Fast Sensor Placement Algorithms for Fusion-based Target Detection

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Motivation

• Target detection is a key component of surveillance systems based on wireless sensor networks.
• Sensor placement is critical.
  – High impact on detection performance.
  – High deployment and sensor cost for large systems.

Contributions

• Realistic detection model.
  – Captures probabilistic properties and fusion.
• Fast sensor placement algorithms.
  – Complex non-linear optimization problem.
• Validation based on real-world acoustic traces.

Detection Model

✘ The (in)famous disc model
  • There is no cookie-cutter “sensing range”!
  • Environment is noisy!
✔ Real-world sensor detection
  – are probabilistic
  – employs sensor fusion

Single Sensor

- Decayed target energy = initial target energy/distance²
- Noise strength follows normal distribution N(μ+σ²)
- Sensor reading = decayed target energy + noise energy

Sensor Fusion

- A set of surveillance spots to be monitored.
- Sensors within fusion radius send readings to cluster head
- Cluster head compares average reading to threshold η
  – Targeted detected if average reading > η
- Sensor within the fusion radius to multiple spots is a shared sensor; otherwise it is a dedicated sensor.
Detection Requirements

- System detection probability (e.g., >90%).
- System false alarm rate (e.g., <1%).
- Must meet requirements in noisy environments!

Detection with Sensor Fusion

- System detection probability:  \( P_D = 1 - X_\eta(n-\eta - I W(d)/\sigma^2) \)
  - \( X_\eta \): CDF of Chi-square distribution
  - \( W(d) \): Energy measurement of sensor that is \( d \) from target
- System false alarm rate:  \( P_F = 1 - X_\eta (n/\sigma^2) \)
  - Probability that the average noise energy \( \geq \eta \)

Insights
- Sensor placement significantly affect detection performance
- System detection depends on combinations of individual sensor readings

Sensor Placement Problem

- \((\alpha, \delta)\)-coverage for a surveillance spot,
  - False alarm rate:  \( P_{fa} = \delta \)
  - Detection probability of any target on spot:  \( P_{dt} = \alpha \)
- Objective:
  - Find the smallest set of sensor locations
- Subject to:
  - All surveillance spots are \((\alpha, \delta)\)-covered.
- Non-linear optimization with prohibitive complexity!

Global Optimization

- Constrained Simulated Annealing (CSA) \([\text{Wah 07]}\]
- Exponential complexity with respect to number of required sensors

Divide and Conquer (D&C)

- Key: handle interdependency between spots
- Each spot has an impact region with radius \( 2 \times \) fusion radius
  - Spots within its impact region may share a sensor with it
- For each spot:
  - Account for sensors already deployed in its fusion region.
  - Add sensors in its fusion region to cover all spots in its impact region.

Reduce Dedicated Sensors

- Sensors added for later spots may add redundancy for earlier ones.
- For each spot:
  1. Remove all its dedicated sensors.
     - Note: Does not affect other spots → guarantee convergence.
  2. Compute a new local placement.
  3. Accept new placement if the number of sensors is reduced.
- Repeat until no more improvement.
Reduce Shared Sensors

- Problem when spots are dense
  - Process spots one by one → high time cost
  - Overlapping fusion regions → redundant shared sensors

- Solution: Clustering spots
  - Group nearby spots into clusters
  - Process clusters one by one → speed up placement
  - Place sensors for all spots in a cluster → reduce redundancy

Trace-driven Validation

- Acoustic data traces in DARPA SemiT experiments [Duarte 04]
- 196 regularly distributed spots, D&C places 67 sensors.
- Accuracy of sensing model
  - Detection probability: 95% spots > 90%
  - False alarm rate: 44% spots < 1%, max 1.8%

Comparison with Optimal

- Up to 7-fold faster than the global optimal placement for small number of sensors.

Comparison with Greedy

- Randomly selected surveillance spots, from 20 to 200.
- Greedy: place the next sensor in the fusion radius of spot with min $P_D$.
- Clustered D&C reduce the number of sensors by 30% on average.

Conclusions

- Realistic detection model
  - Probabilistic
  - Sensor fusion
  - Detection probability, false alarm rate

- Fast and practical sensor placement heuristics
  - Divide and Conquer
  - Local improvement
  - Spot clustering
  - Validated by acoustic vehicle detection trace

Paper