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

Rui Tan¹, Guoliang Xing², Benyuan Liu³, Jianping Wang¹

¹ City University of Hong Kong
² Michigan State University
³ University of Massachusetts Lowell
Outline

1. Motivation
   Limitations of current studies on coverage & delay

2. Problem Definition
   $\alpha$-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/wns/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

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

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

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

\[
\sum_{i} y_i \geq \eta
\]

- False alarm rate

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

- Detection prob.

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

- $N$: # 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 $\rho$

- 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 $\alpha$-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 $P_D$

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

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

\[
r = \sqrt{\frac{\text{SNR}}{Q^{-1}(\alpha) - Q^{-1}(\beta)} - 1}
\] (2)

- \( \beta \): constant close to 1, deterministic nature of disc model

- \( \alpha \)-delay (based on [Liu 2004])

\[
\tau = \frac{1}{1 - e^{-\rho \pi r^2}}
\] (3)
\(\alpha\)-delay under Fusion Model

\(\alpha\)-delay:

\[ \tau = \frac{1}{\mathbb{E}[P_D]} \]  \hspace{1cm} (4)

- \(P_D\): the system detection prob. in any detection period
  
  \[ P_D = f(\alpha, \text{SNR}, N), \quad N \sim \text{Poi}(\rho \pi R^2) \]

- Numerically computed
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Disc Model vs. Fusion Model

- $\rho_d$ and $\rho_f$: network densities under disc and fusion models
- Tight bound

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

- $\rho_f/\rho_d$ decreases if $\alpha$ decreases
  
  data fusion reduces false alarms

- $\rho_f/\rho_d$ increases with SNR
  disc model is suitable for high-SNR detections

- $\rho_f < \rho_d$ if SNR < 20 dB
  - SNR $\leq$ 17 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 $R = 25\text{ m}$

Graphs showing:

- $\lim_{\tau \to 1} \rho_f / \rho_d$ increases with $\alpha$
  - $\rho_d = 2\rho_f$ if $\alpha = 5\%$

- $\lim_{\tau \to 1} \rho_f / \rho_d$ increases with SNR
  - $\rho_d = 2\rho_f$ if SNR = 13 dB
Trace-driven Simulations

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

![Graph showing network density vs. $\alpha$-delay with two models: probabilistic disc model and fusion model (R = 100 m and 200 m). The disc model requires twice the sensors compared to the fusion models.](image-url)
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