Impact of Data Fusion on Real-Time Detection in Sensor Networks

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Outline

1. **Motivation**
   Limitations of current studies on coverage & delay
2. Problem Definition
   α-delay under disc and fusion models
3. Scaling laws of Network Density for Instant Detection
   Disc model *vs.* data fusion model
4. Simulations

Mission-critical Sensing Applications

SensIT @ UW
75 WINS nodes detect AAV
[Duarte 2004]

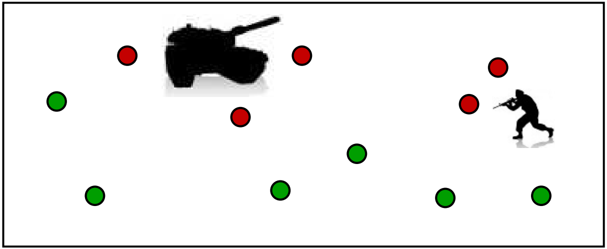
VigilNet @ UV
scale to 1000 motes
http://www.cs.virginia.edu/wsn/vigilnet/

- Resource-constrained sensor nodes
- Large spatial deployment region
- Stringent performance requirements
    - Short detection delay, e.g., 5 seconds
    - Low false alarm rate, e.g., 1%

Target Detection Delay

- Fundamental metric of real-time surveillance apps
  - Timeliness of the system
  - **Instant detection**: any target is detected once it appears

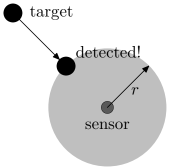
- Network density to achieve instant detection
  - Critical cost metric
  - Reducing deployment cost
  - Extending network lifetime



State of the Art

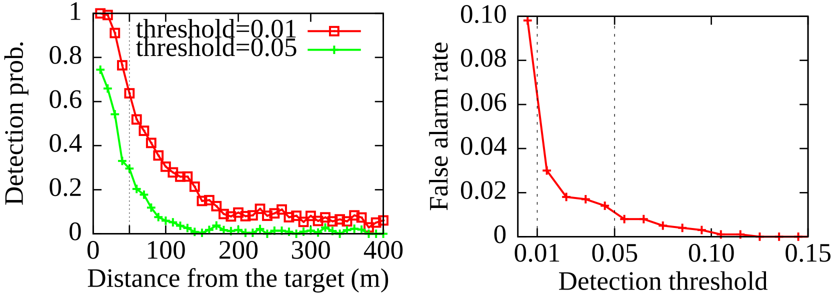
- Numerous studies on coverage and detection delay
- Most existing results are based on simplistic models
  - The (in)famous disc model
  - Ignore sensing uncertainties and sensor collaboration
- Collaborative signal processing theories
  - Focus on small-scale networks
  - Make performance analysis difficult
- Our recent work [mobicom09] on sensing coverage
  - Accounts for stochastic nature of sensing
  - Exploits sensor collaboration

Sensing Model



- The (in)famous disc model
  - Any target within *r* is detected
  - Deterministic and independent sensing

- Real-world target detection
  - Probabilistic, no cookie-cutter like “sensing range”!



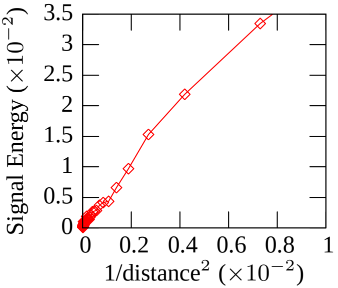
Real acoustic vehicle detection experiment [Duarte 2004]

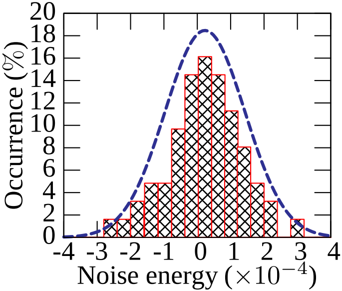
Sensor Measurement Model

- Reading of sensor i is $y_i = s_i + n_i$
- Decayed target signal energy

$$s_i = \frac{S}{1 + x^2} \tag{1}$$

- Gaussian noise: $n_i \sim \mathcal{N}(\mu, \sigma^2)$
- Signal-to-noise ratio $\mathrm{SNR} = S/\sigma$





Real acoustic vehicle detection experiment [Duarte 2004]

Data Fusion Model

- Sensors within R meters from target fuse their readings
    - R: fusion range
- Detection decision is made by

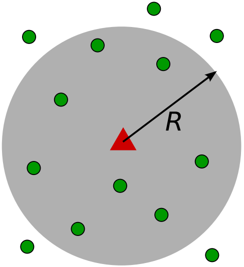
$$\sum_i y_i \underset{0}{\overset{1}{\gtrless}} \eta$$

- False alarm rate

$$P_F = Q\left(\frac{\eta - N \cdot \mu}{\sqrt{N} \cdot \sigma}\right)$$

- Detection prob.

$$P_D = Q\left(\frac{\eta - N \cdot \mu - \sum s_i}{\sqrt{N} \cdot \sigma}\right)$$



● sensor
▲ target

- N: # of sensors in fusion range
- $Q(\cdot)$: the Q-function of $\mathcal{N}(0,1)$
- s_i: target signal at sensor i

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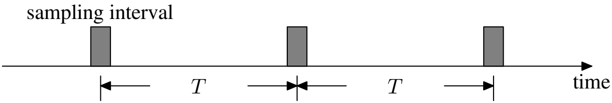
Network Model

- Random network deployment
  - 2-D Poisson process of density ρ
- Target moves freely in the deployment region
- Each sensor detects target every T seconds
  - T: detection period
  - Detection in each period is probabilistic



Temporal view of a sensor's operation

Definition of α-delay

- Fundamental trade-off between P_F and P_D

$$P_D = 20\%,\, P_F = 1\%$$
$$P_D = 50\%,\, P_F = 10\%$$

- Detection delay is closely related to P_D

$$P_D = 20\%,\text{ average delay} = \frac{1}{P_D} = 5,\, P_F = 1\%$$
$$P_D = 50\%,\text{ average delay} = \frac{1}{P_D} = 2,\, P_F = 10\%$$

- α-delay is the average # of detection periods before a target is first detected subject to system $P_F \leq \alpha$
  - Instant detection: α-delay $\rightarrow 1$

α-delay under Disc Model

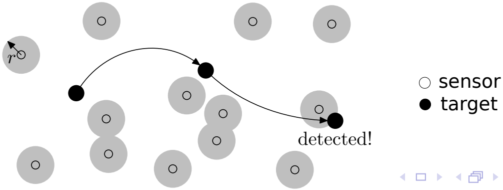
- Choose sensing range r such that
  - The sensor's $P_F \leq \alpha$
  - Any target covered by the sensor is detected with $P_D \geq \beta$

$$r = \sqrt{\frac{\mathrm{SNR}}{Q^{-1}(\alpha) - Q^{-1}(\beta)} - 1} \tag{2}$$

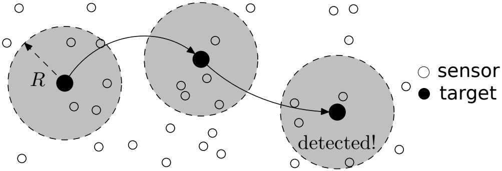
  - β: constant close to 1, deterministic nature of disc model

- α-delay (based on [Liu 2004])

$$\tau = \frac{1}{1 - \mathrm{e}^{-\rho\pi r^2}} \tag{3}$$



α-delay under Fusion Model



- α-delay:

$$\tau = \frac{1}{\mathbb{E}[P_D]} \tag{4}$$

  - P_D: the system detection prob. in any detection period

$$P_D = f(\alpha, \mathrm{SNR}, N), \quad N \sim \mathrm{Poi}(\rho \pi R^2)$$

  - Numerically computed

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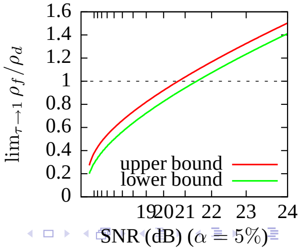
Disc Model *vs.* Fusion Model

- ρ_d and ρ_f: network densities under disc and fusion models
- Tight bound

$$\lim_{\alpha\text{-delay}\to 1} \frac{\rho_f}{\rho_d} = \Theta\left(\frac{\text{SNR}}{Q^{-1}(\alpha)}\right) \tag{5}$$

  - ρ_f/ρ_d decreases if α decreases
    data fusion reduces false alarms
  - ρ_f/ρ_d increases with SNR
    disc model is suitable for high-SNR detections

- $\rho_f < \rho_d$ if $\text{SNR} < 20\,\text{dB}$
  - $\text{SNR} \leq 17\,\text{dB}$ for low-cost sensors (MICA2, ExScal, ...)
  - data fusion is suitable



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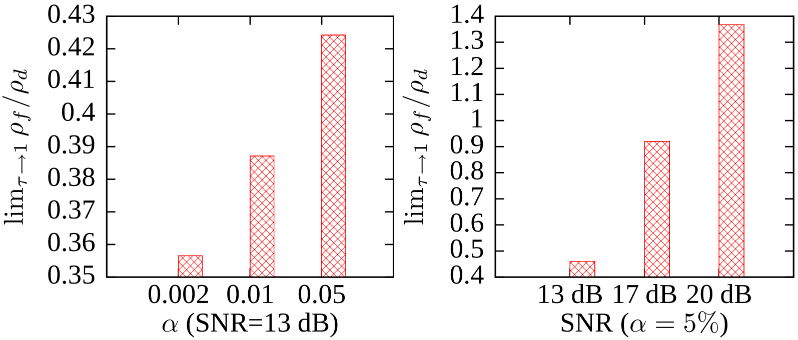
Simulations on Synthetic Data

- Target moves straightly in the network
- Fusion range $R = 25\,\mathrm{m}$

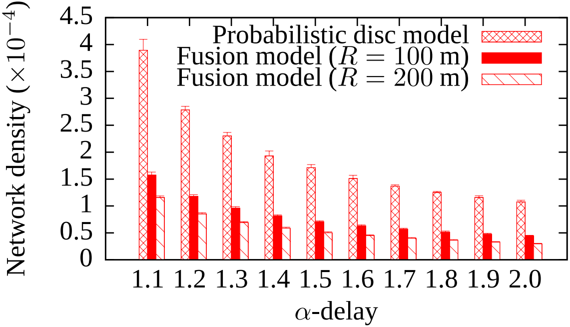


- ρ_f/ρ_d increases with α
- $\rho_d = 2\rho_f$ if $\alpha = 5\%$

- ρ_f/ρ_d increases with SNR
- $\rho_d = 2\rho_f$ if SNR $= 13\,\mathrm{dB}$

Trace-driven Simulations

- Data traces collected from 75 acoustic sensors in vehicle detection experiments [Duarte 2004]
  - $\alpha = 5\%$



Disc model requires twice sensors

Conclusions

- Reveal limitations of current theoretical results
  - Only applicable for high-SNR scenarios
  - Disc model underestimates the achievable detection performance
- Provide insights into the design of fusion-based networks
  - Data fusion significantly reduces detection delay and false alarms
- First step toward bridging the gap between CSP and performance analysis of WSNs

Future Work

- Extensions
    - General signal decay model
    - Regular deployment
    - Decision fusion model
- Deployment algorithms for fusion-based networks