**Title:** Sensor Relocation in Mobile Sensor Networks

**Authors:** Guiling Wang, Guohong Cao, Tom La Porta, and Wensheng Zhang

**From:** Infocom 2005

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**Motivation**

- When a sensor fails
  - Identify redundant sensors
  - Relocate to the location of the failed sensor
Environment

• Grid head can monitor its group members and initiate a relocation process

Finding the redundant sensor
- Grid-Quorum

• Supply quorum
  – The grid heads belong to the grids in one row are organized into one quorum
Finding the redundant sensor - Grid-Quorum

- **Demand quorum**
  - The grid heads belong to the grids in a **column** are organized into one quorum

- **Supply quorum**

When a grid has redundant sensors, the grid head propagates this information through the supply quorum which it belongs

The grid head of (1,3) propagates its redundant sensor information through its supply quorum ((0,3), (1,3), (2,3), (3,3), (4,3))
Finding the redundant sensor
- Grid-Quorum

• When any grid wants more sensors, the grid head needs only to search its demand quorum.

The grid head of (3,0) searches its demand quorum \[((3,0), (3,1), (3,2), (3,3), (3,4))\]

Finding the redundant sensor
- Grid-Quorum

• The grid head of (3,3) and (3,4) reply the information about redundant sensors.

• The grid head of (3,0) knows the Most proximal redundant sensor in the grid head of (1,3).
Sensor relocation – direct movement

• The redundant sensor directly moves to the location of the failed sensor
  – Waste energy

Sensor relocation - cascaded movement

• Find some intermediate nodes and use them for relocation
  – Reduce delay and balance power
Sensor relocation - cascaded movement

- A node \( S_j \) moves to replace another node \( S_i \)
  - \( S_i \) is \( S_j \)'s predecessor
  - \( S_j \) is \( S_i \)'s successor

\[ S_0 \rightarrow S_j \rightarrow S_i \]

Sensor relocation - cascaded movement

- \( S_0 \) broadcasts a request message
- Each sensor node receives all the messages from neighbors which are further away from the redundant sensor than itself
- The message includes
  - \( E \): total energy consumption of the moving path
  - \( E_{min} \): minimum remaining energy of the moving path

\[ S_0 \rightarrow S_j \rightarrow S_i \rightarrow S_o \]
Sensor relocation - cascaded movement

- A node $S_j$
  - Calculate $E_j = d_{ij} + E_i$ and $E_{	ext{min}_j} = \min(P_j - d_{ij}, E_{\text{min}_j})$
  - Choose a neighbor which can minimize $E$ as predecessor
  - If two neighbors have the same $E$, then $S_j$ chooses the neighbor which has a larger $E_{\text{min}}$

Sensor relocation - example

$E$: total power consumption from A to destination
$E_{\text{res}}$: minimal remaining power of node in the path from A to destination
Pred: Prefer predecessor
Sensor relocation - example

- The moving path: $S_r \rightarrow S_8 \rightarrow S_6 \rightarrow S_4 \rightarrow S_1 \rightarrow S_0$

- All relevant sensors to move at the same time
Conclusion

• Define the problem of sensor relocation
  – Propose a Grid-Quorum solution to locate the closest redundant sensor
  – Propose to use cascaded movement to relocate the redundant sensor

Coverage Hole Handling: Paper 7

Title: Mobile Sensor Deployment for a Dynamic Cluster-based Target Tracking Sensor Network

Authors: Niaoning Shan and Jindong Tan

From: 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems
Motivation

- Presents a mobile sensor deployment algorithm within a hybrid sensor network
  - Most of the static sensors
    - To form a CLUSTER
  - Some mobile sensors
    - Used to fill coverage holes inside the clusters
    - Improve the tracking quality
- A cluster is formed to track the event and be updated according to the evolvement of the event

Introduction
Cluster construction

- Holes and Hole traverse
  - A hole is defined as a face with more than 3 vertices
  - Each sensor can locally decide whether it is on the edge of a hole
    - By checking its adjacent neighbor pairs
  - Hole node
    - If any of its adjacent neighbor pairs is disconnected
  - Messages can be traversed to all nodes on a hole along the hole edges

Nodes a - p - b - n - m forms a hole

Cluster construction

- In order to easily terminate a hole traversing, a message traverse a hole along two directions, then stop whenever the same message from different directions meet at a certain node
Cluster construction

- Cluster construction protocol
  - For a sparsely deployed sensor network
  - Sensors outside the cluster area are needed for routing
    - Because of the existence of Holes

Algorithm 1 Cluster Construction Protocol

1: $\text{MyMessage} \leftarrow \text{msg}$
2: // Continue traversing all holes that pass $p$
3: if $\text{First time to receive this message}$ then
4: if Some holes need $p$ to continue traversing then
5: Continue traversing for all these holes;
6: Set $p$'s parent;
7: else
8: if $p$ is within the current cluster area then
9: Set $p$'s parent and start possible new holes;
10: end if
11: end if
12: else
13: // Continue traversing for possible concave holes
14: Continue traversing for all holes, which passed $p$ in the same direction;
15: end if
16: Broadcast $\text{MyMessage}$ if it has been changed
Mobile sensor deployment

• Sensors’ sensing range is slightly larger than 1/2 of their communication range

Proposition 4.1: For a small hole, the coverage hole can be completely filled if each hole node has at least one additional mobile sensor as its neighbor after the mobile sensor deployment.

Mobile sensor deployment

• The static sensors in group Gi are \{Sj|^Gi| j = 1, 2, ..., N_Gi\}
  – There exists at least one point Ci that the distances from Ci to Sj|^Gi|, j = 1, 2, ..., N_Gi are less than the sensors’ communication range
Mobile sensor deployment

• Decision of the first group

They are sorted in clockwise direction to form a circular array

Node a's first-group candidate is a - b – c
Node i's first-group candidate is i- j - a - b - c

first-group i- j - a - b - c  two ends (terminators): i and c
Mobile sensor deployment

The grouping process is initialized by these two terminators.
The terminators of the previous group search group members for new group.

Second group c-d-e-h-i
Terminators h and e

Mobile sensor deployment

• One terminator acts as the group head and the other one as group rear.
• Two possible situations exist:

1. Group head and rear overlap on one node
2. No more neighbors of head or rear can be incorporated into the group.
Mobile sensor deployment

one direction until no more sensors can be incorporated

Conclusion

- Deployment Algorithm enables mobile sensors
  - To fill coverage holes inside a dynamic cluster
  - Enhance the cluster's sensing capability
Current Research 2: Hole Regulation

HONOR: HOle NORmalization Protocol for Mobile Sensor Networks

Introduction

• The existence of large hole
  – Unbalanced deployment
  – A region of sensor nodes failure due to power exhaustion
  – Some sensor nodes are took away because of natural phenomena such as a large group of animals moving or a fierce wind blowing
Introduction

• The impact of a large hole
  – Low accuracy of the environment monitoring
  – Poor efficiency of sensing and communication

Introduction

• Dealing with the large hole
  – Redeploying sensor nodes on the hole area with robots or mobile sensors
  – Patrolling the hole area with robots or mobile sensors
Introduction

- Previous works -

- Mobile Sensor Deployment for a Dynamic Cluster-based Target Tracking Sensor Network
  - *IEEE/RSJ International Conference on Intelligent Robots and Systems 2005*
  - Niaoning Shan and Jindong Tan
    - Department of Electrical and Computer Engineering
      Michigan Technological University

- Goal
  - Redeploy sensor nodes with mobile sensors

Introduction

- Previous works -

- Main method
  - Mobile sensors move simultaneously to the position which could communicate with other sensors as many as possible
Introduction

- Previous works -

• Disadvantage
  – A irregular hole will result in deploying redundant sensors on the unnecessary area

• Mobility Improves Coverage of Sensor Networks
  – ACM MobiHoc 2005
  – Benyuan Liu*, Peter Brass, Olivier Dousse
    • University of Massachusetts

• Goal
  – Patrol the hole area with mobile sensors or robots
Introduction

- Previous works-

• Main idea
  – Uncovered region (hole) will be covered for a time interval \([0, t)\)

  ![Diagram of uncovered region being covered over time]

• Patrol irregular hole with uniform path
  – Redundant patrol path
  – Consume more energy
  – Require more time for full coverage

  ![Diagram of patrol paths with coverage over time]
Introduction

• Base on the shape of the hole to plan the patrol path
  – Too complex
  – Not easy to plan

Introduction -Motivation-

• Normalizing irregular hole to regular hole
  – More easy to redeploy sensor nodes
  – More easy to patrol the hole area
  – Energy saving
Introduction

-Motivation-

Move convex parts of hole to concave area

Move sensors which are on the concave area to convex parts of hole
Introduction

- Motivation -

It's easy to redeploy or patrol in the regular hole

Challenges

- Which nodes have to move?
- How to move?
- Distributed mechanism?
Current Research 3:  
Hole Movement

Energy-Balanced Strategy for Hole Movement  
in Mobile Wireless Sensor Networks

Introduction

• The coverage of a sensor network represents the quality of surveillance
• Coverage loss may cause sensors’ communication to break
Introduction

-Motivation-

• Hole movement improves communication efficiency
• Hole movement can maintain full coverage within limited time period

-Previous works-

• Sensor Relocation in Mobile Sensor Networks
  – *Infocom 2005*
  – Guiling Wang, Guohong Cao, Tom La Porta, and Wensheng Zhang

• Goal
  – Relocate sensors to deal with sensor failure
Introduction

- Previous works -

• Main method
  – to find some cascading (intermediate) nodes, and use them for relocation to reduce the delay and balance the power.

• Disadvantage
  – It requires surplus mobile sensor
  – Only repair the coverage of one sensor’s sensing area
Goal

- make the existing large-sized sensing hole moves to the boundary of the sensing area

- Minimize each sensors' power consumption during hole movement procedure
Moving 1 hop
Introduction

• Change shape of hole into a belt
  • Enable more sensors to participate in moving hole scheme and reduce each sensor’s power consumption in moving hole scheme

Introduction

• How to change the shape a existing large-sized hole into a belt
• Let mobile sensor only move forward

Sensors only move $D_1, D_2, D_3$ direction