CS649
Sensor Networks
IP Track Lecture 2: An Introduction to Collaborative Signal and Information Processing

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Outline

- What is CSIP? Common CSIP Tasks in Sensor Networks.
- Why do we need “collaboration” in Sensor Networks?
- Basic Questions involved in CSIP and Generic Approaches
- Key Challenges in CSIP
- Three “Models” for CSIP
- Quick review of two representative CSIP approaches
  - An information-directed approach
  - Space-time sampling and space-time cells

Collaborative Signal and Information Processing

- A Simple Definition: Sensor nodes cooperatively processing data from multiple sources in order to serve a high-level tasks
- Common tasks:
  - *Detect* events, physical phenomenon, targets
  - *Classify* signal types, targets
  - *Locate* signal sources, targets
  - *Track* the propagation of a physical process, the trajectory of targets
  - *Predict* the location/trajectory of targets
  - *Estimate* the parameters of a global phenomenon

Why do we need collaboration among sensor nodes?

- Each individual sensor has limited spatial and temporal coverage
  - Inferring target state requires spatial diversity not achieved by a single sensor (e.g. target localization)
  - Characterizing spatial-temporal processes (e.g. mobile targets)
- Capacity of wireless network per node decrease as $O\left(1/\sqrt{n}\right)$
  - Cannot send all the raw sensor data to a centralized location for processing
  - In-network processing requires collaboration to balance contribution of information from each sensor and its resource consumption or its utility to other applications
- Taking advantage of redundancy
  - Achieve more robust overall performance
  - Manage power consumption to prolong the lifetime of the network

Basic Questions Addressed in CSIP

- Which sensor nodes to participate in collaboration?
  - Application query driven (e.g. interested in…)
  - Event driven (e.g. nodes with strong detection)
  - Information utility based approach
  - Predetermined partition or clustering of spatial-temporal space
- Where is the collaborative processing done?
  - Centralized at a server
  - Predetermined or elected leader within each cluster
  - Dynamically elect leader nodes
  - Distributed (flat, peer-to-peer)
- Which algorithms to use?
  - Local signal processing
  - Specific computation/aggregation
  - Necessary information exchange
- Other related issues
  - Sensor control and tasking
  - Failure diagnosis and responses

Key Challenges in CSIP

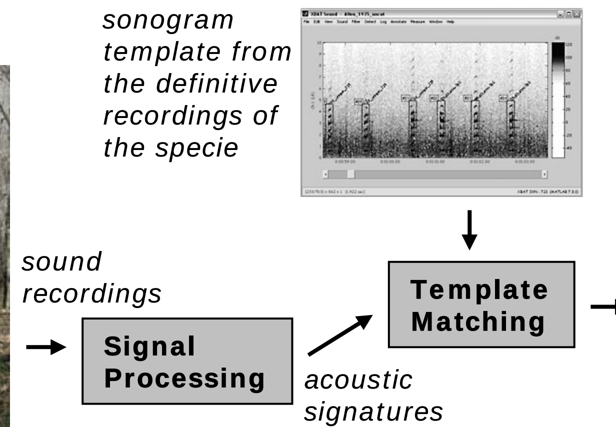
- Combine (potentially a large number of) distributed and possibly diverse data to produce meaningful global results
- Often require asynchronous processing over the wireless network
- Achieve robustness to dynamic changes in connectivity, node failure, target behaviors, environmental condition
- Breaking the traditional abstraction barrier between signal processing and networking; require optimizing across processing, fusion, communications, and sensor control

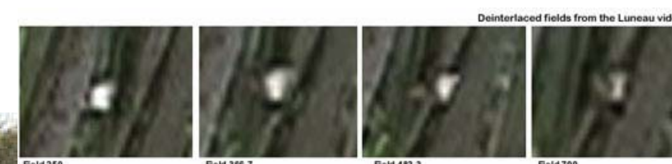
Three Key Abstractions (Models) for CSIP

- Underlying Data Models
  - Target signal models
  - Sensor data models
  - Environments
  - Dependency among sensor measurements
- Communications Models
  - Connectivity
  - Bandwidth
  - Link state/quality
- Application-driven Information Flow Models
  - Where is the information needed
  - What is the required quality/resolution

Extinct or Not – Rediscovering The Ivory-Billed Woodpecker*

- "The ivory-billed woodpecker, long suspected to be extinct, has been rediscovered in the Big Woods region of eastern Arkansas…" *Science* 3 June 2005.
- Key Evidences
  - Visual encounters during 2004 and 2005
  - Matches between sound recordings from autonomous recording units and definitive recordings of the specie made in 1935
  - Detailed analysis of "the Luneau video"

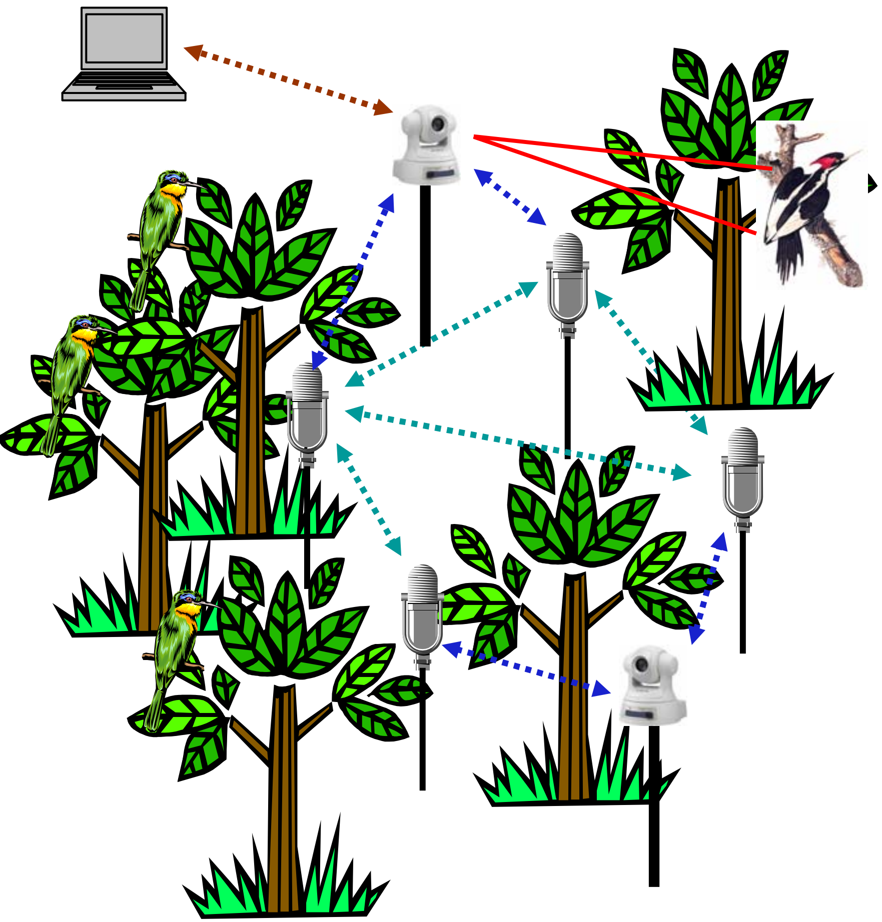




Luneau and Henderson obtained a video of an Ivory-billed Woodpecker on 4/25/2004 by canoeing around Bayou de View in the Cache River NWR with a constantly running video camera.

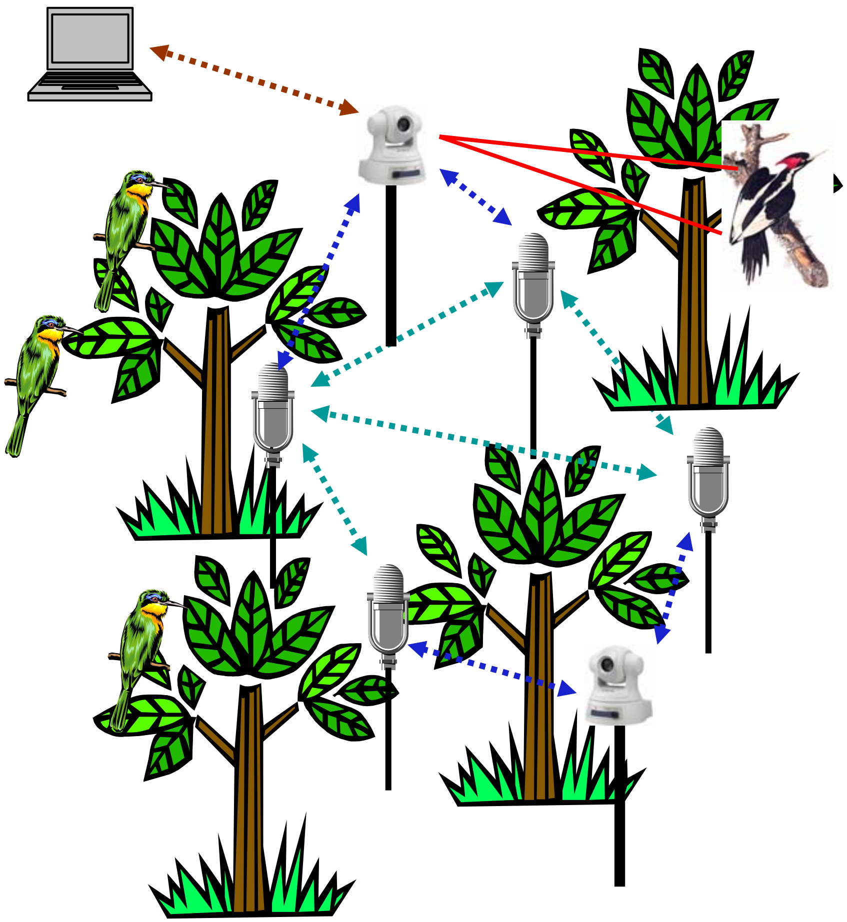
*Source: http://www.birds.cornell.edu/ivory (Cornell Lab of Ornithology)

An Idealized Wireless Sensor Network Approach



- Required Information Processing:
  - Acoustic sensors detect and classify bird callings of unique target acoustic signatures
  - Acoustic sensors collaborates to localize the target acoustic source
  - Acoustic sensors trigger the appropriate camera to zoom in and take a closed-up picture of the detected target
  - The camera runs an image classifier on the captured images and transmits the relevant images back to a base station for analysis
- Key Challenges
  - Noisy acoustic environments can lead to significant false alarms
  - Cameras could have poor line-of-sight due to foliage
  - Potentially stringent latency requirement between acoustic detection and camera movements for successful image capture

Three Models for the CSIP Problem



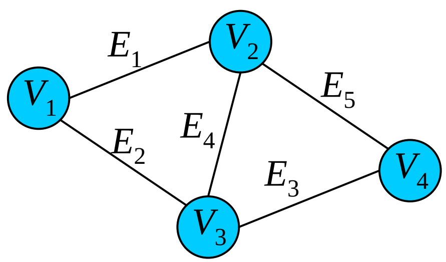
- Data models
- Communications models
- Application-driven information flow models

Collaborative Signal and Information Processing: An Information-Directed Approach

Feng Zhao
Jie Liu
Juan Liu
Leonidas Guibas
James Reich
Proceedings of IEEE, August 2003

Problem Formulation: Tracking as a canonical problem for CSIP

- A sensor network is defined as a tuple $Sn = \langle V, E, P_V, P_E \rangle$



V_i —— P_i^V node properties/states

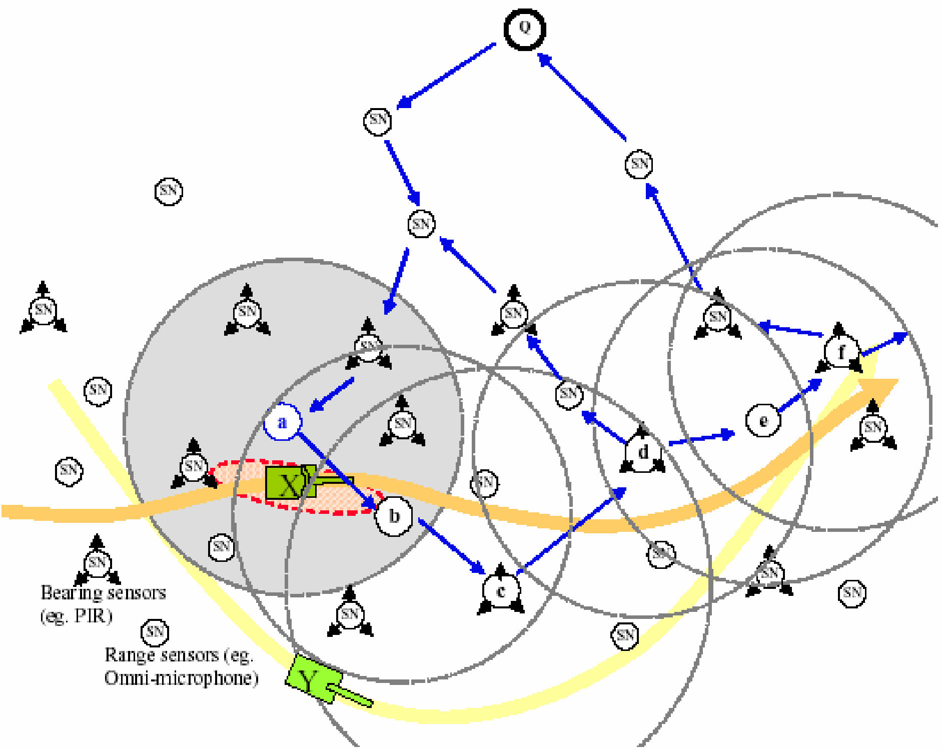
E_i —— P_i^E link properties/states

- A tracking task can be formulated as a constrained optimization problem:

$$Tr = \langle Sn, Tg, Sm, Q, O, C \rangle$$

- Tg: Set of targets and properties
- Sm: Signal models for targets
- Q: Set of user queries
- O: Objective function
- C: Set of constraints

A Tracking Scenario

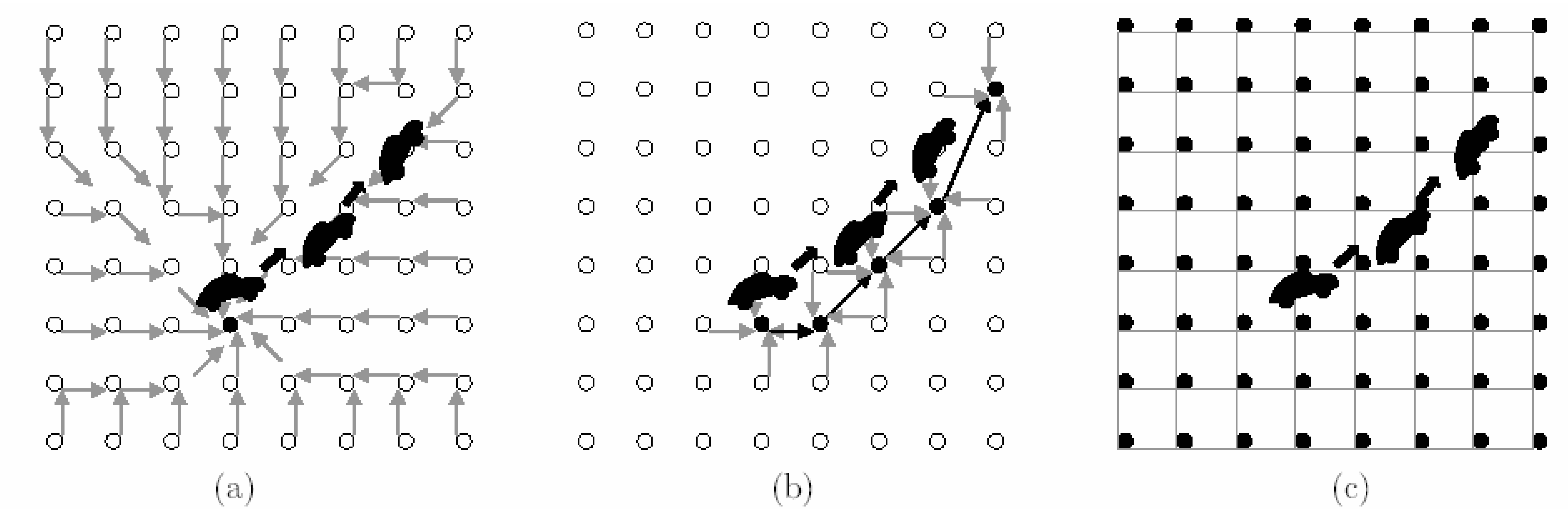


- *Discovery*: Node *a* detects *X* and initializes tracking
- *Query Processing*: A query is routed toward region of interest (around *a*)
- *Collaborative Processing*: Node *a* collaborate with other nodes to estimate the target states
- *Communication*: *a* hands off estimate to *b*, *b* to *c*, etc.
- *Reporting*: Node *d* or *f* reports tracking information back to the querying node
- *Data Association* if multiple targets

Three Generic Designs for Distributed Tracking

$$p(\mathbf{x}^{(t+1)} | \overline{\mathbf{z}^{(t+1)}}) \propto p(\mathbf{z}^{(t+1)} | \mathbf{x}^{(t+1)}) \cdot \int p(\mathbf{x}^{(t+1)} | \mathbf{x}^{(t)}) \cdot p(\mathbf{x}^{(t)} | \overline{\mathbf{z}^{(t)}}) \, d\mathbf{x}^{(t)}$$

updated belief — new data — current belief



Centralized processing at a fixed node

Processing at sequentially selected leader nodes

Leaderless distributed processing (e.g. belief propagation)

Information-Directed Approach

- Basic idea: Select sensors to collaborate (and the leader node for handoff) based on information utility measures and appropriate cost function (e.g. communications, energy)

measurements including data from node *j*

measurement from node *j*

$$O(p(\mathbf{x}|\overline{\mathbf{z}_j^{(t)}})) = \alpha\phi(p(\mathbf{x}|\overline{\mathbf{z}_{j-1}^{(t)}}, \mathbf{z}_j^{(t)})) - (1-\alpha)\psi(\mathbf{z}_j^{(t)})$$

Overall value by incorporating measurement from node *j*

Information utility of measurement from node *j* (e.g. mutual information)

Cost of incorporating measurement from node *j*

$$\hat{j} = \arg\max_{j\in A} O\left(p\left(\mathbf{x} \mid \{\mathbf{z}_i\}_{i\in U} \cup \{\mathbf{z}_j\}\right)\right)$$

- Issues?

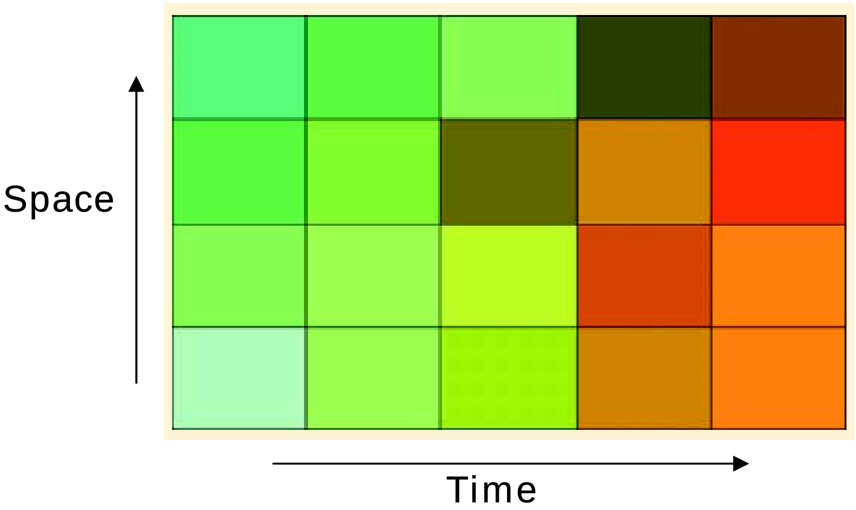
Detection, Classification, and Tracking of Targets

Dan Li
Kerry D. Wong
Yu Hen Hu
Aknar M. Sayeed

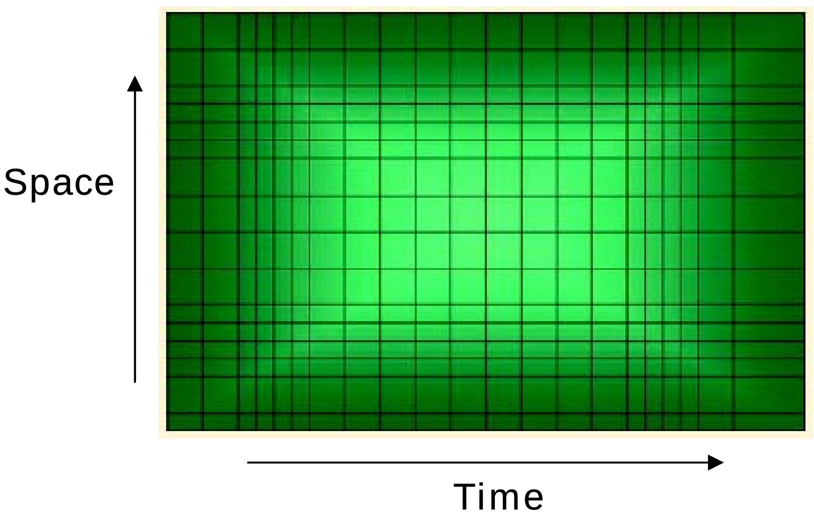
IEEE Signal Processing Magazine, March 2002

Space-Time Sampling and Space-Time Cells

Uniform sized space-time cell

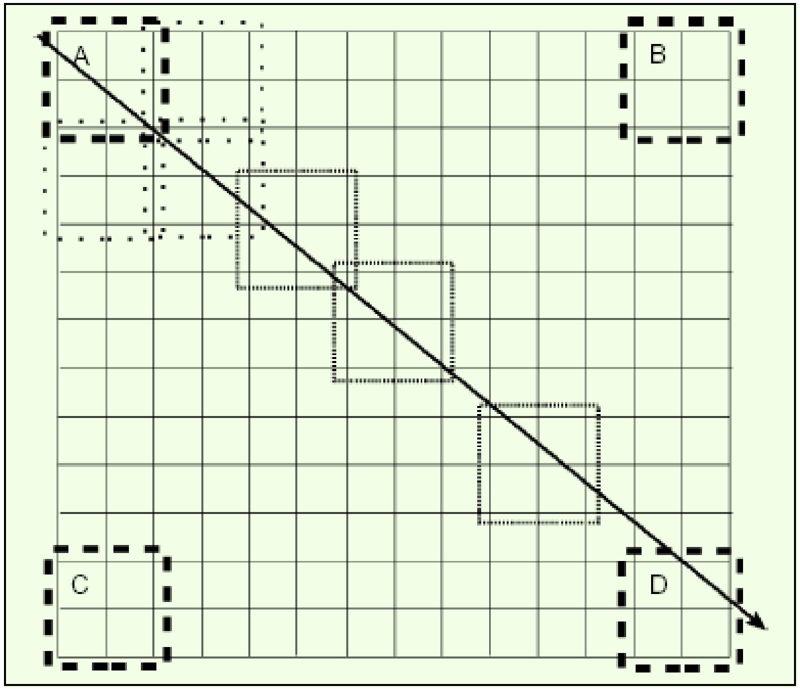


Non-uniform sized space-time cell



- Dividing the space-time region into cells to facilitate and organize local collaborative processing
- Space-time cells are defined such that the space-time signature field remains approximately nearly constant over each cell

Basic Detection and Tracking Framework with Spatial Cells



Assume a target may enter the monitored area only via one of the four corner cells