Collaborative Target Detection in Wireless Sensor Networks with Reactive Mobility

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Outline

1. **Motivation**
2. Preliminaries
3. Problem Formulation
4. Near-optimal Solution
5. Performance Evaluation

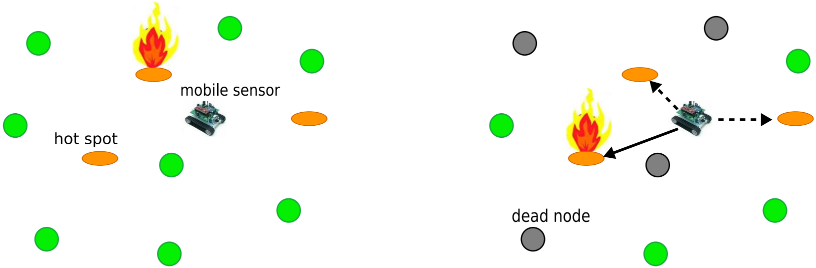
Challenges for Mission-critical Sensing Applications

- Stringent QoS requirements
  - Target detection/tracking, security surveillance
  - High detection probability
  - Low false alarm rate
  - Bounded detection delay
- Unpredictable network dynamics
  - Coverage holes caused by death of nodes
- Changing physical environments
  - Different spatial distribution of events

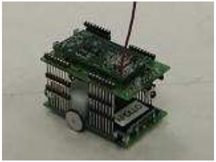
Exploit Mobility in Target Detection

- Sense better signal by moving sensors closer to targets
- Adapt to the changes of network condition and physical environments

Example: fire detection



Mobile Sensor Platforms


Robomote @ USC


Koala @ NASA GRC


PackBot @ iRobot.com

Challenges

- Low movement speed ($0.1 \sim 2m/s$)
  - Increase detection latency
- High manufacturing cost
  - A small number of mobile sensors available
- High energy consumption
  - Locomotion consumes much higher power than wireless communication

Overview of Our Approach

- Data-fusion based target detection
  - Explore the collaboration between mobile and static sensors
- Near-optimal sensor movement scheduling algorithm
  - Reduce moving distance of sensors
  - Satisfy QoS requirements:
    - Low false alarm rate
    - High detection probability
    - Bounded detection delay
- Performance evaluation using real data traces

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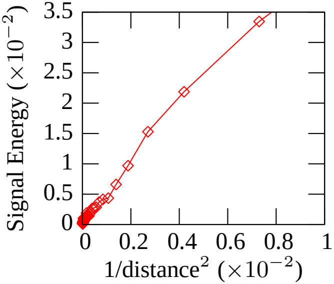
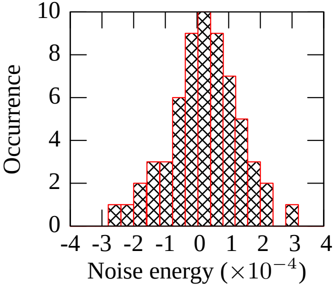
Signl Energy Model and Noise Model





- Plotted using real data traces from DARPA SensIT experiments

$$e(x) = \frac{\text{initial target energy}}{x^2} \qquad \text{noise} \sim N(\mu, \sigma^2)$$

$$\text{Measurement} = e(x) + \text{noise}$$

Single-sensor Detection Model

- Local decision of sensor *i*

$$= \begin{cases} 1 & \text{if } e_i \geq \lambda \\ 0 & \text{if } e_i < \lambda \end{cases}$$

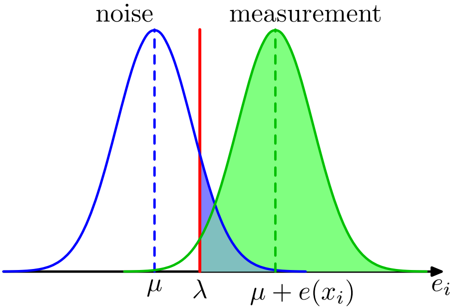
- The false alarm rate of sensor *i*

$$P_F^i = Q\left(\frac{\lambda - \mu}{\sigma}\right)$$

- The detection probability

$$P_D^i = Q\left(\frac{\lambda - \mu - e(x_i)}{\sigma}\right)$$

CCDF: $Q(x) = 1 - \int_{-\infty}^{x} \phi(t)\mathrm{d}t$



- closer to the target, higher P_D

Decision Fusion Model

- System detection decision

$$\text{Majority Rule: } \begin{cases} 1 & \text{if more than } n/2 \text{ sensors decide 1} \\ 0 & \text{otherwise} \end{cases}$$

- The system false alarm rate

$$P_F = Q\left(\frac{\frac{n}{2} - \sum_{i=1}^{n} P_F^i}{\sqrt{\sum_{i=1}^{n} P_F^i + \sum_{i=1}^{n} (P_F^i)^2}}\right)$$

- The system detection probability

$$P_D = Q\left(\frac{\frac{n}{2} - \sum_{i=1}^{n} P_D^i}{\sqrt{\sum_{i=1}^{n} P_D^i + \sum_{i=1}^{n} (P_D^i)^2}}\right)$$

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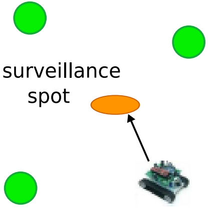
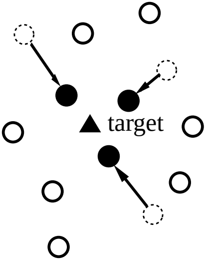
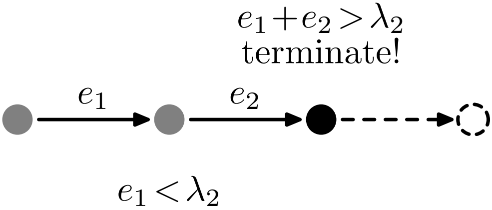
Target Detection with Mobile Sensors



- Long distance movement can
    - quickly deplete the battery of a mobile node
    - disrupt the network topology
- Problem formulation: minimize the moving distance of sensors subject to
    - $P_F \leq \alpha$, *e.g.*, 5%
    - $P_D \geq \beta$, *e.g.*, 95%
    - Average detection delay $\leq D$, *e.g.*, 15s

A Two-phase Detection Approach





- 1st phase: each sensor makes local decision by $e_0 \gtrless \lambda_1$
    - If the system decision is 1, the 2nd phase is initiated
- 2nd phase: mobile sensors move and periodically sense
    - A sensor terminates the detection and decides 1 if

$$e_1 + e_2 + \cdots + e_j \geq \lambda_2$$

    - Make final detection decision

Advantages of Reactive Mobility

- Sensors move reacting to positive decision in the 1st phase
- Avoid unnecessary movement by consensus check in the 1st phase
  - Reduce the probability of movement when the target is absent
- Terminate moving once enough signal energy is obtained
  - If a loud target appears, mobile sensors can terminate movement quickly

Problem Formulation

Objective: Find the two detection thresholds λ_1, λ_2 and a movement schedule to minimize the expected moving distance:

$$\underbrace{\boxed{P_a \cdot P_{D1} \cdot \mathcal{L}_1}}_{\text{correct detection}} + \underbrace{\boxed{(1 - P_a) \cdot P_{F1} \cdot \mathcal{L}_0}}_{\text{false alarm}}$$

- P_a: the probability that a target appears
- $\mathcal{L}_0(\mathcal{L}_1)$: the expected moving distance when the target is absent (present)

Constraints:

- $P_{F1} \cdot P_{F2} \leq \alpha$
- $P_{D1} \cdot P_{D2} \geq \beta$

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The Structure of Optimal Solution

- **Theorem 1:** Total moving distance decreases with the system detection probability in the 2nd phase, *i.e.*, P_{D2}
- Linear approximation using the 1st order Taylor expansion

$$Q^{-1}(P_{D2}) = \frac{\frac{n}{2} - \sum_{i=1}^{n} P_{D2}^{i}}{\sqrt{\sum_{i=1}^{n} P_{D2}^{i} - \sum_{i=1}^{n} (P_{D2}^{i})^{2}}}$$

$$\simeq -\frac{2}{\sqrt{n}} \sum_{i=1}^{n} P_{D2}^{i} + \text{constant}$$

P_{D2} increases with $\sum_{i=1}^{n} P_{D2}^{i}$ with high probability

- Simplified problem formulation
  - Maximize $\sum_{i=1}^{n} P_{D2}^{i}$ subject to the constraints:

$$P_{F1} \cdot P_{F2} \leq \alpha \qquad P_{D1} \cdot P_{D2} \geq \beta$$

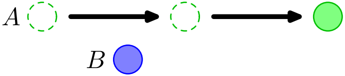
The Structure of Optimal Solution (Cont.)

- Combination of sensor movement is exponential
    - Finding maximized $\sum_{i=1}^{n} P_{D2}^{i}$ is exponential
- **Theorem 2:** In the optimal solution, each mobile sensor move in parallel and consecutively
- Implication
    - $\sum_{i=1}^{n} P_{D2}^{i}$ can be maximized by Dynamic Programming

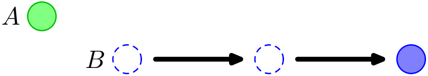
Dynamic Programming: An Example

- Two sensors: A and B
- Budget: two sensor moves
- Suppose:
  $P_D^A(0) = 0.40, P_D^A(1) = 0.50, P_D^A(2) = 0.60$
  $P_D^B(0) = 0.46, P_D^B(1) = 0.60, P_D^B(2) = 0.67$

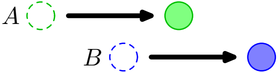
$P_D^A(2) + P_D^B(0) = 1.06$



$P_D^A(0) + P_D^B(2) = 1.07$



$P_D^A(1) + P_D^B(1) = 1.10$



This procedure can be implemented via Dynamic Programming

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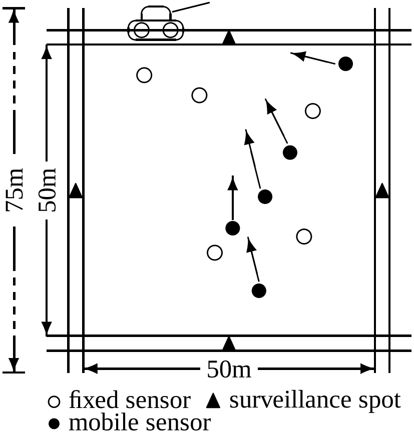
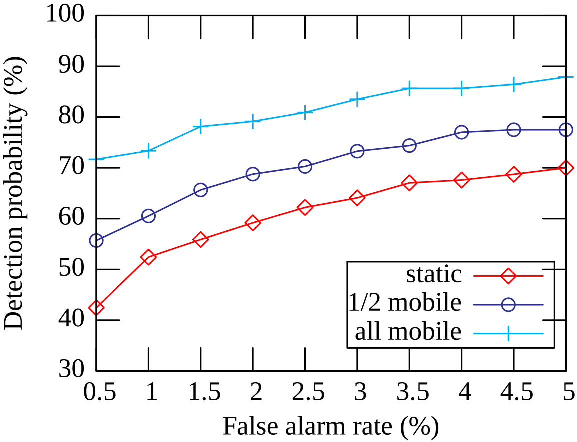
Simulation Settings

- Data: public dataset of DARPA SensIT experiment
- Targets: Amphibious Assault Vehicles (AAVs)
- Sensors are randomly deployed in a 50m×50m field



Impact of The Number of Mobile Sensors

- Total 12 sensors
- 10% to 35% performance improvement by 6 mobile sensors



Conclusions

- Propose a two-phase detection approach
  - Reactive mobility
  - Collaboration between static and mobile sensors
- Develop a near-optimal movement scheduling algorithm
- Provide insights into detection system design
  - Efficient movement schedule of a small number of mobile sensors significantly boost the detection performance

Thanks!