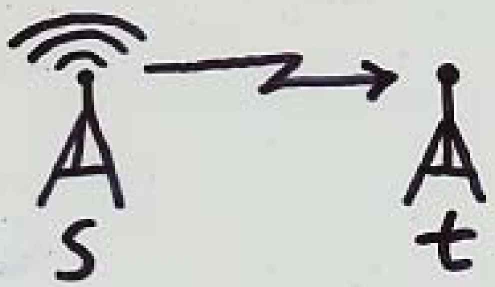
ENERGY CONSUMPTION IN RADIO NETWORKS: SELFISH AGENTS AND REWARDING MECHANISMS

CHRISTOPH AMBÜHL[1], ANDREA CLEMENTI[1], PAOLO PENNA[2], GIANLUCA ROSSI[1], RICCARDO SILVESTRI[3]

1 DIPARTIMENTO DI MATEMATICA, UNIV. ROMA "TOR VERGATA"

2 DIP. INFORMATICA ED APLICAZIONI, UNIVERSTÀ DI SALERNO

3 DIPARTIMENTO DI INFORMATICA, UNIV. DI ROMA "LA SAPIENZA"

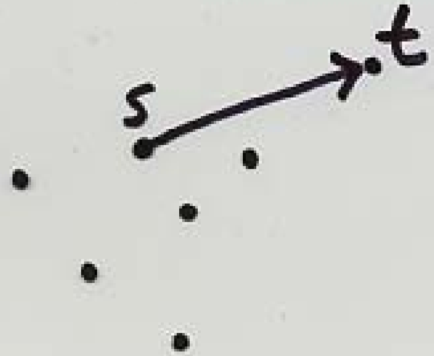


$\text{POWER}(s) \geq d(s,t)^{\alpha}$ $\quad\quad$ $\alpha \geq 1$

OVERALL ENERGY:

MULTIHOP $\Rightarrow O(n)$

ONE HOP $\Rightarrow O(n^{\alpha})$



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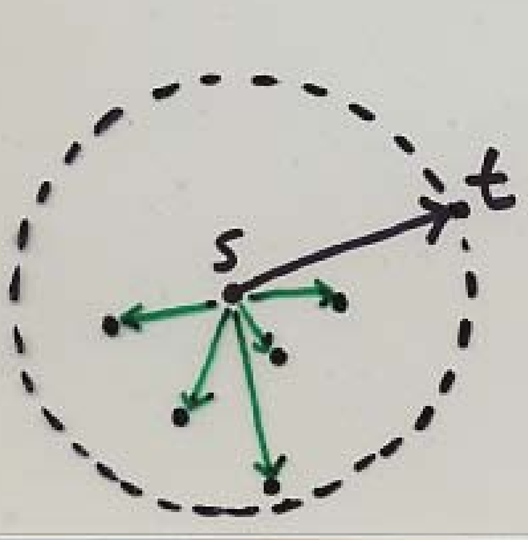
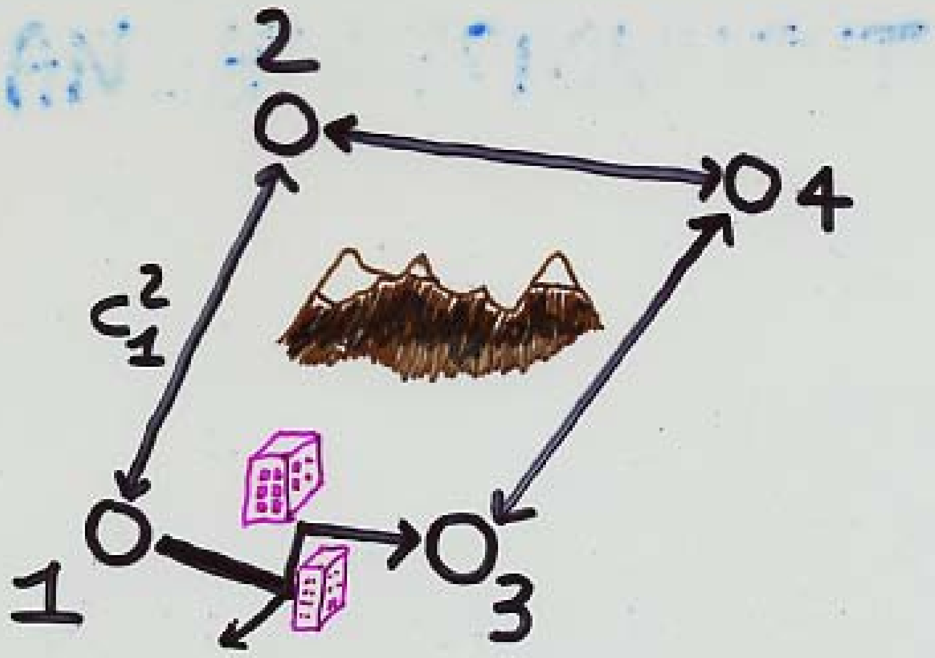




c_i^j = POWER FOR TRANSMISSION

$i \rightarrow j$ **ONE HOP**

$c_1^2 = d(1,2)^2 \qquad \alpha = 2$

$c_1^3 = d(1,3)^{2,5\ldots}$ RIFRACTION

$c_1^4 = \infty$ OBSTACLE

$c_3^4 = \infty$ TOO FAR

E = CONNECTIONS = $\{(1,2), (1,3), \ldots\}$

COST(E,C) = POWER(1) + POWER(2) + $\cdots$

$= \text{MAX}\{c_1^2, c_1^3\} + \cdots$

RANGE ASSIGNMENT

<u>INPUT</u>: $S = \{1, \dots, n\}$ STATIONS

$$C : S \times S \longrightarrow \mathbb{R}^+$$

C_i^j = COST/POWER TRANSMIT $i \longrightarrow j$ ONE HOP

<u>SOL</u>: $E \subseteq S \times S$ EDGES s.t.

$G(S,E)$ IS STRONGLY CONNECTED

<u>MEASURE</u>: OVERALL ENERGY

$$COST(E,C) := \sum_{i \in S} COST_i(E,C)$$

$$COST_i(E,C) := MAX\{C_i^j \mid (i,j) \in E\}$$

PREVIOUS WORK

GEOMETRIC INSTANCES $c_i^j = d(i,j)^\alpha$

1D POLYNOMIAL

[KIROUSIS, KRANAKIS, KRIZANC, PELC '97]

2D NP-HARD

[CLEMENTI, P., SILVESTRI '99]

3D APX-HARD

[CPS'99]

GENERAL COSTS c_i^j

2-APX ALGORITHM

[KKKP '97]

METRIC CASE $c_i^j \leq c_i^k + c_k^j$

1.61-APX ALGORITHM

[CALINESCU, ZARAGOZA '02]

NP-HARD

[CPS'99]

AD-HOC NETWORKS

NO INFRASTRUCTURE

$\Downarrow$

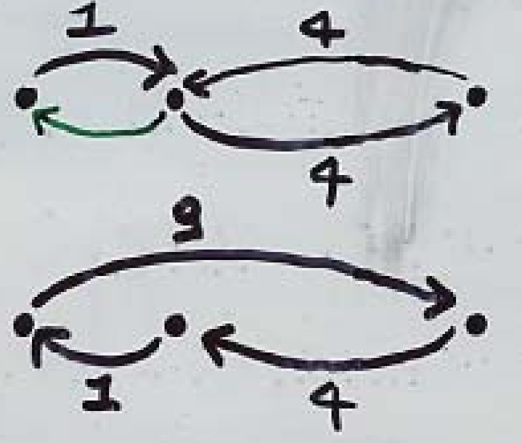
NO "EXTERNAL" ENTITY
IMPOSING ITS OWN WILL
(GOVERNMENTS, PROVIDERS, PRIVATE COMPANIES)

$\Downarrow$

SELF-ORGANIZATION

$\Downarrow$

COOPERATION, ALTRUISTIC BEHAVIOR



OPT = 9

COST = 14

AD-HOC NETWORKS

NO INFRASTRUCTURE

⇓

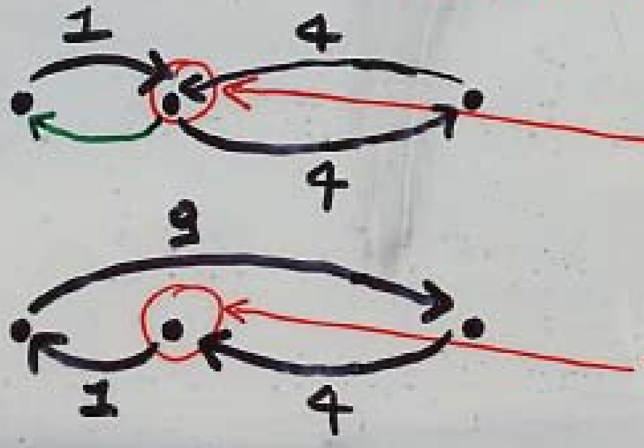
NO "EXTERNAL" ENTITY IMPOSING ITS OWN WILL (GOVERNMENTS, PROVIDERS, PRIVATE COMPANIES)

⇓

SELF-ORGANIZATION

⇓

COOPERATION, ~~ALTRUISTIC~~ SELFISH BEHAVIOR



OPT = 9
POWER = 4

COST = 14
POWER = 1

DIFFERENT OWNERS ⇒ <u>SELFISH</u> STATIONS

THE MODEL

PRIVATE INPUT:

$$C_i = \{C_i^1, C_i^2, \ldots, C_i^n\}$$

KNOWN TO STATION i ONLY

AGENTS:

AGENT i OWNS STATION i

" " DECLARES COST VECTOR

$$D_i = \{D_i^1, \ldots, D_i^n\}$$

ALGORITHM ALG COMPUTES

$$ALG(D_1, \ldots, D_i, \ldots, D_n) = E$$

$$E = \{E_1, \ldots, E_i, \ldots, E_m\}$$

COST FOR AGENT i

$$COST_i(E_i, C) = MAX\{C_i^j \mid (i,j) \in E_i\}$$

$$= COST_i(D_i; C_i, ALG)$$

THE MODEL (CNTD.)

MECHANISM: ALGORITHM
+
PAYMENT FUNCTION

$$M = (ALG, P^{ALG})$$

$$P^{ALG} = (P_1^{ALG}, \ldots, P_m^{ALG})$$

$$P_i^{ALG} = P_i^{ALG}(D_1, \ldots, \underline{D_i}, \ldots, D_m)$$

AGENTS' UTILITY

$$U_i(D_i) := P_i^{ALG}(D_1, \ldots, D_i, \ldots, D_m) - COST_i(D_i, C_i, ALG)$$

SELFISH AGENTS: AGENT i WANTS TO MAXIMIZE $U_i(D_i)$

$$\Downarrow$$

LIE ONLY IF $U_i(D_i) > U_i(C_i)$

TRUTHFULNESS

$M = (ALG, P^{ALG})$ IS TRUTHFUL

IF

$$\forall i,\ \forall D_{-i} = (D_1, \ldots, D_{i-1}, D_{i+1}, \ldots, D_m)$$

$$\forall D_i,$$

$$P_i^{ALG}(D_1, \ldots, D_{i-1}, C_i, D_{i+1}, \ldots, D_m)$$
$$- COST(C_i, C_i, ALG) \geq$$
$$P_i^{ALG}(D_1, \ldots, D_{i-1}, D_i, D_{i+1}, \ldots, D_m)$$
$$- COST(D_i, C_i, ALG)$$

PARTICIPATION CONSTRAINT

$$\forall D_{-i},\ P_i^{ALG}(D_1, \ldots, C_i, \ldots D_m) -$$
$$COST(C_i, C_i, ALG) \geq 0$$

TRUTHFULNESS

$M = (ALG, P^{ALG})$ IS TRUTHFUL IF

$\forall i,\ \forall D_{-i} = (D_1, \ldots, D_{i-1}, D_{i+1}, \ldots, D_m)$

$\forall D_i,$

$$
\begin{array}{l}
U_i(C_i) \begin{cases} P_i^{ALG}(D_1, \ldots, D_{i-1}, C_i, D_{i+1}, \ldots, D_m) \\ -\,COST(C_i, C_i, ALG) \geq \end{cases} \\
\quad\ \ \text{IV} \\
U_i(D_i) \begin{cases} P_i^{ALG}(D_1, \ldots, D_{i-1}, D_i, D_{i+1}, \ldots, D_m) \\ -\,COST(D_i, C_i, ALG) \end{cases}
\end{array}
$$

PARTICIPATION CONSTRAINT

$$\forall D_{-i},\ P_i^{ALG}(D_1, \ldots, C_i, \ldots D_m) - COST(C_i, C_i, ALG) \geq 0$$

VCG PAYMENTS

UTILITARIAN PROBLEMS

$$COST(SOL, C) = \sum_i COST_i(SOL, C_i)$$

$$P_i^{ALG}(D_i, D_{-i}) := R_i(D_{-i}) - \sum_{j \neq i} COST_j(ALG(D_i, D_{-i}), D_j)$$

$$\Downarrow$$

$$U_i(D_i) = P_i^{ALG}(D_i, D_{-i}) - COST_i(ALG(D_i, D_{-i}), C_i)$$

$$= R_i(D_{-i}) - COST(ALG(D_i, D_{-i}), (C_i, D_{-i}))$$

VCG PAYMENTS

UTILITARIAN PROBLEMS

$$\mathrm{COST}(\mathrm{SOL}, C) = \sum_i \mathrm{COST}_i(\mathrm{SOL}, C_i)$$

$$P_i^{ALG}(D_i, D_{-i}) := h_i(D_{-i}) - \sum_{j \neq i} \mathrm{COST}_j(\mathrm{ALG}(D_i, D_{-i}), D_j)$$

$$\Downarrow$$

$$U_i(D_i) = P_i^{ALG}(D_i, D_{-i}) - \mathrm{COST}_i(\mathrm{ALG}(D_i, D_{-i}), C_i)$$

$$= h_i(D_{-i}) - \mathrm{COST}(\underbrace{\mathrm{ALG}(D_i, D_{-i})}_{\text{SOLUTION}}, \underbrace{(C_i, D_{-i})}_{\text{INPUT}})$$

VCG PAYMENTS

UTILITARIAN PROBLEMS

$$\mathrm{COST}(\mathrm{SOL}, C) = \sum_i \mathrm{COST}_i(\mathrm{SOL}, C_i)$$

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<u>THEOREM</u> [VICKREY '61, CLARKE '71, GROVES '73]

$M = (\mathrm{ALG}, P^{\mathrm{ALG}})$ IS TRUTHFUL IF THE PROBLEM IS UTILITARIAN AND ALG COMPUTES THE OPTIMUM

VCG PAYMENTS

UTILITARIAN PROBLEMS

$$\mathrm{COST}(\mathrm{SOL}, C) = \sum_i \mathrm{COST}_i(\mathrm{SOL}, C_i)$$

$$P_i^{\mathrm{ALG}}(D_i, D_{-i}) := h_i(D_{-i}) - \sum_{j \neq i} \mathrm{COST}_j(\mathrm{ALG}(D_i, D_{-i}), D_j)$$

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<u>THEOREM</u> [NISAN, RONEN '00]

$M = (\mathrm{ALG}, P^{\mathrm{ALG}})$ IS TRUTHFUL IF

THE PROBLEM IS UTILITARIAN AND
ALG IS RESTRICTED OPTIMAL:

OPTIMAL
W.R.T.
Θ_{ALG} ONLY

VCG PAYMENTS

UTILITARIAN PROBLEMS

$$\mathrm{COST}(\mathrm{SOL}, C) = \sum_i \mathrm{COST}_i(\mathrm{SOL}, C_i)$$

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$$U_i(D_i) = P_i^{\mathrm{ALG}}(D_i, D_{-i}) - \mathrm{COST}_i(\mathrm{ALG}(D_i, D_{-i}), C_i)$$

$$= R_i(D_{-i}) - \mathrm{COST}(\underbrace{\mathrm{ALG}(D_i, D_{-i})}_{\text{SOLUTION}}, \underbrace{(C_i, D_{-i})}_{\text{INPUT}})$$

THEOREM [NR '00] THERE EXISTS A CLASS OF UTILITARIAN PROBLEMS CMAP S.t.

$$\Pi \in \mathrm{CMAP}, \quad M = (\mathrm{ALG}, P^{\mathrm{ALG}})$$

TRUTHFUL FOR Π

$\Swarrow$ ALG IS OPTIMAL

$\Searrow$ $\forall R, \exists c$:

$$\frac{\mathrm{COST}(\mathrm{ALG}(c), c)}{\mathrm{OPT}(c)} \geq R$$

OUR RESULTS

GENERAL COSTS:

- IN CMAP

$$\begin{array}{c} M=(ALG, p^{ALG}) \\ \text{TRUTHFUL} \\ \text{POLY-TIME} \\ \text{VCG-BASED} \end{array} \Rightarrow \forall R\ \exists c: \frac{COST(ALG(c), c)}{OPT(c)} \geq R$$

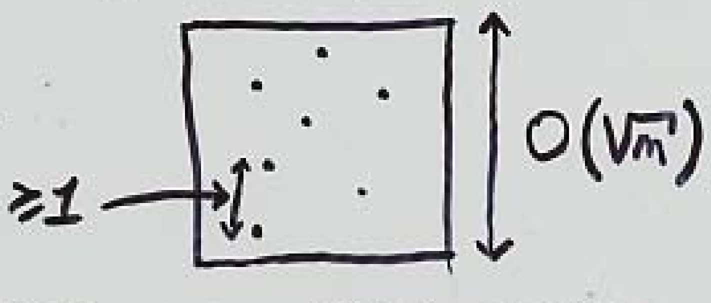
- $\exists$ POLY-TIME TRUTHFUL MECHANISM

$$M^{HUB} = (HUB, p^{HUB})$$

(HUB IS RESTRICTED OPTIMAL)

GEOMETRIC CASE

- 2D, $\alpha=2$, WELL-SPREAD



HUB IS O(1)-APX

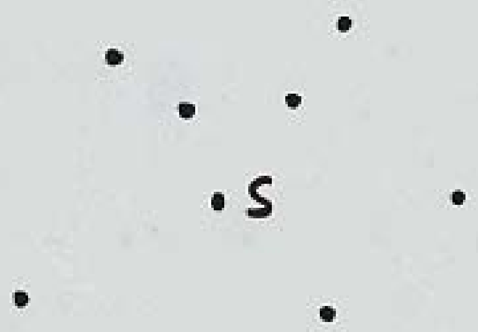
METRIC CASE $c_i^j \leq c_i^k + c_k^j$ (NP-HARD)

- HUB IS 1.5-APX
- M^{HUB} SATISFIES PARTICIPATION CONSTRAINT

HUB ALGORITHM

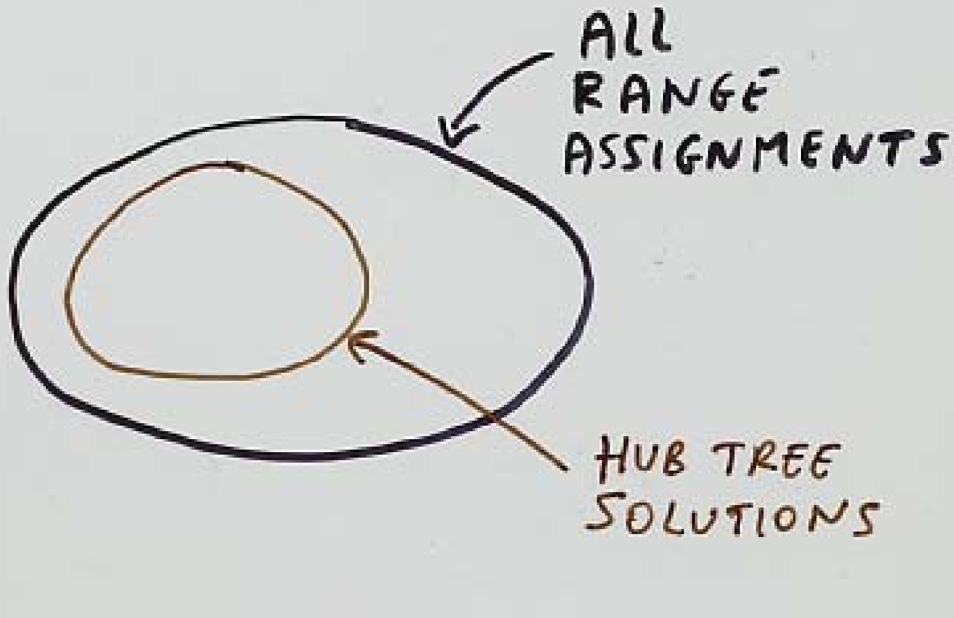
FOR ALL $s \in S$ DO COMPUTE

- ALL-TO-s SOLUTION
- s-TO-ALL SOLUTION



RETURN THE BEST "HUB_TREE"

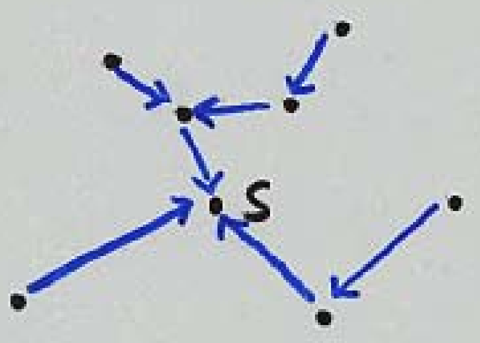
RESTRICTED OPTIMALITY



HUB ALGORITHM

FOR ALL $s \in S$ DO COMPUTE

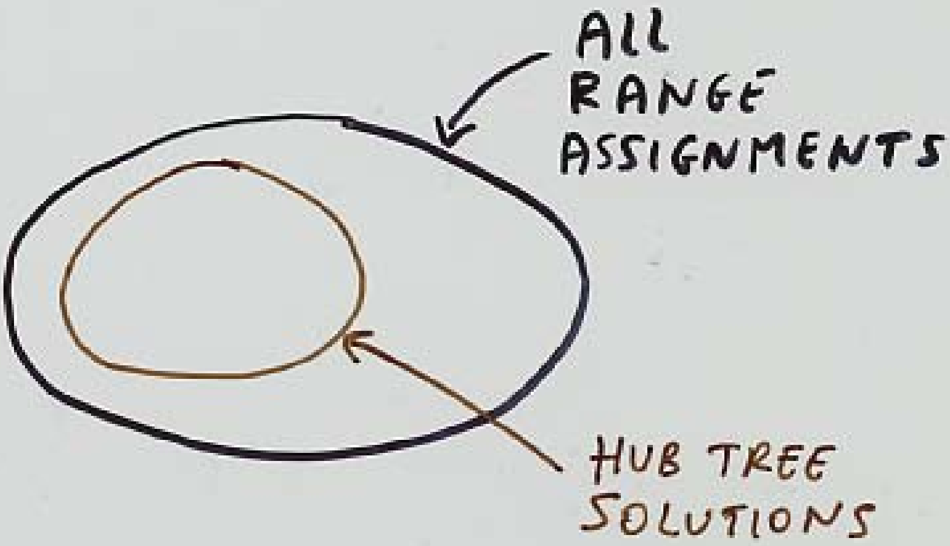
- ALL-TO-s SOLUTION
- s-TO-ALL SOLUTION



OPTIMAL ALL-TO-s = MST

RETURN THE BEST "HUB_TREE"

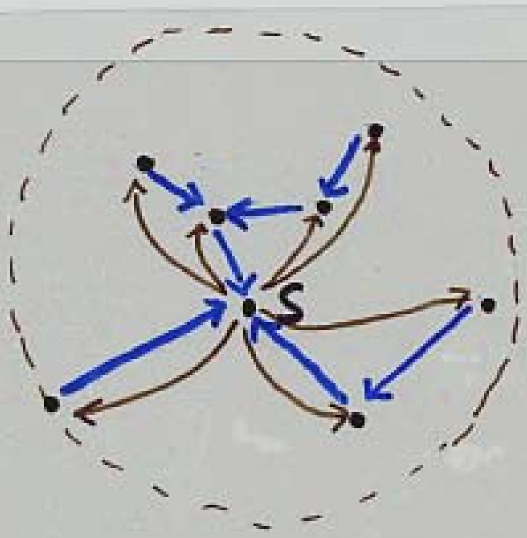
RESTRICTED OPTIMALITY



HUB ALGORITHM

FOR ALL $s \in S$ DO COMPUTE

- ALL-TO-s SOLUTION
- s-TO-ALL SOLUTION

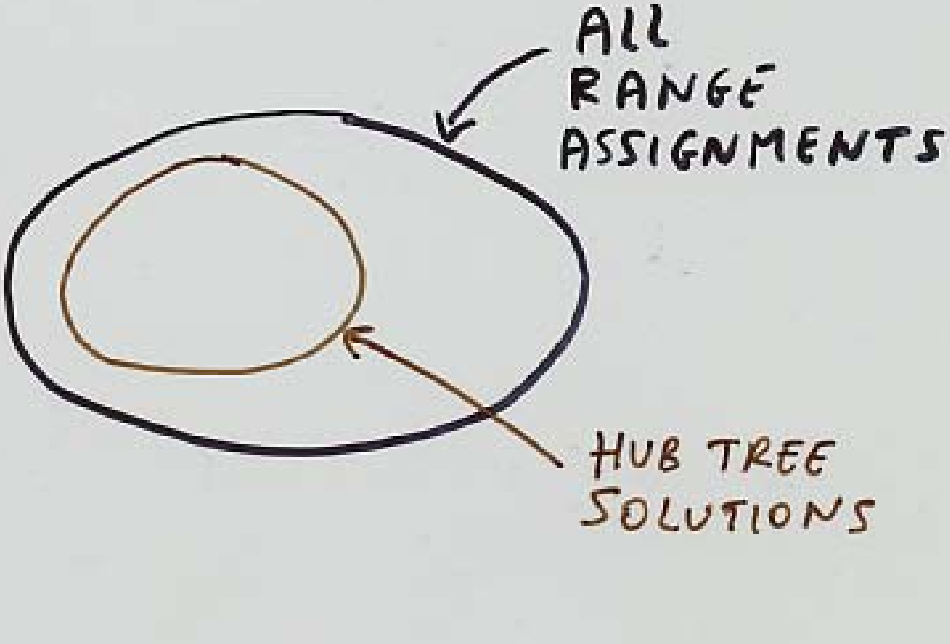


OPTIMAL ALL-TO-s = MST

s-TO-ALL = 1 HOP

RETURN THE BEST "HUB_TREE"

RESTRICTED OPTIMALITY



APPROXIMATION ANALYSIS.

ALL-TO-ALL SOLUTION

CONTAINS — ALL-TO-1 SOLUTION

CONTAINS — 1-TO-ALL SOLUTION

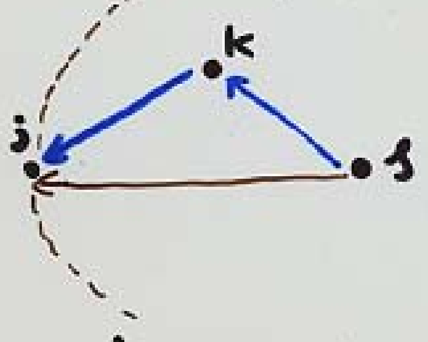
$$OPT \geq OPT_{ALL\text{-}TO\text{-}1} \,,\, OPT_{1\text{-}TO\text{-}ALL}$$

$$APX_{HUB} \leq OPT_{ALL\text{-}TO\text{-}1} + COST(1\text{-}1HOP)$$

METRIC OR WELL-SPREAD

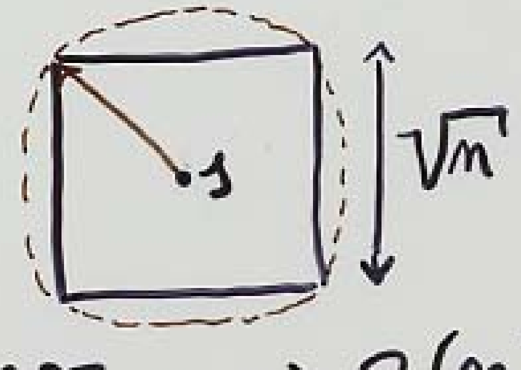
$$COST(1\text{-}1HOP) \leq OPT_{1\text{-}TO\text{-}ALL} \cdot c$$

metric



$$c_1^j \leq c_1^k + c_k^j$$

well-spread



$$OPT_{1\text{-}TO\text{-}ALL} \geq \Omega(n)$$

$$(\alpha = 2)$$

OPEN PROBLEMS

- 2D GEOMETRIC CASE
  $O(1)$-APX TRUTHFUL ?

- NON VCG-BASED MECHANISM?

- BUDGET BALANCE
  $\sum P_i \simeq$ COST

- BROADCAST (1-TO-ALL)