The role of optimization in sensor networks: Localization and energy-aware routing

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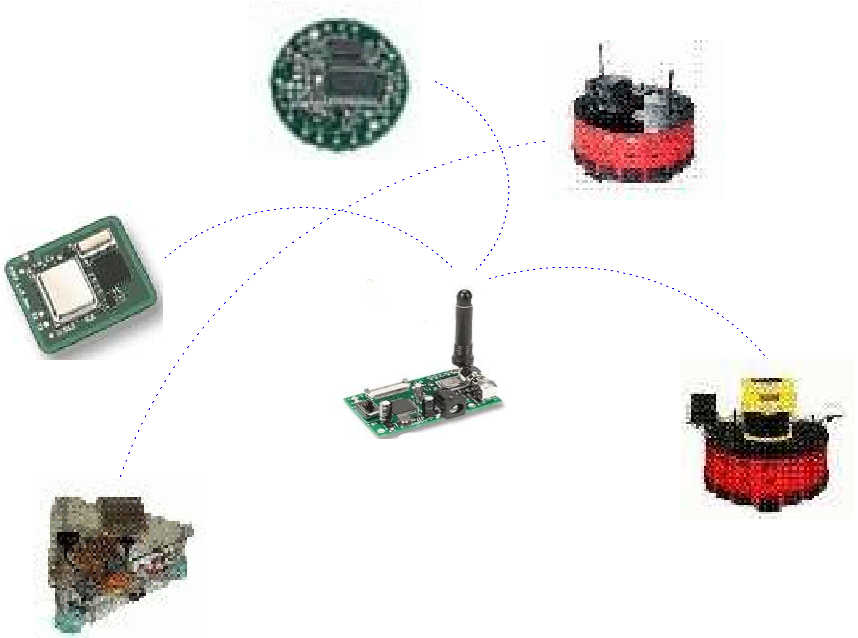
(joint work with **Saikat Ray**, **Wei Lai**, and **David Starobinski, BU**)

The CISE Sensor Network Consortium:

- MITRE, L3 Communications, Textron
- Crossbow, Echelon, Ember, Millennial Net, Sensicast
- Honeywell, IBM, Siemens
- BP, SAP
- Inetco, Radianse

The Application Context: Wireless Sensor Networks

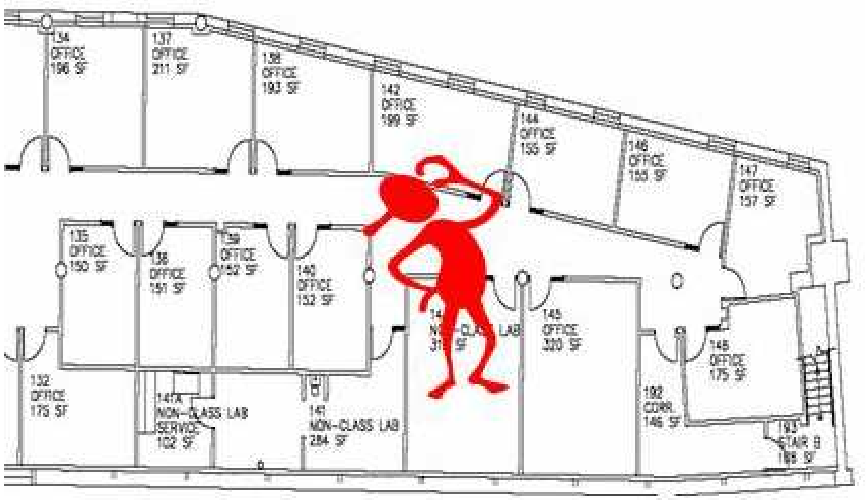


- **SNETs** consist of many (often small) devices — **the sensors**
- that communicate wirelessly, are powered by batteries, and have limited processing capabilities.
- Driving force: **wireless monitoring**, but ... they offer many opportunities for new functionality ...
- **Efficient (i.e., optimized) operation**: not merely a desirable luxury but rather an indispensable necessity.

OUTLINE

- **Optimizing location detection services**
  - **Location Detection**
  - **Optimizing deployment**
- **Energy-aware transmission scheduling and routing**
  - **Problem formulation as utility maximization problem**
  - **Large-scale optimization approach**
- **Concluding Remarks**

Location Detection

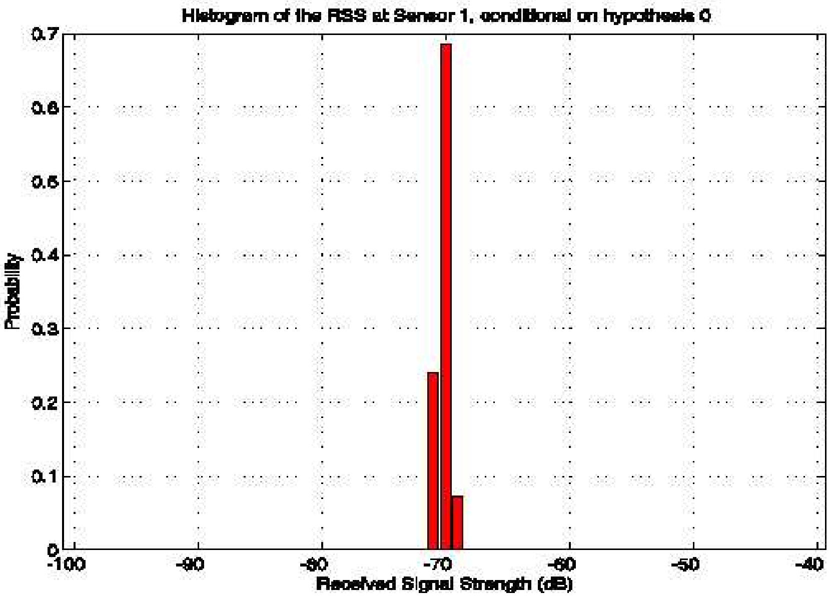


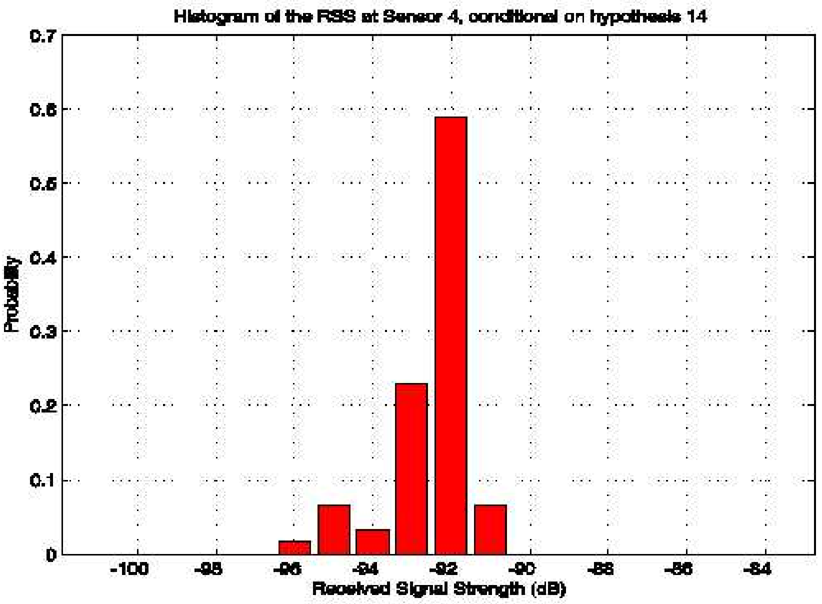
Applications:

- Location-based services: "intelligent" active maps, "smart" office applications, "smart" home applications.
- "Active" RFIDs: tracking personnel and equipment (e.g., in hospitals, ports).
- Fault localization and maintenance in SNETs.
- Surveillance.
- Counter-action and rescue of victims in natural or man-made disasters.

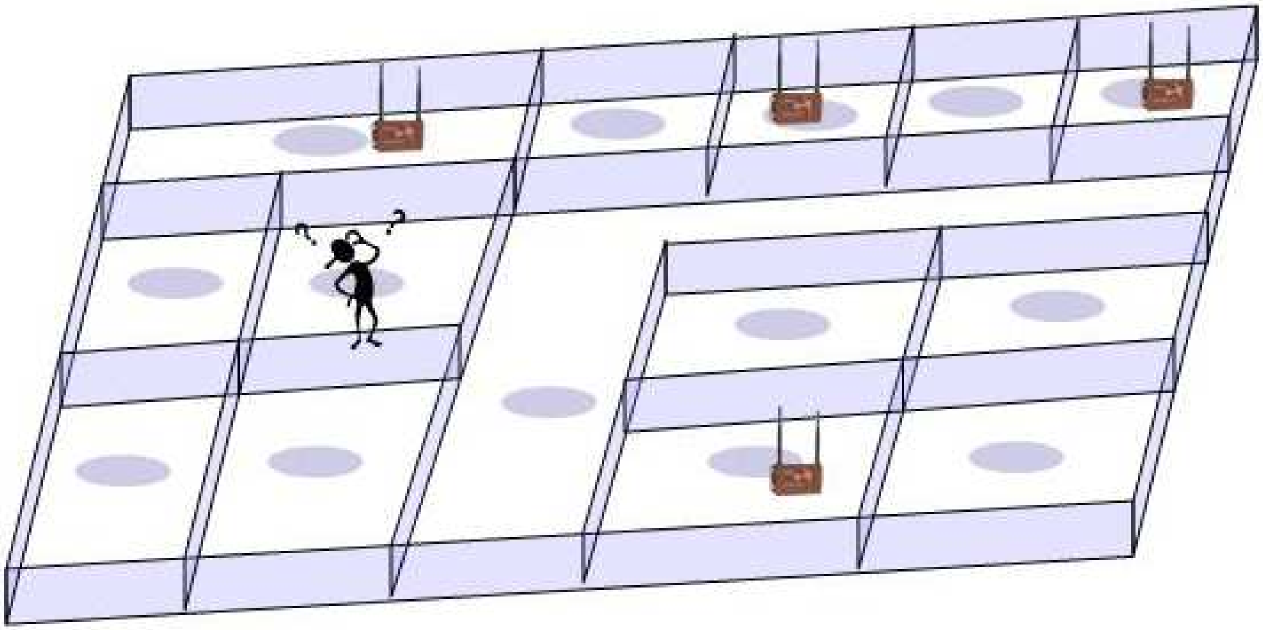
Key Challenges

- Indoors, thus, **no GPS**.
- Signal landscape is **highly variable** indoors.





Proposed RF-based Approach



- Hierarchical SNET deployment: **sensors** and (stationary) **clusterheads**.
- When sensors transmit clusterheads receive the signal and measure **signal characteristics** (e.g., signal strength) — the **observation vector**.
- From **random** observation vector infer sensor location.

Questions

- How can we determine the location of the transmitting sensor ?
- Can we characterize the system's performance (probability of error) ?
- Can we deploy the system (i.e., place the clusterheads) in order to minimize the probability of error ?
  - Our system: determines **optimal deployment** and provides **performance guarantees**.

The Location Detection Engine

- K available clusterheads to be placed at positions in $\mathscr{B} = \{B_1, B_2, \ldots, B_M\}$.
- Resolve sensors' positions to one of N distinct locations $\mathscr{L} = \{L_1, L_2, \ldots, L_N\}$.
- A sensor transmits resulting in observation vectors $\mathbf{y}^{(i)}$ at clusterhead i.
- We know (or can measure) $p_{\mathbf{Y}^{(i)}|L_j}(\mathbf{y}^{(i)}|L_j)$ for all possible locations L_j and clusterheads B_i.
- Clusterheads make n consecutive observations $\mathbf{y}_1, \ldots, \mathbf{y}_n$, assumed i.i.d. Find the location L of the sensor.
- The problem is a standard N-ary hypothesis testing problem (MAP rule).

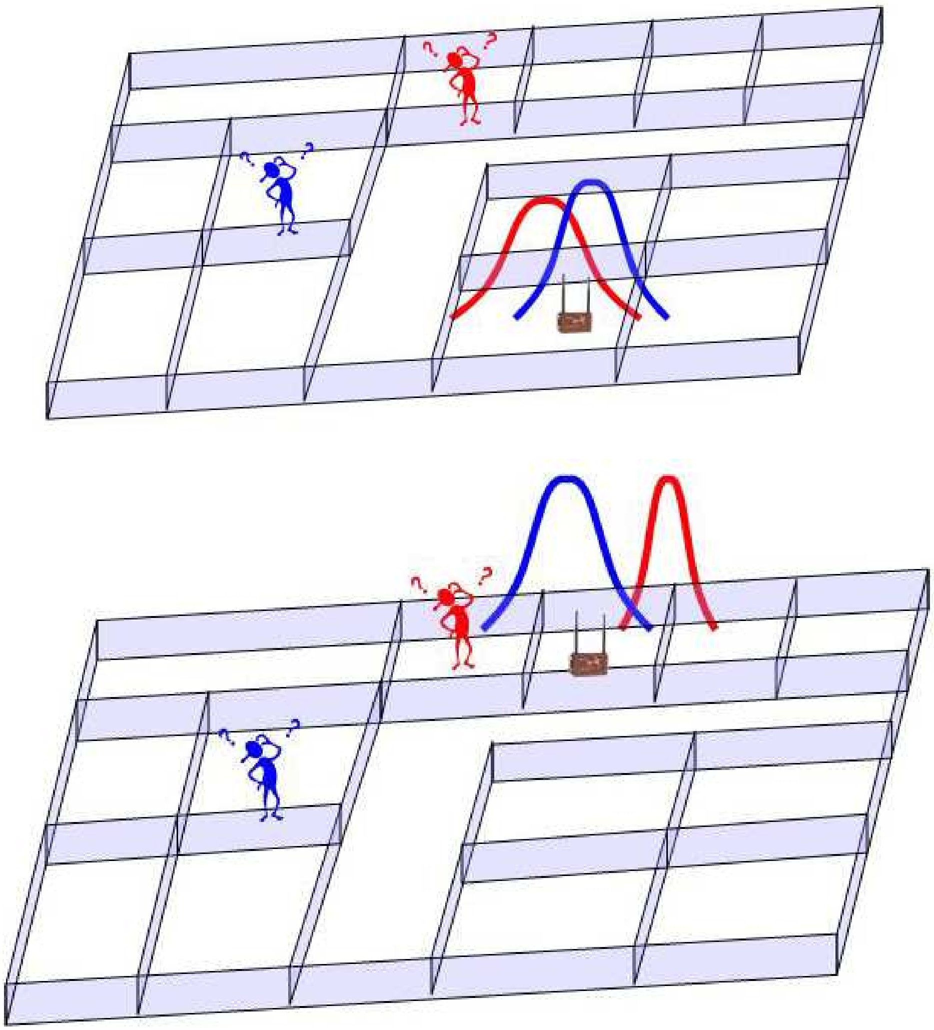
Asymptotics for the Probability of Error

- Consider 2-ary hypothesis testing between L_i or L_j from n i.i.d. observations $\mathbf{y}_1^{(k)}, \ldots, \mathbf{y}_n^{(k)}$ at clusterhead B_k. Let $\mathscr{S}^n$ the optimal decision rule.
- Probability of error:

$$P_n^{(e)} \approx e^{-n d_{ijk}},$$

where d_{ijk} is the **Chernoff distance** between $p_{\mathbf{Y}^{(k)}|L_i}(\mathbf{y}|L_i)$ and $p_{\mathbf{Y}^{(k)}|L_j}(\mathbf{y}|L_j)$.

Optimizing the Deployment



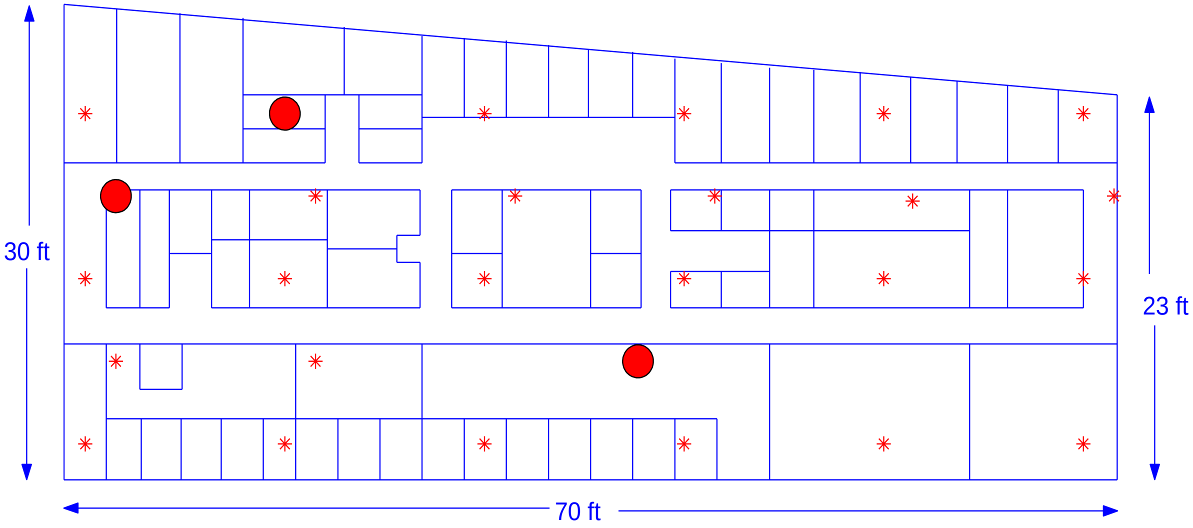
Place clusterheads to maximize worst case Chernoff distance over all hypotheses pairs.

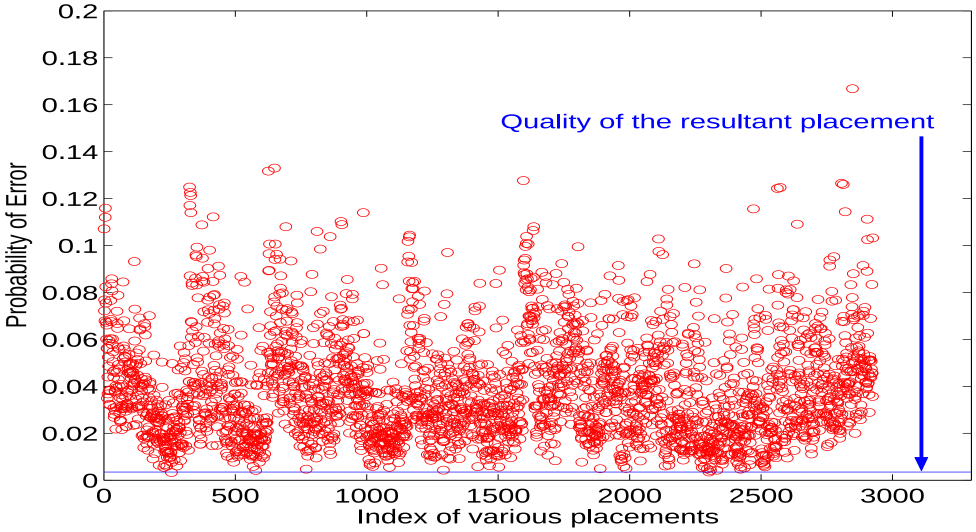
Clusterhead placement

- Combinatorial optimization problem that can be formulated as a Mixed Integer Linear Programming (MILP) problem.
- For variable K (number of clusterheads) the problem is NP-hard.
- Have developed a very efficient algorithm that uses ideas from **facility location** theory
  - Can solve problems of size $K = N = 100$ in less than 5 min.
  - MILP approach can solve problems of size $K = N = 100$ in 24 hours.
- Output of the algorithm: optimal placement and a value ϵ^*.
- **Performance Guarantee**: $P_n^{(e),\text{opt}} \leq e^{-n\epsilon^*}$ for large n.

Numerical Results: the impact of optimal placement

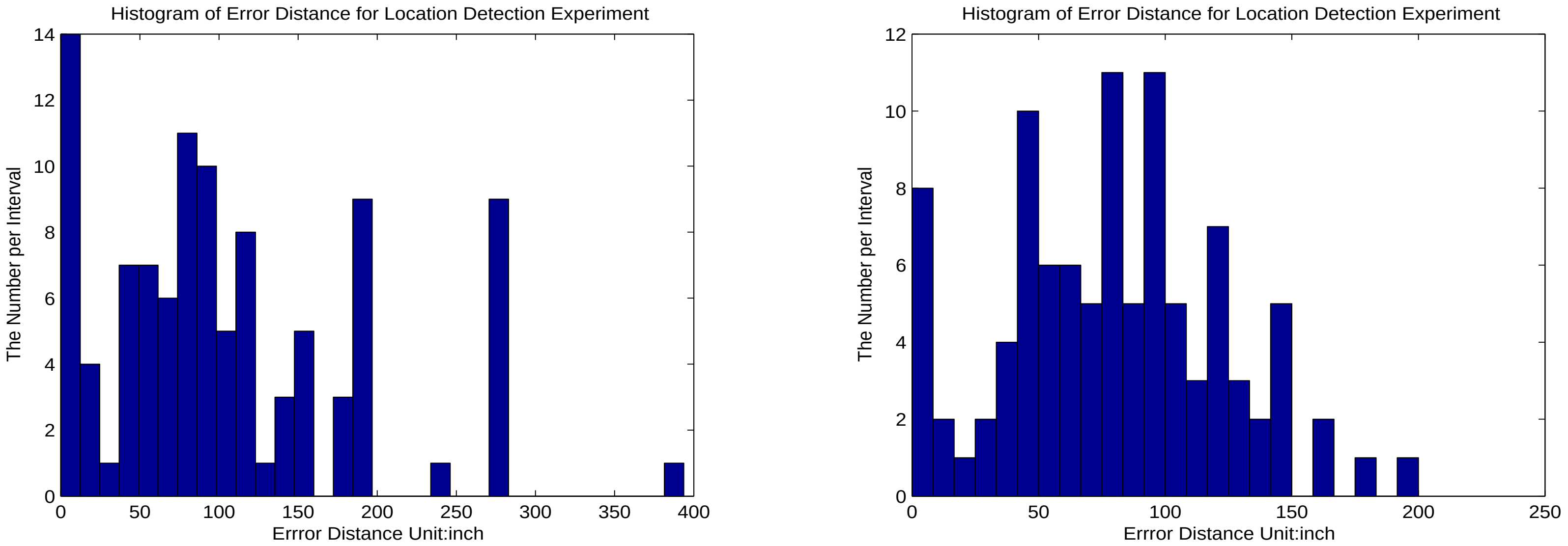
Simulations for the 4th floor of BU PHO building:





Testbed I

- Cover 7–8 rooms in BU MFG building. Locate the room where the sensor is. **Training is automated (no site survey !)**
- Hypothesis Density: 1 per 60 $(\text{feet})^2$. Clusterhead density: 1 per 210 $(\text{feet})^2$.

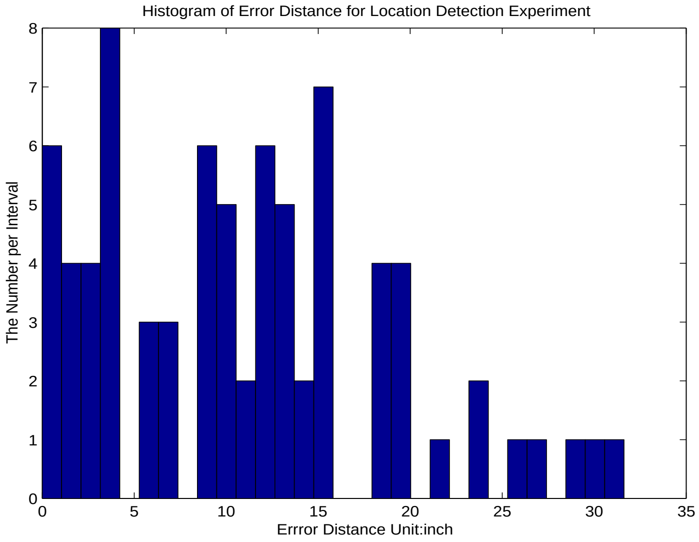


(a) Single frequency, single power, $P_e = 15\%$, $\bar{D}_e = 8.9$ feet

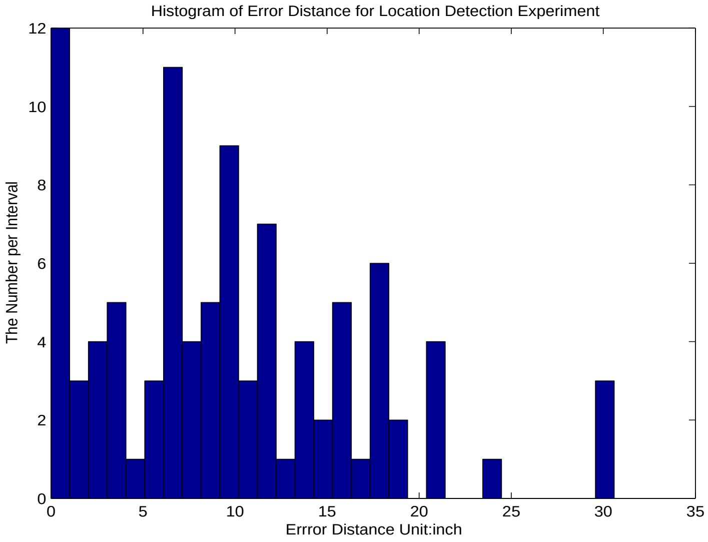
(b) Frequency & Power diversity, $P_e = 3\%$, $\bar{D}_e = 6.5$ feet

Testbed II – Microscale

Place points on a table 6in apart, determine the point at which the sensor is.



(c) Single frequency, single power, $\bar{D}_e = 11.10$ in



(d) Frequency & Power diversity, $\bar{D}_e = 9.77$ in

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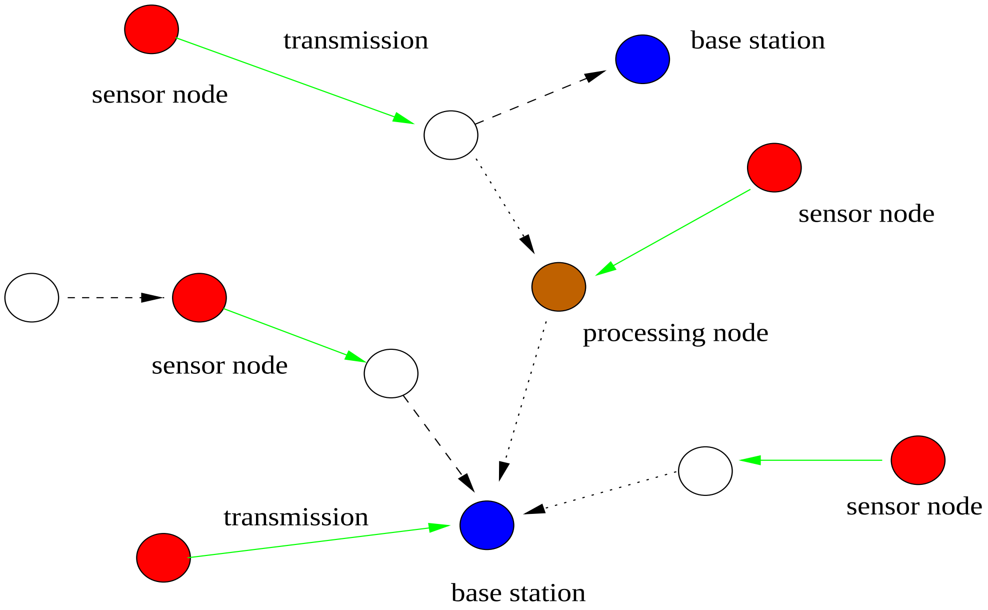
Wireless Sensor Networks (SNETs)



- Nodes communicate **wirelessly**, generally with **low power levels**.
- Nodes can only do one task at a time (send or receive) and concurrent transmissions cause **interference**.
- Stringent **energy constraints** (i.e., random MAC is often inefficient, benefits from multihop).

Objective and Approach

- Formulation:

Maximize	Utility of transmission rates
subject to	Physical layer constraints
	Node exclusion constraints
	Fairness Constraints

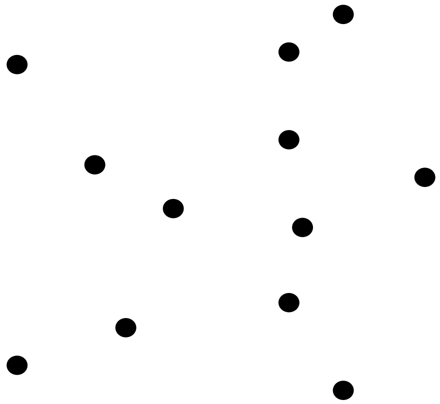
- Key ideas: **characterize the region of achievable rates**, $\mathscr{R}$, and optimize efficiently.
- Our approach is based on **decomposition** methods in large-scale optimization.
- Can we trade-off energy (i.e., network lifetime) vs. performance ?
- Can we address scalability issues ?
- Can we recover from node failures ?

Achievable Region

Valid transmission schemes and **Achievable transmission rates**

$$\mathscr{P} \overset{\triangle}{=} \{\mathbf{p} \mid \text{power limits \& node exclusion constraints}\}$$

$$\mathscr{R} = \{\mathbf{r} \mid \mathbf{r} = \mathbf{H}\mathbf{p},\ \mathbf{p} \in \mathscr{P}\}$$



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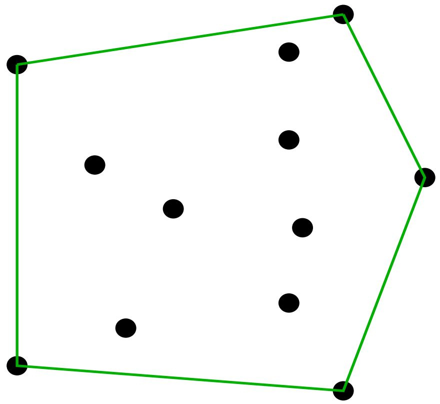

- Enlarge the achievable region by **time-sharing**. Conv($\mathscr{P}$) and Conv($\mathscr{R}$) are polytopes.

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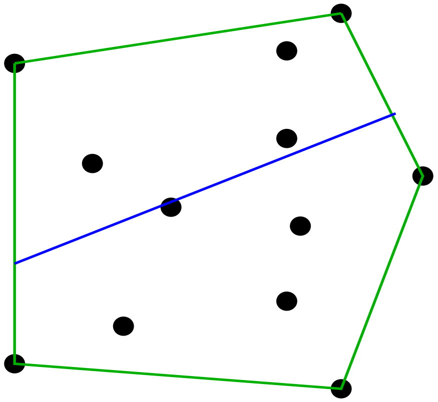


- Enlarge the achievable region by **time-sharing**. $\mathrm{Conv}(\mathscr{P})$ and $\mathrm{Conv}(\mathscr{R})$ are polytopes.
- Introduce **fairness** and **flow-conservation** constraints (set $\mathscr{S}$).
- **Utility Maximization Problem**:

$$\begin{aligned} \max \quad & F(\mathbf{r}) \\ \text{s.t.} \quad & \mathbf{r} \in \mathrm{Conv}(\mathscr{R}) \cap \mathscr{S}. \end{aligned}$$

Key results

- **Polynomial Solvability**: Under some regularity assumptions the problem can, in principle, be solved in polynomial time.
- Developed a decomposition approach to solve large instances.
- **Optimal Policy**: TDMA, use **transmission mode** $\mathbf{r}^j$ w.p. α_j.
- Can effectively deal with **node failures** (re-optimize).
- Can effectively trade-off energy consumption vs. utility.

Numerical Results

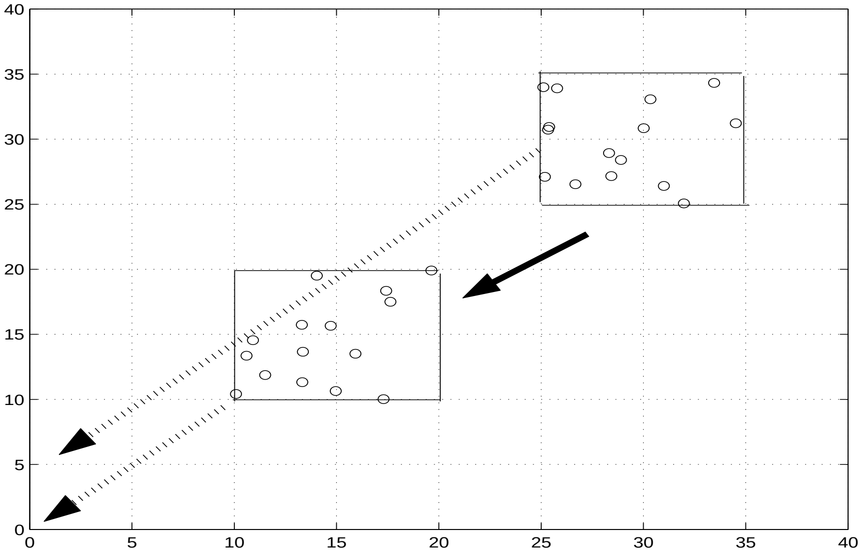
- **Accuracy of our approach and efficiency**. Considered SNET with single gateway; max. total throughput s.t. fairness constraints (power levels at 0.1 Watts)

N	Enumeration	Time	Decomposition	Time	Single-hop
2	14.44	0.02	14.44	0.01	14.4
3	122.28	0.02	122.28	0.01	122.2
4	689.16	0.13	689.16	0.02	167.6
5	7962.63	63.4	7960.87	0.02	582.3
6	out of memory	-	6339.97	0.03	191.9

- We can solve problems with 50 nodes in less than 1 min !
- Multihop better than singlehop (by 3000% !).
- Our approach is accurate at much higher power levels (e.g., 40db).

Numerical Results (cont.)

Another example

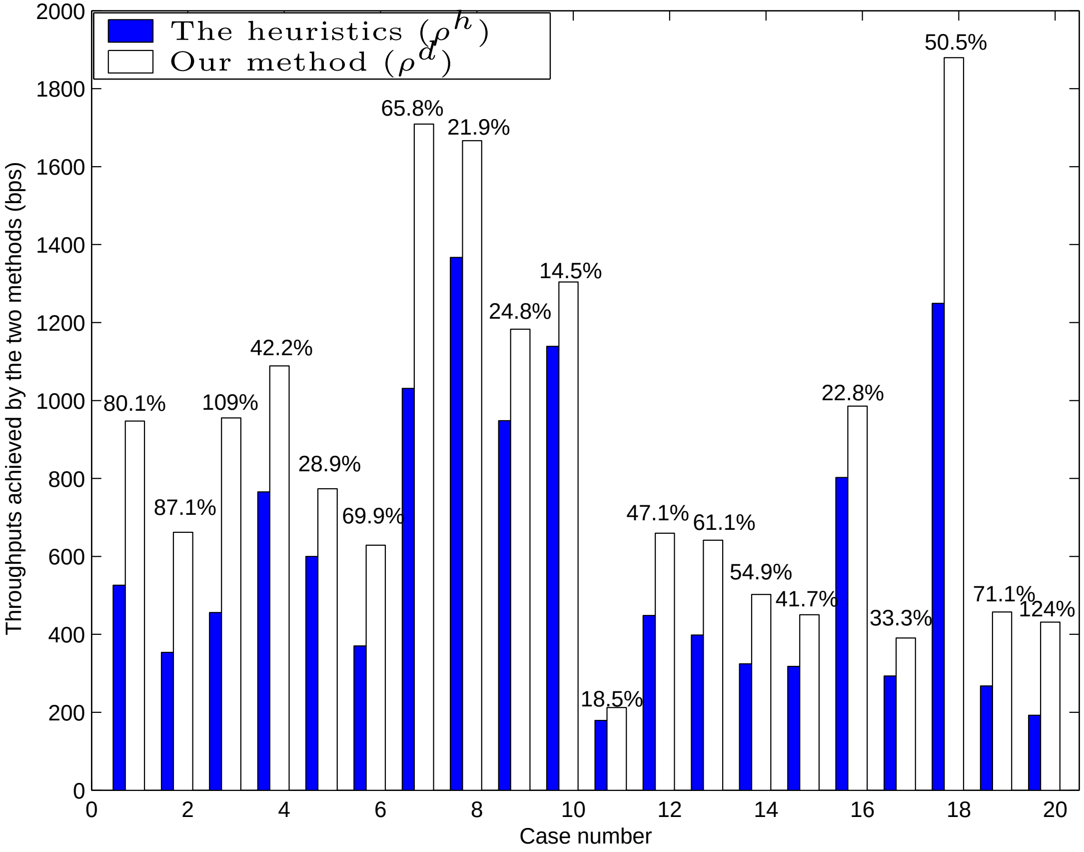


N	Decomposition	Single-hop	2-hop
20	672.99	26.59	625.07
26	851.20	27.09	633.41
30	949.77	31.26	691.12

Last row: 37.5% improvement over 2-hop policy.

Comparisons with recent heuristics

We considered recently proposed heuristics by [Radunovic & Le Boudec], a 40-node SNET, powers at 1 mWatt. Randomly generated SNETs and obtained



Conclusions

- **Location detection**: an enabling service in wireless and sensor networks.
- Developed a new **location detection** system (including a testbed implementation) that
  - accommodates the variability of the signal landscape;
  - optimizes deployment; and
  - provides quantifiable performance guarantees.
- Considered **transmission scheduling and routing**, accommodating sensor diversity (utility maximization), and imposing explicit fairness constraints
  - Developed an **efficient decomposition approach** for solving large problems that
  - produces TDMA policies which time-share among several transmission schemes;
  - can handle node-failures; and
  - can trade-off utility vs. energy.