# Probabilistic Coverage for Object Tracking in Sensor Networks

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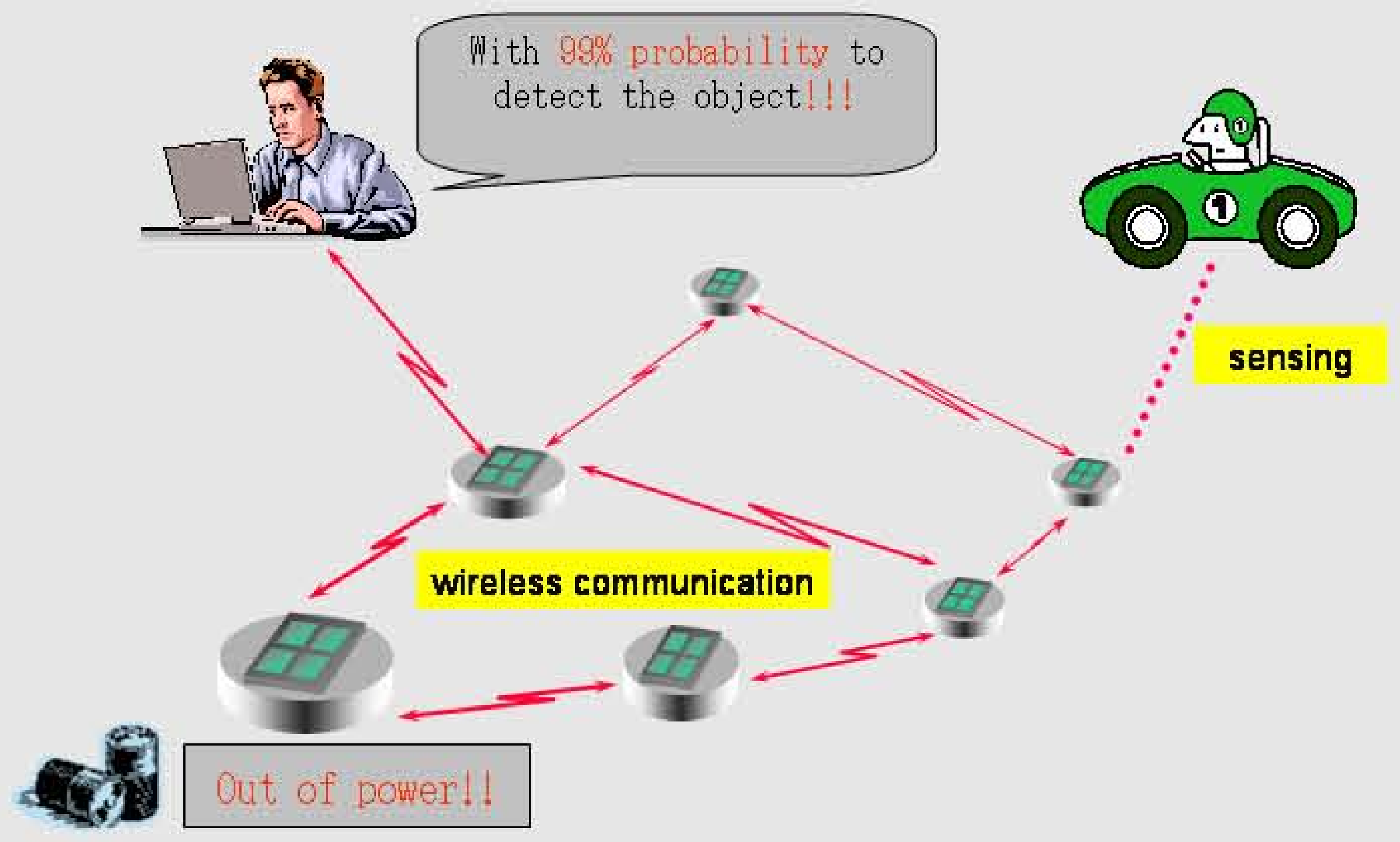
## Motivation

- The object-tracking quality and system lifetime are two conflicting aspects of a sensor network.
- Full coverage is too expensive to support long-time monitoring applications.
- Probabilistic coverage is a more appropriate approach, in which any point in a sensing field is sensed with a certain probability at any time.

## Problem Statement

Given an object-tracking quality requirement, such as the detection probability, how can we schedule sensors at the same time to extend the system lifetime?



## Objective

To quantify the object-tracking quality under given sensing schedules and to guide new protocol design.

## Model Assumption

- Nodes are randomly and independently deployed on a square field;
- An object travels across the field with a constant speed along a straight line.

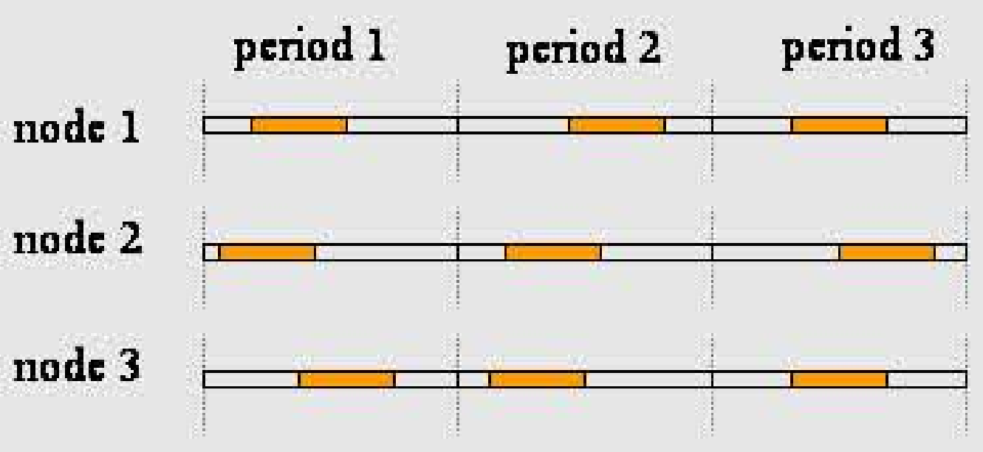
| notation | meaning |
|---|---|
| $d$ | density of sensors |
| $R$ | sensing radius of a sensor |
| $v$ | constant velocity of a motion object |
| $P$ | sensing period of sensors |
| $f$ | active ratio of sensors in P |
| $t_a$ | observation interval |

## Object-Tracking Quality Metrics

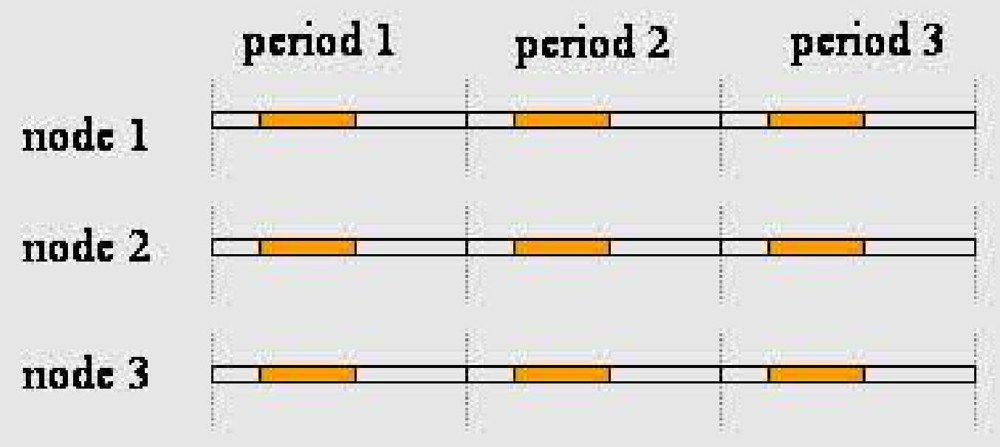
- Detection Probability (*DP*): the expected probability the object being detected in a given observation interval.
- Stealth Distance (*SD*): the average distance the object travelled before it is detected for the first time.
- System Lifetime: the working duration of the system when satisfying the required object-tracking quality.

## Random Sensing Schedule and Synchronized Sensing Schedule

In random schedules, the quality requirement uniquely decide the system lifetime.



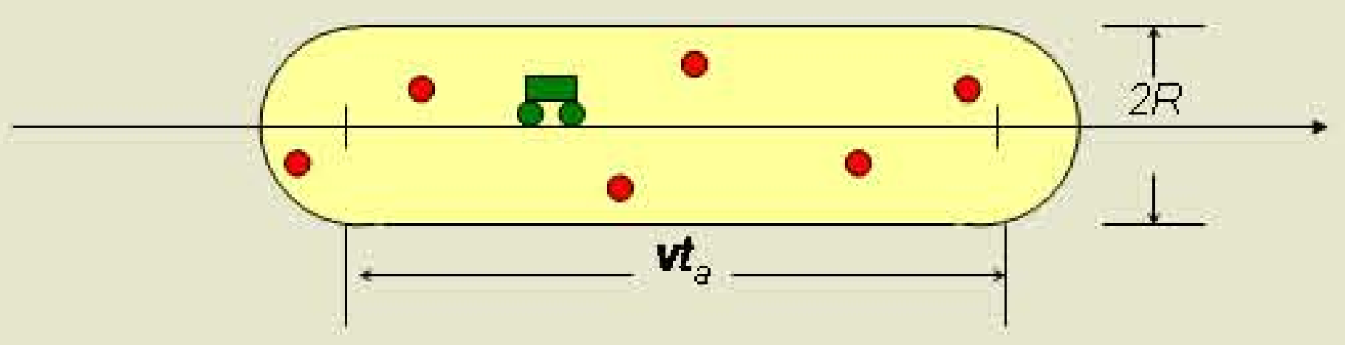
Random Sensing Schedule



Synchronized Sensing Schedule

## Random Schedule Analysis

- For a specific sensor to detect the motion object, two conditions must be satisfied:
  - The sensor must be in a specific oblong area called active area;
  - The sensor is active when the object sweeps through its sensing range.



- The detection probability of one single sensor is the integral of the detection probability at a specific point over the whole active area.
- The DP is an exponential function of the detection probability of a single node: $DP = 1 - e^{-\lambda \tilde{P}r}$, where $\tilde{P}r = f + \frac{\pi R^2 t_a}{(vt_a \cdot 2R + \pi R^2)P}$ for fast objects.
- The SD is the integral of the DP over the positive time domain.

## Comparison of Two Random Schedules

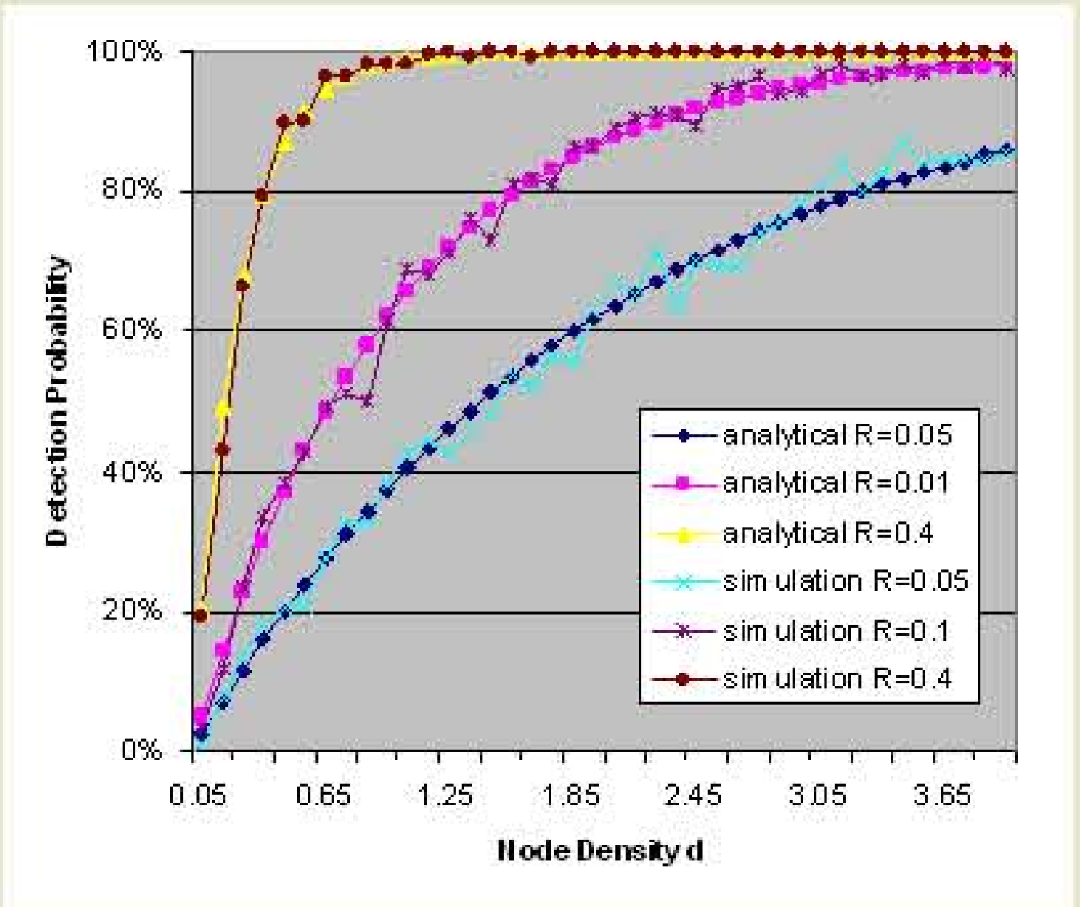
- In uniform schedule, all nodes sense with the same sensing period *P*.
- In set-based schedule, nodes are equally divided into *k* sets and are scheduled with period *P/k* in a rotating fashion.

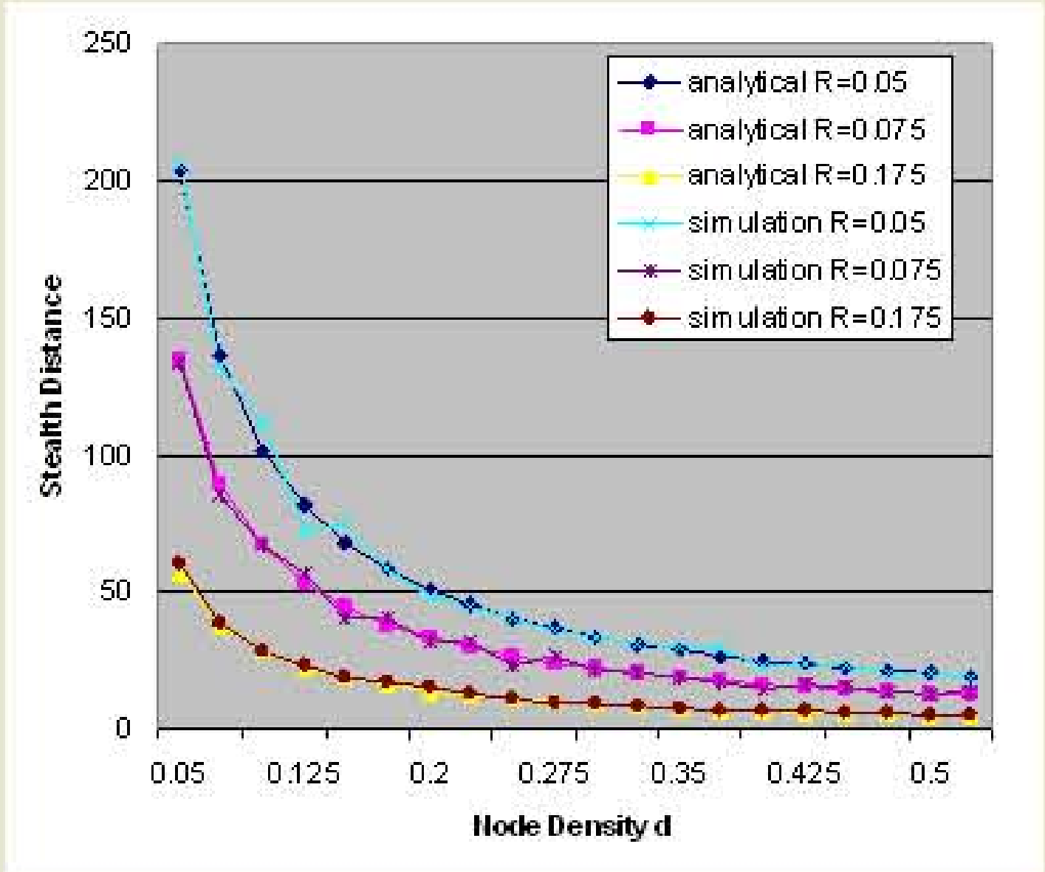
We proved that these two schedules have the same DP and SD for fast objects.

## Synchronized Schedule Analysis

In this case, DP is an exponential function of the node density and the expected detection probability of one single sensor.

## Analytical Results of Random Schedules





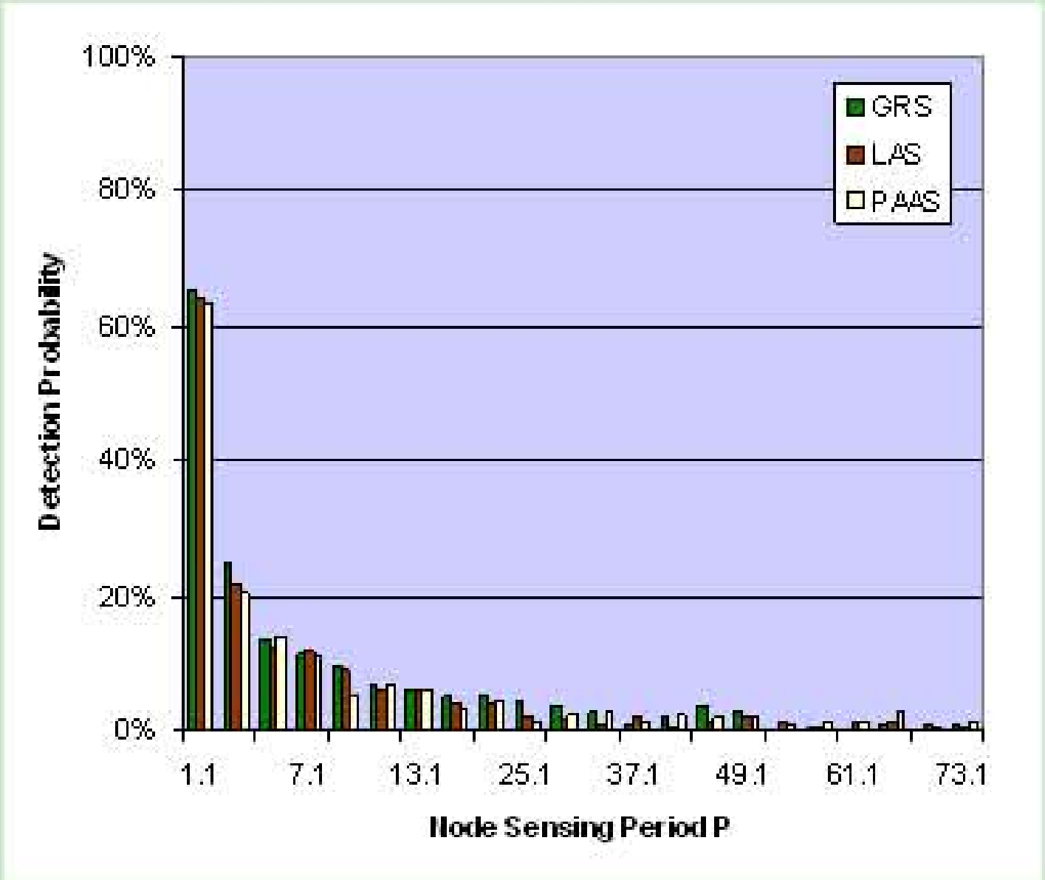
| | *DP* | *SD* |
|---|---|---|
| *d*↑ | ↑ | ↓ |
| *R*↑ | ↑ | ↓ |
| *v*↑ | ↑ | ↑ |
| *ta*↑ | ↑ | |
| *f*↑ | ↑ | ↓ |
| *P*↑ | ↓ | ↑ |

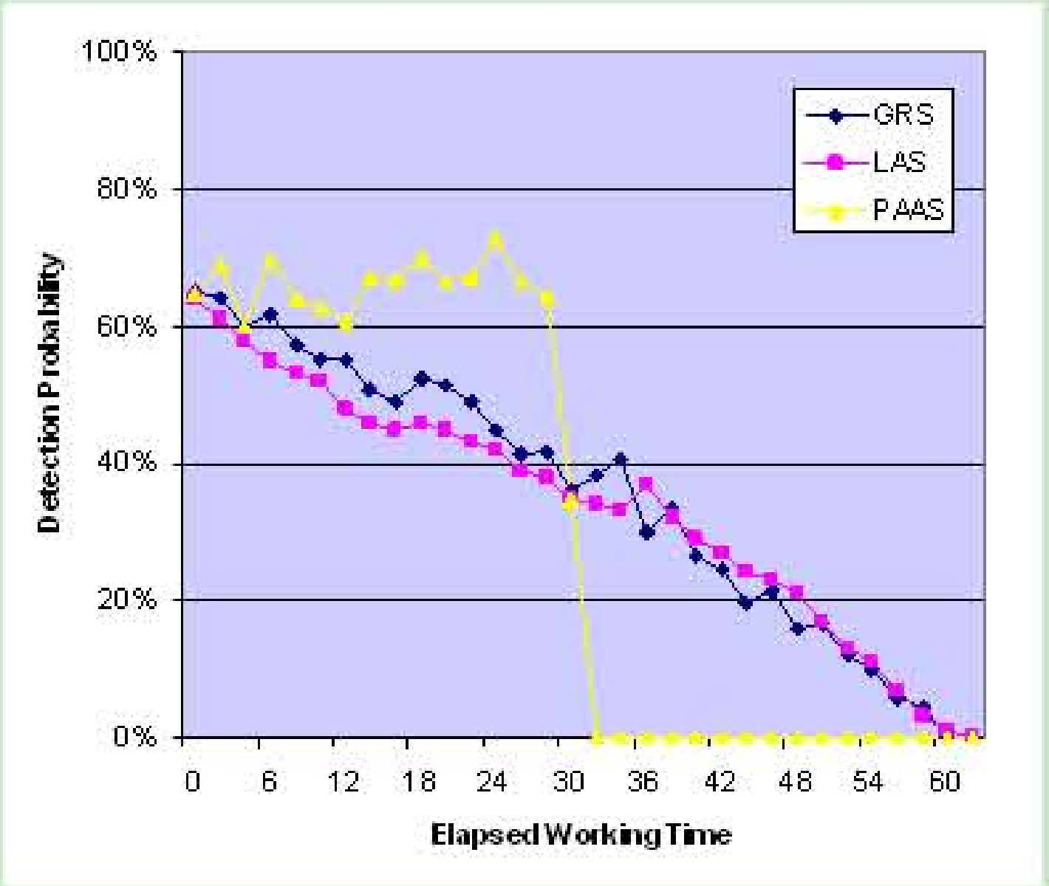
- The simulation results match the analytical curves well, which validates the correctness of our derivations.
- Random schedule outperforms synchronized schedule, but the latter has better performance of worst cases.
- SD increases linearly as the increase of P when fixing *d*.

## Design of Power Efficient Algorithms

- Global Random Schedule (GRS). Nodes sense the field with the maximum possible periods satisfying the object-tracking quality requirements.
- Localized Asynchronous Schedule (LAS). Nodes uses its local density to infer the maximum sensing periods to meet the object-tracking quality requirement.
- Power-Aware Asynchronous Schedule (PAAS). Nodes can sense with periods according to their remaining power and deplete their power simultaneously.

## Protocol Evaluation





- GRS, LAS, and PAAS can achieve the same *DP* at the beginning.
- PAAS have a longer working time than GRS and LAS.
- After the system lifetime, the *DP* in PAAS directly drops to 0. By contrast, GRS and LAS can still provide an exponentially-degraded *DP*.

## Contributions of Our Work

- Our work is one of the earliest to quantify the object-tracking quality of random schedule and synchronized schedule under given assumptions.
- Our model can give solid and thorough understanding about various protocols.
- Many protocols can be incorporated into our model by approximating parameters.
- Our model can direct new protocol design.