“Fault Tolerant Sensor Placement Optimization with Minimum Detection Probability Guaranteed”

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Place the minimum number of sensor nodes (SNs) over a planar grid to guarantee a desired minimum detection probability after some sensors have failed.
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(traditional) fault tolerance in sensing coverage in wireless sensor networks (WSNs)

“$k$-coverage”

area or point of interest is covered by $k$ different sensor nodes (SNs)

3-covered area

sensing range

$\bullet$ : SN

: sensing coverage of 1 SN

(binary sensing model: object inside sensing range detected with probability of 1)
Motivation: probabilistic sensing model more suited for object/signal detection SNs than binary sensing model (signs such as thermal energy, acoustic waves, radio waves, light waves, magnetic field*, seismic **) for fault tolerant coverage

Our Fault Tolerant Coverage

Probabilistic Sensing Model → New Kind of Fault Tolerant Coverage

Minimum Detection Probability across sensing field after SN failures as the performance metric for fault tolerant coverage

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Place the **minimum number of sensor nodes (SNs)** over a planar grid to guarantee a desired min detection probability after some sensors have failed.
Problem Formulation

Sensor Deployment Area

- 2-D uniform grid
- SNs placed on grid points
- Detection probability calculated at each grid point
- Distance between adjacent grid points: $d$

Figure 1. Sensor deployment area in 2-D uniform grid
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**Problem Formulation**

**Objective Function**

\[
\min_{\text{placement}} \beta \cdot (1 - M) + n \cdot M
\]

\( \beta \) : a number sufficiently larger than the total number of grid points in deployment area

\[ M = \begin{cases} 1 & \text{Minimum detection probability after failures } > \text{ threshold} \\ 0 & \text{Otherwise} \end{cases} \]

\( n \) : a number of SNs deployed
Problem Formulation

Cumulative Detection Probability at a Grid Point

\[ P(D_j) = 1 - \prod_{i=1}^{n} \{1 - P(S_i)\} \]

- \( P(D_j) \): detection probability at grid point, \( j \)
- \( P(S_i) \): probability that an SN \( i \), detects the target at grid point \( j \).
Problem Formulation

Sensing Model
(based on Gaussian probability distribution)

\[
P(S_i) = e^{-\frac{\tau_i^2}{2\alpha_s^2}}, \tau_i \in [0, d_s]
\]

\(\tau_i\): distance between a SN \(i\) and a grid point \(j\)

\(d_s\): the maximum detection range of the SNs

\(\alpha_s\): dictates the shape of the detection probability curve

Figure 2. Local detection probabilities on 50 x 50 grid points based on Gaussian sensing model
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Optimization Tool: Genetic Algorithm (GA)

**Genetic Algorithm (GA)**

- Population become fitter and fitter

* Fittest organisms (chromosomes) selected

**Population of Species**

**Reproduction through Crossover and Mutation**

Reasons for choosing GA:

- non-differentiable
- combinatorial
- large solution space

\[ \text{Min } \beta^* (1 - M) + n^* M \]

* brainz.org
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Solution is in the form of bitstring:
0 means no SN placed at grid point
1 means 1 SN placed at grid point

GA fitness function same as the objective function of the problem

\[ \min \beta \cdot (1 - M) + n \cdot M \]
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Experimental Results

Fitness Function in GA:

$$\text{Min} \ \beta \cdot (1 - M) + n \cdot M$$

$$P(S_i) = e^{\frac{-\tau_i^2}{2\alpha_s^2}}, \tau_i \in [0, d_s]$$

- Area: 50 x 50 grid points
- Distance between adjacent grid points: 7.2 units
- Maximum detection range $d_s$: 195 units
- $\alpha_s$: 68 units
- Minimum detection probability threshold: 93%
- $\beta$: 5000

* 93% is the min detection prob from placing 16 SNs uniformly
Experimental Results

Initial Pop: 8, Pop Size: 300 Elite:20
Crossover: 0.85, Scattered
Mutation: 0.01, Uniform
Rank, Stochastic Uniform
Gen Limit: 200; Stall Gens:14

Num of SNs placed = 29, SN @ (6, 20) or 270 fails
Avg Det Prob @ all GPs after SN failure = 99.67%
Min Det Prob after SN failure = 93.49% (> threshold 93%)

* 93% is the min detection prob from placing 16 SNs uniformly

Local Detection Prob’s after worst case of one SN failure
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Experimental Results

Figure 6. Best placement solution by GA for two SN failures

Initial Pop: 13, Pop Size: 200, Elite: 10
Crossover: 0.85, Scattered Mutation: 0.01, Uniform Rank, Stochastic Uniform
Gen Limit: 200; Stall Gens: 14

Num of SNs placed = 38
SN 1@ 627(13,27) fails and SN 2@ 130 (3,30) fails
Avg Det Prob @ all GPs after SN failure = 99.74%
Min Det Prob after 2 SN failures= 93.10% (> threshold 93%)

* 93% is the min detection prob from placing 16 SNs uniformly
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Experimental Results

Figure 7. Uniform placement of 32 SNs and local detection probabilities for worst case of one SN failure

*Uniform placement of 16 SNs results in 93% min detection prob, so *uniform placement of 32 SNs: provides fault tolerance for one SN failure
(*uniform placement of 48 SNs: provides fault tolerance for two SN failures)


Uniform Placement of 32 SNs
16th SN @ fails
Avg Det Prob w/ all 32 SNs = 99.82%
Min Det Prob w/ all 32 SNs= 99.57%
Avg Det Prob after SN failure = 99.78%
Min Det Prob after SN failure= 98.28%

Local Detection Prob’s for 16 SNs Uniformly Placed

Local Detection Prob’s for 32 SNs after worst case of one SN failure
• Proposed **new** kind of fault tolerant coverage: minimum detection probability

• With GA, **successfully** found optimal placement that employed as few SNs as possible while still guaranteed the required minimum detection probability

• Experimental results: Our sensor placements **used fewer SNs** to guarantee the minimum detection probability than uniform placements

• Future work: **analytical study** of coverage to further validate results from GA