Signal Processing & Communication Issues in Sensor Networks

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EURASIP
European Association for Signal Processing

IEEE
Signal Processing Society

Research Team in relevant activities

- **Research Group @ Patras**
  - Kostas Berberidis, Professor
  - Dr. Vassilis kekatos (now with the Univ. of Minnesota)
  - 6 PhD students:
    - D. Ampeliotis, A. Lalos, C. Mavrokefalidis, C. Tsinos, V. Vlachos, G. Alexandropoulos

- **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

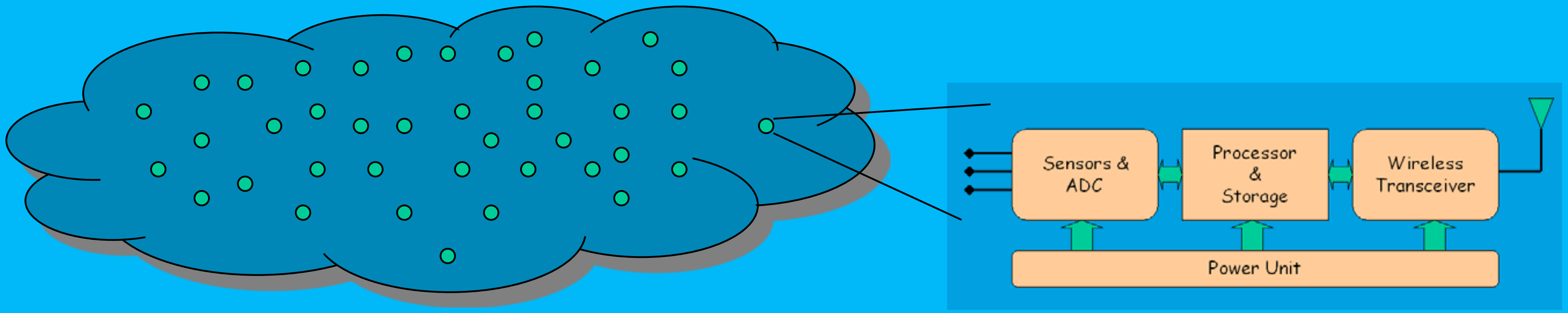
- **Part A: A Brief Introduction to WSNs**
- **Part B - 1st Case Study: Target Localization**
- **Part C: Cooperative Communications**
- **Part D - 2nd Case Study: Distributed Source Coding in WSNs**

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

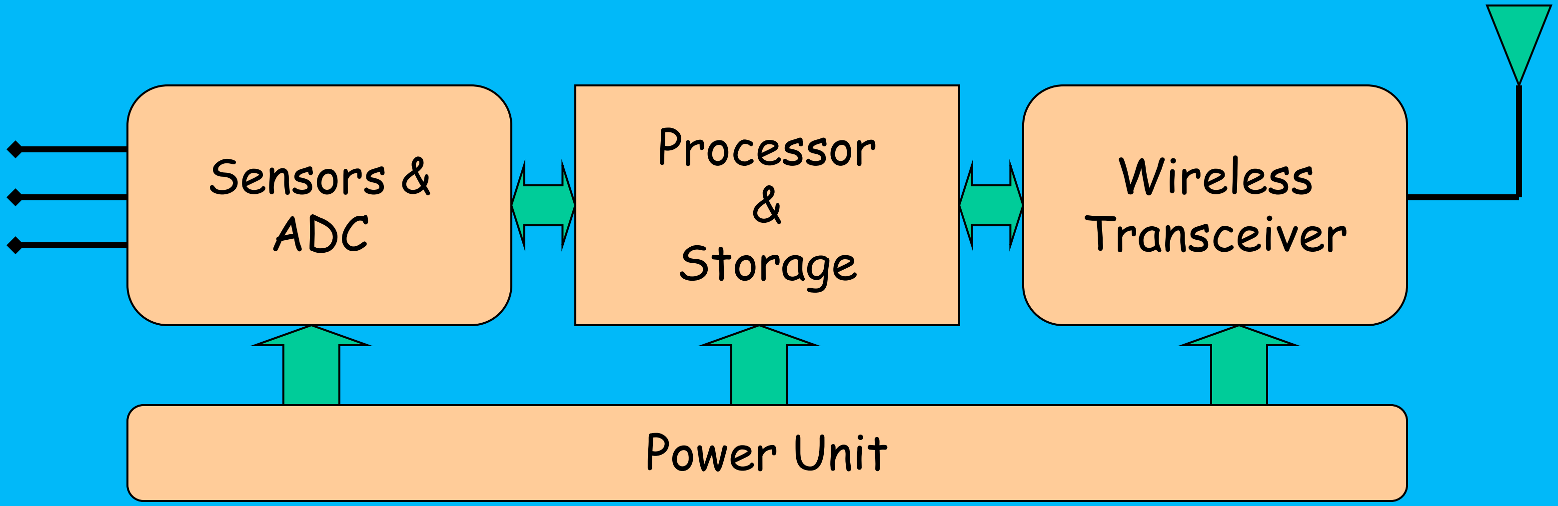
- **WSN: A Collection of sensor nodes, deployed to monitor an area of interest**



- **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.)

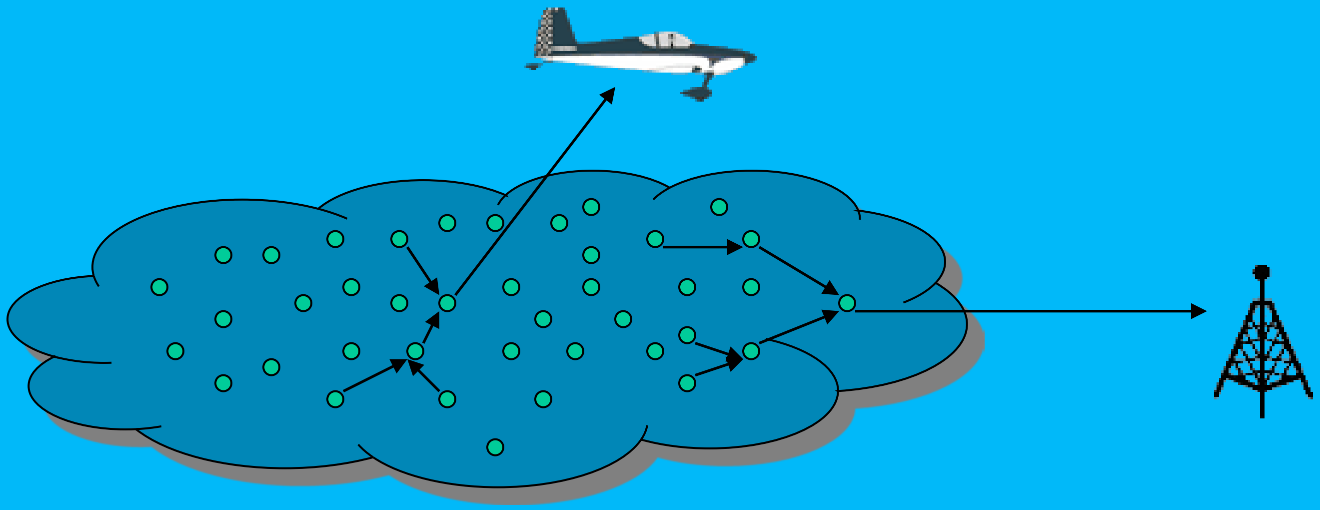
The Sensor Node

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



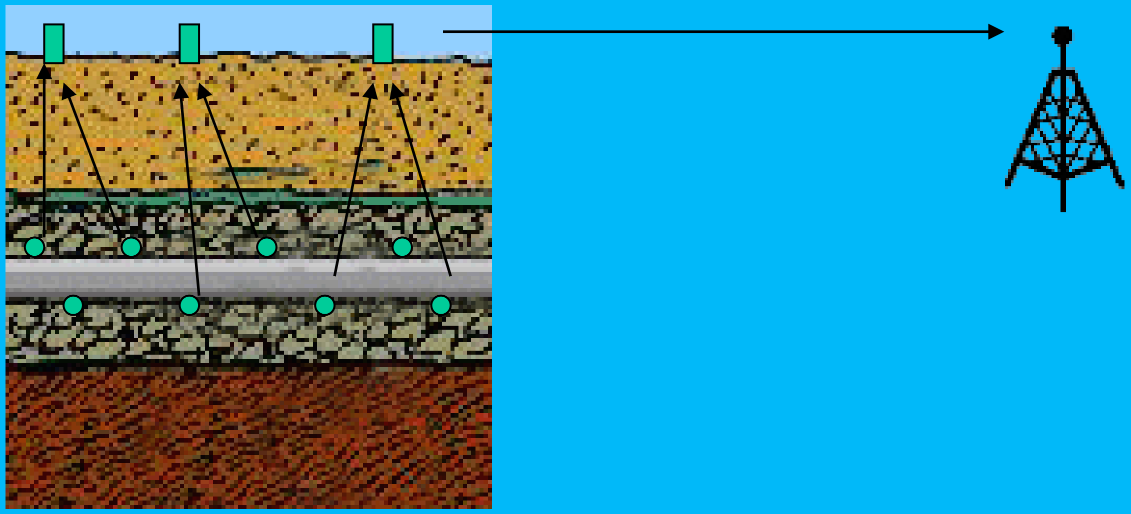
Types of WSNs

- **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)



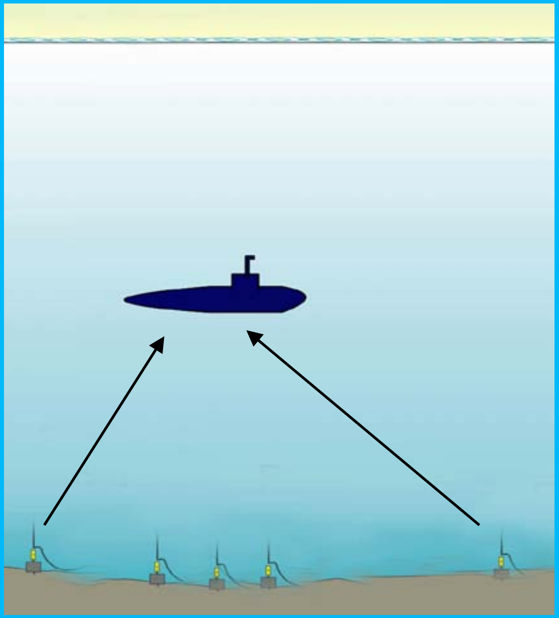
Types of WSNs

- **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



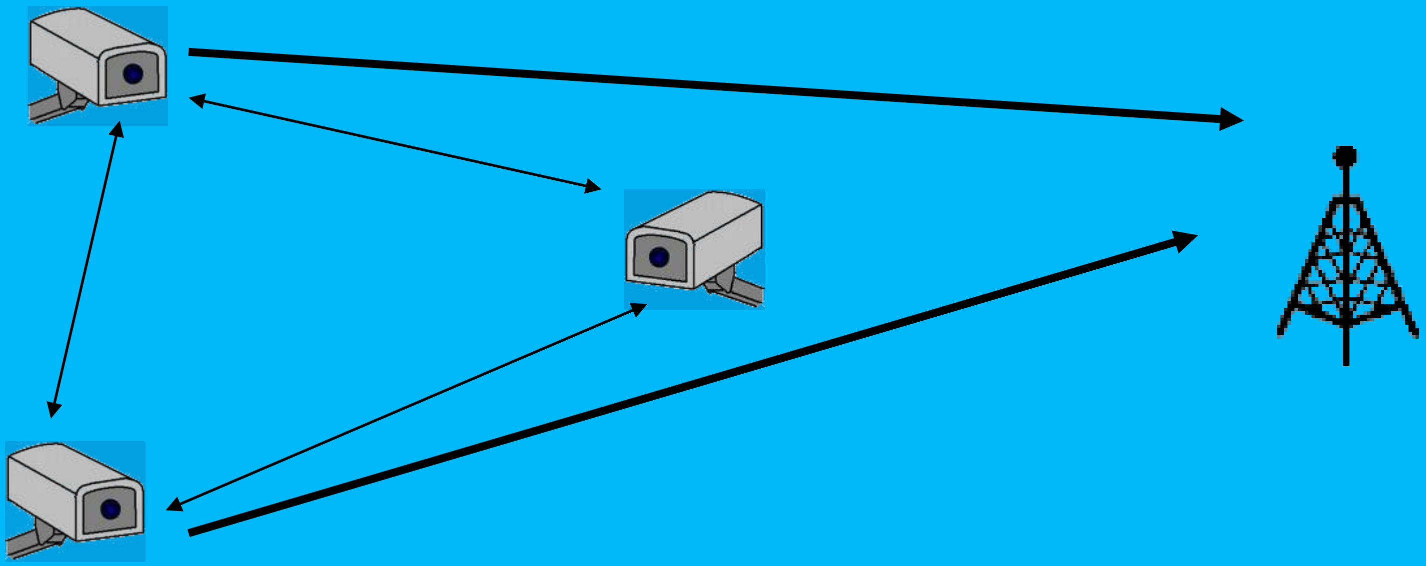
Types of WSNs

- **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



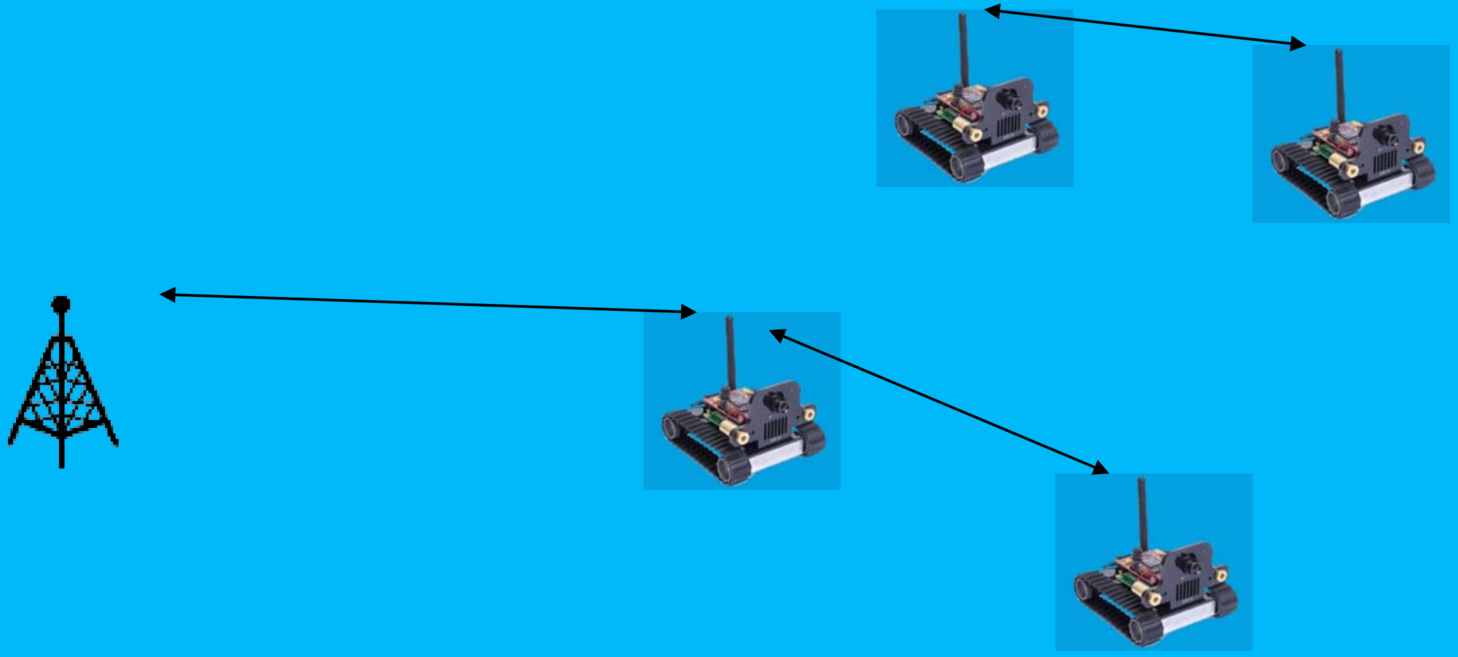
Types of WSNs

- **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

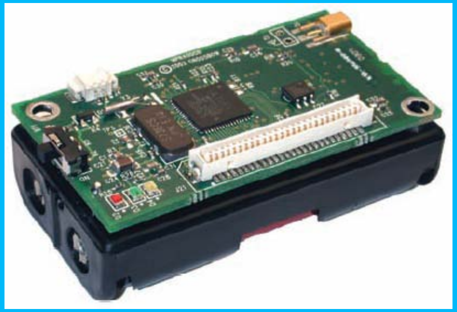
- **Management of natural disasters**
  - Detect events that need urgent treatment (e.g., earthquakes)
  - Provide a communication network for the rescue teams, in the case where the infrastructure has been destroyed
- **Environmental Applications**
  - Monitor the pollution of the atmosphere
  - Early detection of forest fires
  - Flood detection
  - Track populations of animals
  - Precision agriculture (Green Development)

Applications of WSNs

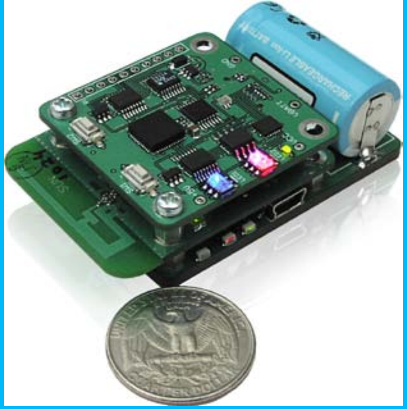
- **Health applications**
  - Tele-monitoring of human physiological data
  - Tracking and monitoring patients and doctors inside a hospital
  - Body Sensor Networks (BSNs)
- **Monitoring of constructions**
  - Detection of cracks / defects / corrosions …
  - Autonomous and progressive assessment of structural integrity of buildings / infrastructures
  - Active cancellation of oscillations in bridges
- **Security Applications**
  - Intrusion detection at sensitive facilities (power plants, military camps)

Existing Hardware

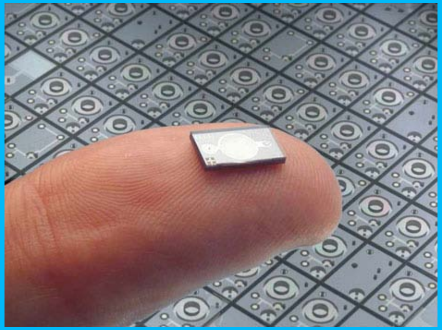
Crossbow MICAz/MICA2 Sensor



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

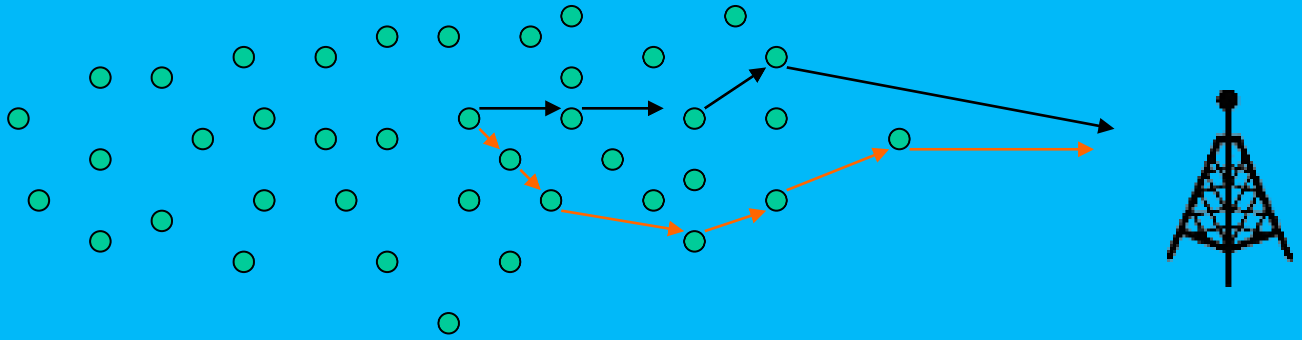
- Usually, the sensor nodes cannot be collected to replace their batteries
- In general, lifetime maximization is accomplished by
  - Minimizing the energy required to transmit data to the sink
  - Minimizing the energy left at the nodes of the network, when the WSN ceases to function

A new direction: Energy harvesting

- Produce energy from
  - Solar Panels
  - Ambient airflow
  - Mechanical motion
  - Pressure
  - Ambient/Targeted electromagnetism
  - Mobile robots to replenish energy

Research Issues in WSNs

Routing protocols



- 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' ?

David Graham as Big Brother in an Apple TV commercial

Research Issues in WSNs

… and many other important challenges related to:

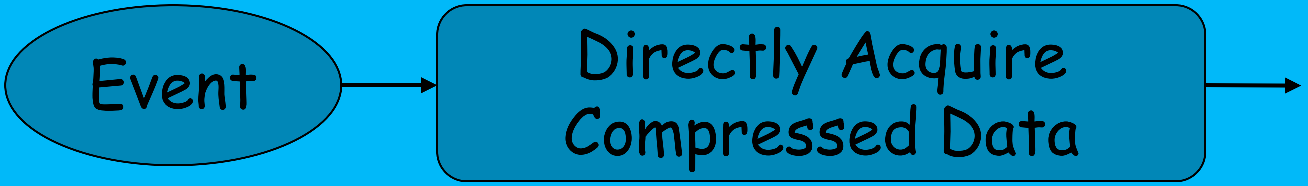
- Sensing and Hardware Platforms
- Operating Systems
- Storage procedures
- Simulation tools / Network Management tools …
- Testbeds

Signal Processing in WSNs

Data Acquisition

- The classical paradigm of acquiring measurements:

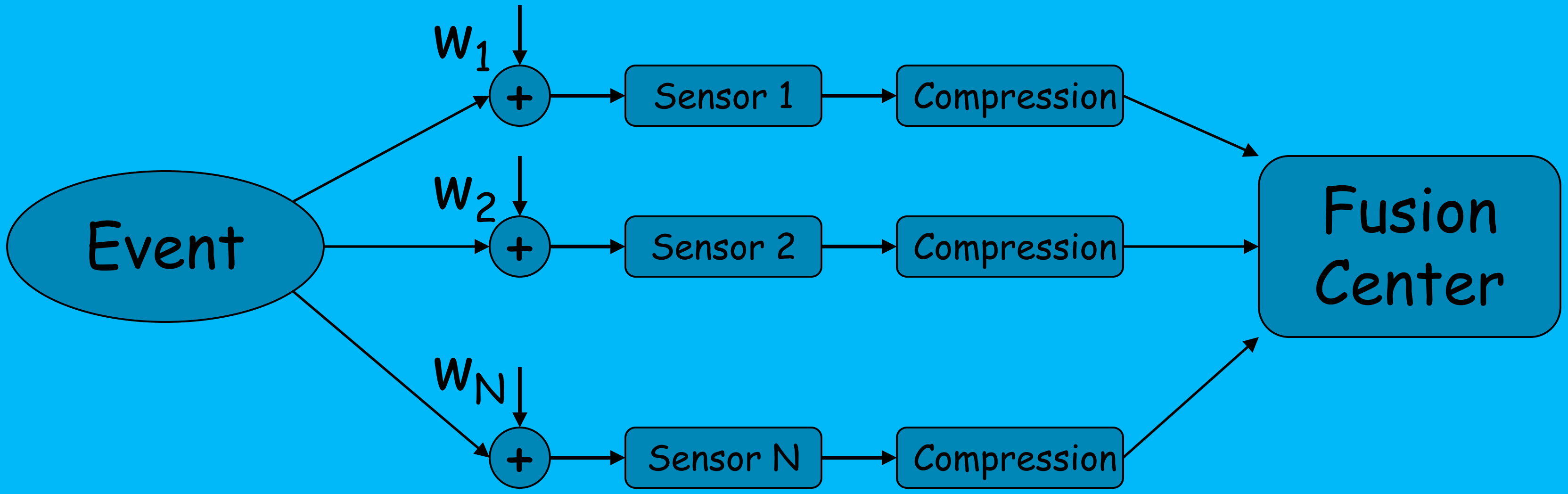
- The approach of "Compressed Sensing":



- It can dramatically reduce the number of transmissions to the Sink

Signal Processing in WSNs

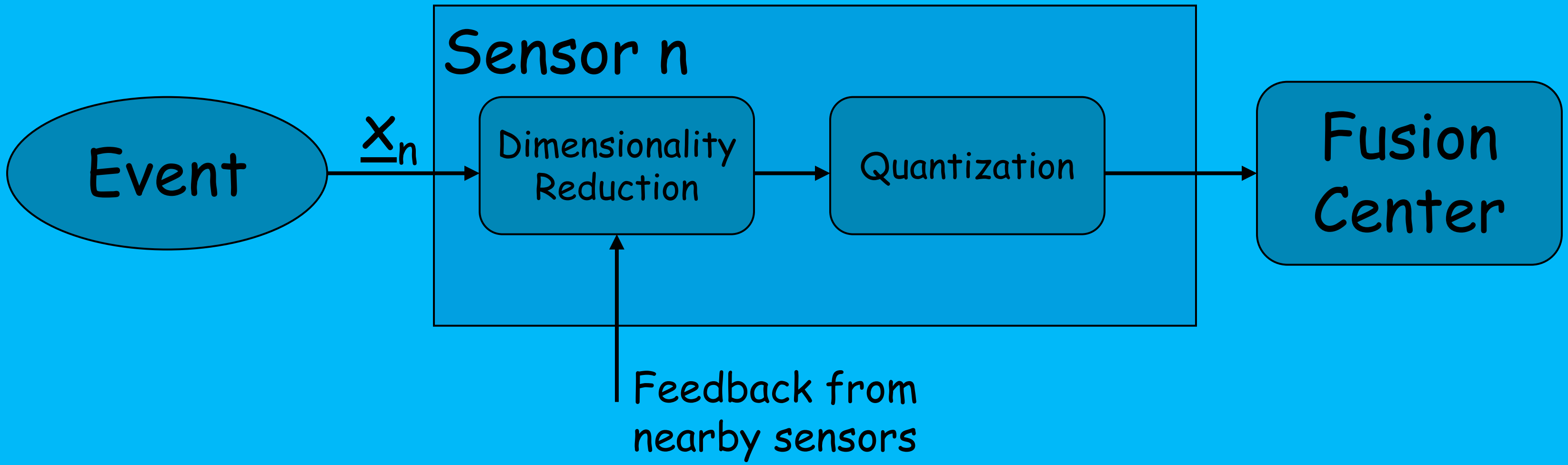
Distributed Detection



- 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

Signal Processing in WSNs

Distributed Estimation under constraints



- Each sensor n measures a vector $\underline{x}_n$, 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

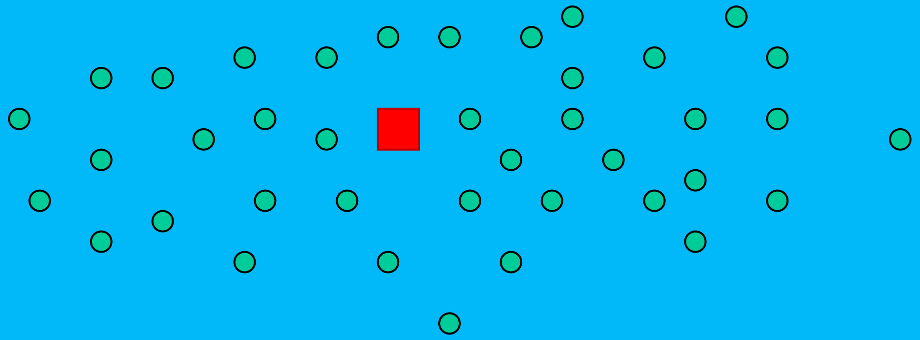
Signal Processing in WSNs

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?

Signal Processing in WSNs

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 polution sources
  - Teleconferencing

Signal Processing in WSNs

… and (again) many other important issues such as:

- Distributed Learning
- Node localization
- Synchronization

Talk Outline

- Part A: A Brief Introduction to WSNs
- **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

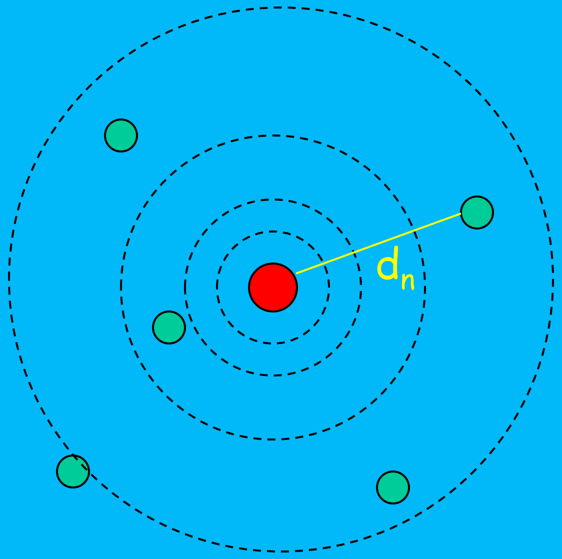
Target Localization

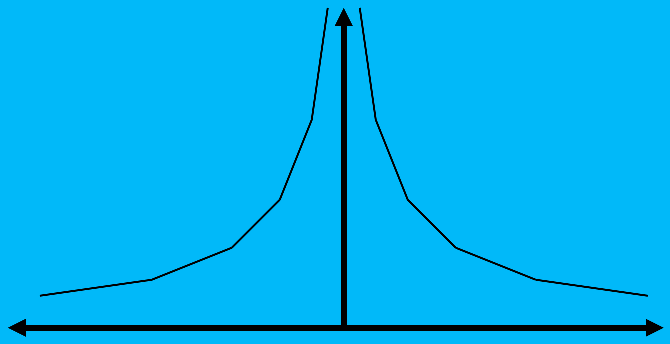
A sensor n **located at a distance** d_n **from the target takes a measurement equal to**

$$y_n = \alpha \cdot g(d_n) + w_n$$

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

$$g(d) = \frac{1}{d^{\beta}}$$





Target Localization

Problem formulation: Given the known locations

$$\mathbf{r}_n \qquad n \in \{1, 2, \dots, N\}$$

of the sensor nodes, the RSS measurements

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

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**

Literature

- **D. Li and Y.-H. Hu.** Energy-based collaborative source localization using acoustic microsensor array. *EURASIP J. Appl. Signal Process., 2003(1):321–337, 2003*

- **X. Sheng and Y.-H. Hu.** Maximum likelihood multiple-source localization using acoustic energy measurements with wireless sensor networks. *Signal Processing, IEEE Transactions on, 53(1):44–53, Jan. 2005.*

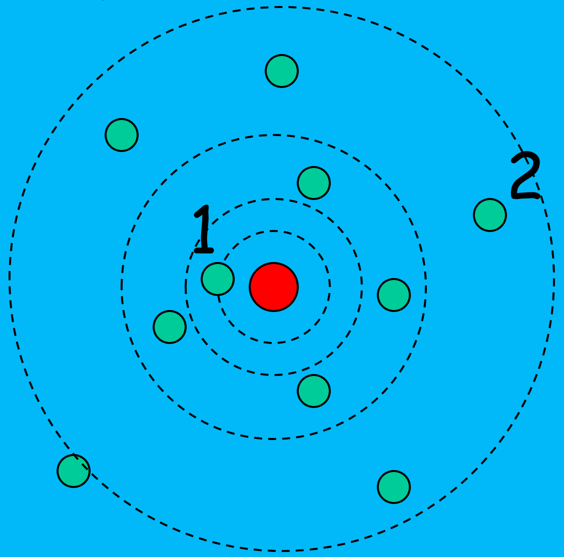
- **M. G. Rabbat, R. D. Nowak, and J. Bucklew.** Robust decentralized source localization via averaging. *In Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), pages 1057–1060, 2005*

- **D. Blatt and A. O. Hero.** Energy-based sensor network source localization via projection onto convex sets. *Signal Processing, IEEE Transactions on, 54(9):3614–3619, September 2006*

Target Localization

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

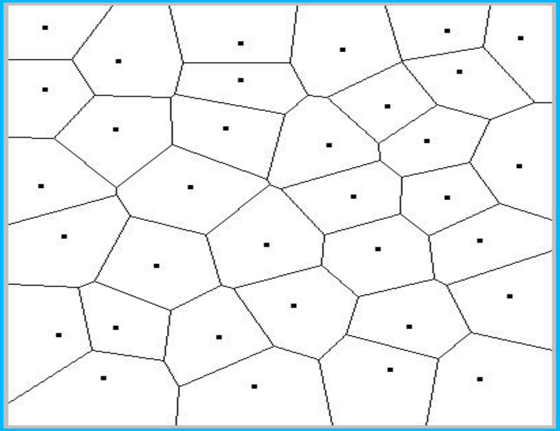
Target Localization

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

- **Definition 1:** Given a set of particles on the plane

$$\Phi = \{\mathbf{r}_1, \mathbf{r}_2, \cdots, \mathbf{r}_N\}$$

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

$$\mathbf{v} = \begin{bmatrix} \mathbf{r}_{k_1} & \mathbf{r}_{k_2} & \cdots & \mathbf{r}_{k_K} \end{bmatrix}, \qquad \mathbf{r}_{k_i} \in \Phi, \qquad \mathbf{r}_{k_i} \neq \mathbf{r}_{k_j}$$

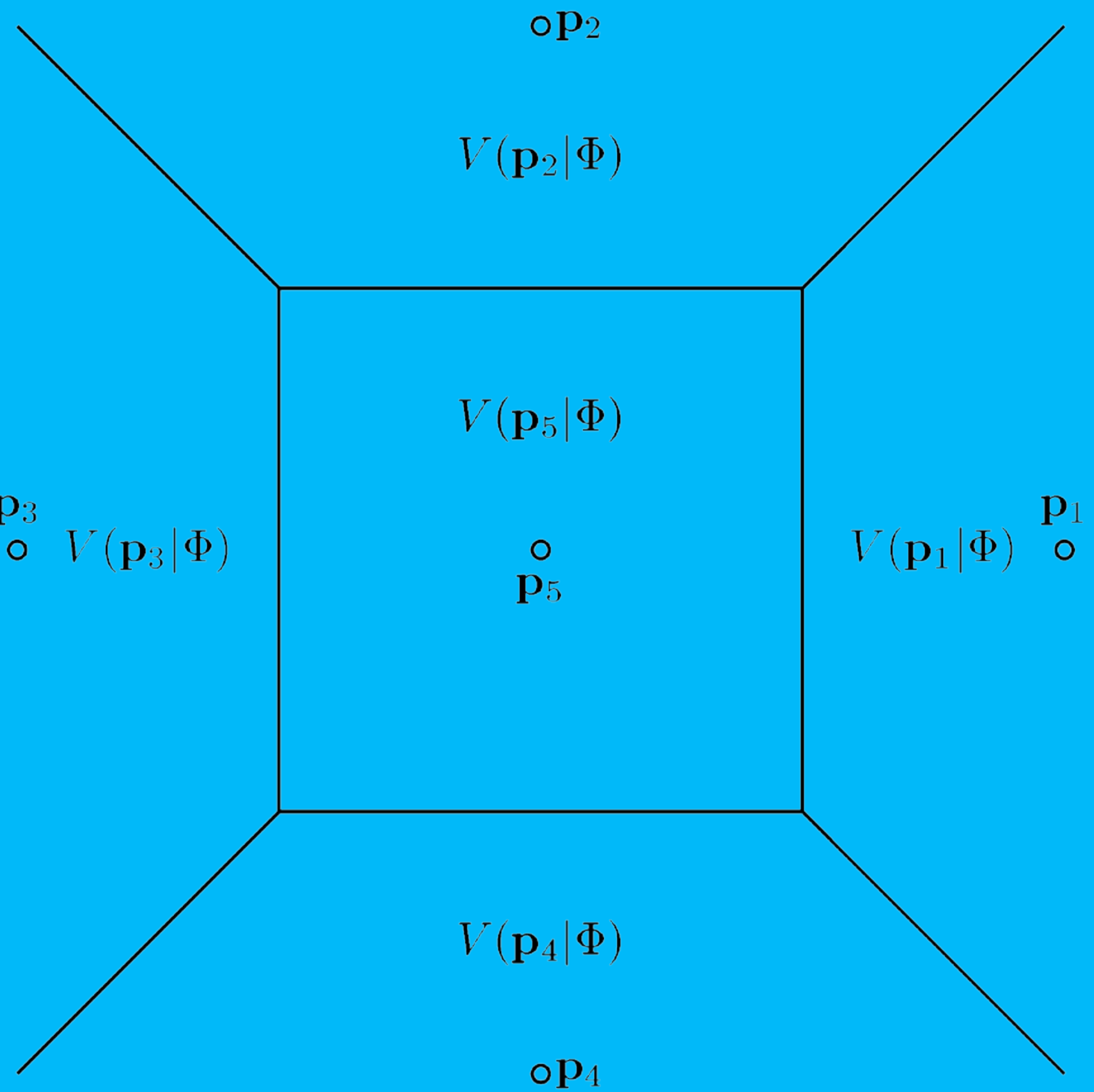
the *sorted order-K Voronoi cell* for this vector is the locus of points for which:

$\mathbf{r}_{k_1}$ is the closest particle, AND

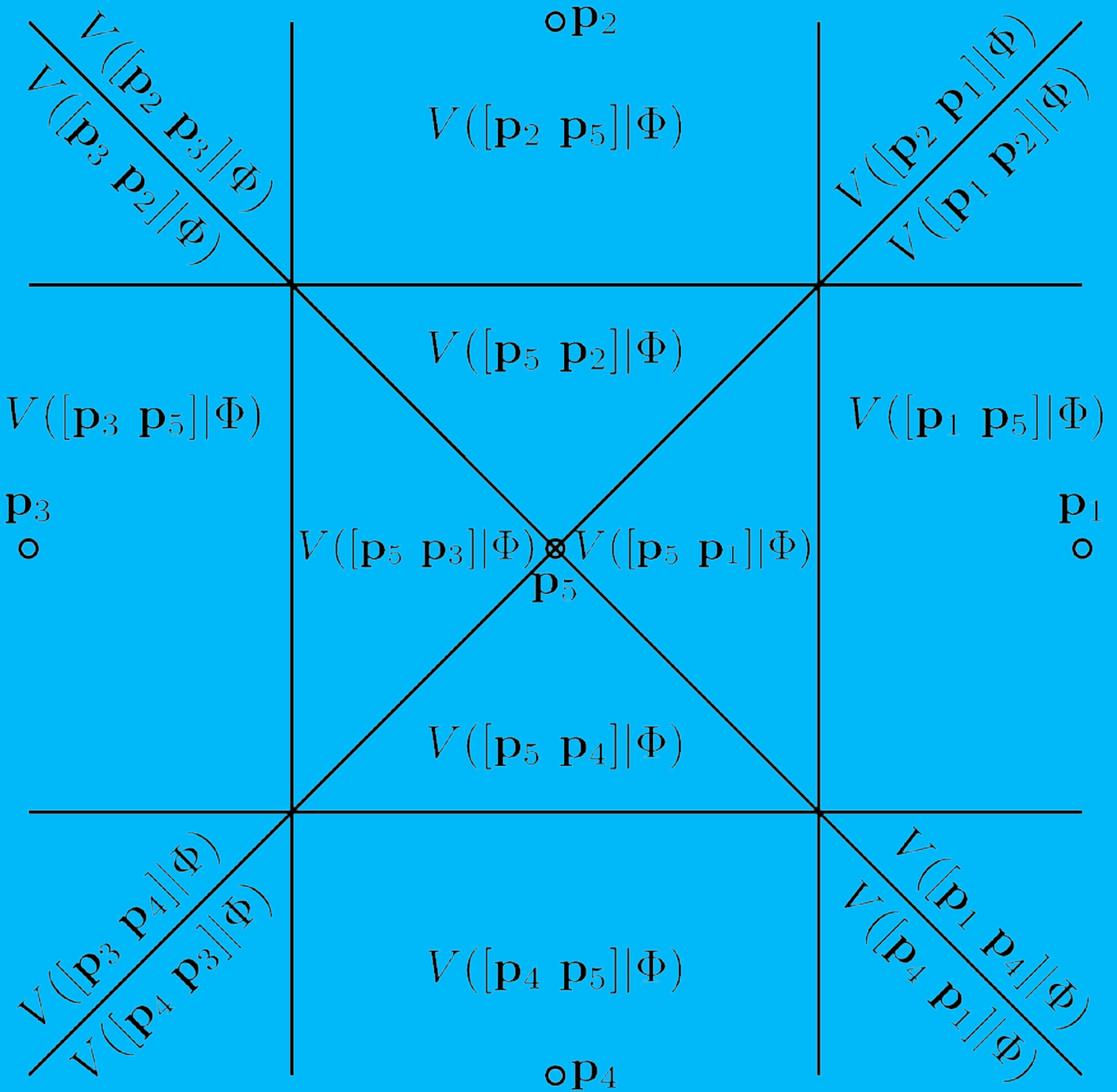
$\mathbf{r}_{k_2}$ is the second closest particle, … ,AND

$\mathbf{r}_{k_K}$ 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**

$$\mathbf{v} = \begin{bmatrix} \mathbf{r}_{k_1} & \mathbf{r}_{k_2} & \cdots & \mathbf{r}_{k_K} \end{bmatrix}, \qquad \mathbf{r}_{k_i} \in \Phi, \quad \mathbf{r}_{k_i} \neq \mathbf{r}_{k_j}$$

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:

$$C(\mathbf{x},a)=\sum_{n\in A}\left(y_n-a\cdot g\left(\left\|\mathbf{r}_n-\mathbf{x}\right\|\right)\right)^2$$

- In our case, a proper cost function is defined, which apart from $\mathbf{x}$ tries to identify a suitable energy decay function as well:

$$J(\mathbf{x},h(\cdot))=\sum_{n\in A}\left(y_n-h\left(\left\|\mathbf{r}_n-\mathbf{x}\right\|\right)\right)^2$$

Target Localization

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

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

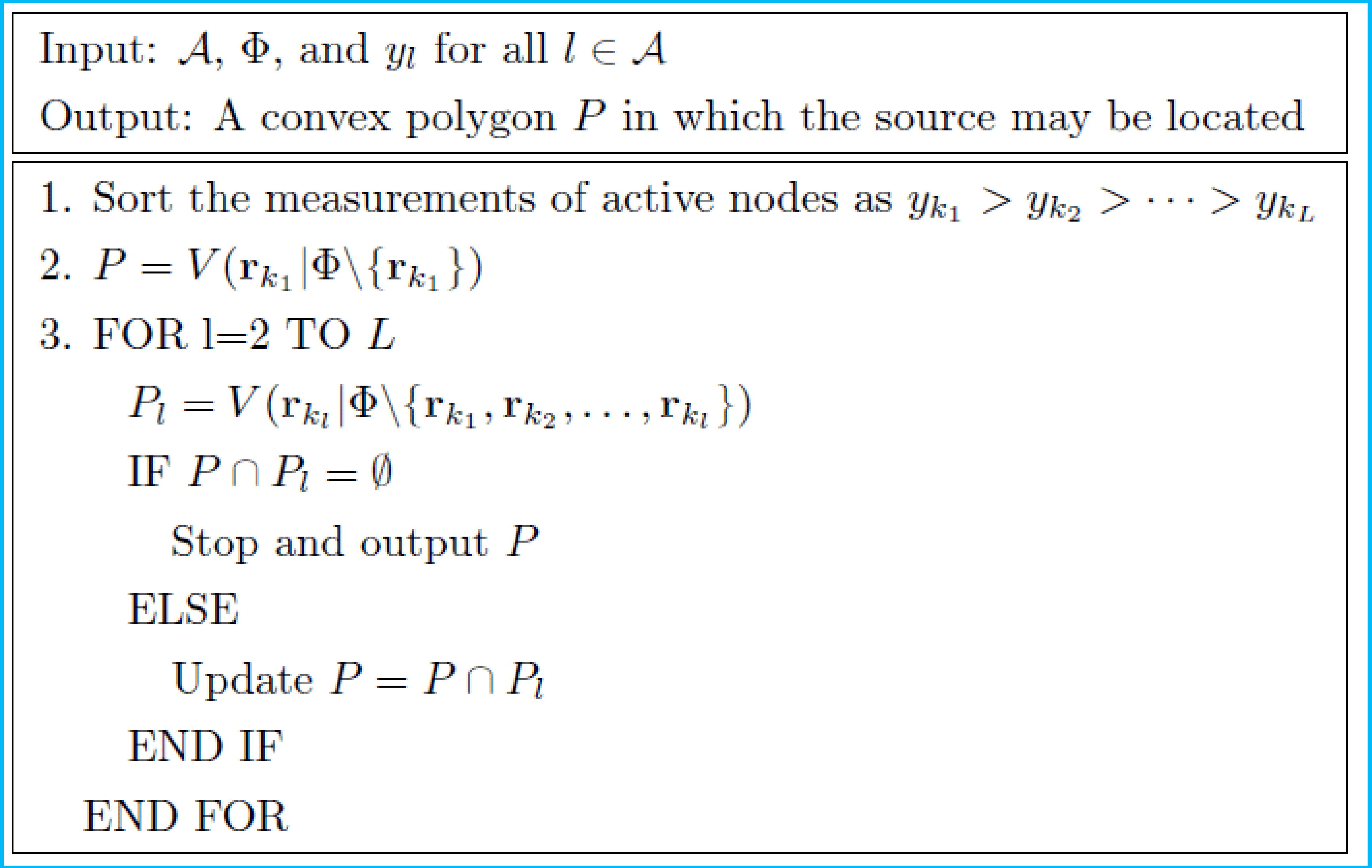
which is defined by the sorting of the respective RSS measurements as

$$y_{k_1} > y_{k_2} > \cdots y_{k_L}$$

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

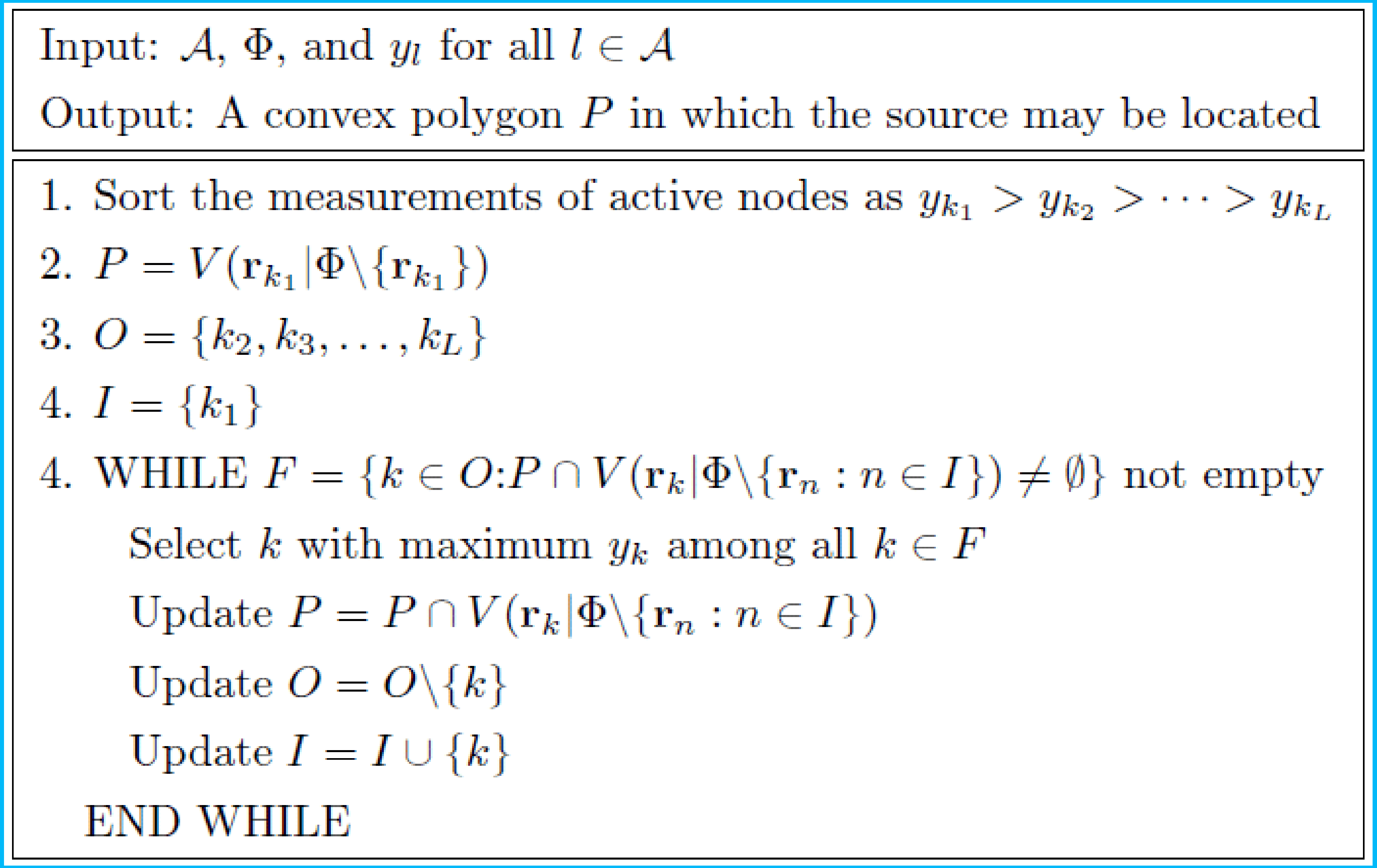


Input: $\mathcal{A}$, Φ, and y_l for all $l \in \mathcal{A}$

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. $P = V(\mathbf{r}_{k_1} | \Phi \backslash \{\mathbf{r}_{k_1}\})$
3. FOR l=2 TO $L$
       $P_l = V(\mathbf{r}_{k_l} | \Phi \backslash \{\mathbf{r}_{k_1}, \mathbf{r}_{k_2}, \ldots, \mathbf{r}_{k_l}\})$
       IF $P \cap P_l = \emptyset$
           Stop and output $P$
       ELSE
           Update $P = P \cap P_l$
       END IF
   END FOR
```

Algorithm A_2



```
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. $P = V(\mathbf{r}_{k_1} | \Phi \backslash \{\mathbf{r}_{k_1}\})$
3. $O = \{k_2, k_3, \ldots, k_L\}$
4. $I = \{k_1\}$
4. WHILE $F = \{k \in O : P \cap V(\mathbf{r}_k | \Phi \backslash \{\mathbf{r}_n : n \in I\}) \neq \emptyset\}$ not empty
      Select $k$ with maximum $y_k$ among all $k \in F$
      Update $P = P \cap V(\mathbf{r}_k | \Phi \backslash \{\mathbf{r}_n : n \in I\})$
      Update $O = O \backslash \{k\}$
      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) λ, it has been proved that:

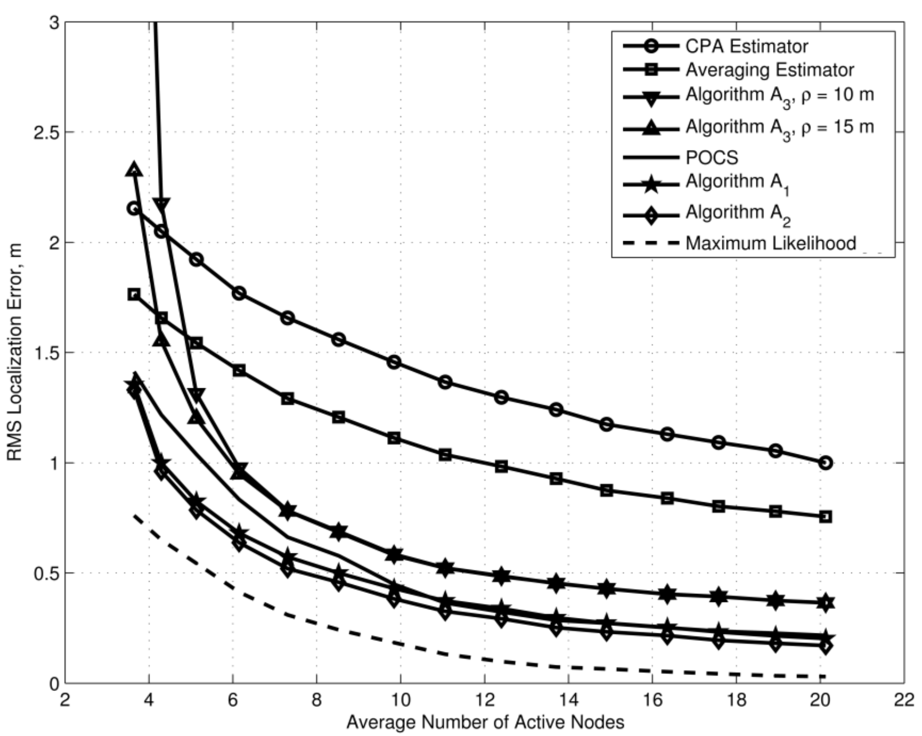
- **Theorem 2:** The expected area of a sorted order-K Voronoi cell, that corresponds to a Poisson point process with intensity λ, is bounded by the expression:

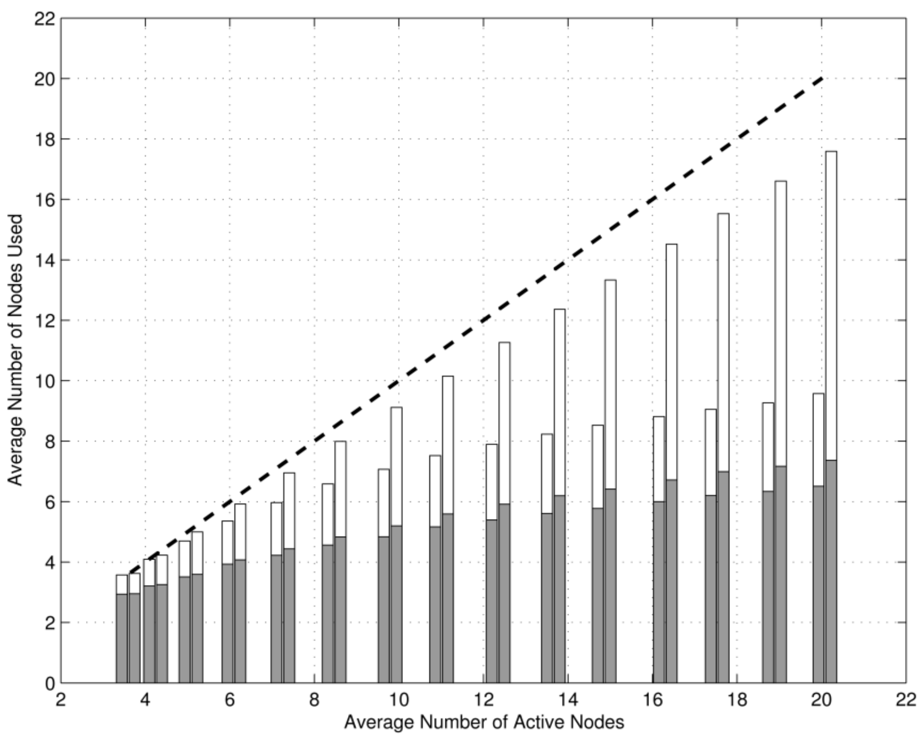
$$E\left[X_K\right] \leq \frac{1}{(2K-1)\lambda}$$

- More details in:

  D. Ampeliotis and K. Berberidis, "Sorted Order-K Voronoi Diagrams for Model-Independent Source Localization in Wireless Sensor Networks", IEEE Trans. on Signal Processing. To appear first quarter of 2010.

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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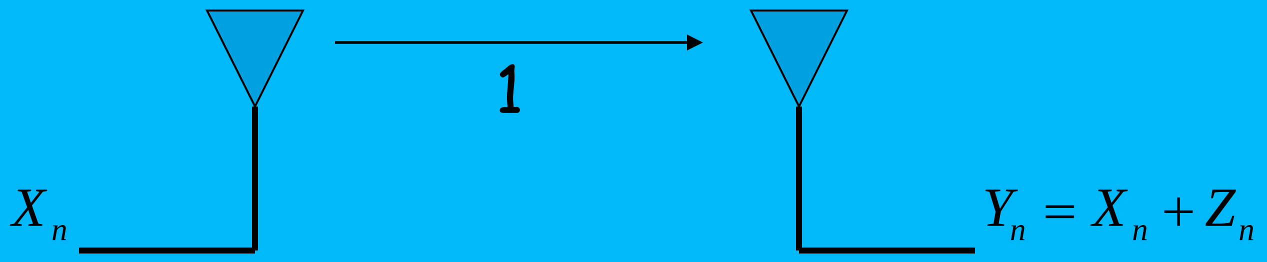
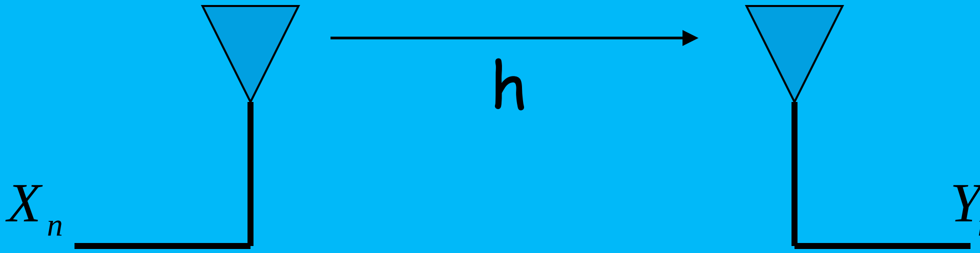
The P-2-P AWGN link



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

P-2-P fading link



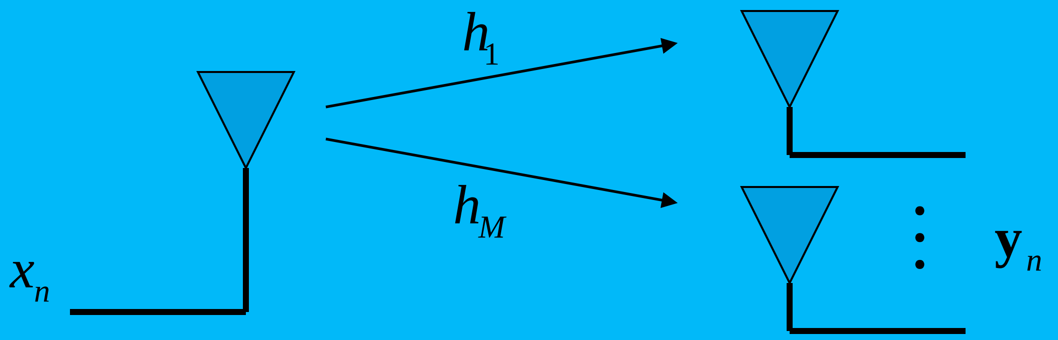
$$Y_n = h \cdot X_n + Z_n$$

$$h \sim CN(0,1)$$

- **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

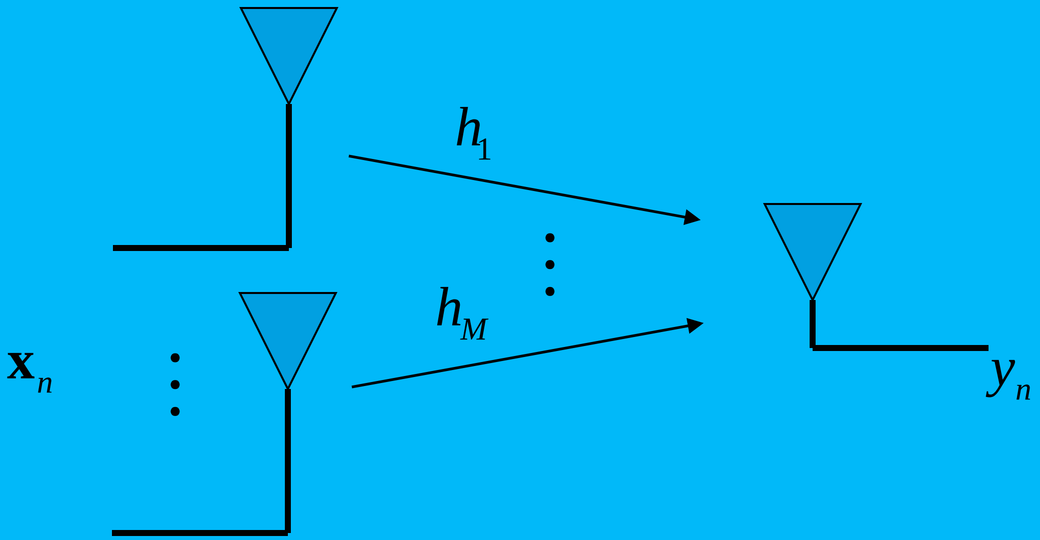
Receive Diversity: A remedy



$$\mathbf{y}_n = \mathbf{h}\cdot x_n + \mathbf{z}_n, \qquad \mathbf{h} = \begin{bmatrix} h_1 \\ \vdots \\ h_M \end{bmatrix}$$

- **If** $\mathbf{h} \sim CN(\mathbf{0}, \mathbf{I}_M)$ **then** $P_e \approx \dfrac{c}{SNR^M}$ ← 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

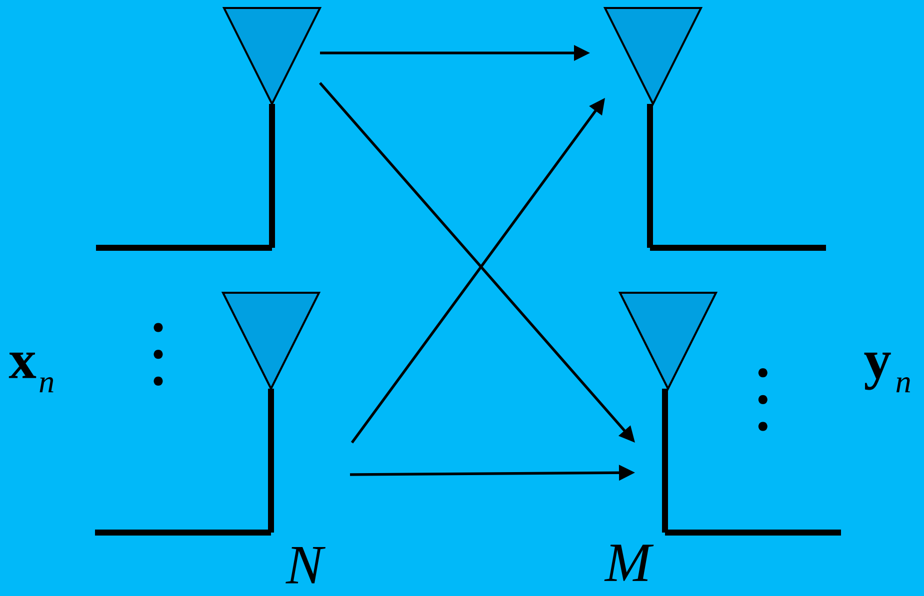
Transmit Diversity: Another remedy



$$y_n = \mathbf{h}^T \cdot \mathbf{x}_n + z_n, \qquad \mathbf{h} = \begin{bmatrix} h_1 \\ \vdots \\ h_M \end{bmatrix}$$

- **If** $\mathbf{h} \sim CN(\mathbf{0}, \mathbf{I}_M)$ **then** $P_e \approx \dfrac{c}{SNR^M}$ ← Diversity order
- **Transmit beamforming (CSI is needed)**
- **Space-Time coding**

TX & RX Diversity: MIMO system



$$\mathbf{y}_n = \mathbf{H} \cdot \mathbf{x}_n + \mathbf{z}_n$$

- **Maximum achievable diversity order = N×M**
- **Capacity: C(MIMO)=r×C(AWGN) (r=multiplexing gain)**
- **Multiplexing – Diversity Trade-off**

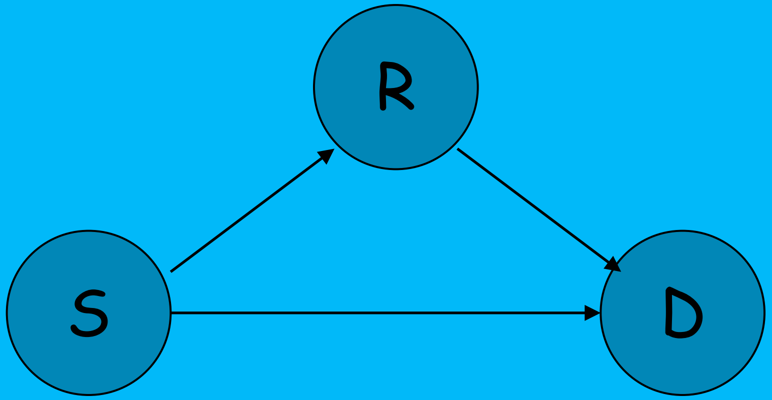
Antenna diversity - conclusion

- **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→D and R→D)

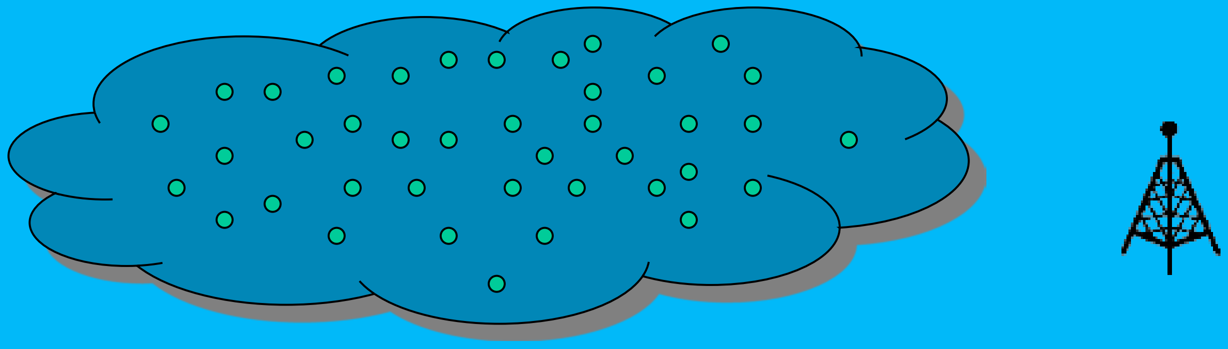
- **Time Slot 1:**
  - S sends a codeword to D (received also by R)

- **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

Talk Outline

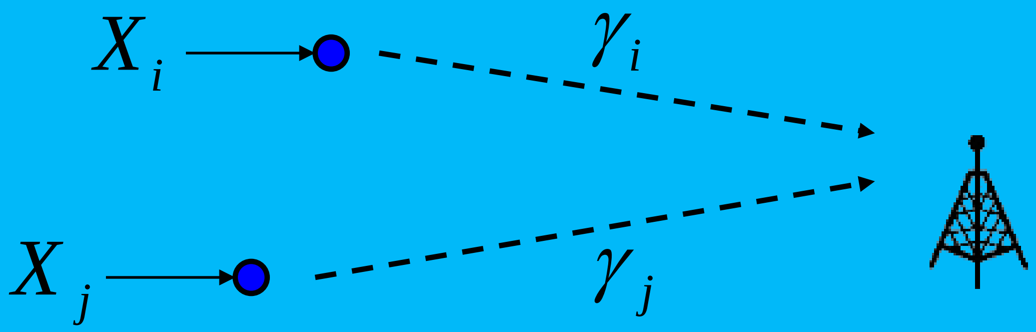
- Part A: A Brief Introduction to WSNs
- Part B: Case Study: Target Localization
- Part C: Cooperative Communications
- **Part D: Distributed Source Coding in WSNs**

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

Distributed Source Coding



Two "key facts" to take into account

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

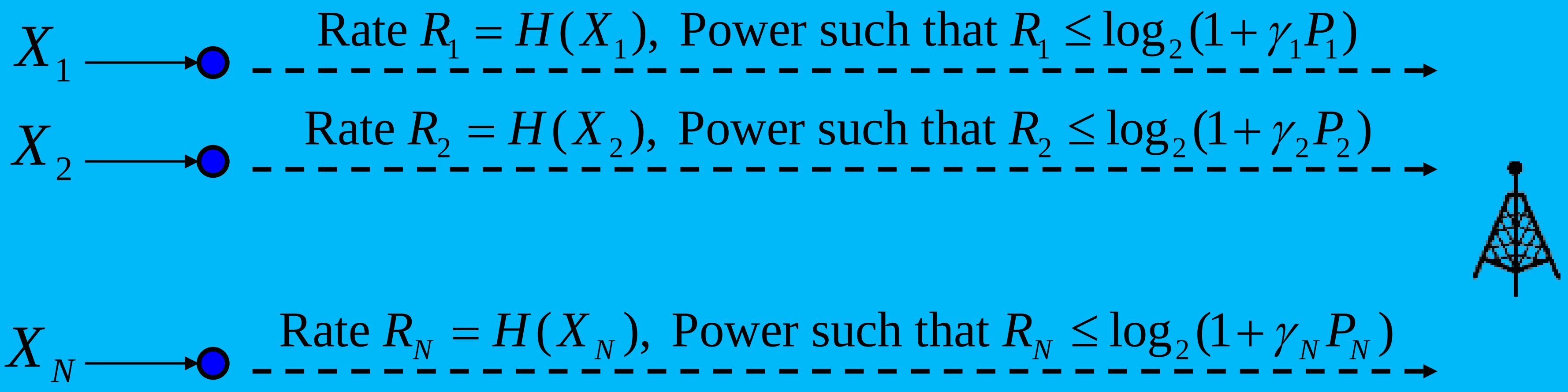
$$H(X_i \mid X_j) < H(X_i)$$

- Cooperative communication can offer considerable power savings

We will try to take into account both facts

Distributed Source Coding

A simple protocol:



X_1 — Rate $R_1 = H(X_1)$, Power such that $R_1 \le \log_2(1+\gamma_1 P_1)$

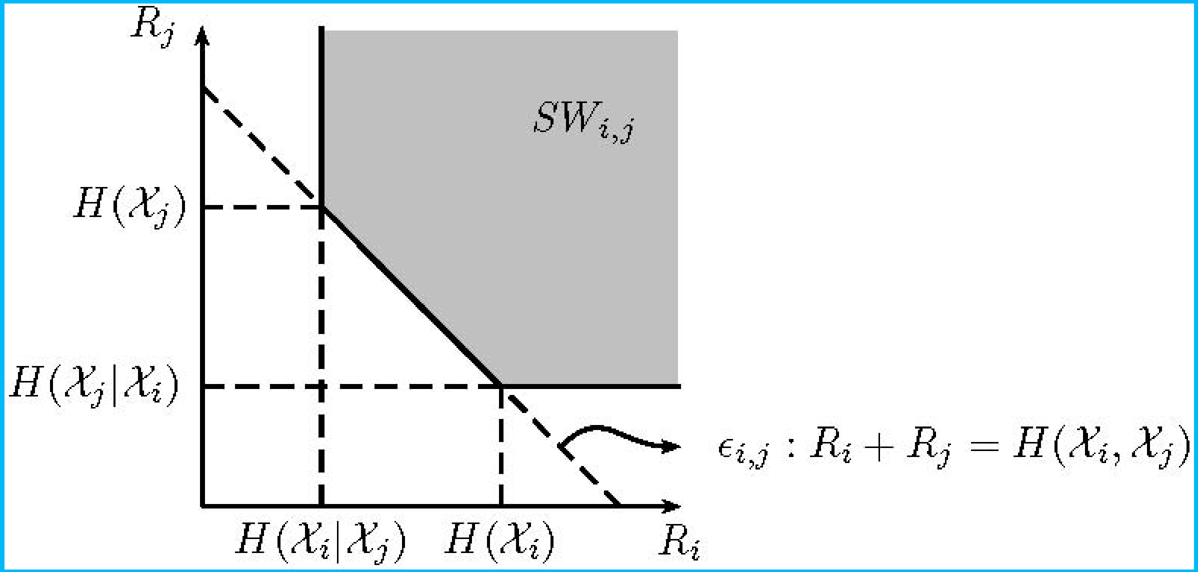
X_2 — Rate $R_2 = H(X_2)$, Power such that $R_2 \le \log_2(1+\gamma_2 P_2)$

X_N — Rate $R_N = H(X_N)$, Power such that $R_N \le \log_2(1+\gamma_N P_N)$

- 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 γ_n . The power P_i is dictated by the Sink (Cooperative communication not considered)

“Optimal Matching”

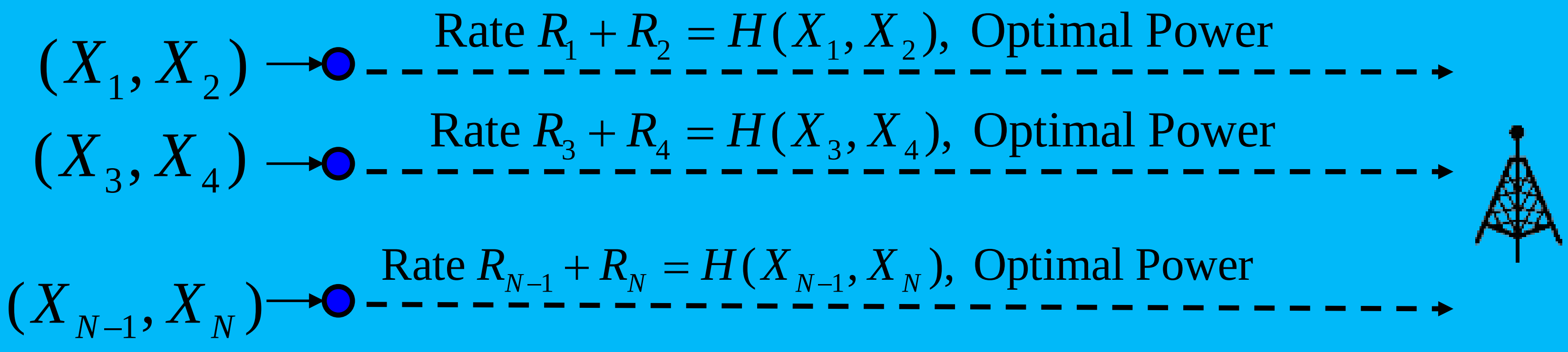
The “optimal matching” protocol (Roumy and Gesbert, 07)



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

"Optimal Matching"

The "optimal matching" protocol (cont.)



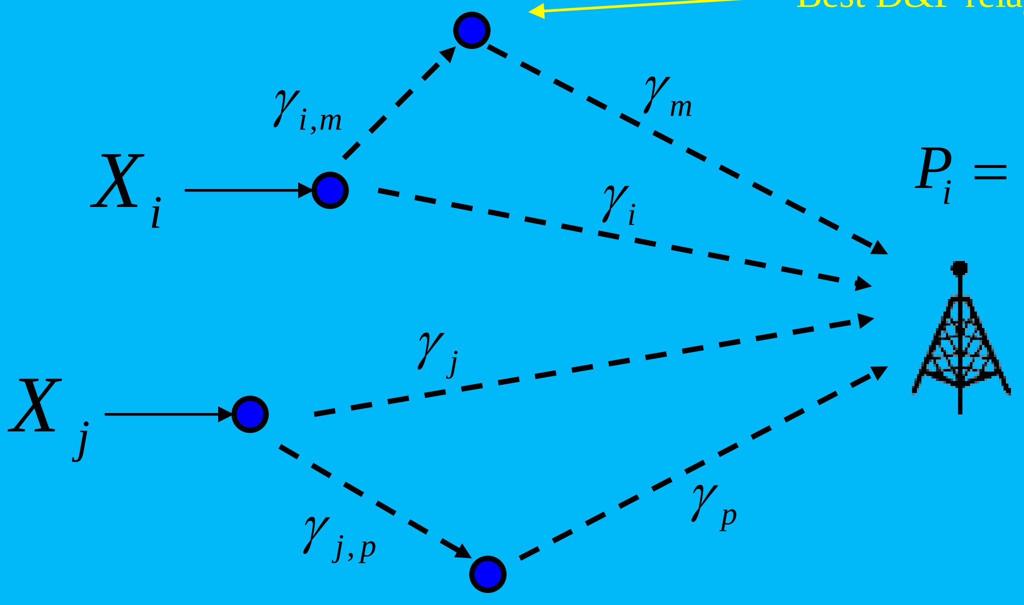
$(X_1, X_2) \rightarrow$ Rate $R_1 + R_2 = H(X_1, X_2)$, Optimal Power

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

$(X_{N-1}, X_N) \rightarrow$ Rate $R_{N-1} + R_N = H(X_{N-1}, X_N)$, Optimal Power

- 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 γ_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 ?)

An extension of the protocol



Best D&F relay for node *i*

Best D&F relay for node *j*

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

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

b_i *is the combined channel gain of* $i \rightarrow m$ *and* $m \rightarrow Sink$

- 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

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

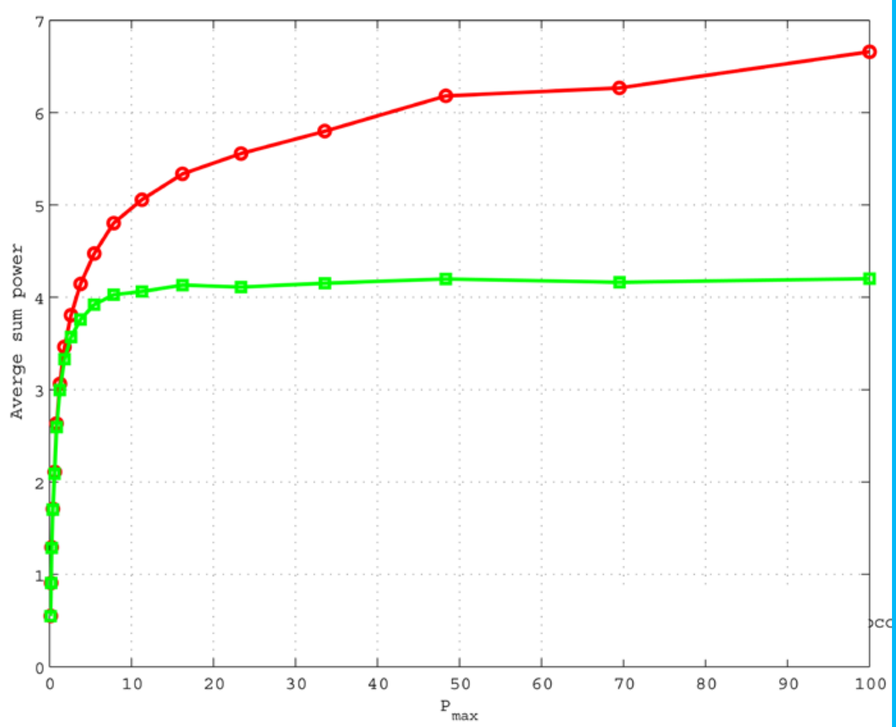
$$E[\gamma_{i,j}] = E[\gamma_{j,i}] = \frac{1}{\left\|\mathbf{r}_i - \mathbf{r}_j\right\|^2}$$

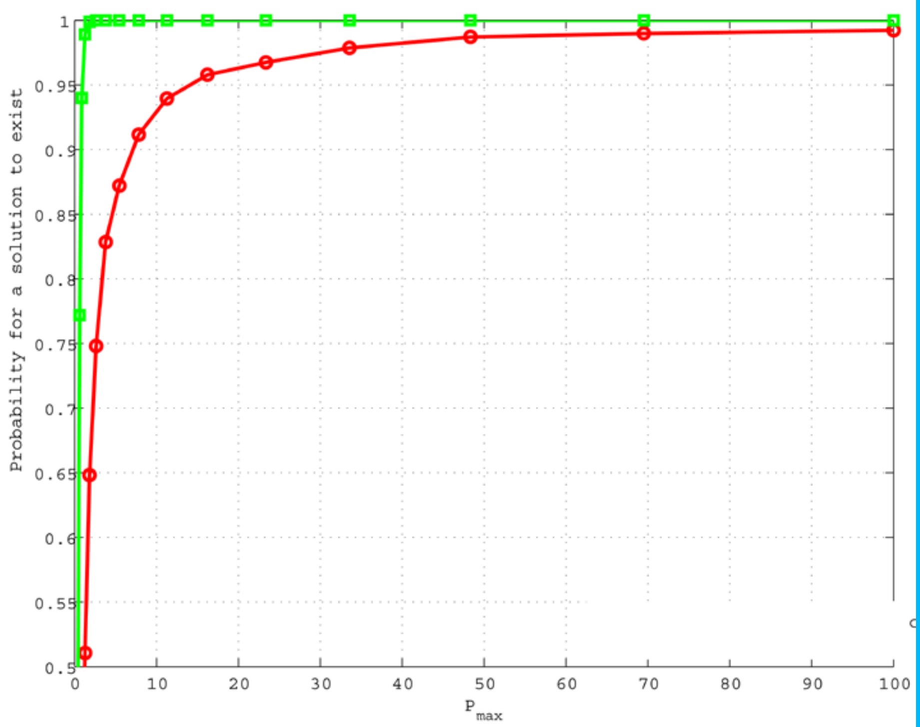
- We assumed the correlation model:

$$H(X_i, X_j) = H(X_i) + \left(1 - \frac{1}{1 + \frac{\left\|\mathbf{r}_i - \mathbf{r}_j\right\|}{c}}\right) \cdot H(X_i)$$

(where c = 1)

Results under a maximum power constraint





- The proposed protocol (green) required less power compared to the 'non-coop'
- For fairness only the experiments where both protocols had a solution were used in this plot

-Higher probability for a solution to exist

-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.

ΤΕΛΟΣ - FIN

Thank you
for your
attention !