Dissertation Proposal

Sensor Deployment Algorithms for Target Positioning Services

Pei-Ling Chiu
Advisor: Prof. Frank Yeong-Sung Lin
Department of Information Management
National Taiwan University

Outline

- Overview
- Research Background
- Research Problems
  - Sensor placement problem for complete coverage and complete discrimination
  - Random deployment problem using adjustable sensing radius
  - Sensor placement problem for differentiated quality of positioning services
  - Energy-efficient sensor networks design
- Conclusion

Overview

- Motivation
- Research Scope
- Research Problems
- Research Methodologies

Motivation

- Wide range of applications in WSNs
  - Surveillance, target positioning, environment monitoring, health caring, and animal tracking
- Trend of user-centric services
  - Location-based services, personalized services
  - Localization capability is one of the most important techniques for supporting these applications

Ref: [DC03], [DCI02], [CIQ02], [RUP03], [ZC03], [RST04], [CL04], [LC05], [CHS04], [CCK06], [DCT05] [KKL06], [LC06], [LXP05]

Motivation

- Localization Systems
  - GPS is not useful in indoor
  - Three techniques of indoor location systems: infrared, ultrasound, and radio
  - Disadvantages: resolution and interference
- Sensor-network-based positioning systems
  - Provide the indoor localization services a simple and feasible solution.

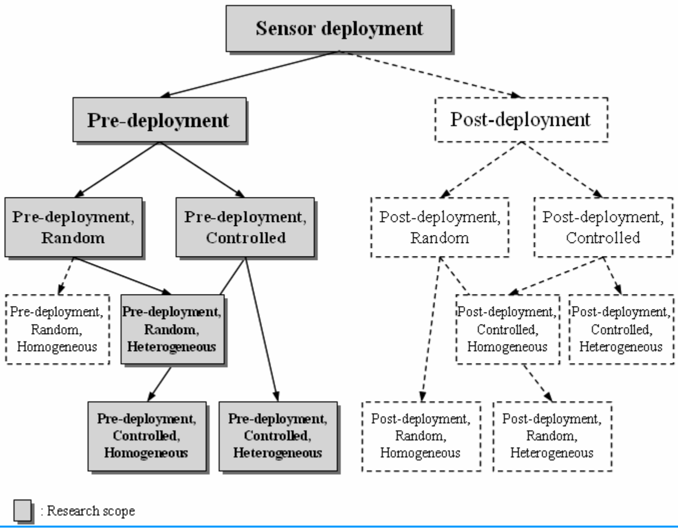
Ref: [RST04], [PCB00], [BP00], [CCR01], [PCB00]

Research Scope

- Timing of topology determination
  - Pre-deployment
  - Post-deployment
- Placement methods
  - Random deployment approach
  - Controlled placement approach
- Types of sensor nodes
  - Homogeneous
  - Heterogeneous

Ref: [ASC02]

Research Scope



Sensor Deployment

Pre-/Post-	R/C	Homo-/Hetero-	papers	goals	considerations
Pre-	R	Homo-	[AS03]	Min sensor density	Coverage
Pre-	R	Homo-	[LRS05]	Min sensor density	Coverage
Pre-	R	Hetero-	[MRK05]	Min cost	Two types of sensors, coverage and connectivity
Pre-	C	Homo-	[DC03] [DCI02]	Min number of sensors	Coverage threshold, grid based method
Pre-	C	Homo-	[RST04]	Min number of sensors	Identifying cod, target location, robust
Pre-	C	Homo-	[[CCZ05]	Min number of sensors	Lifetime, cost
Pre-	C	Homo-	[BKX06]	Min number of sensors	Coverage, 2-connectivity
Pre-	C	Homo-	[GCB06]	Energy efficiency	Data distortion, connectivity
Pre-	C	Homo- Hetero-	[CIQ02]	Min number of sensors	Coverage, target location
Post-	R	Homo-	[SP01] [AGP04]	Energy-efficiency	K-cover
Post-	R	Hetero-	[CWL05] [DVZ06]	Max number of covers	Adjustable sensing radius, reduce radius
Post-	C	Homo-	[ZC03a]	coverage	Mobile sensors, target location
Post-	C	Hetero-	[XWH05]	Min cost	Add relay nodes, lifetime, connectivity, sensing/ relay nodes
Post	R/C	Homo-	[VVB04]	coverage	Incremental deployment
Post-	R/C	Homo-	[KGG06]	Min number of sensors	Coverage, communication efficiency
Post-	R/C	Hetero-	[IMP05]	Number of cluster	Lifetime, two-level

Research Problems

- Difficult problems?
  - The sensor deployment problem where subject to coverage, has been transformed to the classical set-cover/set-*k*-cover problem, that is NP-complete.
  - We have more intractable problems
    - Both surveillance and target positioning ability are considered

[MP03]

Research Methodology

- Mathematical models
  - Optimization problems
- Solution methods
  - Lagrangean relaxation (LR) approach
  - Simulated annealing (SA) approach

Research Background

- QoS in WSNs
- Coverage models
- Target location

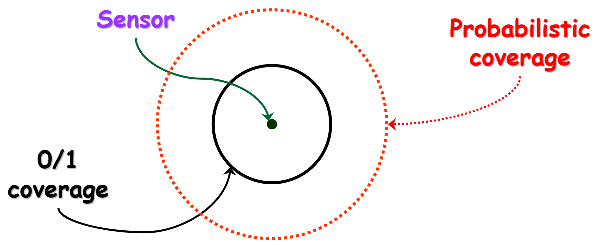
QoS in WSNs

- In reference [WLY06], the authors define the QoS parameters for each function layer.
- Using **positioning ability** as QoS parameter
  - It belongs to application layer QoS parameter

 Ref: [WLY06]

Coverage

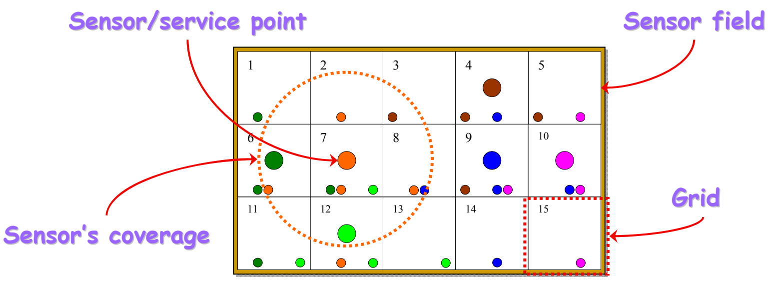
- Sensor coverage models
  - 0/1 model: [CIQC02], [MP03]
  - Probabilistic model: [NKJ05], [DC03]



Ref: [CIQC02], [MP03], [NKJ05], [DC03], [CW04]

Target Location

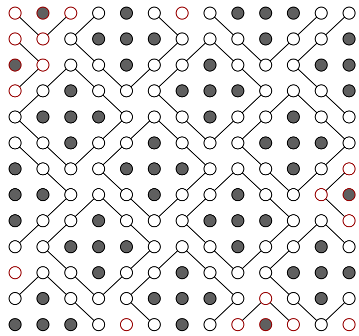
- Grid-based sensor field
  - Sensor field can be represented as a collection of two- or three-dimensional *grid points*.



Ref: [RST04], [KCL98], [CIQ01], [CIQ02], [RUP03], [DC02], [LRS05], [SSS03]

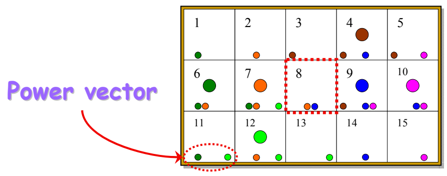
Target Location

- Identifying code
  - The theory is adopted to design a location system with sensor network.
  - The identifying code optimization problem is NP-Complete.



Target Location

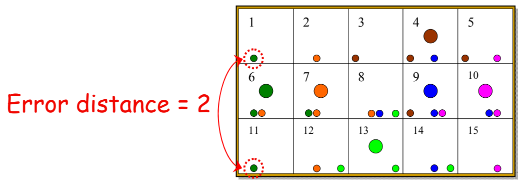
- Power vector
  - Identifying code
  - The power vector of service point 8
    - <0, 0, 1, 1, 0, 0> corresponding to sensors (4, 6, 7, 9, 10, 12)
- Completely covered sensor field
- Completely discriminated sensor field



- F.Y.S. Lin and **P.L. Chiu**, "A Near-optimal Sensor Placement Algorithm to Achieve Complete Coverage/Discrimination in Sensor Networks," *IEEE Communications Letters*, vol. 9, no. 1, January 2005, pp. 43-45.
- **P.L. Chiu** and Frank Y.S. Lin, "A Simulated Annealing Algorithm to Support the Sensor Placement for Target Location," *Proc. IEEE CCECE 2004*, pp. 867-870.

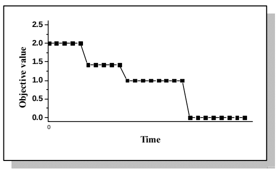
Target Location

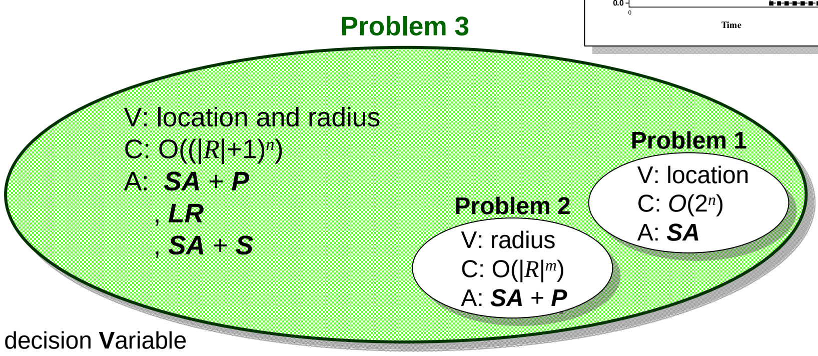
- Error distance
  - One of the most natural criteria to measure positioning accuracy.
- Complete discrimination
  - Maximum error distance in sensor field <1



- F.Y.S. Lin and **P.L. Chiu**, "A Near-optimal Sensor Placement Algorithm to Achieve Complete Coverage/Discrimination in Sensor Networks".
- **P.L. Chiu** and Frank Y.S. Lin, "A Simulated Annealing Algorithm to Support the Sensor Placement for Target Location".

Problem Overview





V: decision **V**ariable
C: time **C**omplexity
A: solution **A**pproach
P: **P**enalty function
S: **S**urrogate function

$|R|$: number of candidate radii
n : number of service points
m: number of deployed sensors, $m \le n$

Research Problem 1

- Sensor Placement Problem for Complete Coverage/Discrimination

- F.Y.S. Lin and **P.L. Chiu**, "A Near-optimal Sensor Placement Algorithm to Achieve Complete Coverage/Discrimination in Sensor Networks," *IEEE Communications Letters*, vol. 9, no. 1, January 2005, pp. 43-45.
- **P.L. Chiu** and Frank Y.S. Lin, "A Simulated Annealing Algorithm to Support the Sensor Placement for Target Location," in *Proc. IEEE CCECE 2004*, pp. 867-870.

Problem Description

- Objective
  - Complete discrimination/minimizing the maximum error distance
- Given
  - Sensor field, set of service points, sensor cost, and detection range of sensor
- Constraints
  - Complete coverage and budget
- Outcomes
  - Sensors' location and power vectors
- Solution approaches
  - Simulated annealing method

Mathematical Model

Given Parameters:

A : Index set of the sensors' candidate locations.
B : Index set of the locations in the sensor field.
r_k : Detection radius of the sensor located at k ; $k \in A$.
d_{ij} : Euclidean distance between location i and j; $i, j \in B$.
c_k : The cost of the sensor allocated at location k ; $k \in A$.
G : Budget limitation.
K : A large number.

Mathematical Model

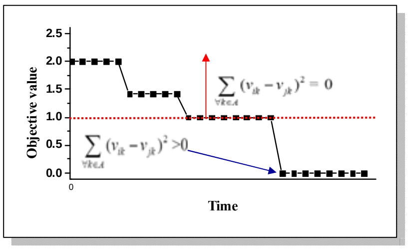
Decision Variables:

y_k : 1, if a sensor is allocated at location k and 0 otherwise, $k \in A$.
$v_i = (v_{i1}, v_{i2}, \ldots, v_{ik})$: The power vector of location i, where v_{ik} is 1 if the target at location i can be detected by the sensor at location k and 0 otherwise, where $i \in B$, $k \in A$.

Mathematical Model

- Objective function

$$Z_{IP3.1} = \min\max \frac{d_{ij}}{1 + K \sum_{\forall k \in A} (v_{ik} - v_{jk})^2} \qquad (IP3.1)$$



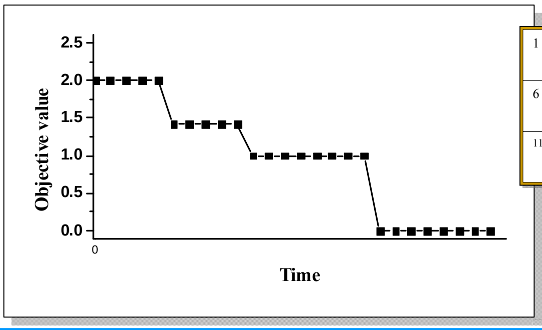
Mathematical Model

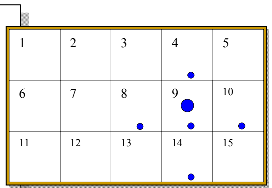
- Constraints

$$\begin{array}{rcllr}
v_{ik} d_{ik} & \le & y_k r_k & \forall k \in A, i \in B, i \ne k & (3.1) \\
\dfrac{d_{ik}}{r_k} & > & y_k - v_{ik} & \forall k \in A, i \in B, i \ne k & (3.2) \\
v_{ik} & = & y_k & \forall k \in A, i \in B, i \ne k & (3.3) \\
\sum_{\forall k \in A} c_k y_k & \le & G & & (3.4) \\
\sum_{\forall k \in A} v_{ik} & \ge & 1 & \forall i \in B & (3.5) \\
v_{ik}, y_k & = & 0 \text{ or } 1 & \forall k \in A, i \in B\,. & (3.6)
\end{array}$$

Solution Space and Structure

- Solution space: $O(2^n)$
- Solution structure:
  - Example: 3x5 sensor field, radius=1.





Simulated Annealing Based Algorithm

$$E = \max \frac{d_{ij}}{1 + K \sum_{\forall k \in A} (v_{ik} - v_{jk})^2}$$

Algorithm 2.1: The skeleton of the SA heuristic

```
Select an energy function E(x);
Select an initial temperature T0>0, and T=T0;
Select initial number of repetitions on initial temperature, r(T0);
Set repetition counter t=0;
Repeat
    Set repetition counter n=0;
    Repeat
        Generate new state x_{i+1}, a neighbor of x_i;
        Calculate ΔE=E(x_{i+1})−E(x_i);
        If ΔE < 0 then x_i=x_{i+1};
        else if random (0,1) < exp(−ΔE/T_t) then x_i=x_{i+1};
        n=n+1;
    Until n=r(T_t);
    t=t+1;
    T_t =α*T_{t-1}, r(T_t)=β* r(T_{t-1});
Until stopping criterion, T_t<T_f is true.
```

Dropping one sensor
or
Altering one sensor's position

Experimental Results

- Scenario
  - Pentium IV-1.4GHz PC
  - Microsoft Window XP Pro.
  - Microsoft Visual C++ 6.0
  - Sensor radius = 1, $c_i=1,\ \forall 1 \le i \le n$.
  - The parameters of the cooling schedule:
    - $\alpha = 0.75$, $\beta = 1.3$, $b_0 = 5n$, (where n is the amount of grids in the sensor field.
    - $t_0 = 0.1$, $t_f = t_0/30$
    - $K = 10000$

Experiment I

Table 3.1: Comparison between exhaustive search and the SA algorithm.

Area	# of sensors		Sensor density	Area	# of sensors		Sensor density
	Opt.	SA			Opt.	SA	
3x3	4	4	44.44%	6x4	10	10	41.67%
4x3	6	6	50.00%	6x5	12	12	40.00%
4x4	7	7	43.75%	7x3	9	9	42.86%
5x3	6	6	40.00%	7x4	12	12	42.86%
5x4	8	8	40.00%	8x3	10	10	41.67%
5x5	10	10	40.00%	9x3	11	11	40.74%
6x3	8	8	44.44%	10x3	12	12	40.00%

Experiment II

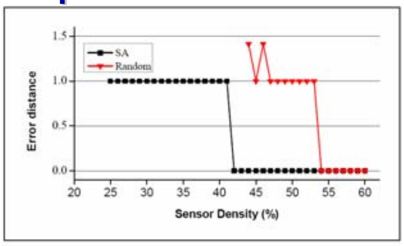


Figure 3.2: Error distance vs. sensor density. (10x10, R=1)

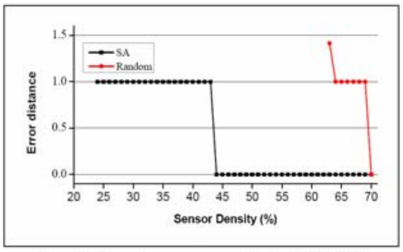


Figure 3.3: Error distance vs. sensor density. (30x30, R=1)

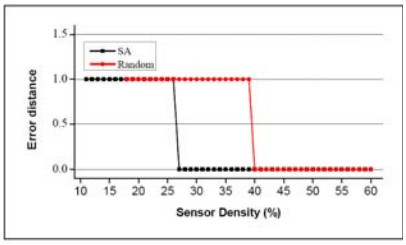


Figure 3.4: Error distance vs. sensor density. (10x10, R=2)

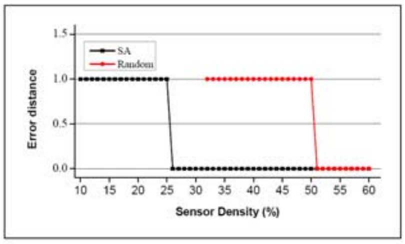


Figure 3.5: Error distance vs. sensor density. (30x30, R=2)

Research Problem 2

- Random Deployment Problem using Adjustable Sensing Radius

Problem Description

- Objective
  - Complete discrimination/minimizing the maximum error distance
- Given
  - Sensor field, set of service points, number of sensor, location of each sensor, and set of candidate detection radius
- Constraints
  - Complete coverage
- Outcomes
  - Sensors' radius and power vectors
- Solution approach
  - Simulated annealing method

Experiment

- Step 1: the initial configurations
  - Random approach
  - 1000 samples
- Step 2: adjusting radius
  - The proposed algorithm
  - 100 selected configurations with complete coverage

Experiment

- Scenario
  - Pentium IV-1.4GHz PC
  - Microsoft Window XP Pro.
  - Microsoft Visual C++ 6.0
  - Sensor field is 150 (10 by 15) service points.
  - Sensor cost, $c_i = 1, \ \forall 1 \le i \le n$.
  - Set of candidate radius *R*= {1, 2, ..., 8}.
  - The parameters of the cooling schedule:
    - $\alpha = 0.7, \beta = 1.3, b_0 = 2000.$
    - $t_0 = 1.0, \ t_f = t_0/2000$
    - $K = 10000$

Results: Adjusting Radii

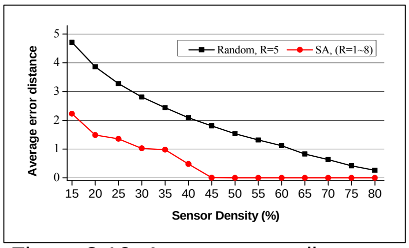


Figure 3.10: Average error distance.

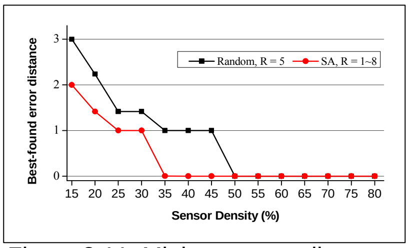


Figure 3.11: Minimum error distance.

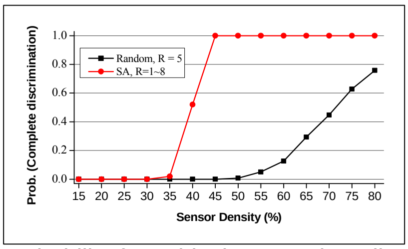


Figure 3.12: Probability for achieving complete discrimination .

Conclusion Remarks (Problem 1 and 2)

- Mathematical model
- Simulated annealing algorithm (Algorithm 3.1)
  - Efficiently obtain high-quality solutions
  - Very effective and scalable
- Simulated annealing algorithm (Algorithm 3.2)
  - Very effective for reducing the error distance and improving the probability of complete discrimination

Problem 3

- Sensor Placement Problem for Differentiated Quality of Positioning Services
  - **P.L. Chiu** and F.Y.S. Lin, "Sensor Placement Algorithms Supporting Differentiated Positioning Services," Submitted to *Globecom* 2007 *Ad-hoc and Sensor Networking Symposium.*

Problem Description

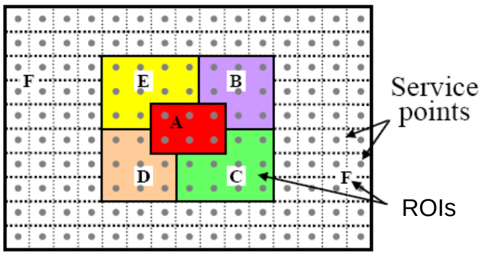
- Differentiated QoS requirements
  - QoS parameter: positioning accuracy
  - Discrimination weight
- Objective
  - Satisfying QoS requirement for all ROIs/minimizing QoS degradation
- Given
  - Sensor field, set of service points, deployment cost for each location, and set of candidate detection ranges
- Constraints
  - Budget, complete coverage, placement limitation, and service priority for each ROI (regions of interest)
- Outcomes
  - Sensors' placement, radius and power vectors
- Solution approaches
  - Lagrangean relaxation method and simulated annealing method

Framework

- Grid based placement
- Placement limitation
- Adjustable detection radius
- ROIs (regions of interest)
- Service priority of ROI
- Types of QoS
  - Completely discriminated
  - Discriminable
  - Surveillance-only
- Goal
  - Satisfy QoS requirement for all ROIs
  - Reduce QoS degradation

Example (museum)

- Three priority classes: high, medium, and low
  - Area A: high service priority
  - Area B, C, D, and E: medium service priority
  - Area F: low service priority



Example (museum)

- Levels of QoS

Table 4.1: The QoS supported for ROIs in the museum example.

Level of QoS	QoS supported for ROIs
1	• **Completely discriminable**: None. • **Discriminable**: ROI A. • **Surveillance-only**: ROIs B, C, D, E, and F.
2	• **Completely discriminable**: ROI A. • **Discriminable**: ROIs B, C, D, and E. • **Surveillance-only**: ROI F.
3	• **Completely discriminable**: ROIs A, B, C, D, and E. • **Discriminable**: ROI F.
4	• **Completely discriminable**: ROIs A, B, C, D, E, and F.

Mathematical Model

Given Parameters:

A	: Index set of the service points in the sensor field.
B	: Index set of the sensor's candidate locations. $B \subseteq A$.
C	: Set of the kinds of cost for sensor
W	: Set of the discrimination weight
R	: Set of candidate detection radiuses for sensor
d_{ij}	: Euclidean distance between location i and j; $i, j \in A$.
c_k	: The cost of sensor located at position k; $k \in B$, $c_k \in C$.
c_{min}	: The minimum cost of sensors.
G	: The budget limitation for sensors.
N	: The maximum number of sensors, $N = G/c_{min}$.
w_{ij}	: Discrimination weight, $i,j \in A$, $w_{ij} \in W$.
K	: A larger number

Mathematical Model

Decision Variables:

y_k	: 1, if a sensor is allocated at position k, and 0 otherwise, $k \in B$.
$v_i = (v_{i1}, v_{i2}, \ldots, v_{ik})$	: A power vector of location i, where v_{ik} is 1 if the target at location i can be detected by the sensor at position k and 0 otherwise, $i \in A$, $k \in B$.
r_k	: Detection radius of sensor located at k, $k \in B$.

Mathematical Model

- The objective function for the original Problem

$$Z_{IP4.1} = \min_{v} \max_{(i,j)} \frac{w_{ij} d_{ij}}{1 + K \sum_{\forall k \in B} (v_{ik} - v_{jk})^2} \qquad (IP4.1)$$

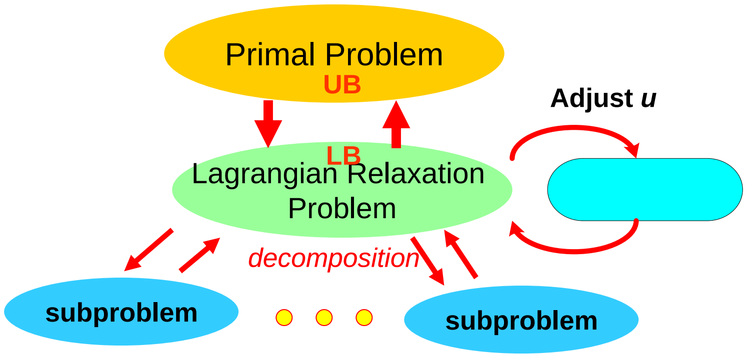
Mathematical Model

- Constraints

$v_{ik} d_{ik} \le y_k r_k$	$\forall i \in A,\ k \in B,\ i \ne k$	(4.1)
$\frac{d_{ik}}{r_k} > y_k - v_{ik}$	$\forall i \in A,\ k \in B,\ i \ne k$	(4.2)
$v_{kk} = y_k$	$\forall k \in A \cap B$	(4.3)
$\sum_{\forall k \in B} c_k y_k \le G$		(4.4)
$\sum_{\forall k \in B} v_{ik} \ge 1$	$\forall i \in A$	(4.5)
$\sum_{\forall k \in B} v_{ik} \le N$	$\forall i \in A$	(4.6)
$r_k \in R$	$\forall k \in B$	(4.7)
$v_{ik} = 0$ or 1	$\forall i \in A, k \in B$	(4.8)
$y_k = 0$ or 1	$\forall i \in A, k \in B$.	(4.9)

Lagrangean Relaxation

LB* ≤ *Optimal solution* ≤ *UB



Equivalent Model

- The original model $Z_{IP4.1} = \min_{v} \max_{(i,j)} \frac{w_{ij} d_{ij}}{1 + K \sum_{\forall k \in B} (v_{ik} - v_{jk})^2}$

  is hard to solve directly.

- Define $S = \max \frac{w_{ij} d_{ij}}{1 + K \sum_{\forall k \in A} (v_{ik} - v_{jk})^2}$

  then $S \geq \frac{w_{ij} d_{ij}}{1 + K \sum_{\forall k \in A} (v_{ik} - v_{jk})^2}$ and $\frac{1}{S} \leq \frac{1 + K \sum_{\forall k \in A} (v_{ik} - v_{jk})^2}{w_{ij} d_{ij}}$

Equivalent Model

$$Z_{IP4.2} = \min_{v} S \qquad (IP4.2)$$

subject to:

$$\frac{1}{S} \le \frac{1 + K \sum_{\forall k \in B} (v_{ik} - v_{jk})^2}{w_{ij} d_{ij}} \qquad \forall i,j \in A, i \ne j \qquad (4.11)$$

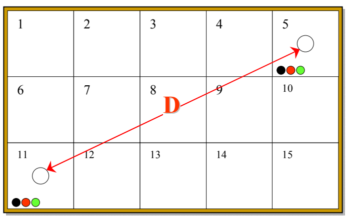
$$\underline{S} \le S \le \overline{S} \qquad (4.12)$$

$\underline{S}$ is lower bound of S;
$\overline{S}$ is upper bound of S.

and (4.1)-(4.9)

Lemma 4.3

- *Upper bound* $\overline{S} = \max_{\forall i,j \in A} \dfrac{w_{ij} d_{ij}}{1 + K \sum_{\forall k \in A} (v_{ik} - v_{jk})^2} \le w_h D$



Hamming distance = 0

Lemma 4.4

- *Lower bound* $\underline{S} \le \max_{\forall i,j\in A} \frac{w_{ij}d_{ij}}{1+K\sum_{\forall k\in A}(v_{ik}-v_{jk})^2}$, $\underline{S} = \frac{w_\ell}{1+KD_h}$

, *where* $D_h = max\{2n, N\}$.

•Case $N \ge 2n$: the maximum Hamming distance is $2n$.

E.g.,

Power vector A = < v_0, v_1, …, v_{n-1}, 0, …, 0, 0, …, 0 >

Power vector B = < 0, 0, …, 0, 0, …, 0, $v_{N-1-n-1}$, …, v_{N-1} >

n elements n elements

•Case $N < 2n$: the maximum Hamming distance is N.

E.g.,

Power vector A = < v_0, v_1, …, v_{n-1}, 0, …, 0 >

Power vector B = < 0, 0, … , $v_{N-1-n-1}$, …, v_{N-1} >

n elements n elements

Transformation

$$\frac{1}{\underline{S}} \le \frac{1+K\sum_{k\in A}(v_{ik}-v_{jk})^2}{w_{ij}d_{ij}} \qquad (4.11)$$

$$\frac{1}{\underline{S}} \le \frac{1+\sum_{k\in A}(v_{ik}-2v_{ik}v_{jk}+v_{jk})}{w_{ij}d_{ij}}$$

- The cutting plane method is applied to transform Constraint (4.11) to a linear Constraint (4.13).
- An auxiliary variable, t_{ijk}, is introduced, where $t_{ijk}=v_{ik}v_{jk}$.

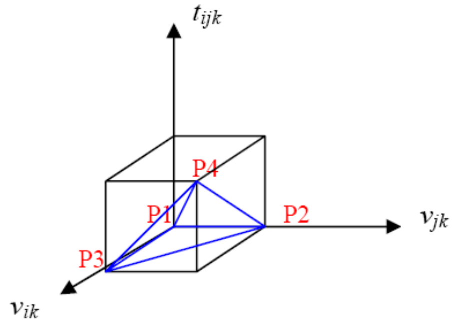
Transformation

- The truth table for variables v_{ik}, v_{jk}, and t_{ijk}.

v_{ik}	v_{jk}	t_{ijk}
0	0	0
0	1	0
1	0	0
1	1	1

Transformation

- The possible values for the three variables only exist in four integer vertices, $p1$, $p2$, $p3$, and $p4$, of the polyhedron.



Transformation

- The *four planes* constructing the polyhedron are presented as following.
- Relationship between v_{ik}, v_{jk}, and t_{ijk}.

$v_{ik} - t_{ijk} \geq 0$	$\forall i,j \in A,\ i \neq j,\ k \in B$
$v_{jk} - t_{ijk} \geq 0$	$\forall i,j \in A,\ i \neq j,\ k \in B$
$v_{ik} + v_{jk} - t_{ijk} \leq 1$	$\forall i,j \in A,\ i \neq j,\ k \in B$
$t_{ijk} \geq 0$	$\forall i,j \in A,\ i \neq j,\ k \in B$

Transformation

$$\textit{Let } t_{ijk} = v_{ik} v_{jk}$$

$$\textit{then } (v_{ik} - v_{jk})^2 = v_{ik} + v_{jk} - 2t_{ijk}$$

Rewrite Constraint (4.11)

$$\frac{1}{S} \leq \frac{1 + K \sum_{k \in B} (v_{ik} - v_{jk})^2}{w_{ij} d_{ij}}$$

$$\textit{to} \quad \frac{1}{S} \leq \frac{1 + K \sum_{k \in B} (v_{ik} + v_{jk} - 2t_{ijk})}{w_{ij} d_{ij}}$$

$$Z_{IP4.3} = \min_{v} S \qquad \text{(IP4.3)}$$

Subject to:

$$\frac{1}{S} \le \frac{1 + K \sum_{\forall k \in B} (v_{ik} + v_{jk} - 2t_{ijk})}{w_{ij} d_{ij}} \qquad \forall i,j \in A, i \neq j \qquad (4.12)$$

$$\underline{S} \le S \le \overline{S} \qquad \underline{S} \text{ is lower bound of } S; \ \overline{S} \text{ is upper bound of } S. \qquad (4.1)$$

$$v_{ik} d_{ik} \le y_k r_k \qquad \forall i \in A, k \in B, i \neq k \qquad (4.2)$$

$$v_{kk} = y_k \qquad \forall k \in A \cap B \qquad (4.3)$$

$$\sum_{\forall k \in B} c_k y_k \le G \qquad (4.4)$$

$$\sum_{\forall k \in B} v_{ik} \ge 1 \qquad \forall i \in A \qquad (4.5)$$

$$\sum_{\forall k \in B} v_{ik} \le N \qquad \forall i \in A \qquad (4.6)$$

$$r_k \in R \qquad \forall k \in B \qquad (4.7)$$

$$v_{ik} = 0 \text{ or } 1 \qquad \forall i \in A, k \in B \qquad (4.8)$$

$$y_k = 0 \text{ or } 1 \qquad \forall i \in A, k \in B \qquad (4.9)$$

$$\sum_{\forall k \in B} t_{ijk} \le N \qquad \forall i,j \in A, i \neq j \qquad (4.13)$$

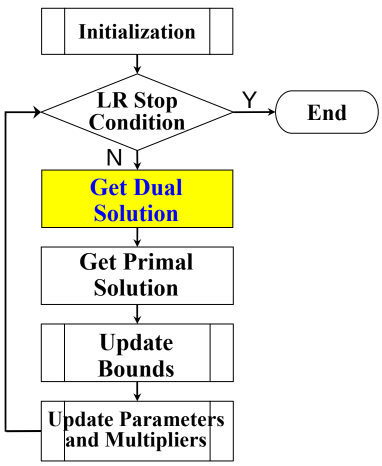
$$v_{ik} - t_{ijk} \ge 0 \qquad \forall i,j \in A, i \neq j, k \in B \qquad (4.14)$$

$$v_{jk} - t_{ijk} \ge 0 \qquad \forall i,j \in A, i \neq j, k \in B \qquad (4.15)$$

$$v_{ik} + v_{jk} - t_{ijk} \le 1 \qquad \forall i,j \in A, i \neq j, k \in B \qquad (4.16)$$

$$t_{ijk} = 0 \text{ or } 1 \qquad \forall i,j \in A, i \neq j, k \in B \qquad (4.17)$$

Procedure of the LR Approach



Dual Problem

- Transform the primal problem (IP4.3) into the LR problem (LR 4.2) by relax constraints (4.1)-(4.3), (4.11), (4.14)-(4.16).
- The multipliers $\{u_{ij}^1\}, \{u_{ik}^2\}, \{u_{ik}^3\}, \{u_{kk}^4\}, \{u_{ijk}^5\}, \{u_{ijk}^6\}, \{u_{ijk}^7\}$
- Decomposition
  - Subproblems (SUB 4.1)-(SUB 4.4)
- Optimally solving each subproblem

Subproblem 1 (for S)

$$Z_{SUB4.1}(u^1) = \min\left(S + \sum_{\forall i \in A} \sum_{\substack{\forall j \in A \\ ,i \neq j}} u_{ij}^1 \frac{1}{S} \right) \qquad (SUB4.1)$$

subject to:

$$\underline{S} \le S \le \overline{S} \qquad (4.11)$$

- To optimal solve the subproblem, the right hand side of Equation (SUB4.1) will be differentiated respected to variable S.
- Let the new equation equals to zero and get the optimal solution of variable S,

$$S_{opt} = \sqrt{\sum_{\forall i \in A} \sum_{\substack{\forall j \in A \\ i \neq j}} u_{ij}^1}$$

Subproblem 1 (for S)

- If $\underline{S} \le S_{opt} \le \overline{S}$ then let $Z_{SUB4.1} = 2\sqrt{\sum_{\forall i \in A} \sum_{\substack{\forall j \in A \\ i \ne j}} u_{ij}^1}$
- Otherwise, $\underline{S}$ and $\overline{S}$ are substituted for S.
- We can get optimal solution such that

$$Z_{SUB4.1}(u^1) = \min\left\{\left(\overline{S} + \sum_{\forall i \in A} \sum_{\substack{\forall j \in A \\ ,i \ne j}} \frac{u_{ij}^1}{\overline{S}}\right), \left(\underline{S} + \sum_{\forall i \in A} \sum_{\substack{\forall j \in A \\ ,i \ne j}} \frac{u_{ij}^1}{\underline{S}}\right)\right\}$$

Subproblem 2 (for y_k , r_k)

$$Z_{SUB4.2}(u^2, u^3, u^4) = \min \sum_{\forall k \in B} \left(\sum_{\substack{\forall i \in A \\ ,i \ne k}} \left(\left(-u_{ik}^2 r_k + u_{ik}^3 \right) y_k - u_{ik}^3 \frac{d_{ik}}{r_k} \right) - \sum_{\forall k \in B} u_{kk}^4 y_k \right) \qquad (SUB4.2a)$$

subject to:

$$\sum_{\forall k \in B} c_k y_k \le G \qquad (4.4)$$

$r_k \in R$ $\qquad \forall k \in B$ $\qquad$ (4.7)

y_k=0 or 1 $\qquad \forall i \in A, k \in B$. $\qquad$ (4.9)

Subproblem 3 (for v_{ik})

$$
Z_{SUB4.3}(u^1,u^2,u^3,u^4,u^5,u^6,u^7) = \min\Bigg(-K \sum_{\forall i\in A} \sum_{\substack{\forall j\in A \\ ,i\neq j}} u^1_{ij} \frac{\sum_{\forall k\in B} v_{ik}}{w_{ij} d_{ij}}
$$

$$
-K \sum_{\forall i\in A} \sum_{\substack{\forall j\in A \\ ,i\neq j}} u^1_{ij} \frac{\sum_{\forall k\in B} v_{jk}}{w_{ij} d_{ij}} + \sum_{\forall i\in A} \sum_{\substack{\forall k\in B \\ ,i\neq k}} u^2_{ik} d_{ik} v_{ik} - \sum_{\forall i\in A} \sum_{\substack{\forall k\in B \\ ,i\neq k}} u^3_{ik} v_{ik} + \sum_{\forall k\in K} \sum_{\forall k\in B} u^4_{kk} v_{kk}
$$

$$
- \sum_{\forall i\in A} \sum_{\substack{\forall j\in A \\ ,i\neq j}} \sum_{\forall k\in B} u^5_{ijk} v_{ik} - \sum_{\forall i\in A} \sum_{\substack{\forall j\in A \\ ,i\neq j}} \sum_{\forall k\in B} u^6_{ijk} v_{jk} + \sum_{\forall i\in A} \sum_{\substack{\forall j\in A \\ ,i\neq j}} \sum_{\forall k\in B} u^7_{ijk} v_{ik}
$$

$$
+ \sum_{\forall i\in A} \sum_{\substack{\forall j\in A \\ ,i\neq j}} \sum_{\forall k\in B} u^7_{ijk} v_{jk} \Bigg) \qquad \text{(SUB4.3)}
$$

- For each term with the variable v_{jk}, index j substitutes for i contrariwise.

Subproblem 3 (for v_{ik})

$$
Z_{SUB4.3}(u^1,u^2,u^3,u^4,u^5,u^6,u^7) = \min \sum_{\forall i\in A} \Bigg\{ \sum_{\forall k\in B} \sum_{\substack{\forall j\in A \\ ,i\neq j}} \left(\frac{-Ku^1_{ij}}{w_{ij} d_{ij}} - \frac{Ku^1_{ji}}{w_{ji} d_{ji}} - u^5_{ijk} - u^6_{jik} + u^7_{ijk} + u^7_{jik} \right)
$$

$$
+ \sum_{\substack{\forall k\in B \\ ,i\neq k}} \left(u^2_{ik} d_{ik} - u^3_{ik} \right) + \sum_{\substack{\forall k\in B \\ ,i=k}} u^4_{ik} \Bigg\} v_{ik} \qquad (SUB4.3a)
$$

subject to:

$\sum_{\forall k\in B} v_{ik} \geq 1$	$\forall i\in A$	(4.5)
$\sum_{\forall k\in B} v_{ik} \leq N$	$\forall i\in A$	(4.6)
v_{ik}=0 or 1	$\forall i\in A,\ k\in B$	(4.8)

Subproblem 4 (for t_{ijk})

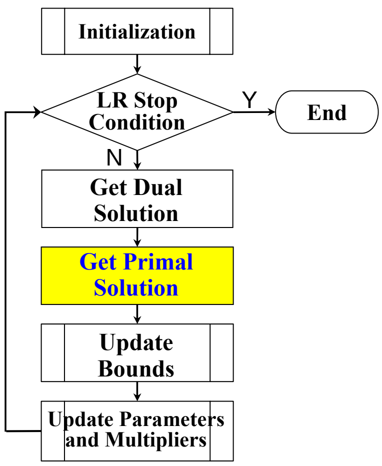
$$Z_{SUB4.4}(u^1,u^5,u^6,u^7) = \min \sum_{\forall i\in A}\sum_{\substack{\forall j\in A \\ ,i\neq j}}\sum_{\forall k\in B}\left(\frac{2Ku^1_{ij}}{w_{ij}d_{ij}} + u^5_{ijk} + u^6_{ijk} - u^7_{ijk}\right) t_{ijk} \quad (SUB4.4a)$$

subject to:

$\sum_{\forall k\in B} t_{ijk} \le N$	$\forall i,j\in A,\ i\neq j$	(4.13)
t_{ijk}=0 or 1	$\forall i,j\in A,\ i\neq j,\ k\in B$	(4.17)

PLChiu Sensor Placement Problem for Differentiated Quality of Positioning Services 63

Procedure of the LR Approach

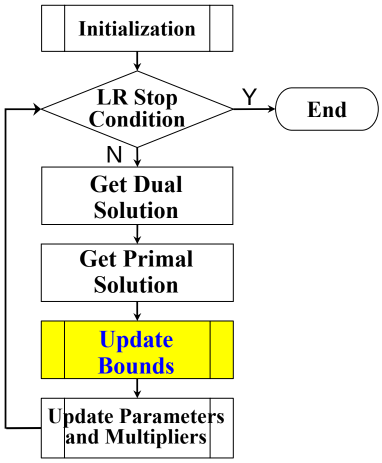


PLChiu Sensor Placement Problem for Differentiated Quality of Positioning Services 64

Getting Primal Feasible

- Adjusting the dual solutions
  - Step 1: initializing the decision variables (y_k, v_{ik}, r_k)
  - Step 2: for satisfying the coverage and budget constraints, the sensor might be *added*, *deleted*, or *changed radius.*
  - Step 3: in order to improving discrimination, the sensor might be *changed position*, *modified radius*.

Procedure of the LR Approach



LB

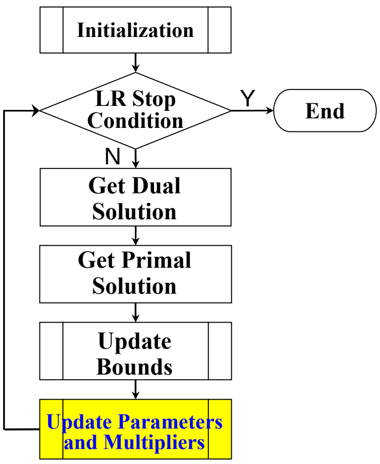
$$Z_D\left(u^1,u^2,u^3,u^4,u^5,u^6,u^7\right) = Z_{SUB4.1} + Z_{SUB4.2} + Z_{SUB4.3} + Z_{SUB4.4}$$

$$+\left(-\sum_{\forall i\in A}\sum_{\substack{\forall j\in A\\ ,i\neq j}} \frac{u^1_{ij}}{w_{ij}d_{ij}} - \sum_{\forall i\in A}\sum_{\substack{\forall j\in A\\ ,i\neq j}}\sum_{\forall k\in B} u^7_{ijk} \right)$$

- According the weak Lagrangean duality theorem [Fis81], [Fis85], the optimal objective value of the dual problem (LR), $Z_D(u^1,u^2,u^3,u^4,u^5,u^6,u^7)$, is a lower bound on primal problem (IP4.3)

$$Z_D = \max_{(u^1,u^2,u^3,u^5,u^6,u^7)\geq 0} Z_D(u^1,u^2,u^3,u^4,u^5,u^6,u^7) \qquad (D1)$$

Procedure of the LR Approach



Update the LR Multipliers

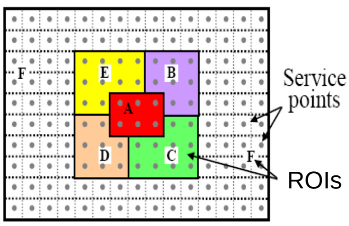
- We denote $\pi=\left(u_{ij}^1,u_{ik}^2,u_{ik}^3,u_{ik}^4,u_{ijk}^5,u_{ijk}^6,u_{ijk}^7\right)$ as the vector of Lagrangean multipliers with respect to relaxed constraints.
- In iteration m of subgradient optimization procedure, the multiplier π^m is updated by $\pi^{m+1}=\pi^m+{}^m g^m$
- The step size ζ^m is determined by

$$\zeta^m=\frac{\lambda(Z_{IP4.3}^*-Z_D(\pi^m))}{\left\|g^m\right\|^2}$$

, where $Z^*_{IP4.3}$ represents an upper bound on the primal objective value, obtained by applying a heuristic to (IP4.3), and λ is a scalar satisfying $0\le\lambda\le2$.

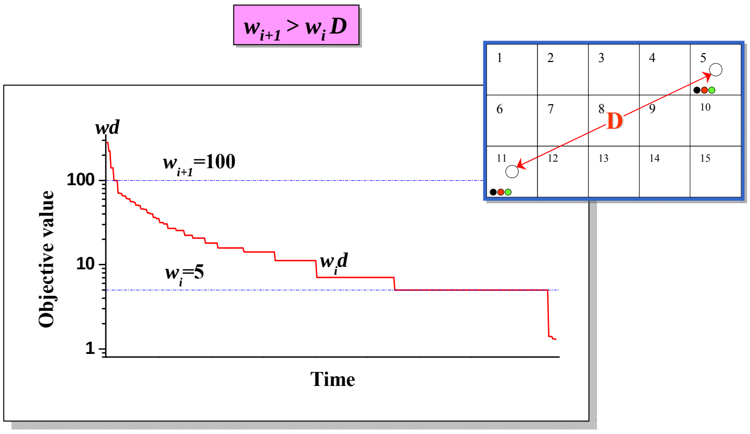
Experimental Results

- Scenario
  - Pentium IV-3.0GHz PC
  - Microsoft Window XP Pro.
  - Microsoft Visual C++ 6.0
  - Sensor fields: 10x15
  - Sensor radius: 1 ~ 8
  - LR parameters:
    - $1< \lambda \le 2$
    - Improvement counter: 45
    - Amount of iteration: 1500

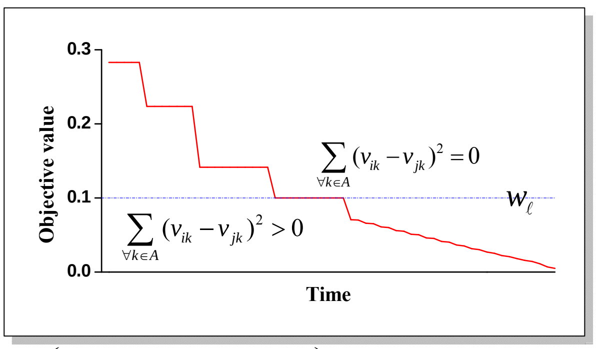


Sensor field in Exp.

Lemma 4.1 (for w_i)



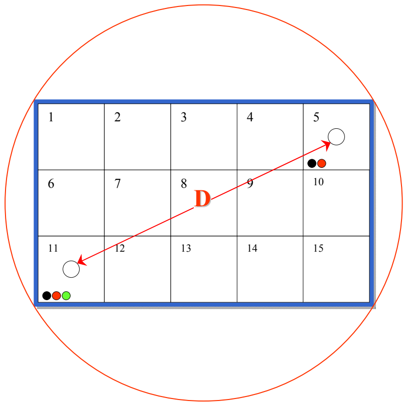
Lemma 4.2 (for K)



$$w_\ell > \max \left(\frac{w_{ij} d_{ij}}{1 + K \sum_{\forall k \in A} (v_{ik} - v_{jk})^2} \right), \quad \sum_{\forall k \in A} (v_{ik} - v_{jk})^2 > 0, \ i \neq j.$$

Lemma 4.2 (for K)

- Case 1: $2r \geq D$

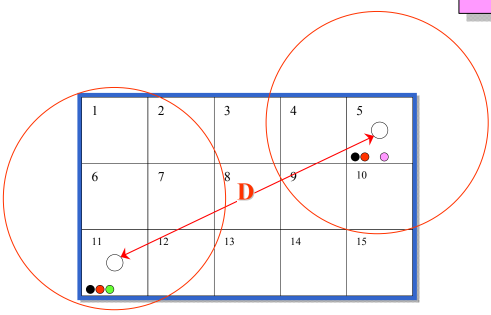


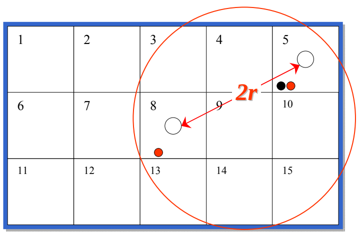
$$w_\ell > \frac{w_h D}{1+K}$$

Lemma 4.2 (for K)

- Case 1: $2r < D$

$$w_\ell > \max\left\{\frac{w_h D}{1+2K}, \frac{w_h(2r)}{1+K}\right\}$$

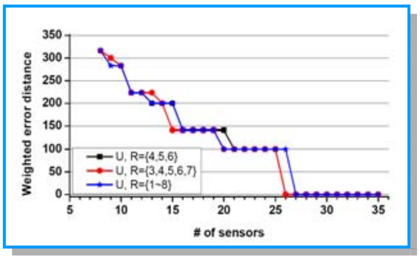




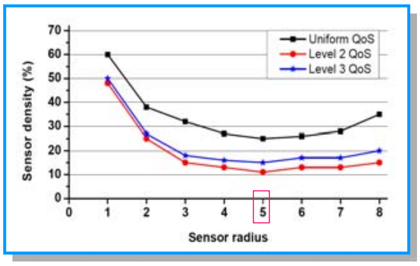
(1) $\frac{w_h D}{1+2K}$ (2) $\frac{w_h(2r)}{1+K}$

Experimental Results (LR, Exp. I)

- Sensor density vs. radius
  - Sensors density depends strongly on sensor radius



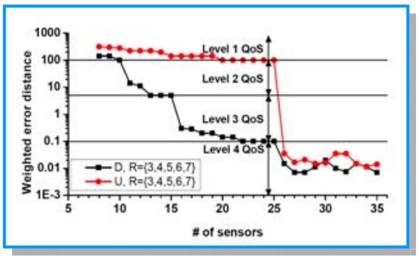
Adjustable radius, Uniform QoS



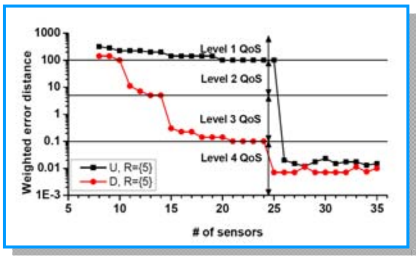
Fixed radius

Experiment Results (LR, Exp. I)

- Uniform vs. differentiated QoS request



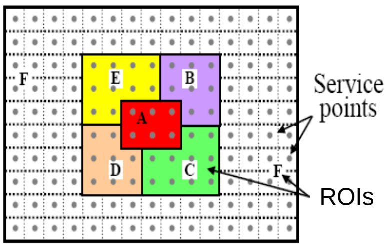
Adjustable radius



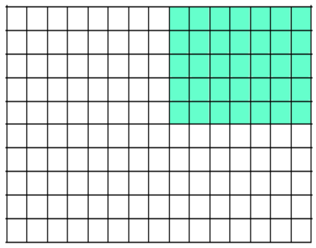
Fixed radius

Experimental Results (LR, Exp. II)

- Placement Limitation



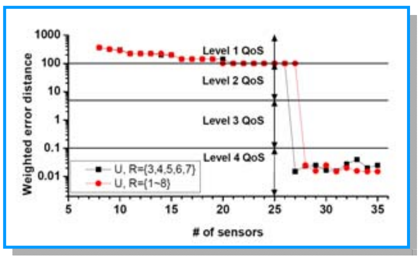
Sensor field in Exp.



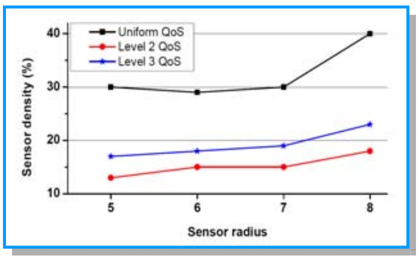
Area with placement limitation

Experimental Results (LR, Exp. II)

- Sensor density vs. radius
  - Sensors density depends strongly on sensor radius



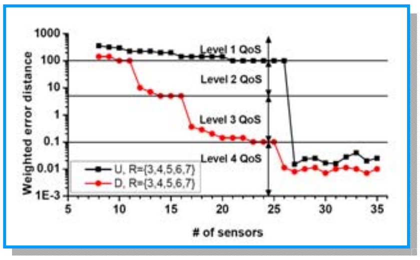
Adjustable radius, Uniform QoS



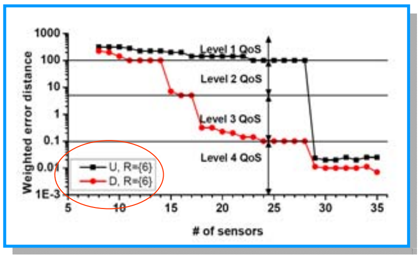
Fixed radius

Experiment Results (LR, Exp. II)

- Uniform vs. differentiated QoS request



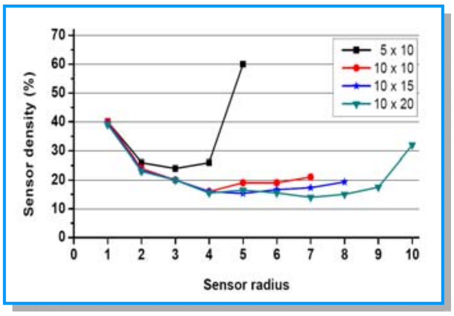
Adjustable radius



Fixed radius

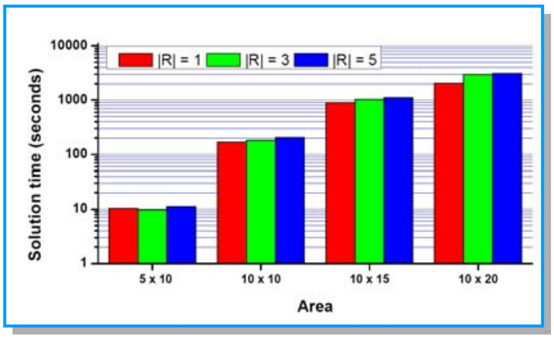
Experimental Results (LR, Exp. III)

- Scalability - solution quality
  - Fixed radius
  - Solution space: $O(2^{50})\sim O(2^{200})$



Experimental Results (LR, Exp. III)

- Scalability – solution time
  - Solution space: $O(2^{25})$~$O(6^{200})$



Simulated Annealing Approach (SA_1)

- Penalizing objective function $Z_{IP4.1}$ in algorithm SA_1.
- Energy function

Penalty

$$E = \max_{(i,j)} \frac{w_{ij} d_{ij}}{1 + K \sum_{k \in B} (v_{ik} - v_{jk})^2} \left(1 + p\left(g + \sum_{i \in A} h_i\right)\right)$$

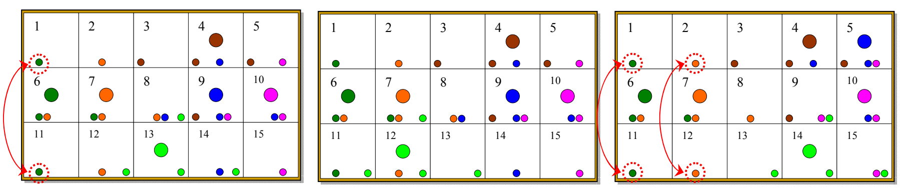
  - g: indicates the over budget
  - $\sum h$: number of uncovered service points
  - p: constant

Simulated Annealing Approach (SA_1)

- Actions for generating a new solution configuration
  - Adding one sensor
  - Dropping one sensor
  - Changing one sensor's location
  - Increasing one sensor's radius
  - Reducing one sensor's radius.

Simulated Annealing Approach (SA_2)

- Max. Error Distance (M.E.D.)

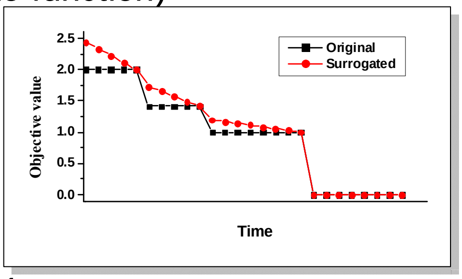


(1) M.E.D.=2 (2) M.E.D.=0 (3) M.E.D.=2

Simulated Annealing Approach (SA_2)

- Energy function (Surrogate function)

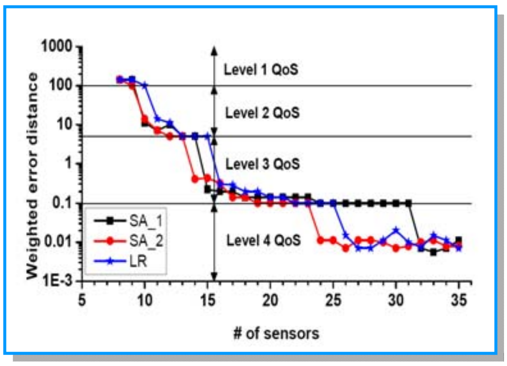
$$E_s = E * \left(1 + \frac{p'}{|A|}\sum_{i\in A} m_i\right)$$



  - E: Energy function in SA_1
  - $\sum m_i/|A|$: ratio of the service points with the maximum weighted error distance
  - p': constant

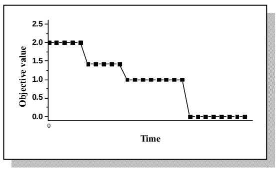
Experimental Results (Comp.)

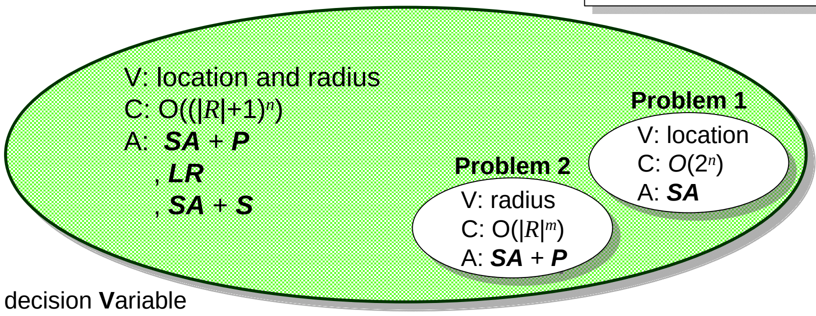
- Solution quality Comparison



Area: 10x15, differentiated QoS, R={3, 4, 5, 6, 7}

Discussion





V: decision **V**ariable
C: time **C**omplexity
A: solution **A**pproach
P: **P**enalty function
S: **S**urrogate function

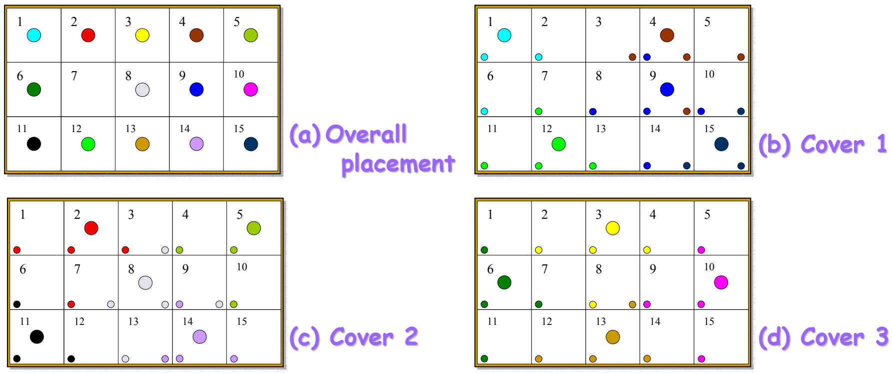
$|R|$: number of candidate radii
n : number of service points
m: number of deployed sensors, $m \leq n$

Problem 4

- Energy-Efficient Sensor Networks Design
  - F.Y.S. Lin and **P.L. Chiu**, "Energy-Efficient Sensor Network Design Subject to Complete Coverage and Discrimination Constraints," in *Second Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks* (*IEEE SECON*), 26-29 September 2005, pp. 586 - 593. (Acceptance ratio=55/202=27.2%)
  - F.Y.S. Lin and **P.L. Chiu**, "A Simulated Annealing Algorithm for Energy Efficient Sensor Network Design," in *3rd International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks* (*WiOpt*) April 3-7, 2005. (Acceptance ratio=44/141=31%)

Energy-Efficiency Approach

- A grid-based sensor field with 3 covers



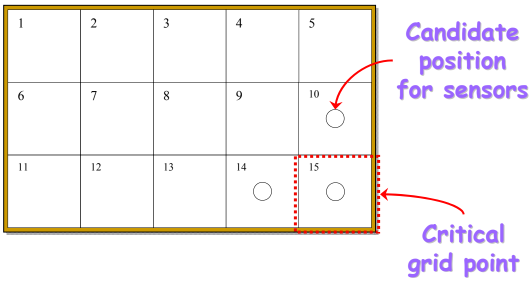
Problem Description

- Objective
  - Minimizing the deployment cost
- Given
  - Sensor field, set of service points, sensor cost, detection radius, and number of covers
- Constraints
  - Complete coverage for each cover and complete discrimination for overall sensor network
- Outcomes
  - Sensors' placement, members of each cover, and power vectors
- Solution approach
  - Lagrangean relaxation method and simulated annealing method

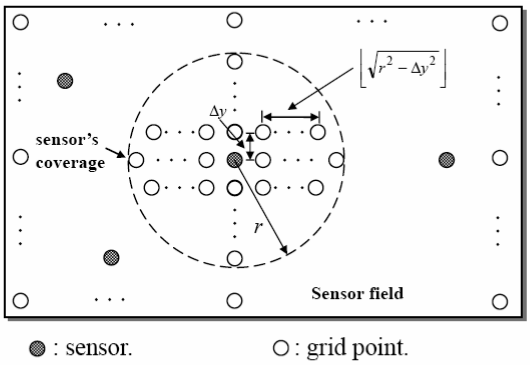
- F.Y.S. Lin and **P.L. Chiu**, "A Simulated Annealing Algorithm for Energy Efficient Sensor Network Design".
- F.Y.S. Lin and **P.L. Chiu**, "Energy-Efficient Sensor Network Design Subject to Complete Coverage and Discrimination Constraints".

Upper Bound on Number of Covers

- Critical grid point
  - Grids 1, 5, 11, and 15
  - Upper bound: 3



Upper Bound on Number of Covers



The theoretic upper bound:

$$U_r = 2r + 1 + \sum_{\Delta y=1}^{r} \left\lfloor \sqrt{r^2 - \Delta y^2} \right\rfloor$$

Mathematical Model

Given Parameters:

A : The set of the index for candidate locations where sensor can be allocated.

B : The set of the index for service points that can be covered and located by the sensor network.

K : The number of covers required for the sensor network.

a_{ij} : Indicator function which is 1 if service point i can be covered by sensor j and 0 otherwise.

c_j : Cost function of sensor j.

Mathematical Model

Decision Variables:

x_{jk} : 1 if sensor j is allocated on cover k of the sensor network.

y_j : Sensor allocation decision variable which is 1 if sensor j is allocated in the sensor network.

Mathematical Model

Problem (IP):

$$Z_{IP5.1} = \min \sum_{\forall j \in A} \sum_{\forall k \in K} c_j x_{jk} \quad \text{(IP5.1)}$$

Subject to:

$$\sum_{\forall j \in A} a_{ij} x_{jk} \geq 1 \quad ,\forall i \in B,\ k \in K \quad (5.1)$$

$$\sum_{\forall k \in K} x_{jk} \leq 1 \quad ,\forall j \in A \quad (5.2)$$

$$y_j = \sum_{\forall k \in K} x_{jk} \quad ,\forall j \in A \quad (5.3)$$

$$\sum_{\forall j \in A} (a_{ij} - a_{lj})^2 y_j \geq 1 \quad ,\forall i, l \in B, i \neq l \quad (5.4)$$

$$x_{jk}, y_j = 0 \text{ or } 1 \quad ,\forall j \in A,\ k \in K \quad (5.5)$$

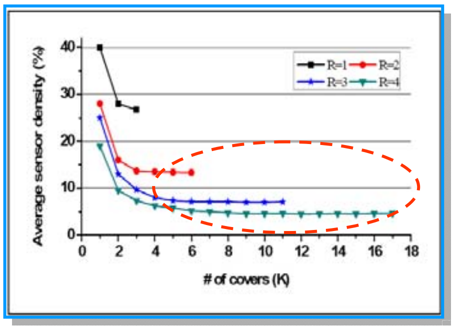
- Solution space: $O((K+1)^m)$

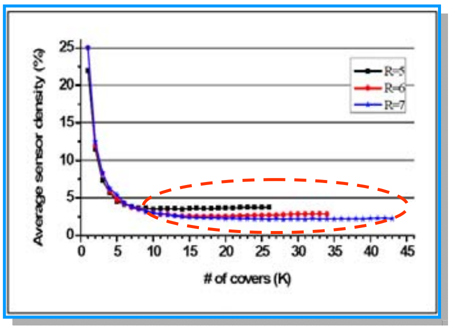
Experimental Results (LR)

- Scenario
  - Pentium IV-1.4GHz PC
  - Microsoft Window XP Pro.
  - Microsoft Visual C++ 6.0
  - Sensor fields: 10x10 service points
  - Sensor radius: 1 ~ 7
  - LR parameters:
    - $1 < \lambda \leq 2$
    - Improvement counter: 35
    - Amount of iteration: 1000

Experiment Results (LR)

- Average deployed density





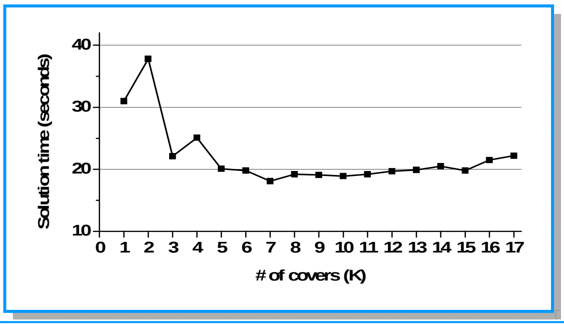
Experimental Results (LR)

- The duplicated deployment vs. the proposed approach
- Deployment cost vs. lifetime extension

Radius	The duplicate deployment		The proposed approach	
	#Duplication	Increased cost	#Cover	Increased cost
1	3	3	3	2.00
2	6	6	6	2.71
3	11	11	11	3.04
4	17	17	17	4.16
5	26	26	26	4.41
6	34	34	34	3.88
7	43	43	43	3.88

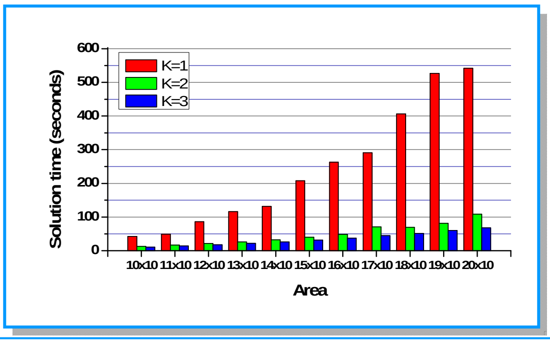
Experimental Results (LR)

- Scalability
  - Solution time vs. # of covers, R=4
  - Solution space: $O(2^{100}) \sim O(18^{100})$



Experimental Results (LR)

- Scalability in terms of number of service points
  - *r* =1
  - Solution space: $O(2^{100}) \sim O(4^{200})$



Simulated Annealing Based Algorithm

$$E = (1 + p\sum_{\forall k\in K}\sum_{\forall i\in B} g_{ik})(1+p^2(1-d_{\min}))\sum_{\forall j\in A}\sum_{\forall k\in K} c_j x_{jk}$$

Penalty

Algorithm 2.1: The skeleton of the SA heuristic.

```
Select an energy function E(x);
Select an initial temperature T_0>0, and T=T_0;
Select initial number of repetitions on initial temperature, r(T_0);
Set repetition counter t=0;
Repeat
    Set repetition counter n=0;
    Repeat
        Generate new state x_{i+1}, a neighbor of x_i;
        Calculate ΔE=E(x_{i+1})−E(x_i);
        If ΔE < 0 then x_i=x_{i+1};
        else if random (0,1) < exp(−ΔE/T_t) then x_i=x_{i+1};
        n=n+1;
    Until n=r(T_t);
    t=t+1;
    T_t =α*T_{t-1}, r(T_t)=β* r(T_{t-1});
Until stopping criterion, T_t<T_f is true.
```

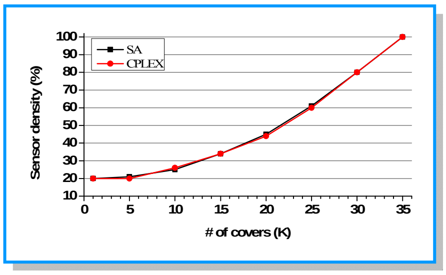
- Remove or add one sensor away/to a cover, or
- Exchange two sensors' status

Experimental Results (SA)

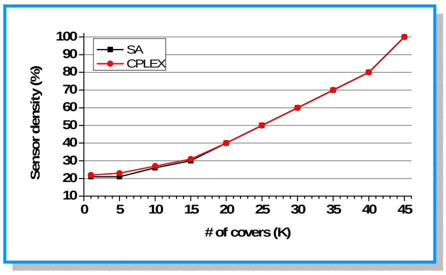
- Scenario
  - Pentium IV-1.4GHz PC
  - Microsoft Window XP Pro.
  - Microsoft Visual C++ 6.0
  - Sensor fields: 10x10 service points
  - Sensor radius: 1 ~ 7
- Benchmark: ILOG CPLEX 9.0

Experiment Results (SA vs. CPLEX)

- Required sensor density vs. # of covers



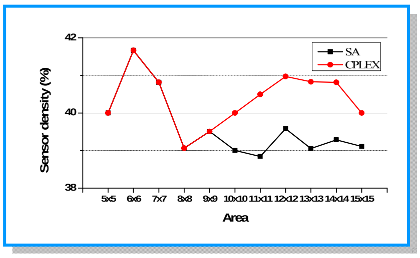
R=6



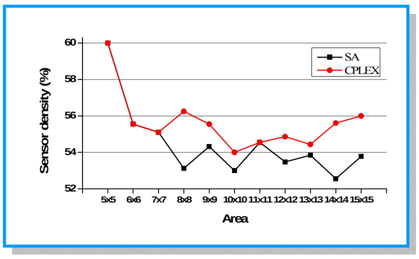
R=7

Experimental Results (SA vs. CPLEX)

- Scalability – sensor density, R=1
  - Max. solution time for CPLEX: **10000 sec.**



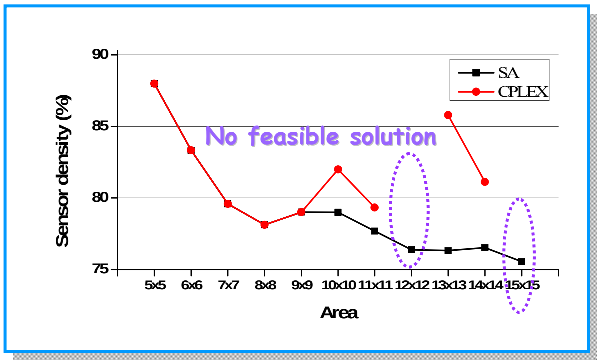
K=1



K=2

Experimental Results (SA vs. CPLEX)

- Scalability – sensor density, R=1



K=3

Experimental Results (LR vs. SA)

- **Lifetime extension**

Radius (r)	1	2	3	4	5	6	7
U_r (theoretic)	3	6	11	17	26	35	45
U_r (SA)	3	6	11	17	26	35	45
U_r (LR)	3	6	11	17	26	34	43

Experimental Results (LR & SA)

- Solution time

Solution time (Seconds)	Sensor radius						
	1	2	3	4	5	6	7
Average (SA)	94	267	227	265	298	478	587
Average (LR)	43	61	85	38	25	91	51

Concluding Remarks

- Energy-efficient sensor placement for surveillance and target location services
- Mathematical model
- Lagrangean relaxation method
- Simulated annealing method
- Prolonging the lifetime up to theoretical upper bound

Concluding Remarks

- Solution time
  - The proposed LR approach outperforms the SA approach.
  - Both approaches outperform CPLEX.
- Scalability
  - Both the proposed LR and SA approaches are scalable in terms of solution quality and solution time, but CPLEX isn't.

Contributions

- Research scope for sensor deployment research
- We first introduced the positioning ability as the QoS parameter in WSNs from application perspective, as well as proposed the error distance to measure the positioning ability.
- A generic framework for sensor placement problem has been proposed to support the differentiated QoS and prioritized service in WSNs.
- Energy-efficient sensor deployment algorithms for target positioning
- The mathematical optimization models were proposed to define the problems strictly.

Contributions

- These optimization problems, since the nonlinear and combinatorial natures, are hard to solve by traditional mathematical programming methods directly. Base on LR and SA methods, we successfully developed many heuristics to solve these optimization problems.
- For sensor network builders and researchers, the results and algorithms proposed in this dissertation are useful.
- More relative problems can be solved by proposed methods with minor modifications.

Future Work

- An energy-efficient deployment approach with mobile sensors
  - Model 1: for positioning
  - Model 2: for surveillance-only
- Survivable sensor networks design

Publication List

Journal papers:

- F.Y.S. Lin and **P.L. Chiu**, "A Near-optimal Sensor Placement Algorithm to Achieve Complete Coverage/Discrimination in Sensor Networks," *IEEE Communications Letters*, vol. 9, no. 1, January 2005, pp. 43-45.

Conference papers:

- **P.L. Chiu** and Frank Y.S. Lin, "A Simulated Annealing Algorithm to Support the Sensor Placement for Target Location," *Proc. IEEE CCECE 2004*, pp. 867-870.
- F.Y.S. Lin and **P.L. Chiu**, "A Simulated Annealing Algorithm for Energy Efficient Sensor Network Design," in *3rd International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks* (*WiOpt*) April 3-7, 2005. (Acceptance ratio=44/141=31%)
- F.Y.S. Lin and **P.L. Chiu**, "Energy-Efficient Sensor Network Design Subject to Complete Coverage and Discrimination Constraints," in *Second Annual IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks* (*IEEE SECON*), 26-29 September 2005, pp. 586 - 593. (Acceptance ratio=55/202=27.2%)
- **P.L. Chiu** and F.Y.S. Lin, "Sensor Placement Algorithms Supporting Differentiated Positioning Services," Submitted to *Globecom* 2007 *Ad-hoc and Sensor Networking Symposium.*

Dissertation Proposal

Sensor Deployment Algorithms for Target Positioning Services

Q&A