Signal Processing & Communication Issues in Sensor Networks

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Research Team in relevant activities

• **Research Group @ Patras**
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• **Research Group @ Athens**
  - Dr. Athanasios Rontogiannis, Researcher, N.O.A.
  - G. Ropokis, PhD student
Projects

The relevant works have been funded by the following projects (and other sources):

- **Sensor networks**: Algorithms development, protocol design and performance evaluation, (GGET, PENED)
- **MIMO Systems**: Development and study of efficient adaptive channel estimation and equalization techniques, (GGET, PENED)
- **COOPCOM**: Cooperative and Opportunistic Communications, (FP6 - FET)
- **SMART EN**: Smart Management for Sustainable Human Environment (FP7-PEOPLE-ITN-2008)
Talk Outline

• Part A: A Brief Introduction to WSNs

• Part B - 1st Case Study: Target Localization

• Part C: Cooperative Communications

• Part D - 2nd Case Study: Distributed Source Coding in WSNs
Historical Background

• The use of networked sensors can be traced back to the 1970s

• However,
  - The networks mainly involved wired communication or a few powerful wireless nodes
  - Processing of the sensor readings was centralized

• One of the early applications was flight attendance involving an array of sensors (radars)
  - Since it was infeasible to send all measurements to the central station, a local compression method was used
Wireless Sensor Networks

• WSN: A Collection of sensor nodes, deployed to monitor an area of interest

• In some applications, the network may also include some Actuator Nodes
  - An actuator node is equipped with suitable electromechanical parts, used to perform some action (for example, signal an alarm, target a camera e.t.c.)
The Sensor Node

- A Sensor Node is a small size electronic device that integrates:
  - **Sensing** (temperature, humidity, pressure, magnetic field, acceleration, acoustics, chemical pollution, ...)
  - **Processing** (detection, estimation, fusion, compression, routing, ...)
  - Short range *wireless communication*
  - **Power unit**
Types of WSNs

- **Terrestrial WSNs:**
  - Consist of a large number of inexpensive nodes, usually deployed in an ad-hoc manner (for example, dropped from a plane)
  - The acquired measurements are sent to a Sink node, which can be at a fixed location or on a vehicle that periodically visits the network
  - Each sensor may or may not have Direct Sink Access (DSA)
Types of WSNs

- **Underground WSNs:**
  - A number of sensor nodes are buried underground or in a cave or mine to monitor underground conditions.
  - Additional sink nodes are located above ground to relay information to a remote sink.
  - Increased cost, careful placement of nodes.
Types of WSNs

• **Underwater WSNs:**
  - A small number of sensors are deployed underwater
  - *Wireless communication uses acoustic waves*
  - Sensor nodes must cope with the extreme conditions
  - An underwater vehicle gathers the data
Types of WSNs

- **Multimedia WSNs:**
  - Sensor nodes are equipped with cameras and microphones
  - To guarantee coverage, nodes are deployed carefully
  - The network collects audio and video streams
Types of WSNs

- **Mobile WSNs:**
  - Sensor nodes have the ability to move on their own
  - The topology of the network is time-varying
  - A dynamic routing algorithm must be employed
Applications of WSNs

• **Management of natural disasters**
  - Detect events that need urgent treatment (e.g., earthquakes)
  - Provide a communication network for the rescue teams, in the case where the infrastructure has been destroyed

• **Environmental Applications**
  - Monitor the pollution of the atmosphere
  - Early detection of forest fires
  - Flood detection
  - Track populations of animals
  - Precision agriculture *(Green Development)*
Applications of WSNs

• **Health applications**
  - Tele-monitoring of human physiological data
  - Tracking and monitoring patients and doctors inside a hospital
  - Body Sensor Networks (BSNs)

• **Monitoring of constructions**
  - Detection of cracks / defects / corrosions ...
  - Autonomous and progressive assessment of structural integrity of buildings / infrastructures
  - Active cancellation of oscillations in bridges

• **Security Applications**
  - Intrusion detection at sensitive facilities (power plants, military camps)
Existing Hardware

Crossbow MICAz/MICA2 Sensor

Sun SPOT

MEMS
Standards

• **Radio standards**
  - IEEE 802.15.4 (2003/2006) for low rates (WPAN)
  - IEEE 802.15.3 (2003) high data rates - multimedia

• **ZigBee Specification (June 2005)**
  - Embedded sensing, medical data collection, consumer devices like television remote controls, and home automation.

• **WirelessHART (September 2007)**
  - Suitable for process measurement and control applications

• **6LoWPAN / ISA100.11a (2009)**
  - IPv6 communication over 802.15.4
  - Low data rates
Research Issues in WSNs

Lifetime maximization
- Usually, the sensor nodes cannot be collected to replace their batteries
- In general, lifetime maximization is accomplished by
  - Minimizing the energy required to transmit data to the sink
  - Minimizing the energy left at the nodes of the network, when the WSN ceases to function

A new direction: Energy harvesting
- Produce energy from
  - Solar Panels
  - Ambient airflow
  - Mechanical motion
  - Pressure
  - Ambient/Targeted electromagnetism
  - Mobile robots to replenish energy
Most routing protocols use a power-related metric to select a path. However, such protocols ignore the specific requirements of the application that the network delivers. Application-dependent routing protocols offer increased power efficiency and constitute an example of the merits related to cross-layer optimization.
Research Issues in WSNs

Security Issues

• **Typical sensor networks operate unattended**
  - How does the network operate in the presence of jammers?
  - How can the network protect sensitive data against eavesdroppers?

• **Privacy**
  - Who decides which human activity to monitor and which not?
  - Do we like a distributed 'big brother'?
Research Issues in WSNs

... and many other important challenges related to:

- Sensing and Hardware Platforms
- Operating Systems
- Storage procedures
- Simulation tools / Network Management tools ...
- Testbeds
Data Acquisition

• The classical paradigm of acquiring measurements:

![Diagram showing the classical paradigm of acquiring measurements with steps: Event, Sampling, Source Coding]

• The approach of “Compressed Sensing”:

![Diagram showing the approach of Compressed Sensing with steps: Event, Directly Acquire Compressed Data]

• It can dramatically reduce the number of transmissions to the Sink
• In a wireless sensor network, all the constituent parts of this system must be designed considering power efficiency

• Also, the fact that the wireless links are unreliable must be taken into account
Distributed Estimation under constraints

- Each sensor $n$ measures a vector $x_n$, applies a dimensionality reduction transform, and quantizes its output.

- Again, the non-ideal link from the sensor to the F.C. is a major difference with conventional estimation.
The “Sensor Reachback” problem

- In a large-scale sensor network, is the capacity of the system adequate to transmit the measurements to the fusion center?
- What source/channel codes must be used?
- What are the rate-distortion characteristics?
Target Localization

- The scope is to estimate and track the location of a source
- This “canonical problem” has many applications
  - Tracking of vehicles
  - Surveillance
  - Localization of pollution sources
  - Teleconferencing
... and (again) many other important issues such as:

- Distributed Learning
- Node localization
- Synchronization
Talk Outline

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• Part B: Case Study: Target Localization

• Part C: Cooperative Communications

• Part D: Distributed Source Coding in WSNs
Target Localization

• The Localization problem: studied for many years in different frameworks: Array SP, Mobile Networks etc

• Most localization methods can be classified into
  - Methods that utilize Direction of Arrival (DOA) measurements - useful for narrowband sources
  - Methods that utilize Time Difference of Arrival (TDOA) measurements - able to localize wideband sources

• However, the above methods are impractical for wireless sensor networks because:
  - They require high sampling rates
  - They require accurate synchronization among the nodes

• In WSNs a third category of methods that utilize Received Signal Strength (RSS) measurements has gained increased attention
Target Localization

A sensor located at a distance \( d_n \) from the target takes a measurement equal to

\[
y_n = \alpha \cdot g(d_n) + w_n
\]

where \( g() \) denotes the energy decay function, \( \alpha \) is the power parameter of the target and \( w_n \) is a noise term. Usually,

\[
g(d) = \frac{1}{d^\beta}
\]
Problem formulation: Given the known locations

\[ \mathbf{r}_n \quad n \in \{1, 2, \ldots, N\} \]

of the sensor nodes, the RSS measurements

\[ y_n = \alpha \cdot g \left( \| \mathbf{r}_n - \mathbf{x} \| \right) + w_n \]

as well as any known information about the energy decay function, the scope is to estimate the location \( \mathbf{x} \) of the target.

Usually, only a subset of active nodes is used

\[ A = \{ n : y_n > T \} \]
Target Localization

• Localization methods that utilize RSS measurements can be classified into
  - Single-source localization methods
  - Multiple-source localization methods

• Also, according to our knowledge about the energy decay function, we have
  - Methods that rely upon a known energy decay function
  - Model-Independent methods, that assume a general monotone decreasing energy decay function

• In the following, we will develop a single-source model-independent localization method


A basic observation: Apart from the information conveyed in the RSS measurements, we also have some geometric constraints.

Example:

It is impossible that node 1 is the closest one to the target AND node 2 is the second closest to the target.

OR EQUIVALENTLY

the locus of possible source locations for which node 1 is the closest one to the target AND node 2 is the second closest, is the EMPTY SET.
Target Localization

• The concept of Voronoi diagrams will help us model such geometric constraints

• Definition 1: Given a set of particles on the plane

\[ \Phi = \{r_1, r_2, \ldots, r_N\} \]

the Voronoi cell of a particle is the locus of points of the plane, that are closer to it than any other particle
Target Localization

• We have suggested a generalization of the Voronoi cells (a new geometric construction)

• **Definition 2:** Given a set of particles on the plane, and a vector of particles

\[ v = \left[ r_{k_1}, r_{k_2}, \ldots, r_{k_K} \right], \quad r_{k_i} \in \Phi, \quad r_{k_i} \neq r_{k_j} \]

the *sorted order-\(K\) Voronoi cell* for this vector is the locus of points for which:

- \(r_{k_1}\) is the closest particle, AND
- \(r_{k_2}\) is the second closest particle, … , AND
- \(r_{k_K}\) is the \(K\)-th closest particle
Example: Voronoi diagram for 5 points
Example: The new sorted order-2 diagram
Target Localization

- And finally, the geometric constraints (i.e. feasible sorting) are given by the following definition:

- **Definition 3:** Given a vector of node locations

\[ v = \left[ r_{k_1} \ r_{k_2} \ \ldots \ r_{k_K} \right], \quad r_{k_i} \in \Phi, \quad r_{k_i} \neq r_{k_j} \]

if the respective sorted order-K Voronoi cell is not the empty set, we will call this vector as feasible. In the opposite case, we will call it infeasible.
Target Localization

• In the case where the energy decay function is known, the Maximum Likelihood cost function is given by:

\[ C(x, a) = \sum_{n \in A} \left( y_n - a \cdot g \left( \| r_n - x \| \right) \right)^2 \]

• In our case, a proper cost function is defined, which apart from \( x \) tries to identify a suitable energy decay function as well:

\[ J(x, h(\cdot)) = \sum_{n \in A} \left( y_n - h \left( \| r_n - x \| \right) \right)^2 \]
Target Localization

- **Theorem 1**: Consider the vector of sensor locations

\[ \mathbf{v} = \begin{bmatrix} \mathbf{r}_{k_1} & \mathbf{r}_{k_2} & \cdots & \mathbf{r}_{k_L} \end{bmatrix}, \]

which is defined by the *sorting* of the respective RSS measurements as

\[ y_{k_1} > y_{k_2} > \cdots > y_{k_L} \]

If the sorted order-\(L\) Voronoi cell of this vector has positive area, then the *optimal points* of the previous cost function are *internal points* of this cell and *vise-versa*.

- For each point in this cell, there exist an energy decay function that is optimal for the given measurements.

- We can use this Theorem to derive localization algorithms.
Algorithm $A_1$

Input: $A$, $\Phi$, and $y_l$ for all $l \in A$

Output: A convex polygon $P$ in which the source may be located

1. Sort the measurements of active nodes as $y_{k_1} > y_{k_2} > \cdots > y_{k_L}$
2. $P = V(r_{k_1} | \Phi \setminus \{r_{k_1}\})$
3. FOR $l = 2$ TO $L$
   
   $P_l = V(r_{k_l} | \Phi \setminus \{r_{k_1}, r_{k_2}, \ldots, r_{k_{l-1}}\})$
   
   IF $P \cap P_l = \emptyset$
   
   Stop and output $P$
   
   ELSE
   
   Update $P = P \cap P_l$
   
   END IF

END FOR
**Algorithm A₂**

**Input:** \( \mathcal{A}, \Phi, \) and \( y_l \) for all \( l \in \mathcal{A} \)

**Output:** A convex polygon \( P \) in which the source may be located

1. Sort the measurements of active nodes as \( y_{k_1} > y_{k_2} > \cdots > y_{k_L} \)
2. \( P = V(r_{k_1} | \Phi \setminus \{r_{k_1}\}) \)
3. \( O = \{k_2, k_3, \ldots, k_L\} \)
4. \( I = \{k_1\} \)
4. WHILE \( F = \{k \in O : P \cap V(r_k | \Phi \setminus \{r_n : n \in I\}) \neq \emptyset\} \) not empty
   
   Select \( k \) with maximum \( y_k \) among all \( k \in F \)
   
   Update \( P = P \cap V(r_k | \Phi \setminus \{r_n : n \in I\}) \)
   
   Update \( O = O \setminus \{k\} \)
   
   Update \( I = I \cup \{k\} \)

END WHILE
Interesting Remarks

• In the case where we are interested in a point estimate, rather than a convex polygon, we can compute the Fermat-Weber center.

• The presented algorithms do not use the exact RSS measurements. Rather, only their sorting is important. Thus we can first execute a distributed sorting algorithm and transmit this sorting to the fusion center.

• In the absence of noise, the algorithms $A_1$ and $A_2$ are equivalent and give the correct polygon.

• By expressing the Voronoi cells as intersections of half-planes, we can develop a distributed version of the method that uses Projections onto Convex Sets (POCS).
Performance Analysis

- Under the assumption that the locations of the nodes constitute a Poisson process on the plane with intensity (sensor density) $\lambda$, it has been proved that:

- **Theorem 2:** The expected area of a sorted order-$K$ Voronoi cell, that corresponds to a Poisson point process with intensity $\lambda$, is bounded by the expression:

$$E[X_K] \leq \frac{1}{(2K - 1)\lambda}$$

- More details in:
Simulation Results

- Better RMS error than other model-independent approaches
- POCS and ML assume known model
- The no. of active nodes increases by increasing the density

- Smaller number of nodes taken into account
- All other methods are in the diagonal
- Two bars → A1 and A2 algs.
- Grey bars: no. of nodes in correct rank
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The P-2-P AWGN link

- Basic performance measures:
  - Signal-to-noise ratio
    \[ SNR = \frac{E[|X_n|^2]}{E[|Z_n|^2]} = \frac{P}{N} \]
  - Probability of error
    \[ P_e = \alpha \cdot Q\left(\sqrt{\beta \cdot SNR}\right) \leq \alpha \cdot e^{-\beta \cdot SNR} \]
  - Capacity
    \[ C = \log_2 \left(1 + SNR\right) \text{ bits/channel use} \]
P-2-P fading link

- The channel $h$ is random:
  - Average receive SNR
    \[
    SNR = \frac{E[|h \cdot X_n|^2]}{E[|Z_n|^2]} = \frac{P}{N}
    \]
  - Mean probability of error
    \[
    P_e \approx \frac{\alpha}{\beta \cdot SNR}
    \]
    (much larger than before !)
  - Capacity: not so simple to define...

Wireless Channel is hostile
Receive Diversity: A remedy

- If $h \sim CN(0, I_M)$ then $P_e \approx \frac{c}{SNR^M}$. Diversity order

- With the same transmit power, dramatically smaller error probability

- However
  - Expensive receivers (M downconversion chains)
  - M cannot be large if the receiver is a mobile
Transmit Diversity: Another remedy

- If $h \sim CN(0, I_M)$ then $P_e \approx \frac{c}{SNR^M}$
- Transmit beamforming (CSI is needed)
- Space-Time coding

$$y_n = h^T \cdot x_n + z_n, \quad h = \begin{bmatrix} h_1 \\ \vdots \\ h_M \end{bmatrix}$$
TX & RX Diversity: MIMO system

- Maximum achievable diversity order = $N \times M$
- Capacity: $C_{\text{MIMO}} = r \times C_{\text{AWGN}}$ ($r$=multiplexing gain)
- Multiplexing – Diversity Trade-off

$y_n = H \cdot x_n + z_n$
Antenna diversity - conclusion

- Exploitation of antenna diversity improves drastically P-2-P fading channel reliability
  - Drawback: Expensive transmitters and/or receivers

- Question: Is it possible to use (many) simple mobile devices and efficiently construct virtual multiple-antenna systems?

- Answer: In some cases, YES
Cooperative Communications

- Initial **Information Theoretic** studies appeared in the 70’s (van der Meulen, Cover – El Gamal)

- **Problem:** A source $S$ wants to transmit information to the destination $D$; the relay $R$ simply helps (does not generate new messages). What is the capacity of this scheme?

- In the general case, the capacity is **unknown**!
Cooperative Protocols

- Most of the recently proposed protocols are:
  - Half-duplex (relay does not receive and transmit at the same time)
  - Usually orthogonal (no interference between transmissions $S \to D$ and $R \to D$)

- Time Slot 1:
  - $S$ sends a codeword to $D$ (received also by $R$)

- Time Slot 2
  - $R$ decodes and transmits a re-encoded codeword (decode-and-forward)
  - $R$ amplifies the received signal and retransmits it (amplify-and-forward)
  - if $R$ is not able to decode, it sends nothing (selective decode-and-forward)
  - The node $S$ may send or may not send a new codeword in the 2nd time slot
• Part A: A Brief Introduction to WSNs
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Distributed Source Coding

• A number of wireless sensor nodes has been deployed over a territory of interest

• Each such node, measures one (or more) physical variables of interest

• The Sensor Reachback Problem: Find an energy efficient transmission protocol to send all measurements to a Sink Node
Two “key facts” to take into account

- The measurements of the sensors (especially when nodes are closely located) are correlated:

\[ H(X_i \mid X_j) < H(X_i) \]

- Cooperative communication can offer considerable power savings

We will try to take into account both facts
**Distributed Source Coding**

**A simple protocol:**

- Each node compresses the measurements it gathers at a rate equal to their entropy (*Correlation is not taken into account*)

- Each node communicates with the sink node using a direct AWGN channel with channel gain equal to $\gamma_n$. The power $P_i$ is dictated by the Sink (*Cooperative communication not considered*)

\[
\begin{align*}
X_1 & \rightarrow \quad \text{Rate } R_1 = H(X_1), \text{ Power such that } R_1 \leq \log_2 (1 + \gamma_1 P_1) \\
X_2 & \rightarrow \quad \text{Rate } R_2 = H(X_2), \text{ Power such that } R_2 \leq \log_2 (1 + \gamma_2 P_2) \\
X_N & \rightarrow \quad \text{Rate } R_N = H(X_N), \text{ Power such that } R_N \leq \log_2 (1 + \gamma_N P_N)
\end{align*}
\]
The “optimal matching” protocol (Roumy and Gesbert, 07)

- The protocol considers Distributed Source Coding in pairs of nodes.
- The most power-efficient pair of rates \((R_i,R_j)\) in the Slepian-Wolf rate region is computed, for all possible pairs of nodes (i.e., the optimal point in the line segment).
The “optimal matching” protocol (cont.)

- The most power-efficient matching of the nodes into pairs is selected using a graph theoretic algorithm.
- Pairs of nodes compress the measurements they gather at a rate equal to their joint entropy (Most of the correlation is taken into account).
- Each node communicates with the sink node using a direct AWGN channel with SNR equal to $\gamma_n$ (Cooperative comm. not considered).
- The Sink dictates to each node the $R_i$ and the $P_i$.
- (Why pairs and not triads or n-tuples?)

$$(X_1, X_2) \rightarrow \text{Rate } R_1 + R_2 = H(X_1, X_2), \text{ Optimal Power}$$

$$(X_3, X_4) \rightarrow \text{Rate } R_3 + R_4 = H(X_3, X_4), \text{ Optimal Power}$$

$$(X_{N-1}, X_N) \rightarrow \text{Rate } R_{N-1} + R_N = H(X_{N-1}, X_N), \text{ Optimal Power}$$
An extension of the protocol

We consider the case where each sensor node is given the option to either use the direct link, or cooperate with a neighbouring sensor node to send its data to the sink node, depending on which option is more power efficient.

\[ P_i = f_i(R_i) = \min \left\{ \frac{2^{R_i} - 1}{\gamma_i}, \frac{4 \cdot 2^{R_i} - 1}{b_i} \right\} \]

\[ b_i = \max_m \left\{ \frac{\gamma_{i,m} \gamma_m}{\gamma_{i,m} + \gamma_m} \right\} \]

\( b_i \) is the combined channel gain of \( i \rightarrow m \) and \( m \rightarrow \text{Sink} \)
An extension of the protocol

Summary of the “optimal cooperative matching” protocol

Part 1: For each node perform the “best relay selection” procedure

Part 2: For each pair of sensors find the minimum pair power (in the S-W sense), (the minimization of P turns out to be performed wrt to one variable, $R_i$)

Part 3: Optimal matching using a graph theoretical algorithm (weighted matching)
An extension of the protocol

The “optimal cooperative matching” protocol:

- Requires only a slightly more difficult optimization problem to be solved, for each pair of nodes

- Is able to take into account both (a) correlation of the sources and (b) cooperative communication, in order to achieve power savings

- In terms of performance
  - More power efficient
  - Increased probability for a solution to exist (i.e., all nodes can afford the transmission power dictated by the Sink)
Simulation Parameters

- A number of sensor nodes were randomly placed in the unit square, and the sink node was placed at point (0,0).

- The gain of the channel between nodes $i$ and $j$ was random, and exponentially distributed with

$$E[\gamma_{i,j}] = E[\gamma_{j,i}] = \frac{1}{\|\mathbf{r}_i - \mathbf{r}_j\|^2}$$

- We assumed the correlation model:

$$H(X_i, X_j) = H(X_i) + \left(1 - \frac{1}{\|\mathbf{r}_i - \mathbf{r}_j\|} \right) \cdot H(X_i) \quad \text{(where } c = 1\text{)}$$
Results under a maximum power constraint

- The proposed protocol (green) required less power compared to the 'non-coop'
- Higher probability for a solution to exist
- For fairness only the experiments where both protocols had a solution were used in this plot
- Recall that 'no solution' means that at least one node cannot afford the required power
General Conclusions

• WSNs differ fundamentally from general data networks and they require the adoption of a different design paradigm
• In many cases they are application specific
• The energy and bandwidth constraints (and possibly the large scale) pose challenges to efficient resource allocation
• The design of a WSN requires the fusion of ideas from several disciplines
• Particularly interesting and important are the theories and techniques of distributed SP, cooperative communications and cross-layer design.
Thank you for your attention!