A hybrid column generation-GRASP approach to extend the lifetime in wireless sensor networks with coverage and connectivity constraints

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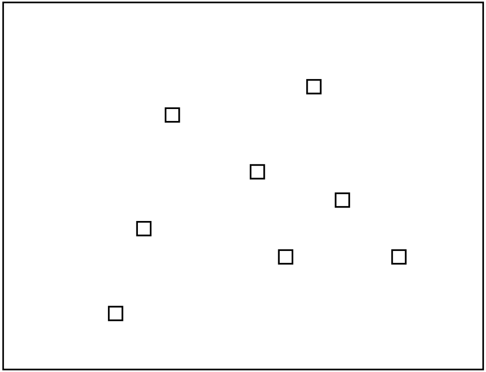
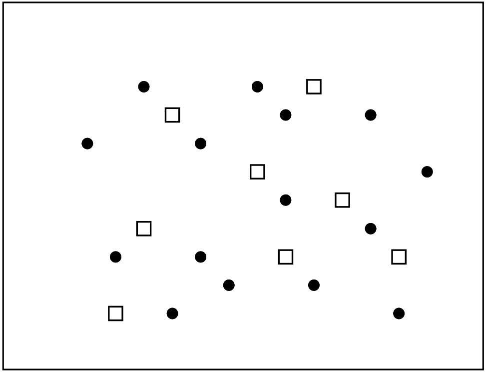
Maximum network lifetime problem with connectivity and coverage constraints (α-CMLP)

- A set of targets T



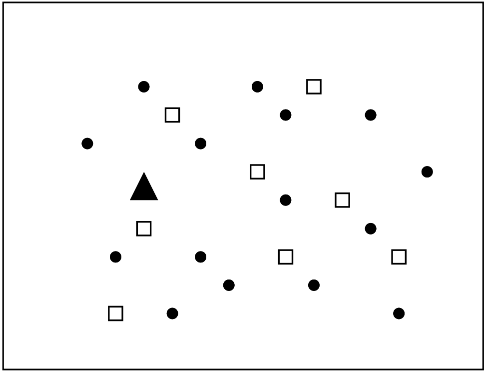
Maximum network lifetime problem with connectivity and coverage constraints (α-CMLP)

- A set of targets T
- A set of sensors S



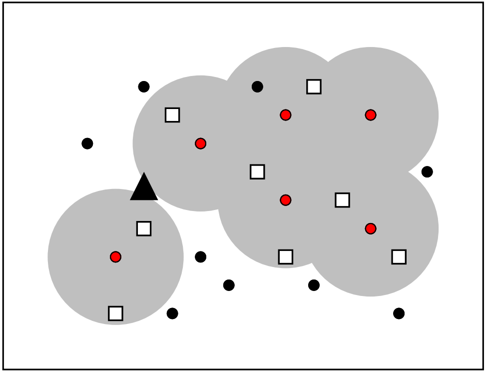
Maximum network lifetime problem with connectivity and coverage constraints (α-CMLP)

- A set of targets T
- A set of sensors S
- A base station B



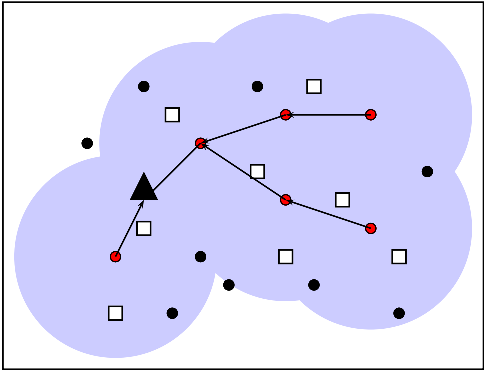
Maximum network lifetime problem with connectivity and coverage constraints (α-CMLP)

- A set of targets T
- A set of sensors S
- A base station B
- Sensing range R_s
- Cover set



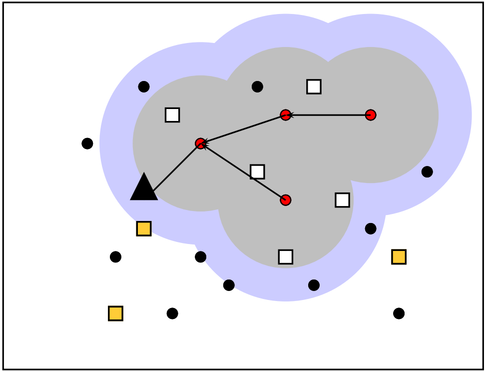
Maximum network lifetime problem with connectivity and coverage constraints (α-CMLP)

- A set of targets T
- A set of sensors S
- A base station B
- Sensing range R_s
- Cover set
- Communication range R_c
- Connectivity required

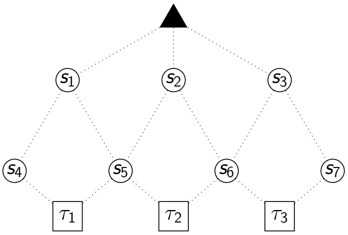


Maximum network lifetime problem with connectivity and coverage constraints (α-CMLP)

- A set of targets T
- A set of sensors S
- A base station B
- Sensing range R_s
- Cover set
- Communication range R_c
- Connectivity required
- Quality of service requirements (α).

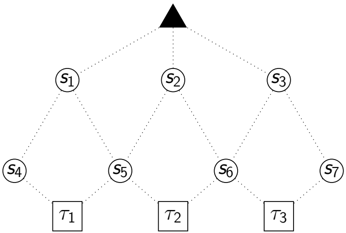


Strategies to extend network lifetime

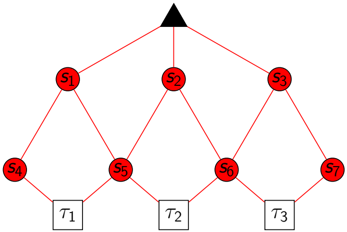


Potential network

Strategies to extend network lifetime

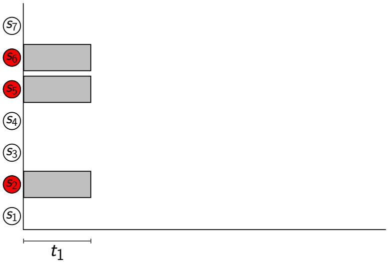


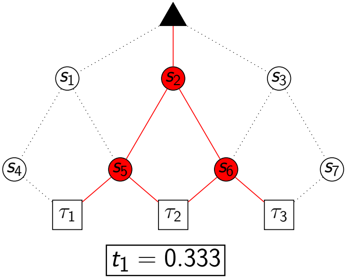
Potential network



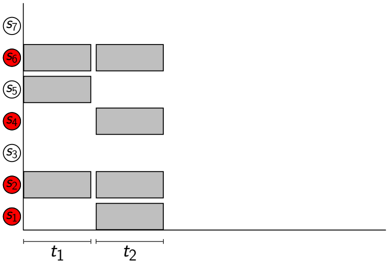
Total Lifetime=1

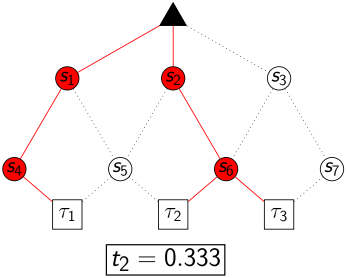
Strategies to extend network lifetime



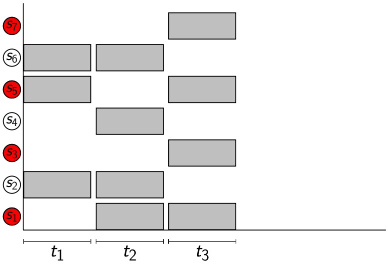


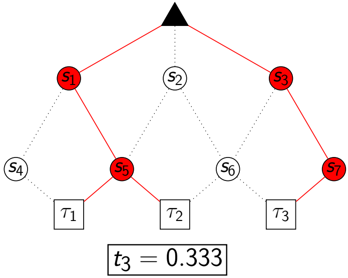
Strategies to extend network lifetime



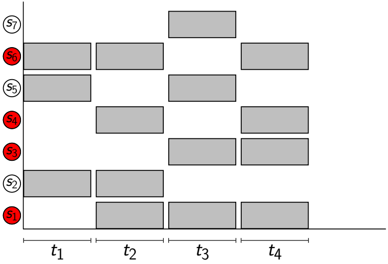


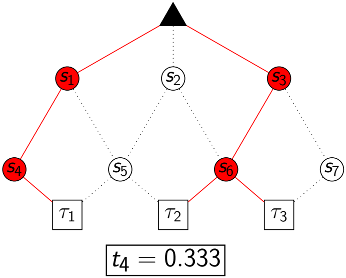
Strategies to extend network lifetime



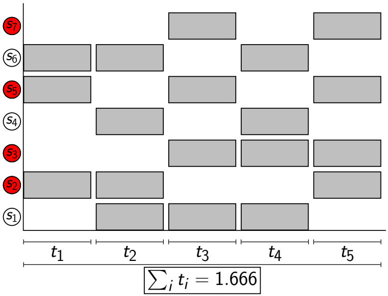


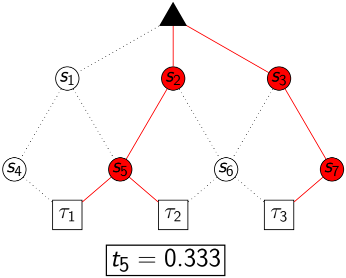
Strategies to extend network lifetime



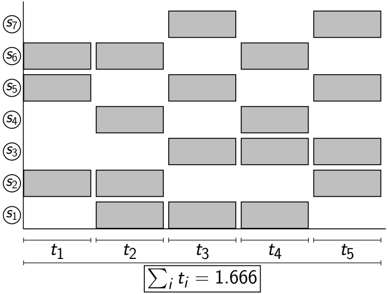


Strategies to extend network lifetime





Strategies to extend network lifetime



Representation

$$\begin{pmatrix} 0 & 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 1 & 0 \end{pmatrix} \begin{pmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \end{pmatrix}$$

Lifetime maximization in wireless sensor networks

Problem representation

Representation

$$\begin{pmatrix} 0 & 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 1 & 0 \end{pmatrix} \begin{pmatrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \end{pmatrix}$$

Model

Maximize:

$$t_1 + t_2 + t_3 + t_4 + t_5$$

Subject to:

$$t_3 + t_5 \leq b \quad (1)$$
$$t_1 + t_2 + t_4 \leq b \quad (2)$$
$$t_1 + t_3 + t_5 \leq b \quad (3)$$
$$t_2 + t_4 \leq b \quad (4)$$
$$t_3 + t_4 + t_5 \leq b \quad (5)$$
$$t_1 + t_2 + t_5 \leq b \quad (6)$$
$$t_2 + t_3 + t_4 \leq b \quad (7)$$
$$t_1, t_2, t_3, t_4, t_5 \geq 0 \quad (8)$$

Decomposition based approach

Master problem

$$\text{Maximize:} \quad \sum_{C_j \in \Omega'} t_j \tag{9}$$

Subject to:

$$\sum_{C_j \in \Omega'} y_{s_u j} t_j \leq b_{s_u} \qquad \forall\ s_u \in S(\pi_u) \tag{10}$$

$$t_j \geq 0 \qquad \forall\ C_j \in \Omega' \tag{11}$$

Decomposition based approach

Master problem

$$\text{Maximize:} \quad \sum_{C_j \in \Omega'} t_j \qquad (9)$$

Subject to:

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$$t_j \geq 0 \qquad \forall\ C_j \in \Omega' \qquad (11)$$

Too many covers

Covers $\simeq \mathcal{O}(2^{|S|})$.

Decomposition based approach

Master problem

$$\text{Maximize:} \quad \sum_{C_j \in \Omega'} t_j \qquad (9)$$

Subject to:

$$\sum_{C_j \in \Omega'} y_{s_u j} t_j \leq b_{s_u} \qquad \forall \; s_u \in S \; (\pi_u) \qquad (10)$$

$$t_j \geq 0 \qquad \forall \; C_j \in \Omega' \qquad (11)$$

Too many covers

Covers $\simeq \mathcal{O}(2^{|S|})$.

Which covers to use?

- Positive reduced cost
- Required level of coverage
- Connectivity constraints

Decomposition based approach

Master problem

$$\text{Maximize:} \quad \sum_{C_j \in \Omega'} t_j \tag{9}$$

Subject to:

$$\sum_{C_j \in \Omega'} y_{s_u j} t_j \leq b_{s_u} \quad \forall\, s_u \in S\ (\pi_u) \tag{10}$$

$$t_j \geq 0 \quad \forall\, C_j \in \Omega' \tag{11}$$

Too many covers

$\#$ Covers $\simeq \mathcal{O}(2^{|S|})$.

Auxiliary problem

$$\text{Maximize: } 1 - \sum_{s_u \in \mathcal{S}} y_{uj} \pi_u \tag{12}$$

Subject to:

$$\sum_{s_u \in \mathcal{S} \mid \exists e(r,u)} f_{ru} = \sum_{s_u \in \mathcal{S}} y_{uj} \tag{13}$$

$$\sum_{s_v \in \mathcal{S} \mid \exists e(v,u)} f_{vu} - \sum_{s_v \in \mathcal{S} \mid \exists e(u,v)} f_{uv} = y_{uj} \quad \forall\, s_u \in \mathcal{S} \tag{14}$$

$$\sum_{s_u \in \mathcal{S} \mid \exists e(u,v)} x_{uv} = y_{vj} \quad \forall\, s_v \in \mathcal{S} \tag{15}$$

$$x_{uv} \leq f_{uv} \leq x_{uv} |\mathcal{S}| \quad \forall\, s_u, s_v \in \mathcal{S} \tag{16}$$

$$\sum_{s_u \in \mathcal{S} \mid \exists e(u,k)} y_{uj} \geq z_k \quad \forall\, k \in \mathcal{K} \tag{17}$$

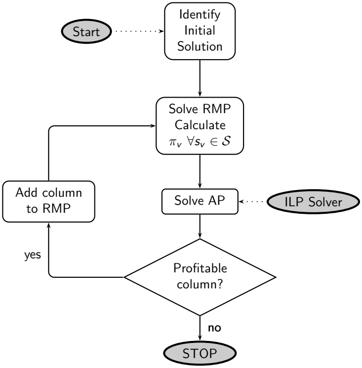
$$\sum_{k \in \mathcal{K}} z_k \geq \lceil \alpha |\mathcal{K}| \rceil \tag{18}$$

$$f_{uv} \in \mathbb{Z}^+ \cup \{0\} \quad \forall\, s_u, s_v \in \mathcal{S} \tag{19}$$

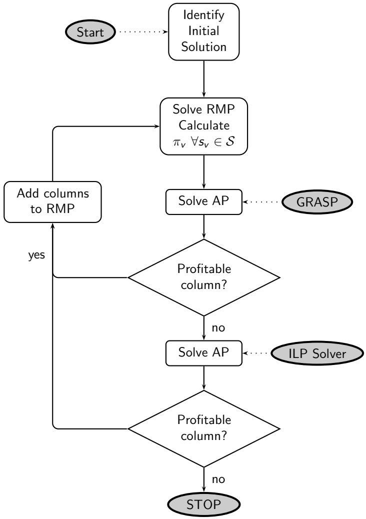
$$y_{uj}, x_{uv} \in \{0, 1\} \quad \forall\, s_u, s_v \in \mathcal{S} \tag{20}$$

$$z_k \in \{0, 1\} \quad \forall\, k \in \mathcal{K} \tag{21}$$

Column generation approach

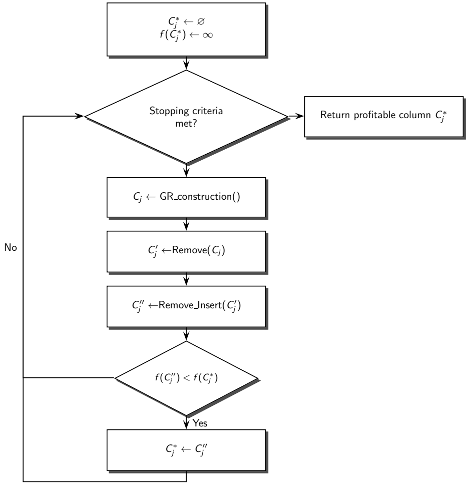


GRASP based column generation



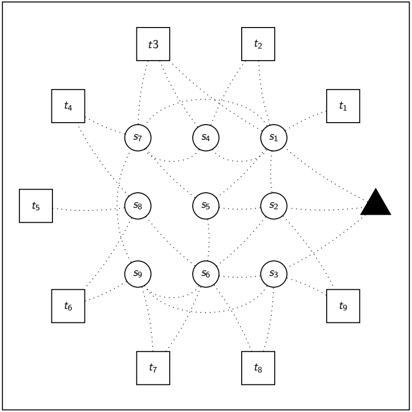
GRASP

Global structure of the proposed GRASP algorithm for AP



GRASP

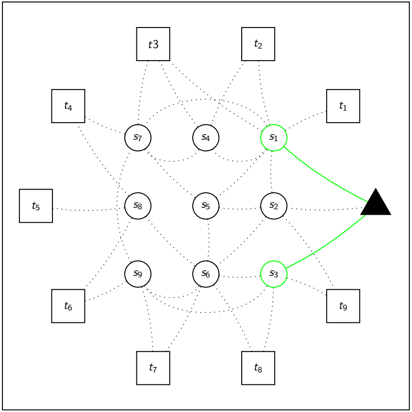
Greedy randomized depth first search



- A connected structure rooted at the base station must be found.

GRASP

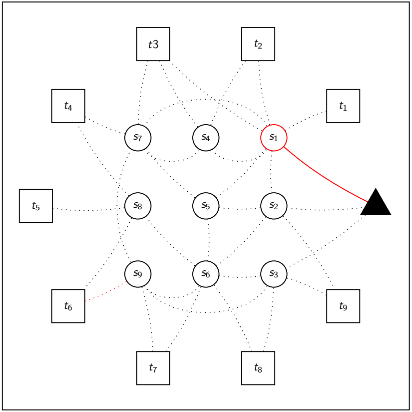
Greedy randomized depth first search



- Create a Restricted Candidate List (RCL)

GRASP

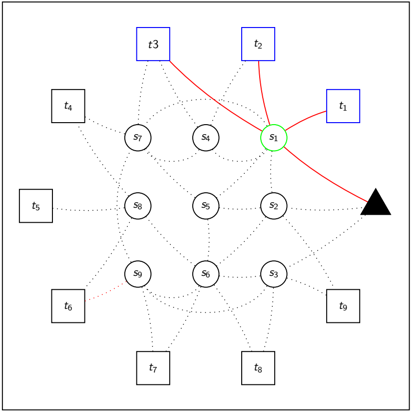
Greedy randomized depth first search



- Randomly select a sensor node from RCL and connect it to the tree

GRASP

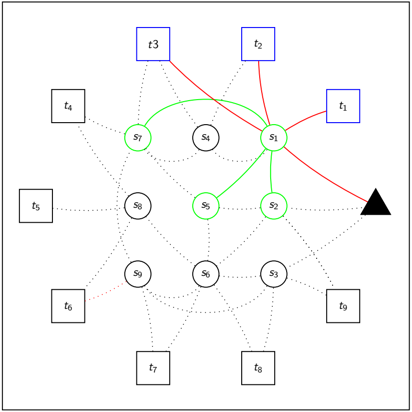
Greedy randomized depth first search



- Mark as covered the targets with a link to the most recently added sensor node

GRASP

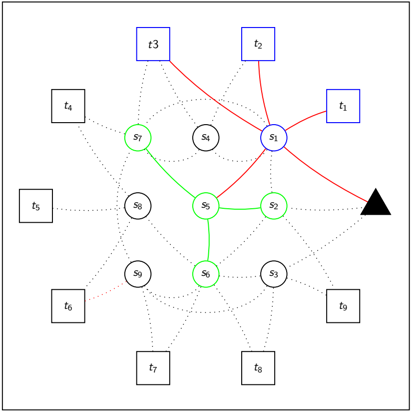
Greedy randomized depth first search



- Create a new RCL of sensor nodes to be connected to the most recently added node

GRASP

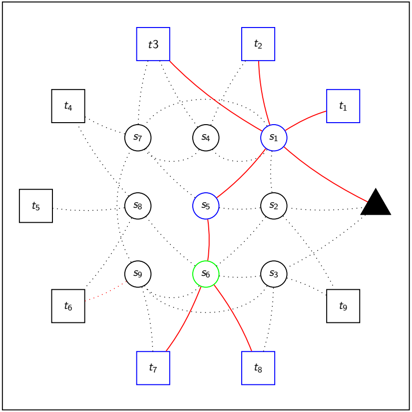
Greedy randomized depth first search



- If no new target is covered keep adding sensor nodes to the tree.
- Create a new RCL of sensor nodes to be connected to the most recently added sensor node

GRASP

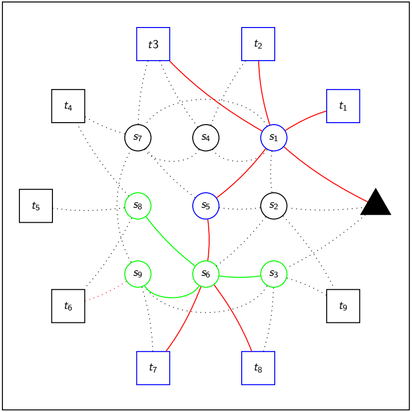
Greedy randomized depth first search



- Mark as covered the targets with a link to the most recently added sensor

GRASP

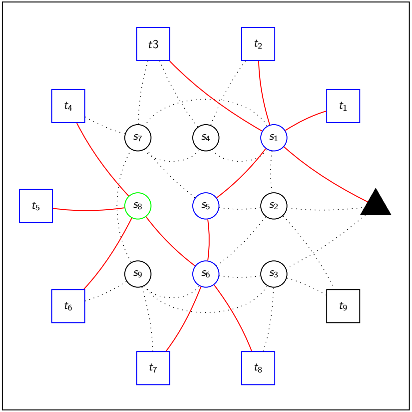
Greedy randomized depth first search



- Create a new RCL of nodes to be connected to the most recently added node

GRASP

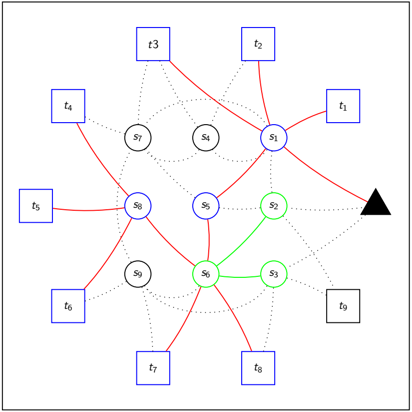
Greedy randomized depth first search



- Randomly select a node from RCL and connect it to the tree
- Mark as covered the targets with a link to the recently added sensors
- The current node is a leaf (deadlock)

GRASP

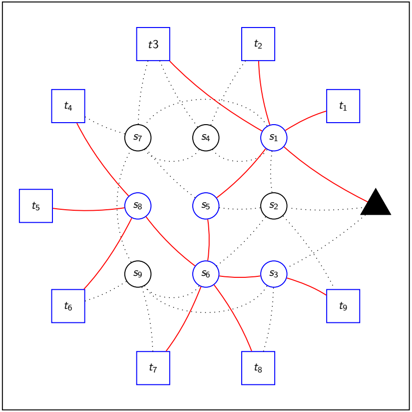
Greedy randomized depth first search



- A backtrack is performed.
- The last visited node is used again to create a new RCL

GRASP

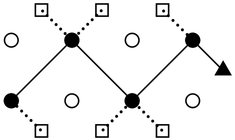
Greedy randomized depth first search



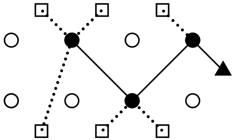
- The process finishes when the required level of coverage is reached

GRASP

Improvement phase I



Initial solution



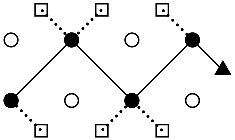
Remove neighborhood

Remove checklist

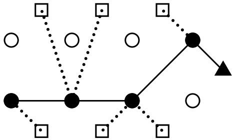
- The coverage level is feasible
- The connectivity will remain after removal

GRASP

Improvement phase II



Initial solution



Remove-Insert neighborhood

Remove-Insert checklist

- The exchange is profitable
- The coverage level is feasible
- The connectivity will remain after the exchange

Instances and settings

Dataset (Raiconi and Gentili (2011))

- Number of sensors in $\{50,75,100,150,200\}$
- With 15 Targets
- α in $\{0.5,0.7,0.85,1\}$
- Scaled to Linpack Benchmarks ($\alpha = 1$)

Strategies

- CG-GRASP
- CG-GRASP++

Results

Full coverage case ($\alpha = 1$)

$\|S\|$	CMLP-Greedy		CMLP-GRASP		CG-GRASP		CG-GRASP++		Opt
	sol	**time**	**sol**	**time**	sol	time	sol	time	
50	2.00	0.02	2.00	3.01	2.00	0.15	2.00	0.42	2
	2.00	0.02	2.50	3.71	2.50	0.02	2.50	0.51	2.5
	3.00	0.02	3.00	3.33	3.00	0.12	3.00	0.17	3
	4.00	0.03	4.00	6.18	4.00	0.28	4.00	0.04	4
	3.00	0.02	4.00	7.70	4.66	4.66	4.66	3.61	4.66
75	5.00	0.05	6.00	24.37	7.00	18.35	7.00	5.76	7
	4.00	0.06	4.00	12.24	4.00	1.81	4.00	0.89	4
	3.00	0.03	3.00	4.10	3.00	0.43	3.00	0.54	3
	6.00	0.08	7.00	26.55	7.00	3.06	7.00	1.97	7
	6.00	0.04	6.00	19.31	7.00	10.06	7.00	6.44	7
100	8.00	0.11	9.00	33.20	10.00	55.26	10.00	26.90	10
	6.00	0.23	7.00	33.11	7.00	22.80	7.00	1.57	7
	6.00	0.06	7.00	17.48	7.00	1.05	7.00	0.92	7
	9.00	0.17	9.00	46.21	9.00	7.92	9.00	2.41	9
	8.00	0.20	8.00	86.49	8.00	2.74	8.00	3.55	8
150	12.00	0.25	15.00	69.22	17.00	95.82	17.00	93.48	17
	11.00	0.33	13.00	67.32	13.68	98.55	14.00	80.12	14
	10.00	0.17	12.00	30.37	15.88	99.55	16.00	56.76	16
	12.00	0.63	13.00	125.56	13.00	53.87	13.00	17.32	13
	13.00	0.29	14.00	131.02	14.00	4.04	14.00	3.81	14
200	18.00	0.58	20.00	160.51	23.99	99.26	25.00	127.73	25
	17.00	0.85	18.00	141.21	20.00	26.97	20.00	55.10	20
	13.00	0.27	14.95	156.00	19.00	91.65	19.00	90.58	19
	16.00	1.30	18.00	225.03	18.00	107.67	18.00	79.67	18
	18.00	0.70	19.00	218.34	19.00	10.26	19.00	6.59	19
#Opt	7		15		23		25		-

Results

Partial coverage case ($\alpha < 1$)

S	$\alpha = 0.5$				$\alpha = 0.7$				$\alpha = 0.85$			
	CG		**CG-GRASP++**		**CG**		**CG-GRASP++**		**CG**		**CG-GRASP++**	
	sol	**time**	**sol**	**time**	**sol**	**time**	**sol**	**time**	**sol**	**time**	**sol**	**time**
50	2.00	7.53	2.00	0.02	2.00	4.65	2.00	0.03	2.00	4.70	2.00	0.03
	5.00	34.79	5.00	0.08	4.00	37.68	4.00	0.25	4.00	62.42	4.00	0.38
	5.00	7.09	5.00	0.05	5.00	26.32	5.00	0.07	5.00	261.13	5.00	0.10
	10.00	54.62	10.00	0.06	9.03	1007.63	9.375	0.38	5.00	10.31	5.00	0.04
	7.00	32.98	7.00	0.05	6.00	56.52	6.00	0.20	6.00	617.80	6.00	0.47
75	7.00	300.38	7.00	0.39	7.00	702.69	7.00	0.60	6.69	-	7.00	0.93
	12.00	638.51	12.00	0.48	10.49	-	12.00	4.20	8.18	-	9.50	2.65
	6.00	23.24	6.00	0.06	6.00	39.15	6.00	0.08	6.00	55.32	6.00	0.15
	14.00	469.12	14.00	0.25	12.33	-	14.00	2.43	8.00	282.35	8.00	0.55
	11.00	214.43	11.00	0.23	9.00	247.17	9.00	0.20	8.60	-	9.00	0.90
100	10.00	268.73	10.00	0.39	9.91	-	10.00	0.69	9.14	-	10.00	2.10
	15.79	-	18.00	2.83	13.56	-	16.71*	33.22	10.48	-	13.97*	49.42
	10.94	-	11.00	0.38	10.53	-	11.00	0.77	10.64	-	11.00	0.82
	19.00	755.54	19.00	0.30	15.81	-	19.00	6.58	12.15	-	13.00	0.88
	18.00	652.40	18.00	0.41	13.85	-	15.00	0.81	11.94	-	15.00	11.51
150	16.60	-	18.00	1.60	15.26	-	18.00	5.18	14.04	-	18.00	14.35
	23.01	-	30.00	11.85	16.19	-	28.09*	379.44	13.68	-	23.19*	415.11
	14.13	-	17.00	2.27	12.59	-	17.00	3.71	14.01	-	17.00	8.06
	27.57	-	33.00	1.72	20.35	-	31.25*	73.38	17.03	-	25.00	49.26
	22.47	-	28.00	1.80	20.53	-	27.00	10.14	16.33	-	25.44*	218.84
200	25.45	-	34.00	4.98	16.90	-	34.00	76.41	13.69	-	34.00	920.36
	23.88	-	60.80*	108.25	11.52	-	45.24*	351.94	13.10	-	37.5881*	862.82
	19.41	-	24.00	2.18	13.75	-	24.00	9.61	13.31	-	24.00	25.71
	24.27	-	47.00	10.66	16.14	-	40.00	107.72	14.00	-	32.00	196.19
	34.65	-	49.00	7.21	21.88	-	44.60*	404.63	18.11	-	37.90*	681.45
Av. Time	643.73		6.34		784.86		58.91		786.63		138.52	
#Opt	13		24		7		20		7		20	

Conclusions and future work

Conclusions

- CG-GRASP is able to obtain optimal solutions for α-CMLP in low CPU times
- CG-GRASP obtains solutions with good quality when is not able to obtain the optimal solution.
- GRASP is an efficient heuristic to solve AP
- CG-GRASP++ is more efficient than CG-GRASP

Future Work

- Different energy consumption models
  - Different consumption profiles
  - Energy consumption based on traffic

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