WIRELESS SENSOR NETWORKS
(18MCA55E)
UNIT – I
"Introduction, Canonical Problems"

FACULTY:

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WIRELESS SENSOR NETWORKS – (18MCA55E) SYLLABUS

UNIT I: Introduction: Unique Constraints and Challenges: Advantages of Sensor Networks: Energy advantage, Detection advantage. – Sensor Network Applications: Habitat monitoring, Tracking chemical plumes, Smart transportation. – Collaborative Processing – Key Definitions of Sensor Networks. **Canonical Problem:** Localization and Tracking: A Tracking Scenario – Problem Formulation: Sensing model, Collaborative localization, Bayesian state estimation. – Distributed Representation and Inference of States: Impact of choice of representation.

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UNIT II: Networking Sensors: Key Assumptions – Medium Access Control: The S-MAC Protocol, IEEE 802.15.4 Standard and ZigBee. – General Issues – Geographic, Energy-Aware Routing: Unicast Geographic Routing, Routing on a Curve, Energy-Minimizing Broadcast. Energy-Aware Routing to a Region. Attribute-Based Routing: Directed Diffusion.

(Chapter: 3)

UNIT III: Infrastructure Establishment: Topology Control – Clustering – Time Synchronization: Clocks and Communication Delays, Interval Methods, Reference Broadcasts. – Localization and Localization Services: Ranging Techniques, Range Based Localization Algorithms, Other Localization Algorithms, Location Services.

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UNIT IV: Sensor Network Databases: Sensor Database Challenges – Querying the Physical Environment – Query Interfaces: Cougar Sensor Database and Abstract Data Types, Probabilistic Queries. – High-Level Database Organization – In-Network Aggregation: Query Propagation and Aggregation, TinyDB query processing, Query processing scheduling and optimization. – Data-Centric Storage – Data Indices and Range Queries: One-Dimensional indices, Multidimensional Indices for Orthogonal Range Searching, Nonorthogonal Range Searching.

(Chapter: 6)

UNIT V: Sensor Network Platforms and Tools: Sensor Network Hardware: Berkeley motes. – Sensor Network Programming Challenges – Node-Level Software Platforms: Operating system: TinyOS, Imperative language: nesC, Dataflow style language: TinyGALS. – Node-Level Simulators: The ns-2 and its Sensor Network Extensions.

(Chapter: 7)

TEXT BOOKS:

1. "Wireless Sensor Networks: An Information Processing Approach", Feng Zhao and Leonidas Guibas, Morgan Kaufmann Publishers (An imprint of Elsevier), 2004.

REFERENCE BOOKS:

1. 1. "Wireless Sensor Networks: A Networking Perspective", Jun Zheng, Abbas Jemalipour, Wiley Publications 2014.
2. 2. "Fundamentals of Wireless Sensor Networks Theory and Practice", Waltenegus Dargie, Christian Poellabauer, Wiley Publications, 2013.

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  - Bayesian State Estimation
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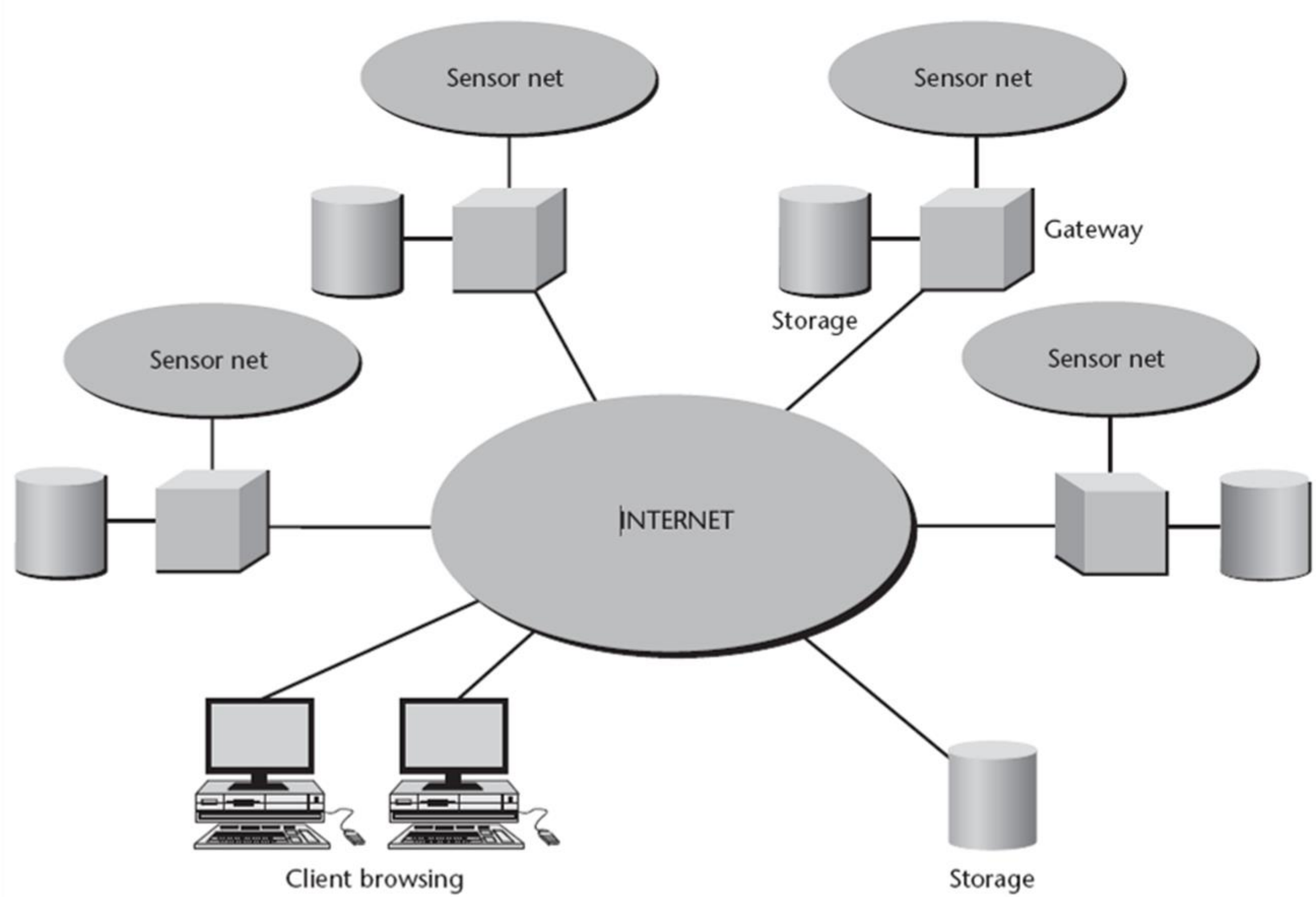
INTRODUCTION

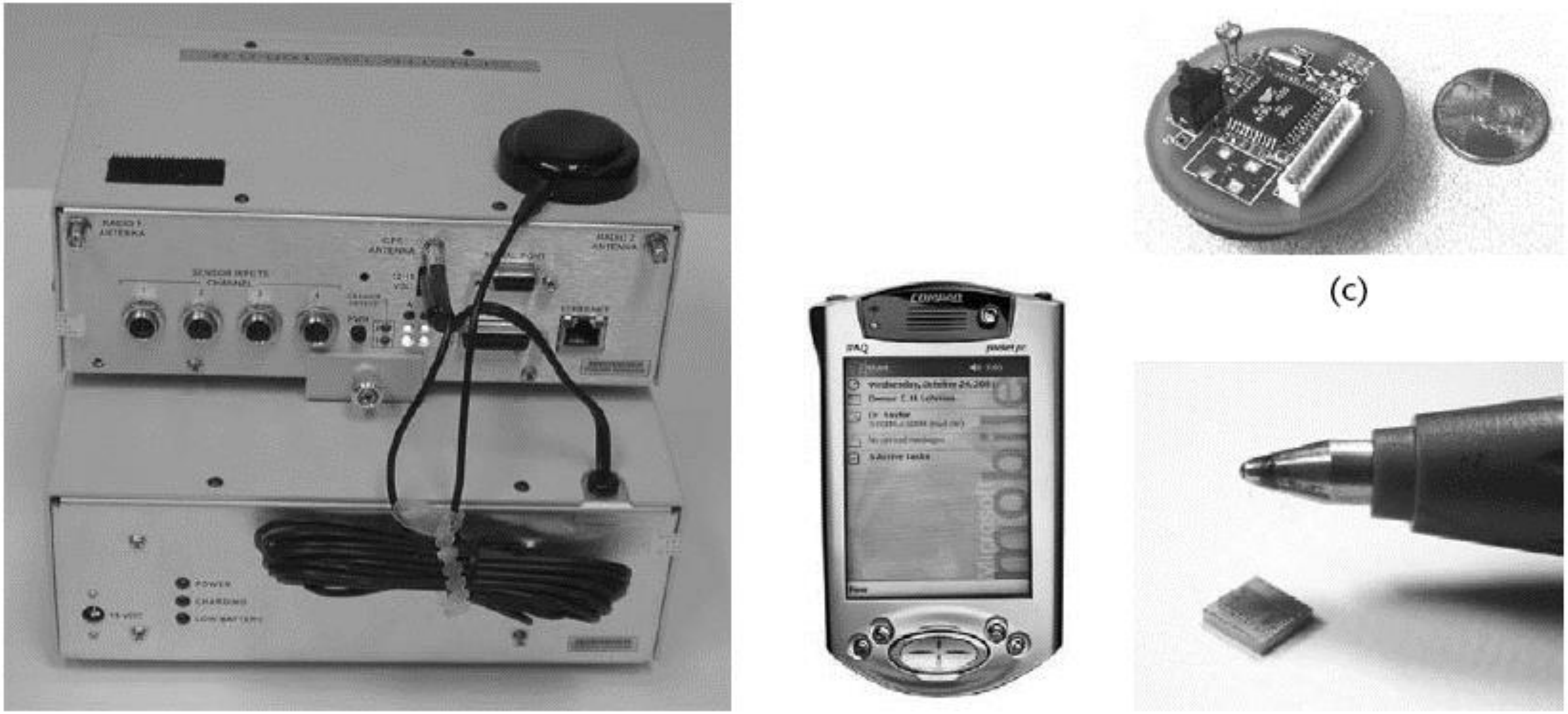
UNIQUE CONSTRAINTS AND CHALLENGES

- A centralized system, a sensor network is subject to a unique set of resource constraints such as finite on-board battery power and limited network communication bandwidth.
- In a typical sensor network, each sensor node operates untethered and has a microprocessor and a small amount of memory for signal processing and task scheduling.
- Each node is also equipped with one or more sensing devices such as acoustic microphone arrays, video or still cameras, infrared (IR), seismic, or magnetic sensors.

- Each sensor node communicates wirelessly with a few other local nodes within its radio communication range.
- Sensor networks extend the existing Internet deep into the physical environment.
- Information collected by and transmitted on a sensor network describes conditions of physical environments—for example, temperature, humidity, or vibration— and requires advanced query interfaces and search engines to effectively support user-level functions.



Sensor networks significantly expand the existing Internet into physical spaces. The data processing, storage, transport, querying, as well as the internetworking between the TCP/IP and sensor networks present a number of interesting research challenges that must be addressed from a multidisciplinary, cross-layer perspective.



(a) (b) (c) (d)

Figure 1.2 Samples of wireless sensor hardware: (a) Sensoria WINS NG 2.0 sensor node; (b) HP iPAQ with 802.11b and microphone; (c) Berkeley/Crossbow sensor mote, alongside a U.S. penny; (d) An early prototype of Smart Dust MEMS integrated sensor, being developed at UC Berkeley. (*Picture courtesy of Kris Pister and Jason Hill*).

Table 1.1 Comparison of the four sensor platforms shown in Figure 1.2.

	WINS NG 2.0 Node	iPAQ with 802.11 and A/D Cards in Sleeve	Berkeley MICA Mote*	Smart Dust**
Parts cost*** (quantity 1000+)	\$100s	\$100s	\$10s	<\$1
Size (cm^3)	5300	600	40	.002
Weight (g) (including battery)	5400	350	70	.002
Battery capacity (kJ)	300	35	15	(Less)
Sensors	Off-board	Microphone & light sensors integrated, others off-board	Integrated on PCB: Acceleration, temperature, light, sound	MEMS sensors to be integrated
Memory	32 MB RAM, 32 MB flash	64 MB RAM, 32 MB flash	4 KB RAM, 128 KB flash	(Less)
CPU	Hitachi SH4	StrongARM or XScale	ATmega 103L	(Less powerful)
Operating system	Linux	WinCE or Linux	TinyOS	(smaller)
Processing capability	400 MIPS/ 1.4 GFLOPS	240 MIPS	4 MIPS	(Less)
Radio range	100 m	100 m	30 m	(Shorter)

*The MICA mote is slightly larger than the WeC mote shown in Figure 1.2(c), and is more widely used.
**Smart Dust is not yet fully operational, but the size goal and power sources are known, and cost and weight are estimated.
***Note that the parts cost is based on large-quantity production.

- To summarize, the challenges we face in designing sensor network systems and applications include:
  - **Limited hardware:** Each node has limited processing, storage, and communication capabilities, and limited energy supply and bandwidth.
  - **Limited support for networking:** The network is peer-to-peer, with a mesh topology and dynamic, mobile, and unreliable connectivity. There are no universal routing protocols or central registry services. Each node acts both as a router and as an application host.
  - **Limited support for software development:** The tasks are typically real-time and massively distributed, involve dynamic collaboration among nodes, and must handle multiple competing events. Global properties can be specified only via local instructions. Because of the coupling between applications and system layers, the software architecture must be codesigned with the information processing architecture.

ADVANTAGES OF SENSOR NETWORKS

- Networked sensing offers unique advantages over traditional centralized approaches.
- Dense networks of distributed communicating sensors can improve signal-to-noise ratio (SNR) by reducing average distances from sensor to source of signal, or target.
- Increased energy efficiency in communications is enabled by the multihop topology of the network.
- A decentralized sensing system is inherently more robust against individual sensor node or link failures, because of redundancy in the network.

1) ENERGY ADVANTAGE

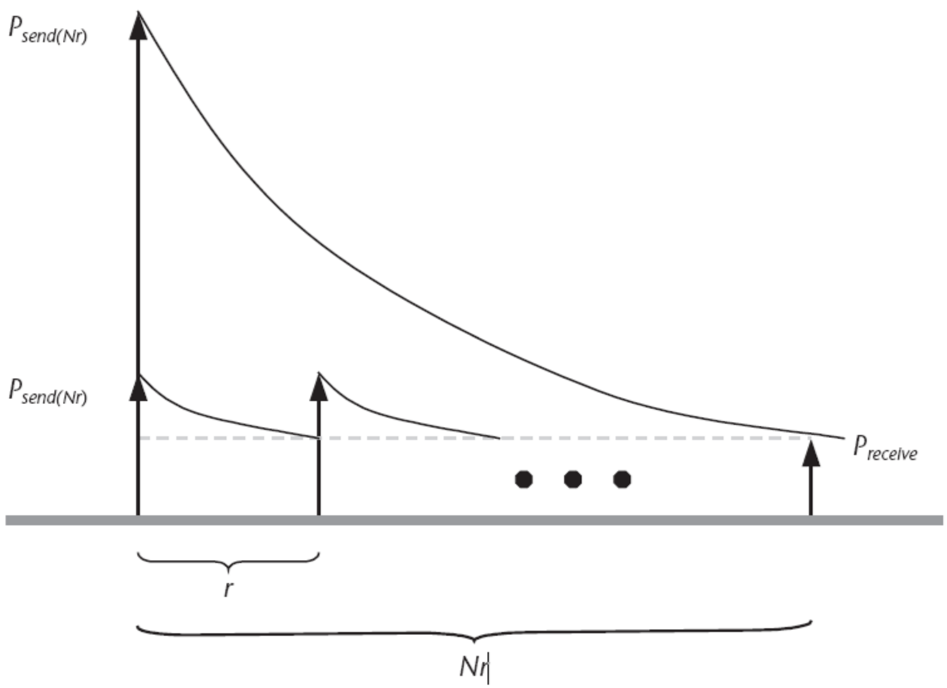
- Because of the unique attenuation characteristics of radio-frequency (RF) signals, a multihop RF network provides a significant energy saving over a single-hop network for the same distance.

$$P_{receive} \alpha \frac{P_{send}}{r^{\alpha}},$$

$$P_{send} \, \alpha \, r^{\alpha} P_{receive},$$

- Therefore, the power advantage of an N-hop transmission versus a Single-hop transmission over the same distance Nr is

$$\eta_{rf} = \frac{P_{send(Nr)}}{N.P_{send(r)}} = \frac{(Nr)^{\alpha} P_{receive}}{N.r^{\alpha} P_{receive}} = N^{\alpha-1}$$



The power advantage of using a multihop RF communication over a distance of Nr.

2. DETECTION ADVANTAGE

- Each sensor has a finite sensing range, determined by the noise floor at the sensor.
- A denser sensor field improves the odds of detecting a signal source within the range.
- Once a signal source is inside the sensing range of a sensor, further increasing the sensor density decreases the average distance from a sensor to the signal source, hence improving the signal-to-noise ratio (SNR).

power received at a distance r is

$$P_{receive} \propto \frac{P_{source}}{r^2},$$

which assumes an inverse distance squared attenuation. The SNR is given by

$$\mathrm{SNR}_r = 10\log\frac{P_{receive}}{P_{noise}} = 10\log P_{source} - 10\log P_{noise} - 20\log r.$$

Increasing the sensor density by a factor of k reduces the average distance to a target by a factor of $\frac{1}{\sqrt{k}}$. Thus, the SNR advantage of the denser sensor network is

$$\eta_{snr} = \mathrm{SNR}_{\frac{r}{\sqrt{k}}} - \mathrm{SNR}_r = 20\log\frac{r}{\frac{r}{\sqrt{k}}} = 10\log k. \qquad (1.2)$$

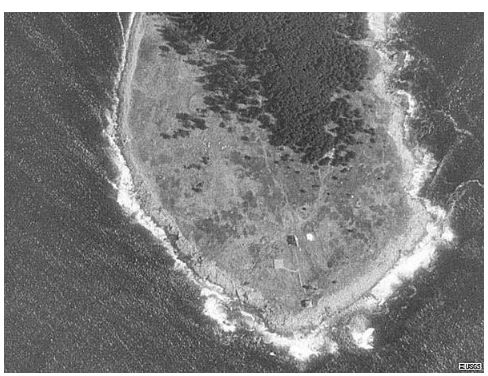
Therefore, an increase in sensor density by a factor of k improves the SNR at a sensor by $10\log k$ db.

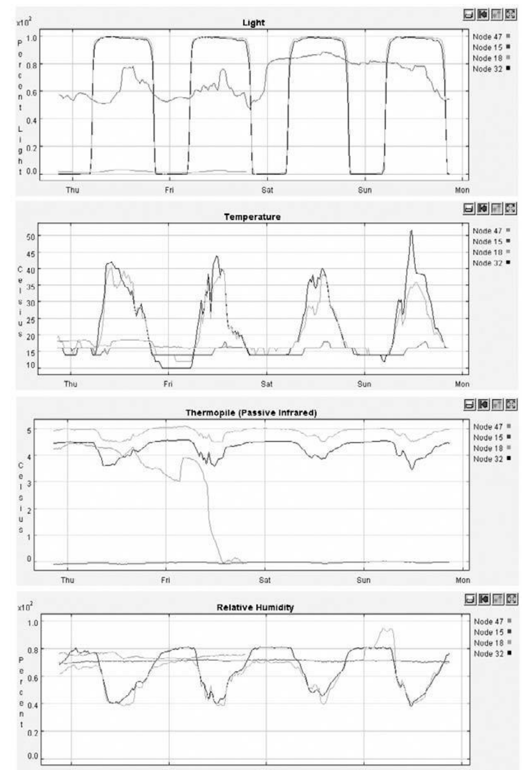
SENSOR NETWORK APPLICATIONS

- A sensor network is designed to perform a set of high-level information processing tasks such as detection, tracking, or classification.
- Measures of performance for these tasks are well defined, including detection of false alarms or misses, classification errors, and track quality.
- Applications of sensor networks are wide ranging and can vary significantly in application requirements, modes of deployment (e.g., ad hoc versus instrumented environment), sensing modality, or means of power supply (e.g., battery versus wall-socket).

- Sample commercial and military applications include:
  - Environmental monitoring (e.g., traffic, habitat, security)
  - Industrial sensing and diagnostics (e.g., appliances, factory, supply chains)
  - Infrastructure protection (e.g., power grids, water distribution)
  - Battlefield awareness (e.g., multitarget tracking)
  - Context-aware computing (e.g., intelligent home, responsive environment)

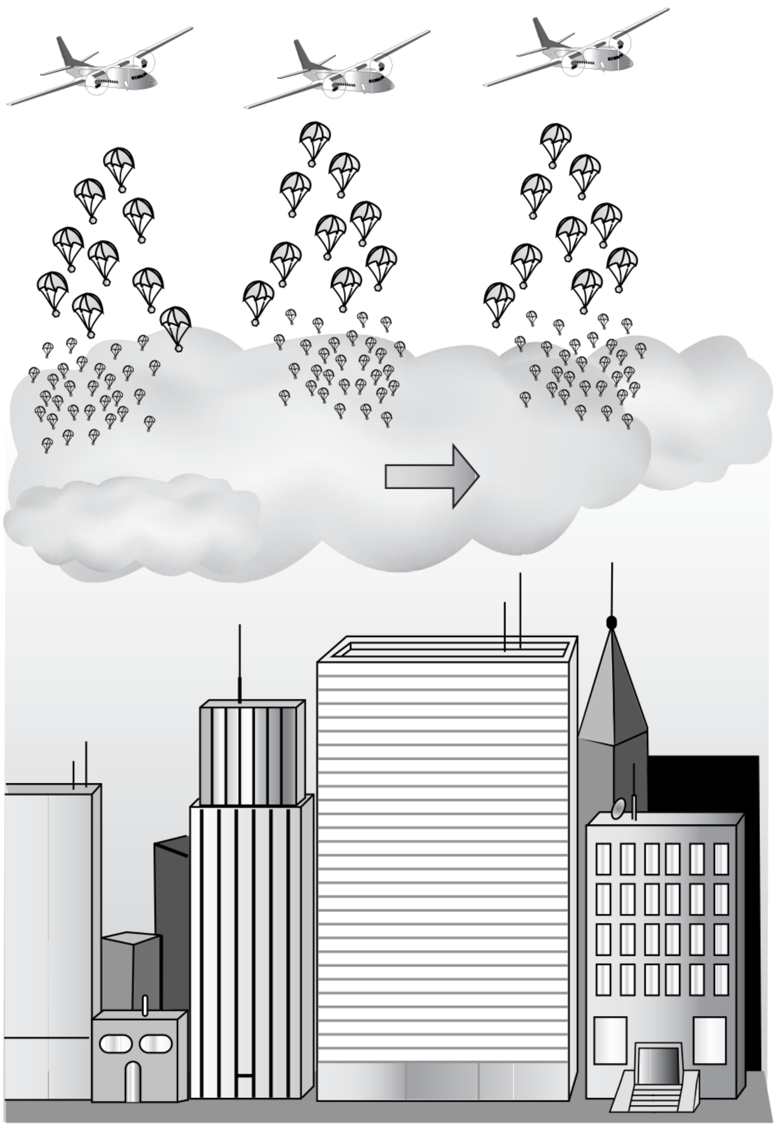
HABITAT MONITORING: WILDLIFE CONSERVATION THROUGH AUTONOMOUS, NONINTRUSIVE SENSING



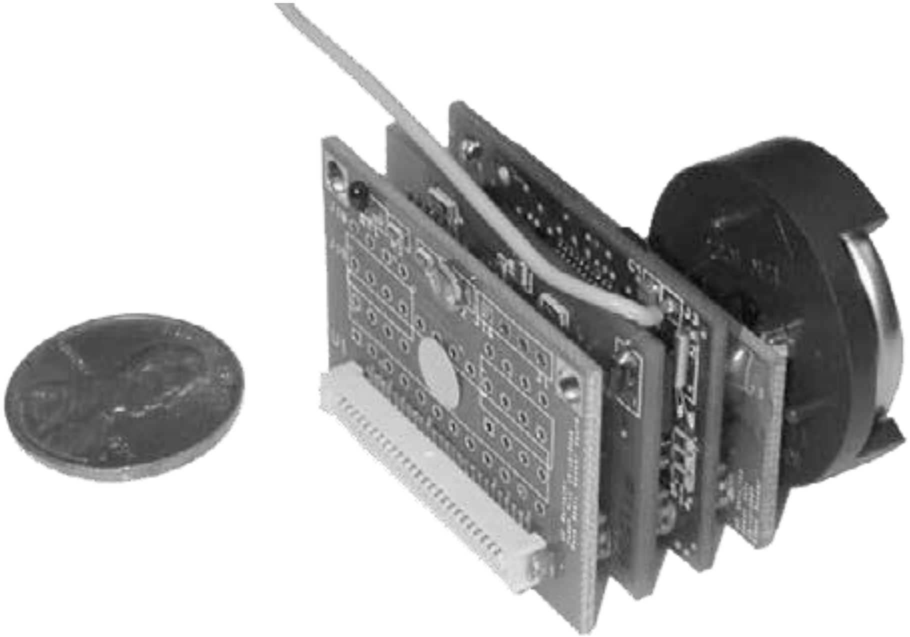


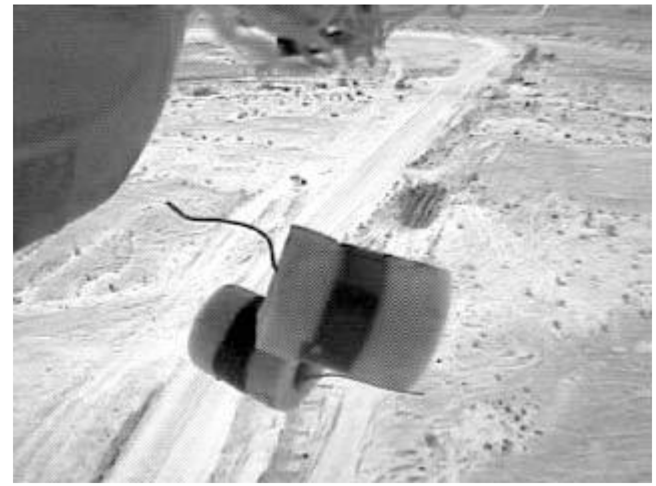
TRACKING CHEMICAL PLUMES: AD HOC, JUST-IN-TIME DEPLOYMENT FOR MITIGATING DISASTERS

- Image the following scenario. The Valley Authority has just declared a region-wide emergency: A large-scale hazardous chemical gas leak occurred at a chemical processing plant twenty minutes ago.
- The National Guard has been activated to evacuate nearby towns and to close roads and bridges. To get a real-time situational assessment of the extent and movement of the gas release and help plan the evacuation, the Sensor Net SWAT Team is called in. Three unmanned aerial vehicles (UAVs) are immediately launched from an open field 15 miles south of the accident site, each carrying 1000 tiny wireless chemical sensing nodes



Tracking chemical plumes using ad hoc wireless sensors, deployed from air vehicles.

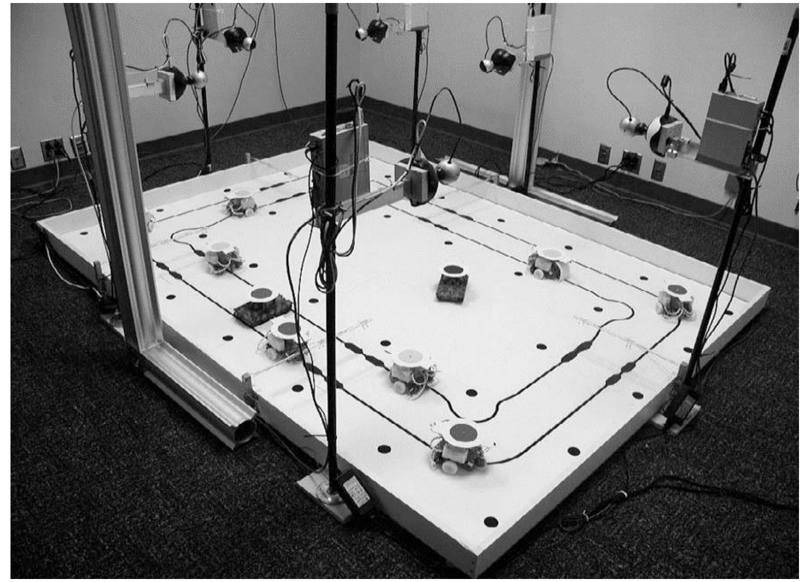


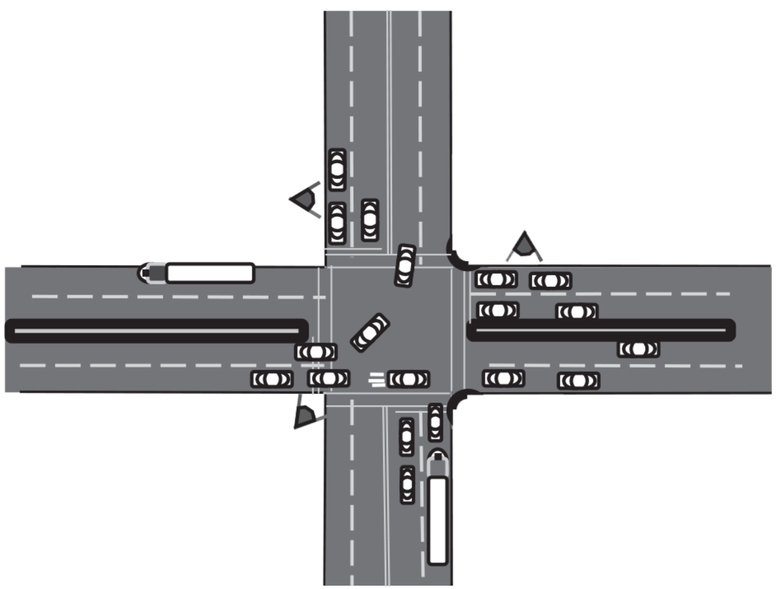


Left: Berkeley wireless sensor mote. Right: Air-drop of six sensor nodes from a UAV. (Picture courtesy of Kris Pister and Jason Hill.)

SMART TRANSPORTATION: NETWORKED SENSORS MAKING ROADS SAFER AND LESS CONGESTED

- Plenty of sensors are already in use for traffic monitoring purposes. Sensors embedded in roadbeds or alongside highways measure traffic flow.
- Cameras at street intersections look for traffic violations. Sensors in vehicles monitor speed and other conditions. But today these sensors do not talk to each other as often as we would like them to.
- When these sensors are networked together to share real-time information, we can begin to create a dynamic infrastructure for smart roads that can be optimized to make roads safer, reduce congestion, or help people find the nearest available parking space in an unfamiliar city.





Distributed video sensor networks for traffic and security applications. Upper figures: Networked cameras and other sensors could be used to monitor traffic flow to reduce congestion, track vehicles on city streets for traffic violations, or detect illegal activities around critical infrastructure such as airports. Lower figure: PARC video sensor network prototype uses in-network intelligence to decide what events to pay attention to and what to ignore, thus reducing the amount of information the network must collect and transport in order to support high-level monitoring applications.

COLLABORATIVE PROCESSING

- Sensors cooperatively processing data from multiple sources in order to serve a high-level task. This typically requires communication among a set of nodes.

- **Sensor:** A transducer that converts a physical phenomenon such as heat, light, sound, or motion into electrical or other signals that may be further manipulated by other apparatus.
- **Sensor node:** A basic unit in a sensor network, with on-board sensors, processor, memory, wireless modem, and power supply. It is often abbreviated as node. When a node has only a single sensor on board, the node is sometimes also referred to as a sensor, creating some confusion.
- **Network topology:** A connectivity graph where nodes are sensor nodes and edges are communication links. In a wireless network, the link represents a one-hop connection, and the neighbors of a node are those within the radio range of the node.

- **Routing:** The process of determining a network path from a packet source node to its destination.
- **Date-centric:** Approaches that name, route, or access a piece of data via properties, such as physical location, that are external to a communication network. This is to be contrasted with address centric approaches which use logical properties of nodes related to the network structure.
- **Geographic routing:** Routing of data based on geographical attributes such as locations or regions. This is an example of date centric networking.
- **Node services:** Services such as time synchronization and node localization that enable applications to discover properties of a node and the nodes to organize themselves into a useful network.

- **Detection:** The process of discovering the existence of a physical phenomenon. A threshold-based detector may flag a detection whenever the signature of a physical phenomenon is determined to be significant enough compared with the threshold.
- **Localization and tracking:** The estimation of the state of a physical entity such as a physical phenomenon or a sensor node from a set of measurements. Tracking produces a series of estimates over time.
- **Resource:** Resources include sensors, communication links, processors, on-board memory, and node energy reserves. Resource allocation assigns resources to tasks, typically optimizing some performance objective.
- **Sensor tasking:** The assignment of sensors to a particular task and the control of sensor state (e.g., on/off, pan/tilt) for accomplishing the task.

- **Data storage:** Sensor information is stored, indexed, and accessed by applications. Storage may be local to the node where the data is generated, load-balanced across a network, or anchored at a few points (warehouses).
- **Embedded operating system (OS):** The run-time system support for sensor network applications. An embedded OS typically provides an abstraction of system resources and a set of utilities.
- **System performance goal:** The abstract characterization of system properties. Examples include scalability, robustness, and network longevity, each of which may be measured by a set of evaluation metrics.

- **Evaluation metric:** A measurable quantity that describes how well the system is performing on some absolute scale. Examples include packet loss (system), network dwell time (system), track loss (application), false alarm rate (application), probability of correct association (application), location error (application), or processing latency (application/system). An evaluation method is a process for comparing the value of applying the metrics on an experimental system with that of some other benchmark system.

CANONICAL PROBLEM

LOCALIZATION AND TRACKING

CANONICAL PROBLEM: LOCALIZATION AND TRACKING

- Localizing and tracking moving stimuli or objects is an essential capability for a sensor network in many practical applications. Moreover, it is a familiar problem that can be used as a vehicle to study many information processing and organization problems for sensor networks.
- Central problem for collaborative signal and information processing (CSIP) is to dynamically define and form sensor groups based on task requirements and resource availability.

- Tracking exposes the most important issues surrounding collaborative processing, information sharing, and group management including which nodes should sense, which have useful information and should communicate, which should receive the information and how often, and so on, all in a dynamically evolving environment.
- In wireless sensor networks, some of the information defining the objective function and constraints is available only at run time.
- Consequently, the decentralized algorithms and protocols for solving the optimization problem are quite different from existing centralized optimization techniques.

A TRACKING SCENARIO

1. **Discovery:** Node a detects X and initializes tracking.
2. **Query processing:** A user query Q enters the network and is routed toward regions of interest—in this case, the region around node a. It should be noted that other types of queries, such as long running queries that dwell in a network over a period of time, are also possible.
3. **Collaborative processing:** Node a estimates the target location, possibly with help from neighboring nodes. The position estimation may be accomplished by a triangulation or a least-squares computation over a set of sensor measurements.
4. **Communication:** As the target X moves, node a may hand off an initial estimate of the target location to node b, b to c, and so on.
5. **Reporting:** Node d or f may summarize track data and send it back to the querying node.

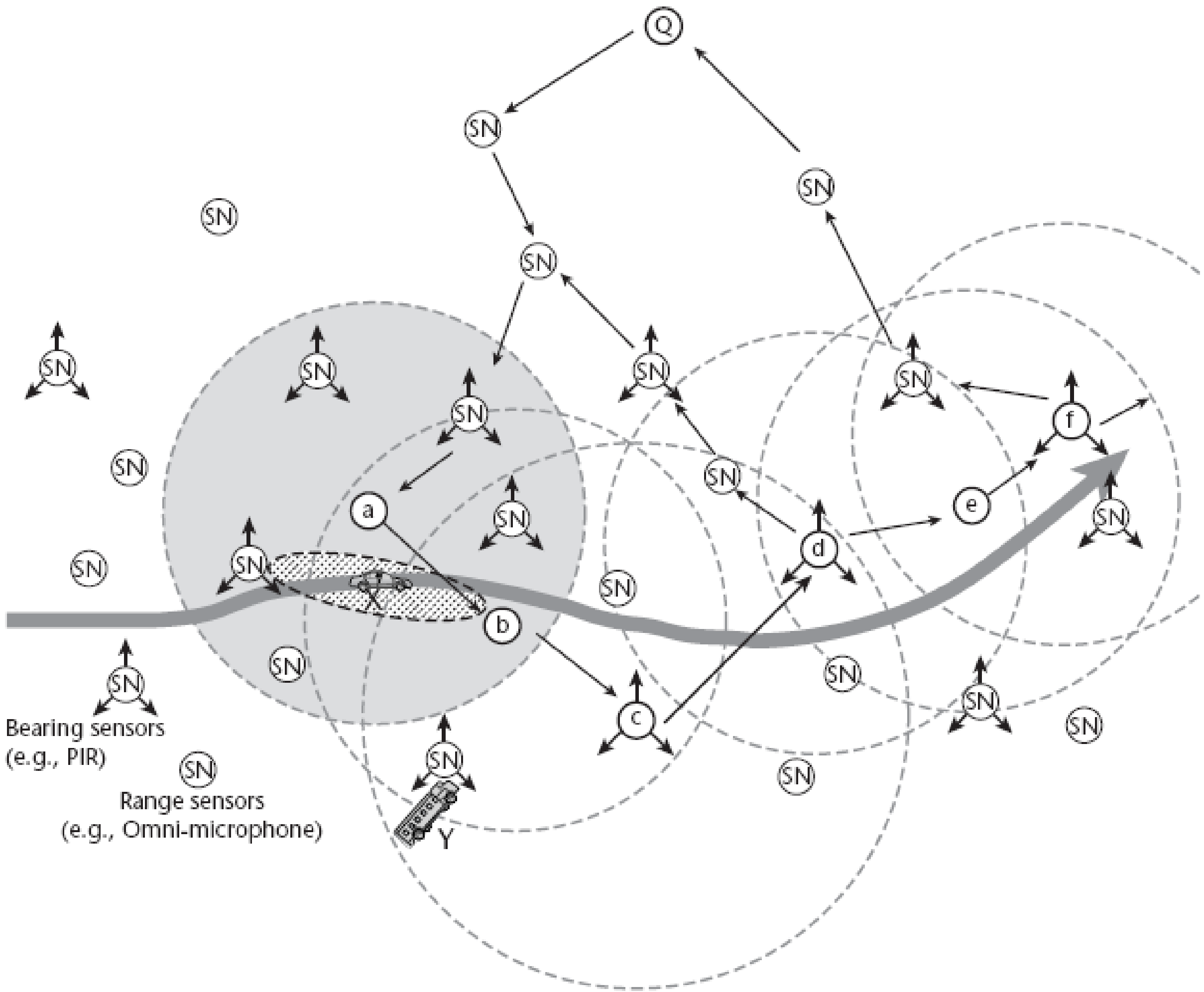


Figure 2.1 A tracking scenario, showing two moving targets, *X* and *Y*, in a field of sensors. Large dashed circles represent the range of radio communication for each node (adapted from [232]).

- This tracking scenario raises a number of fundamental information processing issues in distributed information discovery, representation, communication, storage, and querying:
- In collaborative processing, the issues of target detection, localization, tracking, and sensor tasking and control
- In networking, the issues of data naming, aggregation, and routing
- In databases, the issues of data abstraction and query optimization
- In human-computer interface, the issues of data browsing, search, and visualization
- In infrastructure services, the issues of network initialization and discovery, time and location services, fault management, and security.

PROBLEM FORMULATION

- We use the following notation in our formulation of the tracking problem in a sensor network:
- Superscript t, where applicable, denotes time. We consider discrete times t that are nonnegative integers.
- Subscript $i \in \{1, \ldots, K\}$, where applicable, denotes the sensor index; K is the total number of sensors in the network.
- Subscript $j \in \{1, \ldots, N\}$, where applicable, denotes the target index; N is the total number of targets being observed.

- The target state at time t is denoted as x(t). For a multitarget tracking problem, this is a concatenation of individual target states x(t) j . Without loss of generality, we consider in this chapter the tracking problem, where an individual target state is the location of a moving point object in a two-dimensional plane.
- The measurement of sensor i at time t is denoted as z(t) i . In the context of discussing estimation problems, we will use the terms state and parameter interchangeably.
- The measurement history up to time t is denoted as z(t), that is, z(t) = z(0), z(1), . . . , z(t). The measurements may originate from a single sensor or a set of sensors.
- The collection of all sensor measurements at time t are denoted as z(t), that is, z(t) = z(t) 1 , z(t) 2 , . . . , z(t) K.
- In general, bold-face lowercase symbols denote vector quantities such as position or velocity, while bold-face uppercase symbols denote matrices such as steering matrix used in direction-of-arrival (DOA) estimation.

SENSING MODEL

- The time-dependent measurement, z(t) i , of sensor i with characteristics λ (t) i is related to the parameters, x(t), that we wish to estimate through the following observation (or measurement) model,

$$\mathbf{z}_l^{(t)} = \mathbf{h}\left(\mathbf{x}^{(t)}, \lambda_l^{(t)}\right),$$

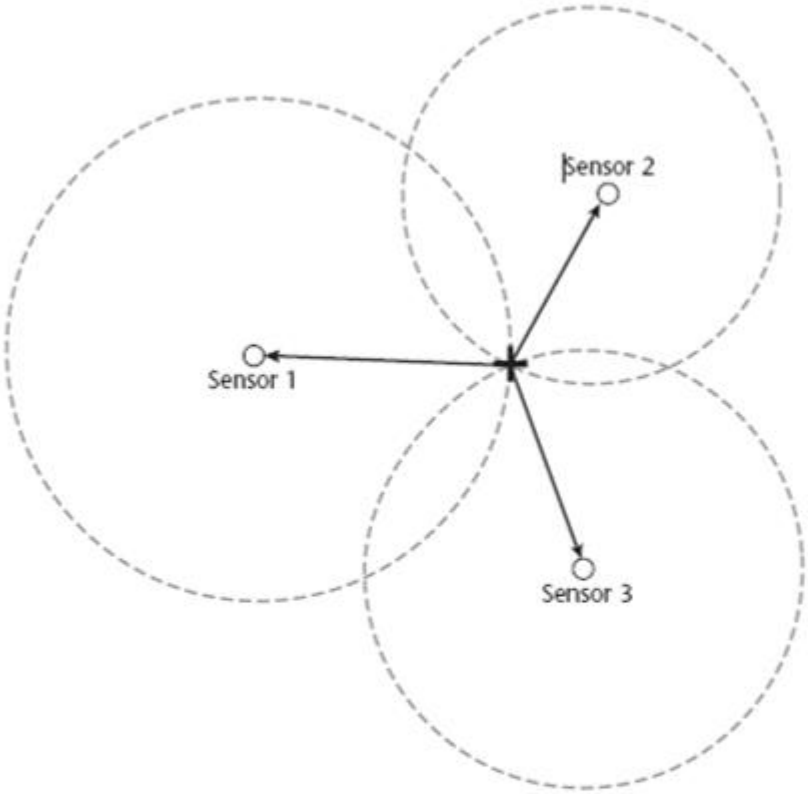
$$\mathbf{h}\left(\mathbf{x}^{(t)}, \lambda_l^{(t)}\right) = \mathbf{f}_l\left(\mathbf{x}^{(t)}, \lambda_l^{(t)}\right) + \mathbf{w}_l^{(t)},$$

$$\mathbf{h}\left(\mathbf{x}^{(t)}, \lambda_l^{(t)}\right) = \mathbf{H}_l^{(t)}\left(\lambda_l^{(t)}\right)\ \mathbf{x}^{(t)} + \mathbf{w}_l^{(t)}.$$

$$\lambda_l = \left[\zeta_l, \sigma_l^2\right]^T,$$

$$z_l = \frac{a_l}{\|\mathbf{x} - \zeta_l\|^{\frac{\alpha}{2}}} + w_l,$$

COLLABORATIVE LOCALIZATION



Localization: Three measurements are used to localize a signal source in a plane.

BAYESIAN STATE ESTIMATION

- The goal of localization or tracking is to obtain a good estimate of the target state x(t) from the measurement history z(t). For this problem, we adopt a classic Bayesian formulation.

$$p(\mathbf{x}|\mathbf{z}) = \frac{p(\mathbf{z}|\mathbf{x})\,p(\mathbf{x})}{\int p(\mathbf{z}|\mathbf{x})\,p(\mathbf{x})\,d\mathbf{x}} = \frac{p(\mathbf{z}|\mathbf{x})\,p(\mathbf{x})}{p(\mathbf{z})},$$

$$p(\mathbf{x}|\mathbf{z}) = k\,p(\mathbf{z}|\mathbf{x})\,p(\mathbf{x})$$

$$p(\mathbf{x}|\mathbf{z}) \propto p(\mathbf{z}|\mathbf{x})\,p(\mathbf{x}).$$

$$\bar{\mathbf{x}} = \int \mathbf{x}\,p(\mathbf{x}\,|\,\mathbf{z}_1,\ldots,\mathbf{z}_N)\,d\mathbf{x},$$

$$\Sigma = \int (\mathbf{x}-\bar{\mathbf{x}})(\mathbf{x}-\bar{\mathbf{x}})^T p(\mathbf{x}\,|\,\mathbf{z}_1,\ldots,\mathbf{z}_N)\,d\mathbf{x}.$$

DISTRIBUTED REPRESENTATION AND INFERENCE OF STATES

- **Impact of Choice of Representation:**
- There are several ways to approximate an arbitrary belief state regarding the targets:
  - We can approximate the belief by a family of distributions M ⊂ P(Rd), parameterizable by a finite dimensional vector parameter θ ∈ , where P(Rd) is the set of all probability distributions over Rd. An example of M is the family of Gaussian distributions on Rd where the finite dimensional parameter space includes the mean and covariance of the Gaussian distributions. In these cases, many efficient prediction and estimation methods exist, such as the Kalman filter.

- We can approximate the belief by weighted point samples. This is a brute force method of discretizing the probability distribution (or density) of a continuous random variable by a probability mass function (PMF) with support in a finite number of points of S. Let $\tilde{S} \subset S$ be some finite set of points of S. Then, we can approximate the density by a PMF with mass at each point of $\tilde{S}$ proportional to the density at that point. Two examples of this approximation are (1) discretizing the subset of S by a grid and (2) the particle filter approximation of distributions. A variant of this point sample approximation is to partition S and assign a probability value to each region—a histogram-type approach.

- We refer to the first approximation as parametric and the second approximation as nonparametric.

MEASUREMENT-BASED REPRESENTATION

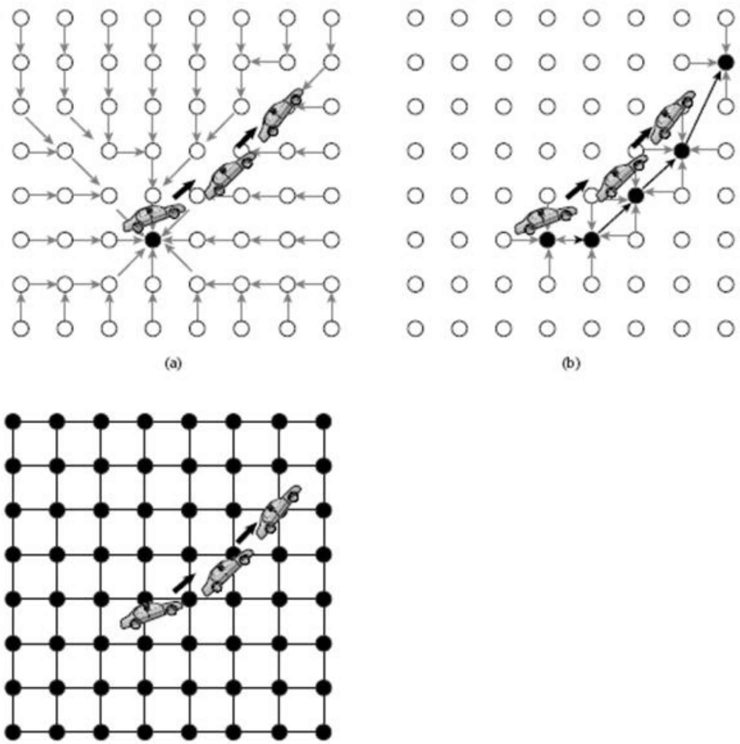
- For the nonparametric case, there is no constant-size parameterization of the belief in general. However, assuming that the model of the measurements is known, we can parameterize the belief by storing a history of all measurements.

DISCRETE SAMPLES

- The observation models for acoustic amplitude and DOA sensors are nonlinear. Consequently, the likelihood p z(t) x(t) is non-Gaussian, as is the a posteriori belief p x(t) z(t). For these non-Gaussian distributions, one may use a grid-based nonparametric representation for probability distributions. The distributions are represented as discrete grids in a d-dimensional space.

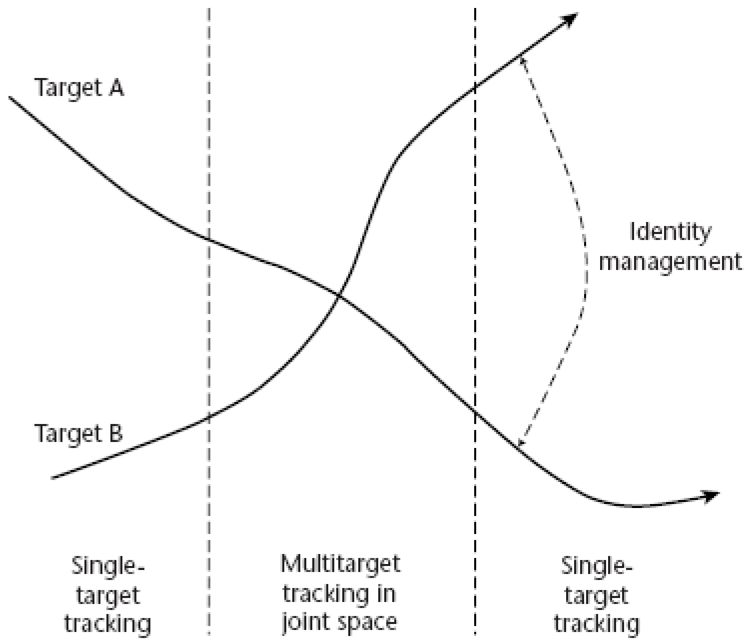
DESIGN DESIDERATA IN DISTRIBUTED TRACKING

- Storage and communication of target state information in a sensor network. In the figures, circles on the grid represent sensor nodes, and some of the nodes (i.e., solid circles) are those that store target state information.
- Narrow, gray arrows or lines denote communication paths among the neighbor nodes. Narrow, black arrows denote sensor hand-offs. A vehicle target moves through the sensor field, as indicated by the thick arrows.
    a) A fixed node stores the target state.
    b) Leader nodes are selected in succession according to information such as vehicle movement.
    c) Every node in the network stores and updates target state information.

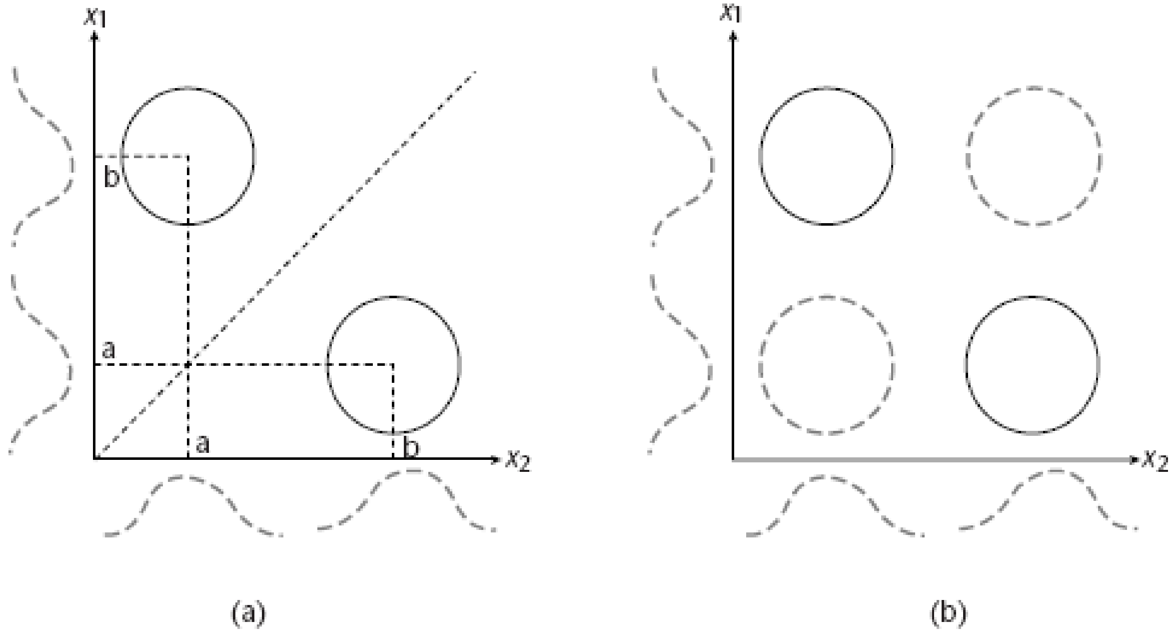


TRACKING MULTIPLE OBJECTS

- We have considered the estimation problem for tracking a single target by a sensor network. Tracking multiple interacting targets distributed over a geographical region is significantly more challenging for two reasons:
  1. Curse of dimensionality: The presence and interaction of multiple phenomena cause the dimension of the underlying state spaces to increase. Recall that the joint state space of multiple targets is a product space of individual state spaces for the targets. Estimating the phenomenon states jointly suffers from the state-space explosion, since the amount of data required increases exponentially with the dimension. This is inherent in any high-dimensional estimation problem, regardless of whether the sensing system is centralized or distributed.
  2. Mapping to distributed platforms: An estimation algorithm for tracking multiple targets will have to be mapped to a set of distributed sensors, as will the state-space model for the estimation problem. To ensure the responsiveness and scalability of the system, the communication and computation should be localized to relevant sensors only.



Modes of interaction in a multitarget tracking problem. The corresponding state representations move from factored to joint and then back to factored spaces (adapted from [146]).

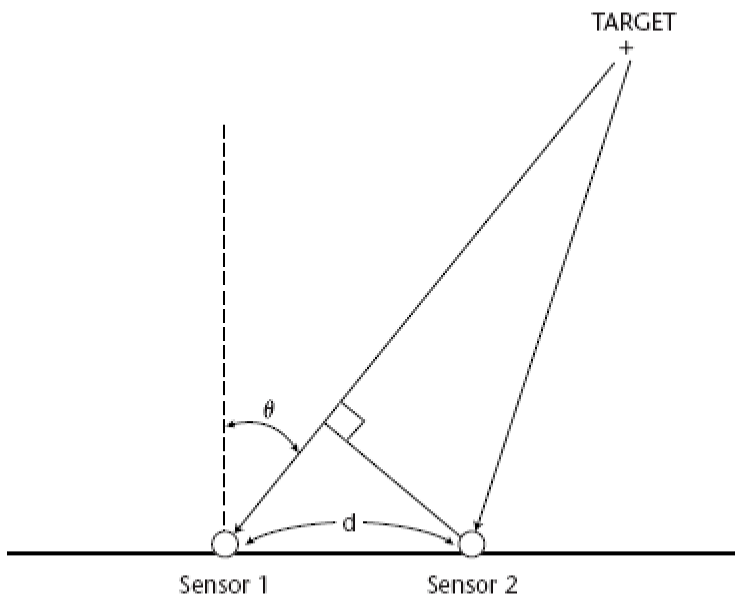


Switching between joint density $p(x_1, x_2)$ and marginal densities $p(x_1)$ and $p(x_2)$ (adapted from [146]).

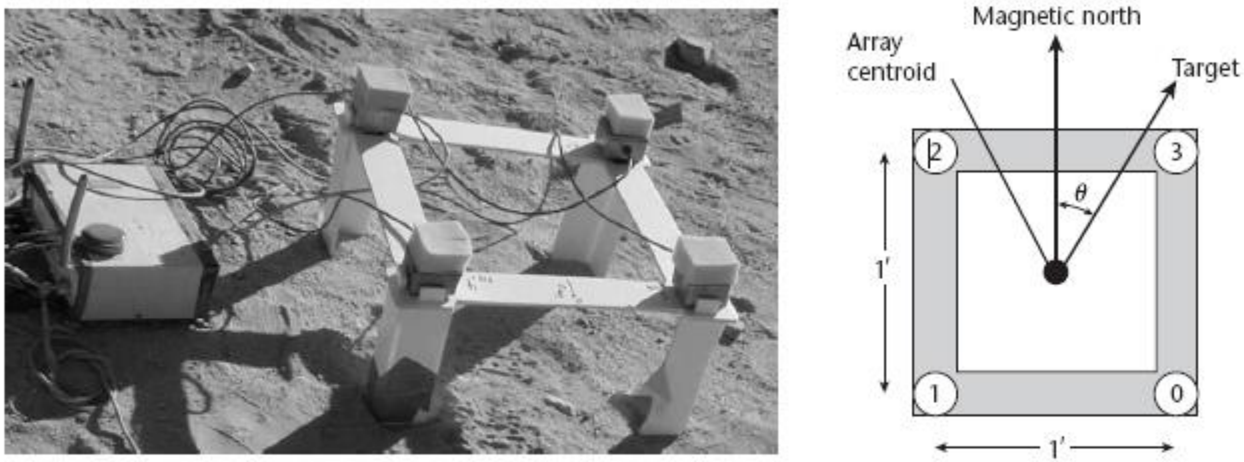
SENSOR MODELS

- We describe two common types of sensors for tracking: acoustic amplitude sensors and direction-of-arrival (DOA) sensors. An acoustic amplitude sensor node measures sound amplitude at the microphone and estimates the distance to the target based on the physics of sound attenuation. An acoustic DOA sensor is a small microphone array. Using beam-forming techniques, a DOA sensor can determine the direction from which the sound comes, that is, the bearing of the target.

- More generally, range sensors estimate distance based on received signal strength or time difference of arrival (TDOA), while DOA sensors estimate signal bearing based on TDOA.
- **DOA Sensor**
  - Amplitude sensing provides a range estimate. This estimate is often not very compact (i.e., not unimodal) and is limited in accuracy due to the crude uniform source amplitude model. These limitations make the addition of a target-bearing estimator very attractive. Beam-forming algorithms are commonly used in radar, speech processing, and wireless communications to enhance signals received at an array of sensors



Coherent spatial signal processing using a sensor array. The signal impinging on the sensors is a planar wave under the far-field assumption.

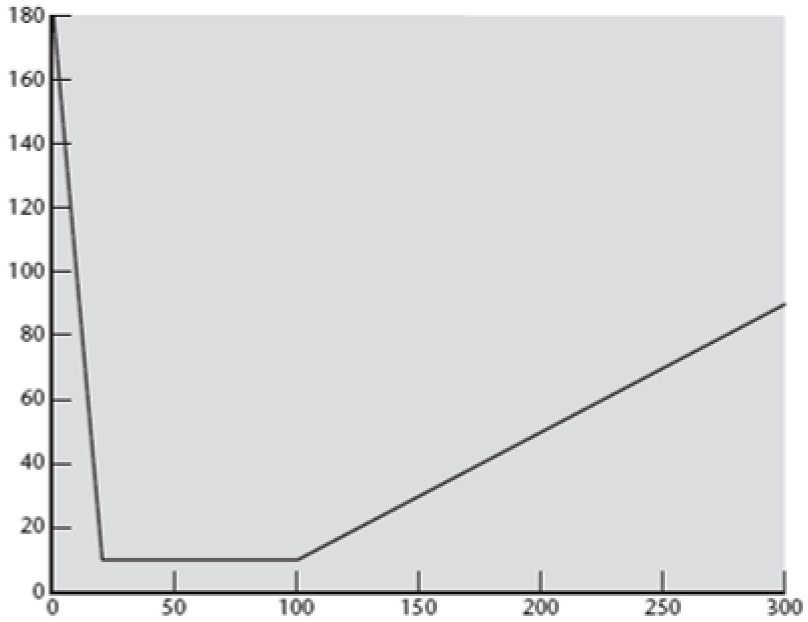


(a) (b)

Figure 2.9 DOA sensor: (a) WINS NG 2.0 sensor node with a DOA-sensing microphone array. (b) DOA sensor arrangement and angle convention (adapted from [144]).

PERFORMANCE COMPARISON AND METRICS

- Since a sensor network is designed for tasks such as detection, tracking, or classification, comparison or measure of performance is only meaningful when it is discussed in the context of these tasks. Here are some of the commonly used measures of performance for these tasks:
  - **Detectability:** How reliably and timely can the system detect a physical stimulus? This may be measured by sensor coverage, detection resolution, dynamic range, or response latency.
  - **Accuracy:** Accuracy is typically characterized in terms of tracking errors (e.g., deviation, smoothness, continuity) or detection and classification errors (e.g., false alarms or misses).



180
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250
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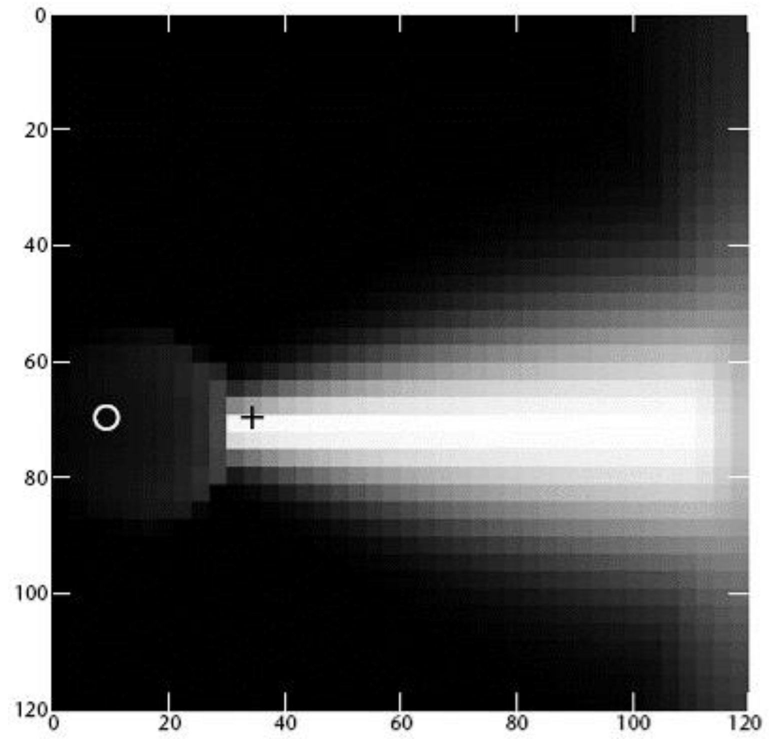

0
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120

- **Scalability:** How does a specific property of the system vary as the size of the network, the number of physical stimuli, or the number of active queries increases?
- **Survivability:** How does the system perform in the presence of node or link failures as well as malicious attacks? Sometimes this is also called robustness.
- **Resource usage:** What is the amount of resources that each task consumes? The resources include energy and bandwidth.

- For tracking problems, performance goals and measures can be stated in terms of target and system parameters. A number of measures are further explained below.
  - **Source SNR:** This is measured as the SNR at a reference distance from the signal source. For an acoustic source, this is defined as the log ratio of sound pressure level (SPL) of source at the reference distance over SPL of background noise.
  - **Obstacle density:** This may be measured by the probability of line of-sight obstruction for a randomly placed target-sensor pair. It is useful in characterizing sensors such as imagers, but less useful when multipath effects on the signal are significant.
  - **Network sleep efficiency:** The number of hours of target tracking versus the total number of node hours in fully awake mode for the entire network.

Table 2.1 Sample performance measures and parameters for tracking and localization problems.

Performance Measures	System and Application Parameters
Detection robustness (% missed and % false alarm)	Source SNR # Distractors
Detection spatial resolution (% counting error)	Intertarget spacing # Nodes
Detection latency (event occurrence to query node notification)	Link delay # Simultaneous targets # Active queries
Classification robustness (% correct)	Source SNR # Distractors
Track continuity (% track loss)	Sensor coverage area # Nodes # Simultaneous targets # Active queries Target maneuvers Obstacle density
System survivability (network partition time; % track loss)	% Node loss
Cross-node DOA estimation (bearing error)	Link capacity
Power efficiency	Active lifetime Sleep lifetime Sleep efficiency

- *Percentage of track loss*: Percentage of runs of a full scenario where continuity of vehicle identity is not correctly maintained.

THANK YOU

THE CONTENTS IN THIS E-MATERIAL IS TAKEN FROM THE TEXTBOOKS AND REFERENCE BOOKS GIVEN IN THE SYLLABUS