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

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Outline

- 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
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 $O(1/\sqrt{n})$
  • 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”

*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 $Sn = \langle V, E, P_V, P_E \rangle$

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

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

Set of targets and properties

Signal models for targets

Objective function

Set of constraints

Set of user queries
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

$\Pr(x(t+1) | z(t+1)) \propto \Pr(z(t+1) | x(t+1)) \cdot \int \Pr(x(t+1) | x(t)) \Pr(x(t) | z(t)) \, dx(t)$

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)

\[
O(p(x | \overline{z_j^{(t)}})) = \alpha \phi(p(x | \overline{z_{j-1}^{(t)}, z_j^{(t)}})) - (1 - \alpha)\psi(z_j^{(t)})
\]

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 \( j \)

\[
\hat{j} = \arg\max_{j \in A} O(p(x | \{z_i\}_{i \in U} \cup \{z_j\}))
\]

- 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