Analysis of Quality of Surveillance in Fusion-based Sensor Networks

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Outline

- **Motivation**
  Limitations of current studies on coverage & delay

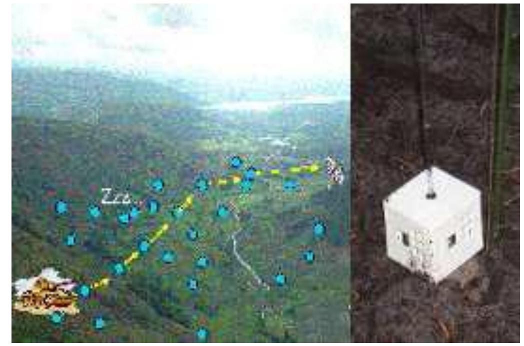
- Problem Definition
  α-delay under disc and fusion models

- Scaling Laws of Network Densities for Instant Detection
  Disc model vs. data fusion model

- Evaluation

Mission-critical Sensing Applications

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



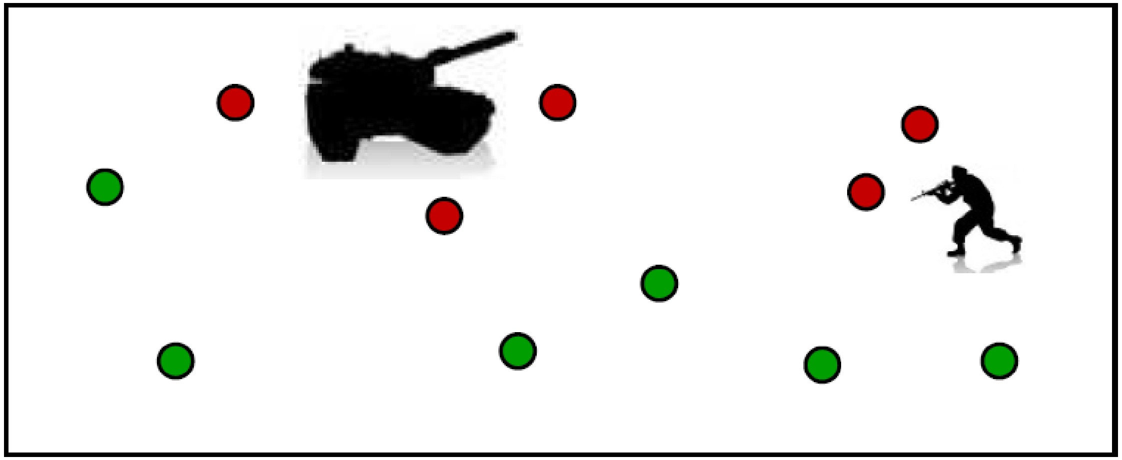
VigilNet @ UV
scale to 1000 motes
http://www.cs.virginia.edu/wsn/vigilnet/

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

Target Detection Delay

- Fundamental metric of real-time surveillance applications
  - 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



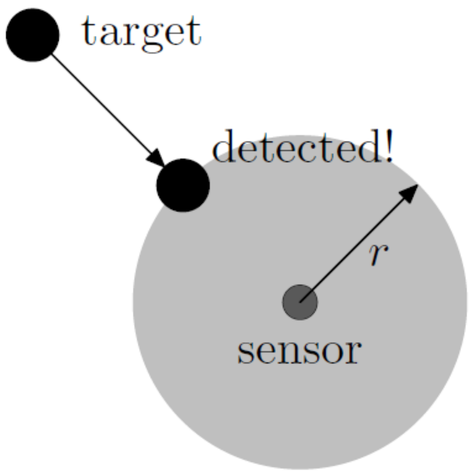
State of the Art

- 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 accounts for stochastic sensing and sensor collaboration
  - MobiCom'09: sensing coverage
  - **RTSS'09: detection delay**

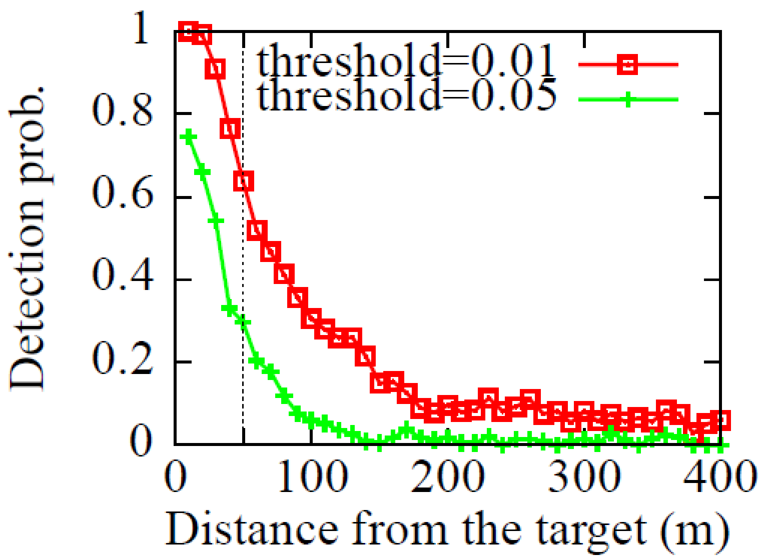
Extensions

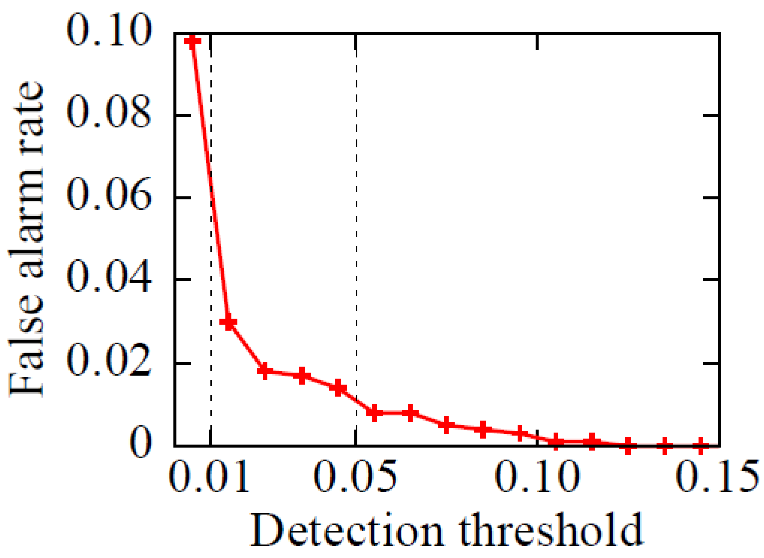
	RTSS'09	This work
Signal decay	A specific inverse-square law acoustic signal in open space	A general power-decay law acoustic, seismic, electromagnetic signals
Target speed	High	Arbitrary

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 $\boldsymbol{y}_i = \boldsymbol{s}_i + \boldsymbol{n}_i$

- Signal follows power-law decay

decay function

$$\boldsymbol{s}_i = \boldsymbol{S} \cdot \boldsymbol{w}(\boldsymbol{x}), \quad \boldsymbol{w}(\boldsymbol{x}) = \Theta(\boldsymbol{x}^{-\boldsymbol{k}})$$

  – Path loss exponent ***k*** is from 2 to 5

- Gaussian noise: $\boldsymbol{n}_i \sim \boldsymbol{N}(\mu, \sigma^2)$

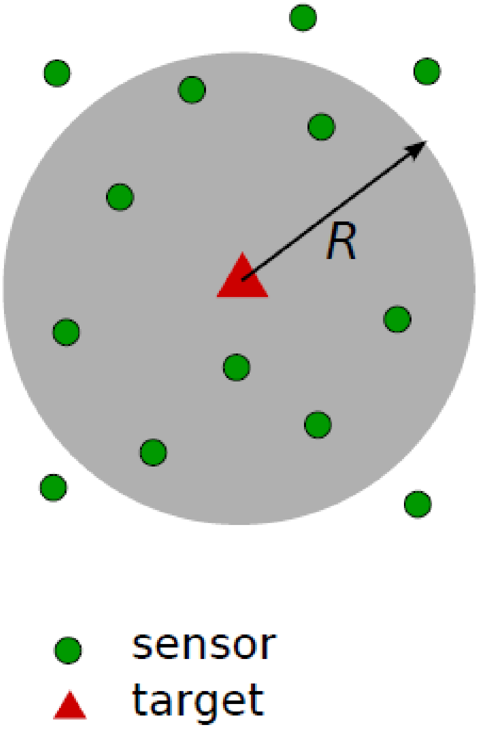
- Signal-to-noise ratio $\mathrm{SNR} = \boldsymbol{S} / \sigma$

Data Fusion Model

- Sensors within ***R*** meters from target fuse their readings
  - ***R***: fusion range

- Detection decision is made by

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



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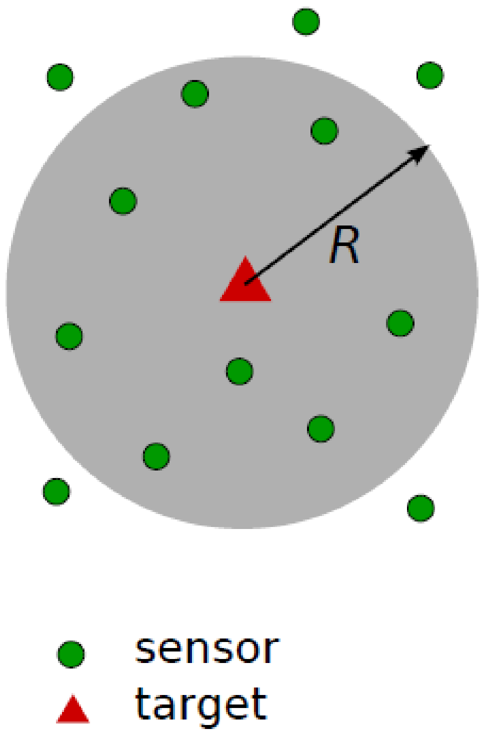
- False alarm rate

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

- Detection probability

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



- ***N***: # of sensors in fusion range
- ***Q*(*x*)**: Q-function of ***N*(0,1)**
- s_i: target signal at sensor ***i***

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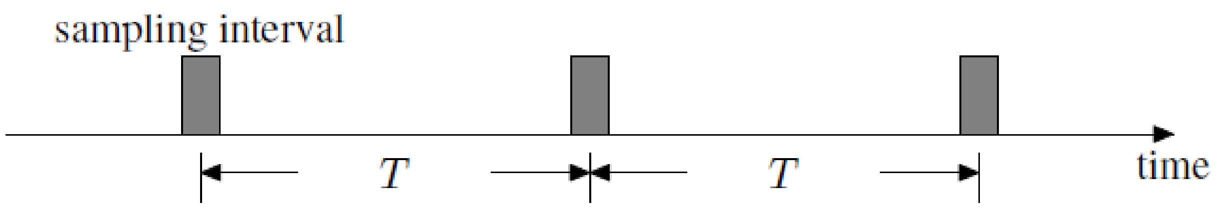
Network Model

- Random network deployment
  - 2D 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

$P_D = 20\%$, average delay = $1/P_D = 5$, $P_F = 1\%$
$P_D = 50\%$, average delay = $1/P_D = 2$, $P_F = 10\%$

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

α-delay under Disc Model

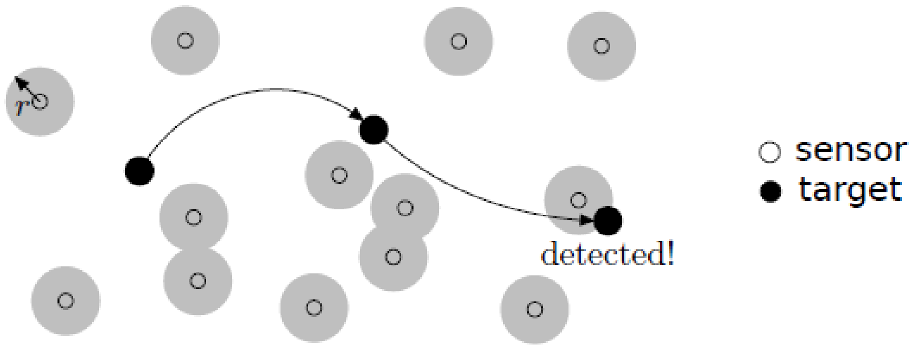
- Choose sensing range ***r*** such that
  - The sensor's $P_F < \alpha$
  - Any covered target is detected with $P_D > \beta$

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

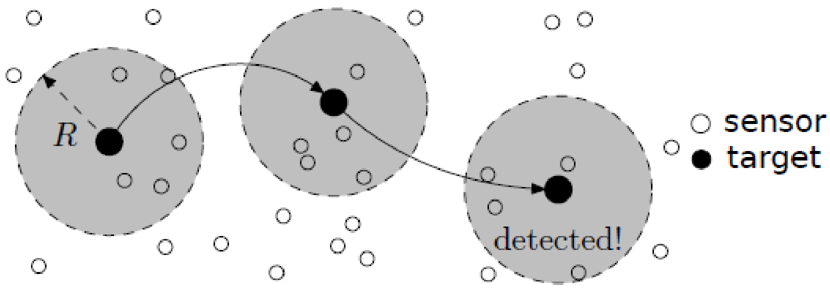
  - **β**: constant close to 1, deterministic nature of disc model

- **α**-delay (based on [Liu 2004])

$$\tau \geq \frac{1}{1 - \exp(-\rho \pi r^2)}$$

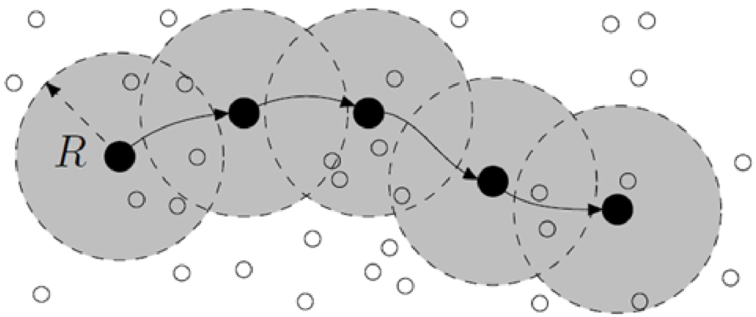


α-delay under Fusion Model



RTSS'09: fusion ranges do not overlap
- Target speed is high enough
- Detection period is long enough

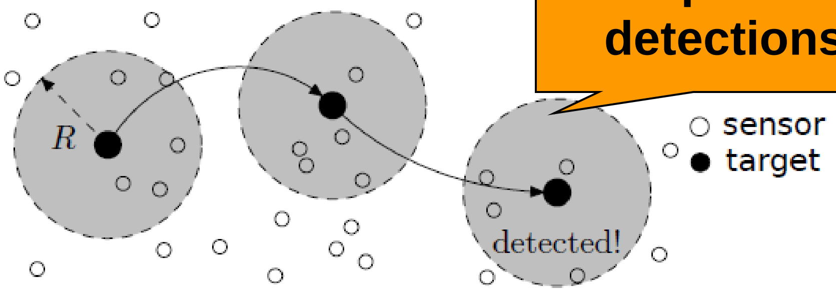
$$\tau = \frac{1}{\boldsymbol{E}[\boldsymbol{P}_D]}$$



Extension: fusion ranges may overlap
- Target speed is low
- Detection period is short

α-delay under Fusion Model

independent detections



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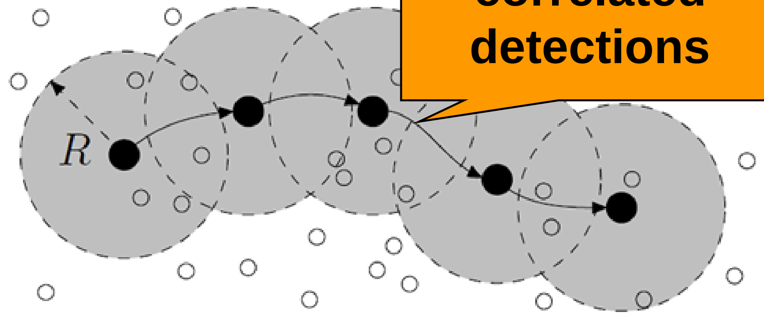

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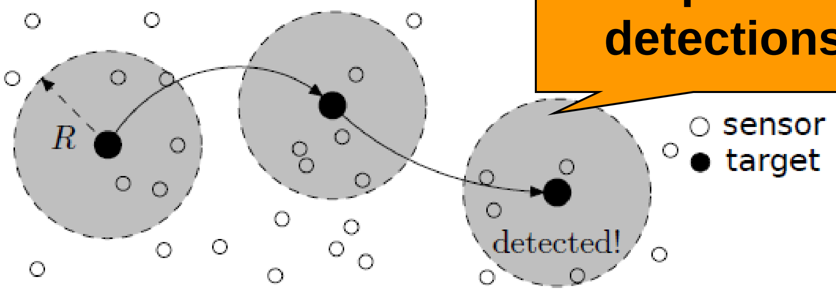

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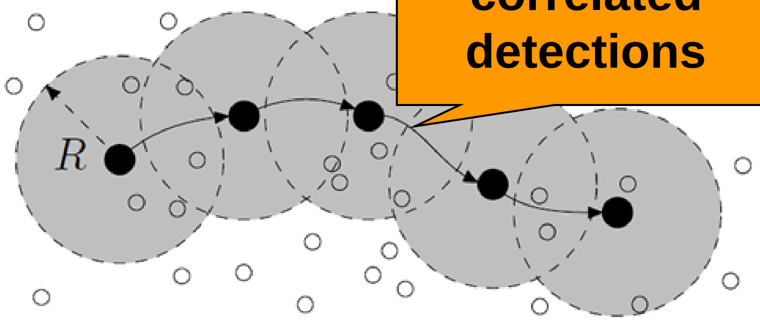

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$$\tau \le \boldsymbol{E}\left[\frac{1}{\boldsymbol{P_D}}\right]$$

- $\boldsymbol{P_D}$: the system detection prob. in any detection period

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

- Numerically computed

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Disc Model vs. Fusion Model

- $\boldsymbol{\rho_d}$ & $\boldsymbol{\rho_f}$: network densities under disc and fusion models
- Upper bound of density ratio

$$\lim_{\alpha\text{-delay}\to 1} \frac{\rho_f}{\rho_d} = O\left(\left(\frac{SNR}{Q^{-1}(\alpha)}\right)^{2/k}\right)$$

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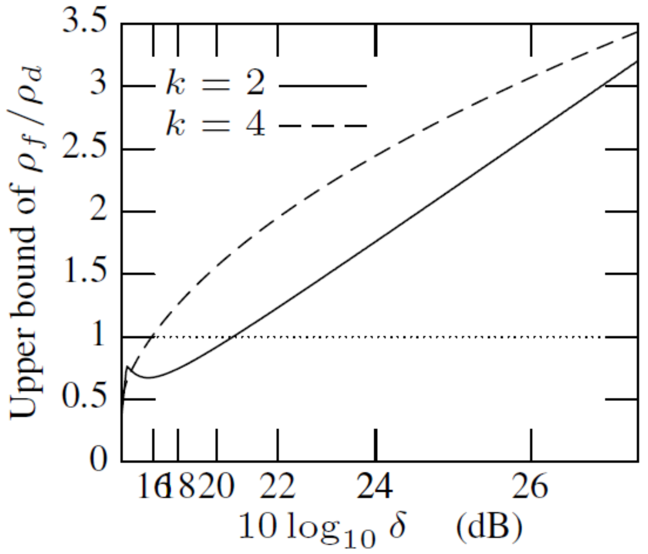
$\rho_f < \rho_d$ is SNR < 17dB

- SNR < 17dB for low-cost sensors (MICA2, ExScal, …)
- Data fusion is suitable



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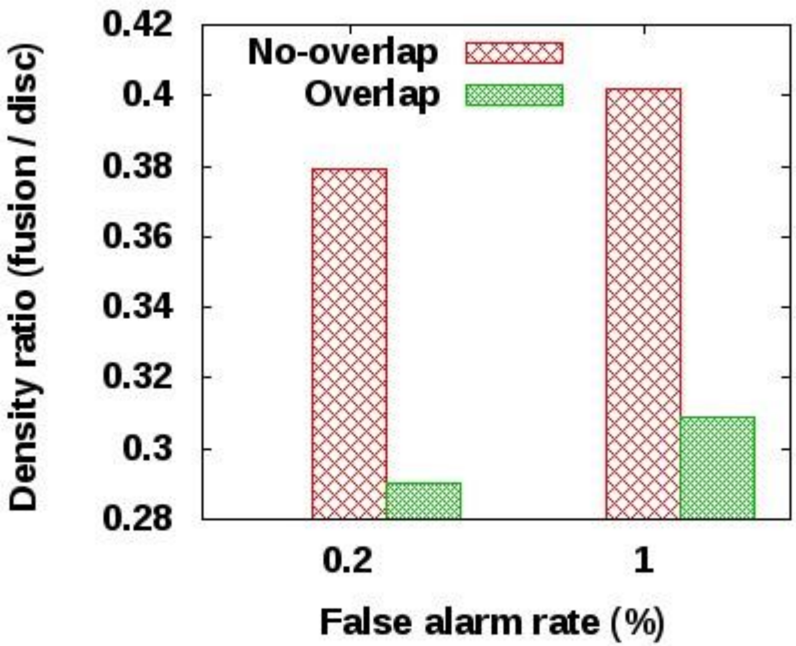
Simulations

- Target moves straightly in the network
- Fusion range = 25 m



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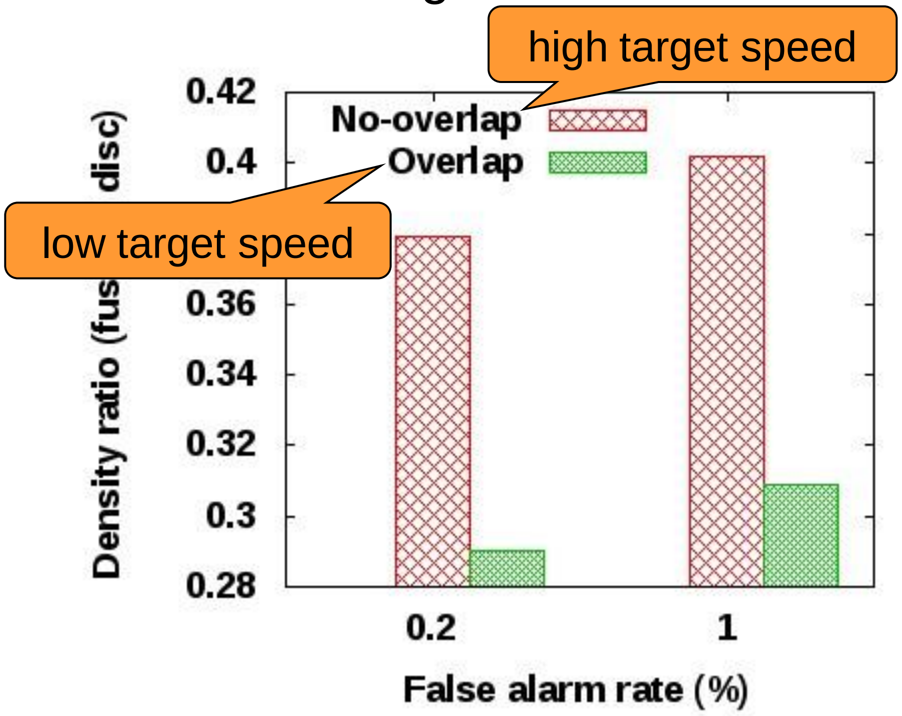

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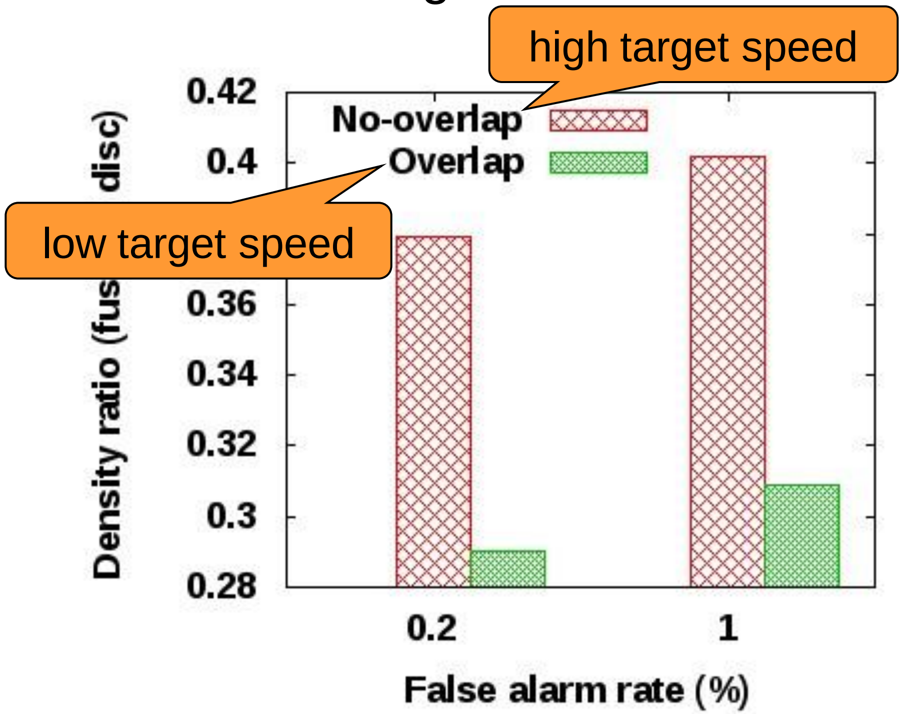

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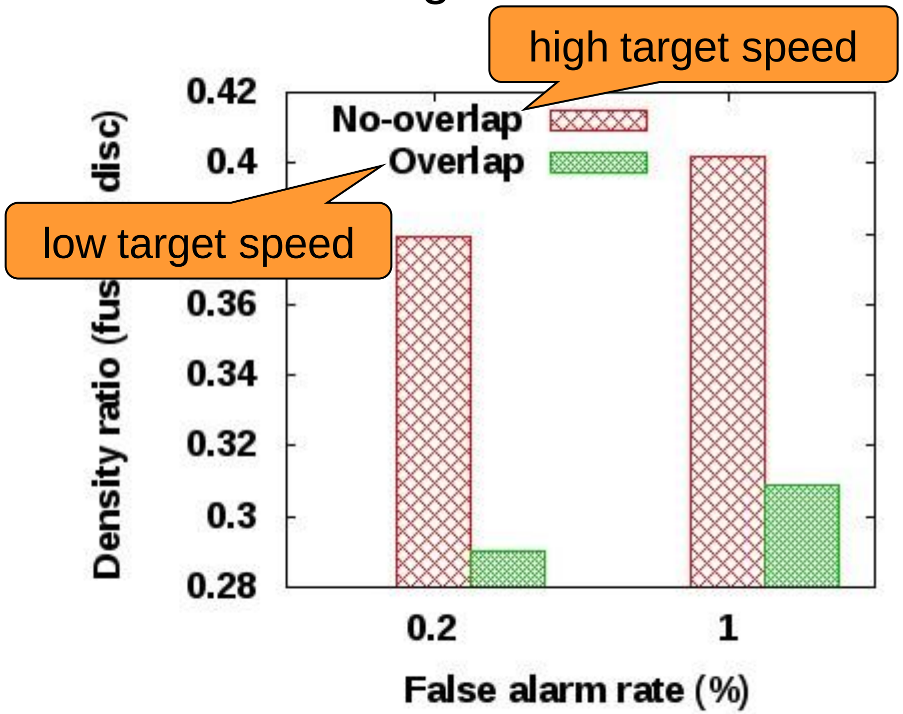

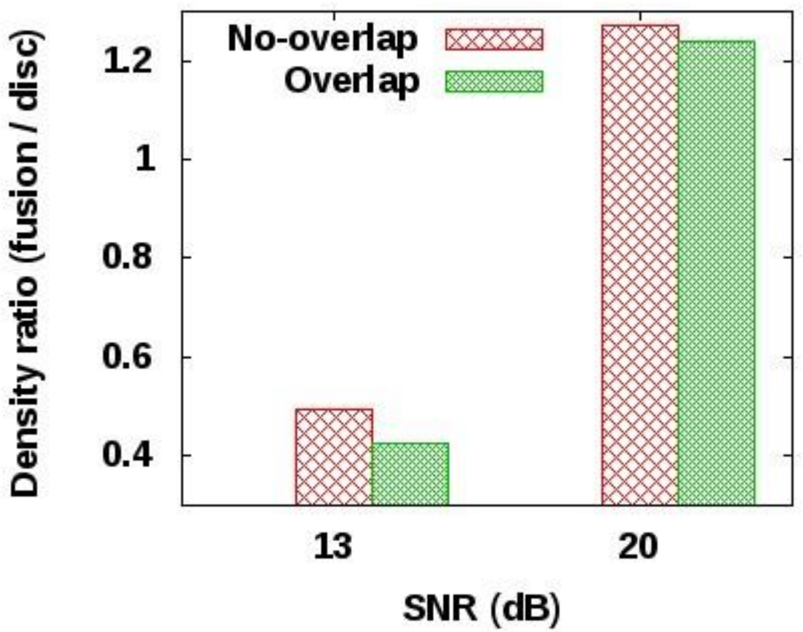

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- Density ratio increases with SNR
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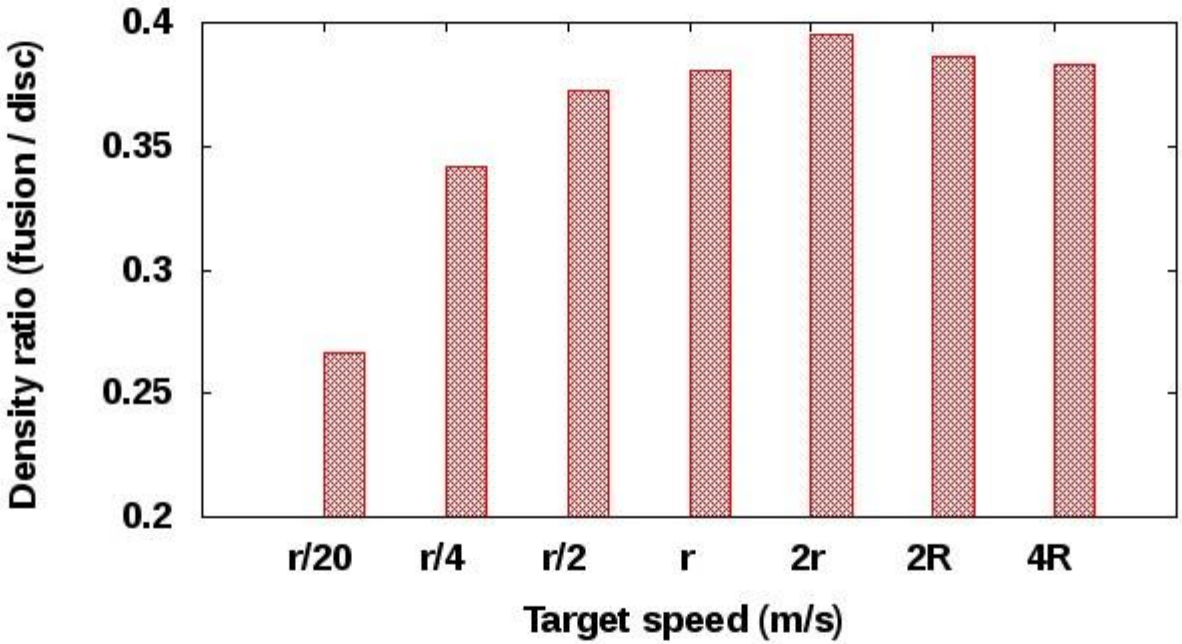
Simulations (cont'd)



- Target speed
  - An important factor of the overlap/no-overlap condition
- Fusion model is more robust in detecting slowly moving targets

Conclusions

- Significant extensions to our previous work
- 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 network
  - Data fusion reduces detection delay and false alarms
  - Data fusion is robust in detecting slowly moving targets