OPTIMAL TASK ASSIGNMENT IN SENSOR NETWORKS

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MOTIVATION

- In-network processing paradigm
- Millions of sensors with processing capabilities
- Vision
  - Reduce the volume of data seen / processed by the application
- Complex application tasks can split into simpler tasks that can be accomplished by separate nodes within the network
- Goal: assign the tasks optimally in terms of energy
  - Sensing
  - Processing
  - Communication
  - …

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Problem Definition

- Definition (Optimal Assignment)

Let W be a WSN and let T be a complex task. Given the set of all mappings $\Phi = \{\phi : T \rightarrow W\}$ where the capabilities of the network fulfill the task and energy requirements, we call an assignment as ***energy-optimal assignment*** ϕ_{opt} if and only if $(\forall \phi \in \Phi) \varepsilon_{W,T}^{\phi_{opt}} \leq \varepsilon_{W,T}^{\phi}$.

- NP-hard [Garey and Johnson, 1979]

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MODELING FRAMEWORK

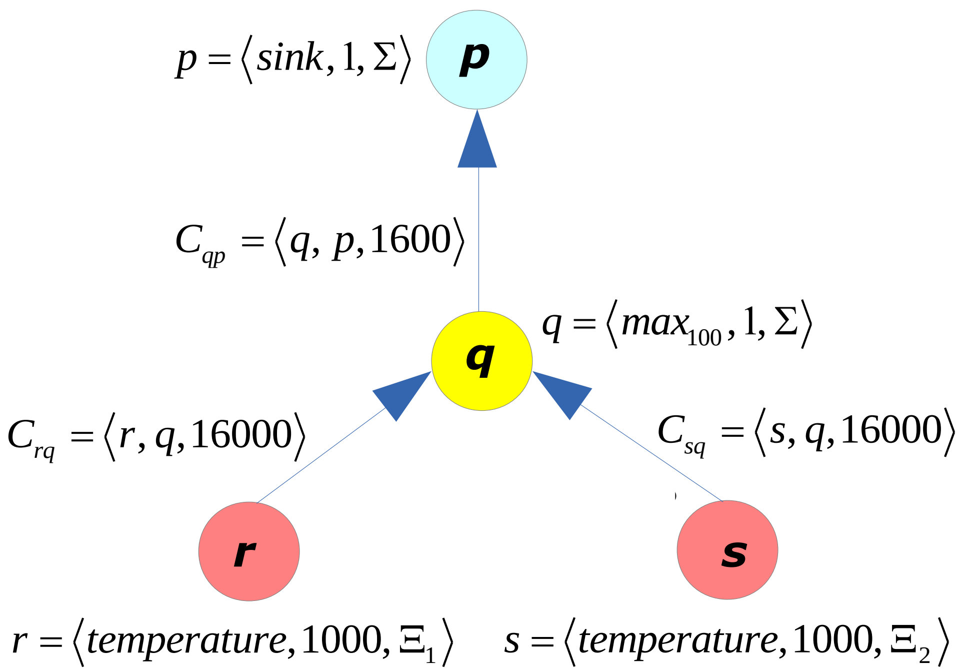
Task Model

Definition (Task). Given a set S of subtask vertices and a set C of directed edges among the subtask vertices, we define a task T as a *directed acyclic graph (DAG)* represented by the tuple $T \equiv \langle S, C \rangle$.

Category	Description	Input From	Output To
Sensing	Sense context from the environment	-	• Processing • Sink
Processing	Process input data and forward results	• Processing • Sensing	• Processing • Sink
Sink	Retrieve final format of data sensed and processed	• Processing • Sensing	-

MODELING FRAMEWORK

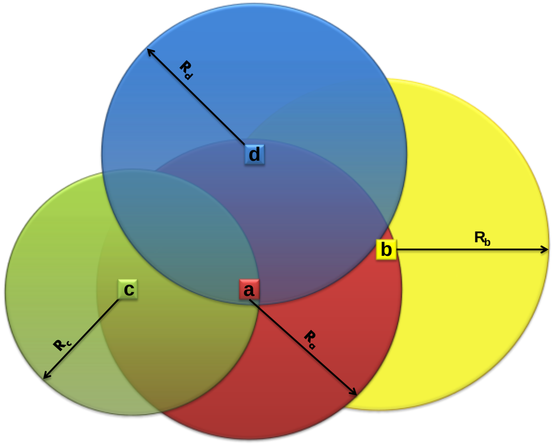
Task Model - Example



MODELING FRAMEWORK

Network Model

Definition (Network). Let N be a set of network nodes and let A be a set of directed network edges. We define a WSN as a *strongly connected directed graph* represented by the tuple $W \equiv \langle N, A \rangle$.



Capability	Sink node	Non-sink node
$Sens_a$	$\{ci_i \in CI\}$	$\{ci_i \in CI\}$
Alg_a	$\{alg_i \in Alg\}$	$\{alg_i \in Alg\}$
$isSink_a$	$\{sink\}$	$\varnothing$
Op_a	$\{ci_i \in CI\} \cup \{alg_i \in Alg\} \cup \{sink\}$	$\{ci_i \in CI\} \cup \{alg_i \in Alg\}$
Loc_a	$\vec{x}_a \in \Sigma$	$\vec{x}_a \in \Sigma$

MODELING FRAMEWORK

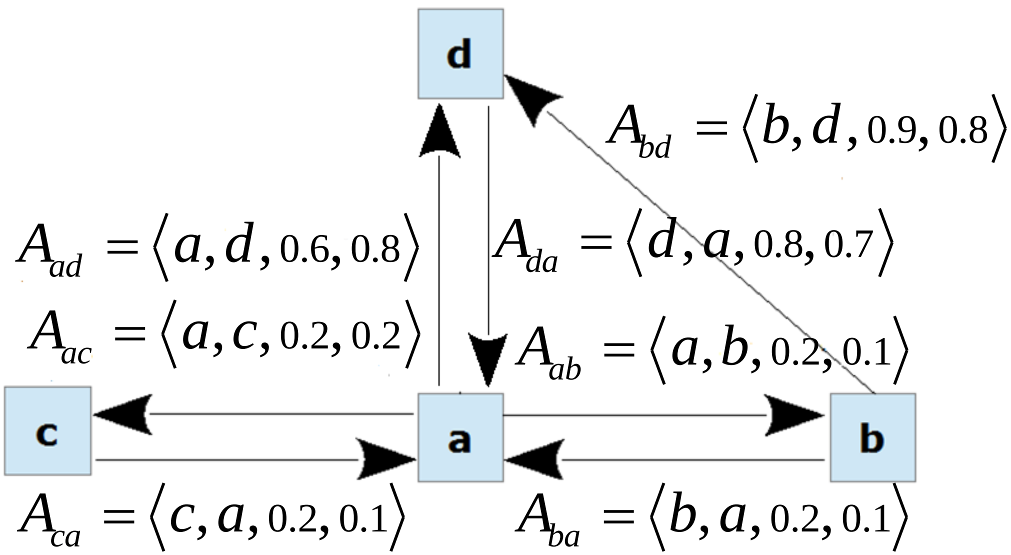
Network Model - Example

$$a = \left\langle \{\text{humidity, max}\}, \vec{x}_4, 38000, \{M_a(\text{humidity}) = 0.001, M_a(\text{max}) = 0.01\} \right\rangle$$

$$b = \left\langle \{\text{temperature, max}\}, \vec{x}_3, 50000, \{M_b(\text{temperature}) = 0.002, M_b(\text{max}) = 0.005\} \right\rangle$$

$$c = \left\langle \{\text{temperature, max}\}, \vec{x}_1, 10800, \{M_c(\text{temperature}) = 0.001, M_c(\text{max}) = 0.01\} \right\rangle$$

$$d = \left\langle \{\text{sink, temperature}\}, \vec{x}_2, \infty, \{M_d(\text{sink}) = 0, M_d(\text{temperature}) = 0.002\} \right\rangle$$



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MODELING FRAMEWORK

Assignment Model

Definition (Assignment). Let $T \equiv \langle S, C \rangle$ be a complex task and $W \equiv \langle N, A \rangle$ be a WSN with $\Pi = \{\Pi_{ab}\}, \forall a, b \in N$ representing the set of all paths among the network nodes. We define the assignment $\zeta : T \to W$ as the pair of mappings $X_\zeta : S \to N$ and $Y_\zeta : C \to \Pi$ that satisfy the *consistency constraint*:

$$(\forall C_{pq} \in C)(\forall \Pi_{ab} \in \Pi) \quad Y_\zeta(C_{pq}) = \Pi_{ab} \Leftrightarrow$$

$$\left(\left(X_\zeta(p) = Src(\Pi_{ab}) \right) \wedge \left(X_\zeta(q) = Dst(\Pi_{ab}) \right) \right)$$

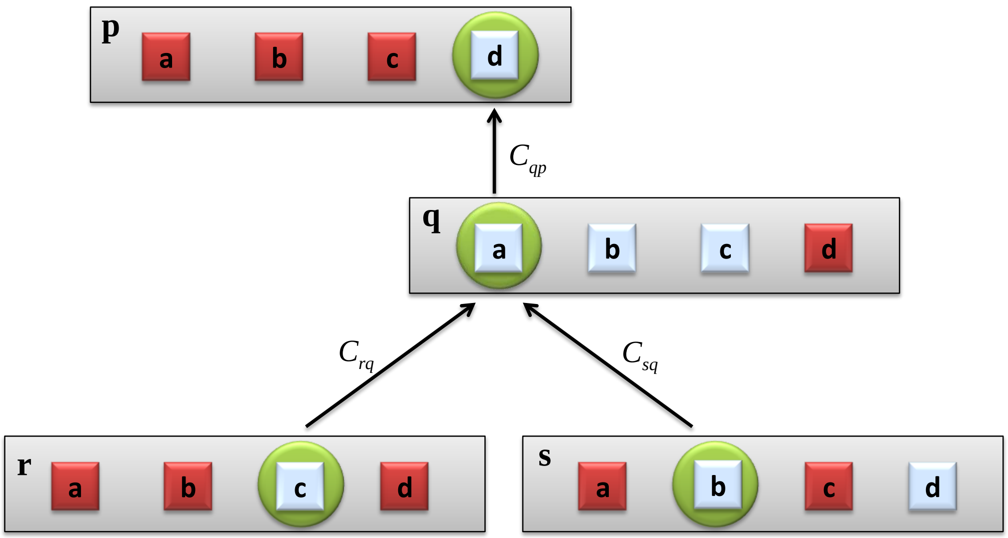
and we represent it by $\zeta \equiv \langle X_\zeta, Y_\zeta \rangle \in Z$ where Z is the set of all possible assignments between T and W.

MODELING FRAMEWORK

Assignment Model - Example

$$X_\zeta = \{p \to d, q \to a, r \to c, s \to b\}$$

$$Y_\zeta = \{C_{qp} \to \Pi_{ad}, C_{rq} \to \Pi_{ca}, C_{sq} \to \Pi_{ba}\}$$



OPTIMIZATION

ILP Variables

Symbol	Type	Size	Description
$x_{p,a}$	Binary Matrix	$\|S\|\cdot\|N\|$	Vertex assignment of subtask vertex $p \in S$ to network node $a \in N$
$y_{pq,ab}$	Binary Matrix	$\left(\frac{\|S\|\cdot(\|S\|-1)}{2}\right)\times\|N\|^2$	Edge assignment of subtask edge C_{pq} to network path Π_{ab}
β_{pq}	Integer Column	$\frac{\|S\|\cdot(\|S\|-1)}{2}$	Data bits exchanged over subtask edge C_{pq}
ρ_{ab}	Real Column	$\|N\|^2$	Total energy rate (per bit) when the network path Π_{ab} is activated
$\rho_{ab,c}$	Real Matrix	$\|N\|^3$	Energy rate (per bit) for network node $c \in N$ when network path Π_{ab} is activated
$\varepsilon_{c,p}$	Real Column	$\|S\|\cdot\|N\|$	Execution energy cost of subtask vertex $p \in S$ in network node $c \in N$
ε_c	Real Column	$\|N\|$	Available energy of network node $c \in N$

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OPTIMIZATION

ALGORITHM 1. ILP Formulation

Input: Sets $C, S, N, \Pi, I_p, J_{pq}$, Variables $\beta_{pq}, \rho_{ab}, \rho_{ab,c}, \varepsilon_{c,p}, \varepsilon_c$

Output: Variables $x_{p,a}$, $y_{pq,ab}$

Objective function: *minimize* $\left\{\sum_{c\in N}\left(\sum_{p\in S}\varepsilon_{c,p}\cdot x_{p,c} + \sum_{C_{pq}\in C}\sum_{\Pi_{ab}\in\Pi}\beta_{pq}\cdot y_{pq,ab}\cdot\rho_{ab,c}\right)\right\}$

Constraints set:

$(\forall p\in S)\ \sum_{a\in N} x_{p,a} = 1$ //Unique subtask vertex assignment constraint

$(\forall C_{pq}\in C)\ \sum_{\Pi_{ab}\in\Pi} y_{pq,ab} = 1$ //Unique subtask edge assignment constraint

$(\forall C_{pq}\in C)(\forall a\in N)\ \sum_{\Pi_{ab}\in \widetilde{Src}(a)} y_{pq,ab} = x_{p,a}$ //Edge-to-source-vertex consistency constraint

$(\forall C_{pq}\in C)(\forall b\in N)\ \sum_{\Pi_{ab}\in \widetilde{Dst}(b)} y_{pq,ab} = x_{q,b}$ //Edge-to-destination-vertex consistency constraint

$(\forall c\in N)\ \sum_{p\in S}\varepsilon_{c,p}\cdot x_{p,c} + \left\{\sum_{C_{pq}\in C}\sum_{\Pi_{ab}\in\Pi}\beta_{pq}\cdot y_{pq,ab}\cdot\rho_{ab,c}\right\} \le \varepsilon_c$ //Node energy conservation constraint

$(\forall p\in S)(\forall a\in N/I_p)\ x_{p,a} = 0$ //Vertex compatibility constraint

$(\forall C_{pq}\in C)(\forall \Pi_{ab}\in\Pi\setminus J_{pq})\ y_{pq,ab} = 0$ //Edge compatibility constraint

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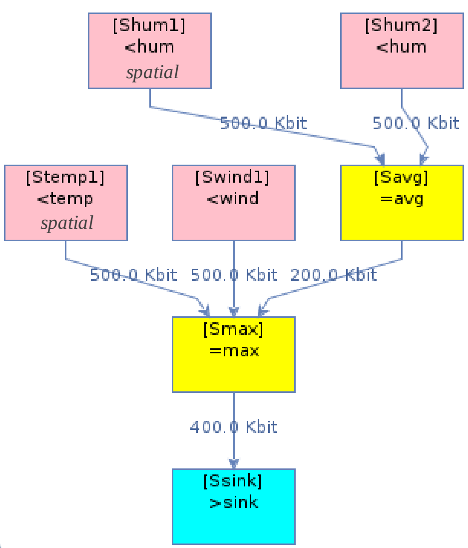
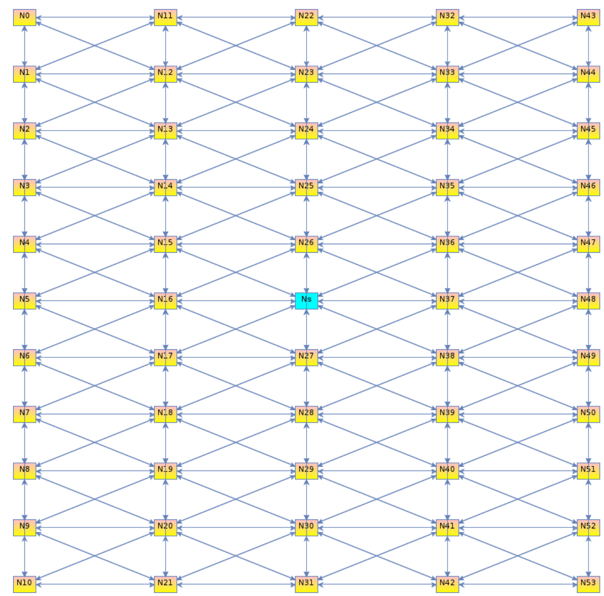
RESULTS

Experimental setting

Parameter	Value
$\lvert CI \rvert$	10
$\lvert Alg \rvert$	15
$\lvert Sens_{aver} \rvert$	4
$\lvert Alg_{aver} \rvert$	2
$Quant_{aver}$	6000
$\# SinkSubtasks$	1
$\beta_{pq,aver}$	320 Kbit
Spatial constraint	1:5 sensing subtasks

Parameter	Value
$\lvert Sens_{aver} \rvert$	5
$\lvert Alg_{aver} \rvert$	10
$\# SinkNodes$	1
$M_{aver}(op_i)$	0.005mJ
$\rho_{trx,aver} = \rho_{rcv,aver} = \rho_{aver}$	0.0001mJ/bit
ε_{aver}	300J





Optimal Task Assignment in Sensor Networks

RESULTS

Energy status of the network after Run #100

N0 100%	N21 100%	N42 100%	N63 100%	N84 92%	N105 83%	N126 50%	N147 23%	N168 27%	N189 9%	N210 9%	N230 9%	N251 31%	N272 45%	N293 50%	N314 67%	N335 92%	N356 100%	N377 100%	N398 100%	N419 100%
N1 100%	N22 100%	N43 100%	N64 100%	N85 84%	N106 51%	N127 42%	N148 29%	N169 5%	N190 9%	N211 9%	N231 9%	N252 19%	N273 18%	N294 50%	N315 75%	N336 83%	N357 100%	N378 100%	N399 100%	N420 100%
N2 100%	N23 100%	N44 100%	N65 100%	N86 92%	N107 42%	N128 45%	N149 18%	N170 1%	N191 9%	N212 9%	N232 22%	N253 1%	N274 10%	N295 42%	N316 51%	N337 42%	N358 92%	N379 100%	N400 100%	N421 100%
N3 100%	N24 100%	N45 100%	N66 96%	N87 71%	N108 46%	N129 41%	N150 41%	N171 1%	N192 9%	N213 10%	N233 9%	N254 1%	N275 6%	N296 37%	N317 43%	N338 75%	N359 100%	N380 100%	N401 100%	N422 100%
N4 100%	N25 100%	N46 100%	N67 96%	N88 60%	N109 42%	N130 46%	N151 11%	N172 10%	N193 31%	N214 22%	N234 5%	N255 10%	N276 10%	N297 29%	N318 42%	N339 42%	N360 84%	N381 100%	N402 100%	N423 100%
N5 100%	N26 100%	N47 100%	N68 100%	N89 39%	N110 37%	N131 18%	N152 36%	N173 23%	N194 22%	N215 9%	N235 35%	N256 10%	N277 10%	N298 20%	N319 39%	N340 59%	N361 75%	N382 100%	N403 100%	N424 100%
N6 100%	N27 100%	N48 96%	N69 68%	N90 47%	N111 38%	N132 33%	N153 1%	N174 28%	N195 5%	N216 5%	N236 18%	N257 44%	N278 1%	N299 2%	N320 42%	N341 42%	N362 59%	N383 100%	N404 100%	N425 100%
N7 100%	N28 100%	N49 96%	N70 47%	N91 42%	N112 43%	N133 36%	N154 11%	N175 6%	N196 44%	N217 1%	N237 11%	N258 18%	N279 38%	N300 2%	N321 38%	N342 35%	N363 51%	N384 100%	N405 100%	N426 100%
N8 100%	N29 100%	N50 100%	N71 40%	N92 47%	N113 29%	N134 46%	N155 36%	N176 37%	N197 22%	N218 49%	N238 8%	N259 2%	N280 25%	N301 39%	N322 20%	N343 43%	N364 42%	N385 75%	N406 100%	N427 100%
N9 100%	N30 100%	N51 80%	N72 80%	N93 77%	N114 62%	N135 41%	N156 14%	N177 36%	N198 42%	N219 10%	N239 5%	N260 17%	N281 45%	N302 2%	N323 30%	N344 80%	N365 100%	N386 100%	N407 100%	N428 100%
N10 100%	N31 100%	N52 64%	N73 71%	N94 57%	N115 88%	N136 43%	N157 4%	N178 20%	N199 16%	Ns 100%	N240 7%	N261 34%	N282 11%	N303 15%	N324 63%	N345 52%	N366 53%	N387 100%	N408 100%	N429 100%
N11 100%	N32 100%	N53 88%	N74 67%	N95 69%	N116 28%	N137 5%	N158 1%	N179 0%	N200 1%	N220 1%	N241 5%	N262 17%	N283 12%	N304 18%	N325 25%	N346 10%	N367 56%	N388 100%	N409 100%	N430 100%
N12 92%	N33 92%	N54 41%	N75 33%	N96 44%	N117 2%	N138 0%	N159 18%	N180 10%	N201 8%	N221 13%	N242 14%	N263 8%	N284 7%	N305 7%	N326 9%	N347 41%	N368 40%	N389 48%	N410 50%	N431 75%
N13 100%	N34 88%	N55 92%	N76 42%	N97 29%	N118 28%	N139 32%	N160 1%	N181 10%	N202 1%	N222 4%	N243 4%	N264 15%	N285 15%	N306 7%	N327 6%	N348 47%	N369 47%	N390 54%	N411 92%	N432 92%
N14 100%	N35 88%	N56 92%	N77 55%	N98 46%	N119 35%	N140 46%	N161 7%	N182 23%	N203 18%	N223 4%	N244 2%	N265 6%	N286 25%	N307 8%	N328 54%	N349 56%	N370 63%	N391 82%	N412 100%	N433 100%
N15 100%	N36 100%	N57 100%	N78 87%	N99 42%	N120 33%	N141 0%	N162 8%	N183 23%	N204 18%	N224 18%	N245 5%	N266 3%	N287 0%	N308 51%	N329 52%	N350 56%	N371 83%	N392 100%	N413 100%	N434 100%
N16 100%	N37 100%	N58 96%	N79 75%	N100 57%	N121 44%	N142 46%	N163 5%	N184 2%	N205 5%	N225 2%	N246 4%	N267 4%	N288 12%	N309 49%	N330 64%	N351 56%	N372 100%	N393 100%	N414 100%	N435 100%
N17 100%	N38 100%	N59 100%	N80 100%	N101 47%	N122 47%	N143 40%	N164 31%	N185 1%	N206 1%	N226 9%	N247 4%	N268 36%	N289 6%	N310 56%	N331 64%	N352 53%	N373 100%	N394 100%	N415 100%	N436 100%
N18 100%	N39 100%	N60 100%	N81 100%	N102 82%	N123 46%	N144 50%	N165 16%	N186 1%	N207 8%	N227 9%	N248 5%	N269 19%	N290 13%	N311 43%	N332 65%	N353 65%	N374 100%	N395 100%	N416 100%	N437 100%
N19 100%	N40 100%	N61 100%	N82 92%	N103 92%	N124 82%	N145 44%	N166 49%	N187 33%	N208 5%	N228 4%	N249 34%	N270 5%	N291 63%	N312 57%	N333 56%	N354 83%	N375 92%	N396 100%	N417 100%	N438 100%
N20 100%	N41 100%	N62 100%	N83 100%	N104 92%	N125 74%	N146 50%	N167 50%	N188 41%	N209 43%	N229 86%	N250 86%	N271 57%	N292 57%	N313 50%	N334 56%	N355 100%	N376 100%	N397 100%	N418 100%	N439 100%

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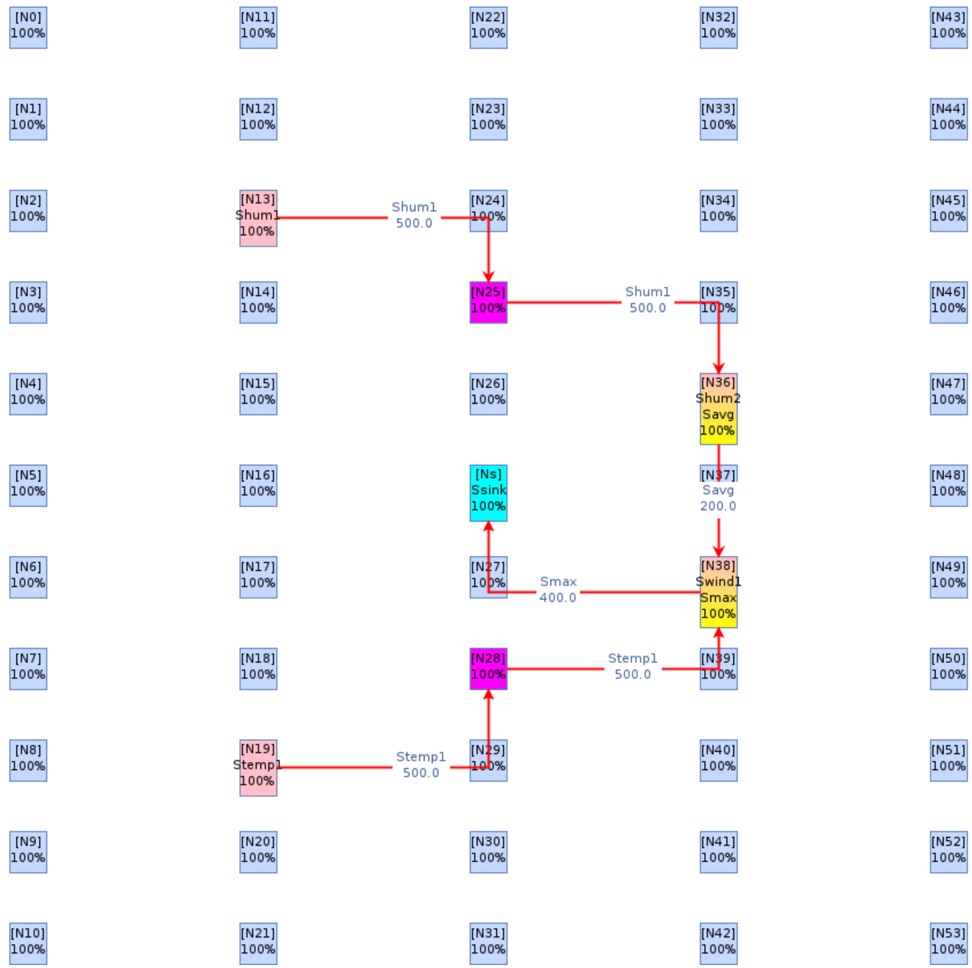
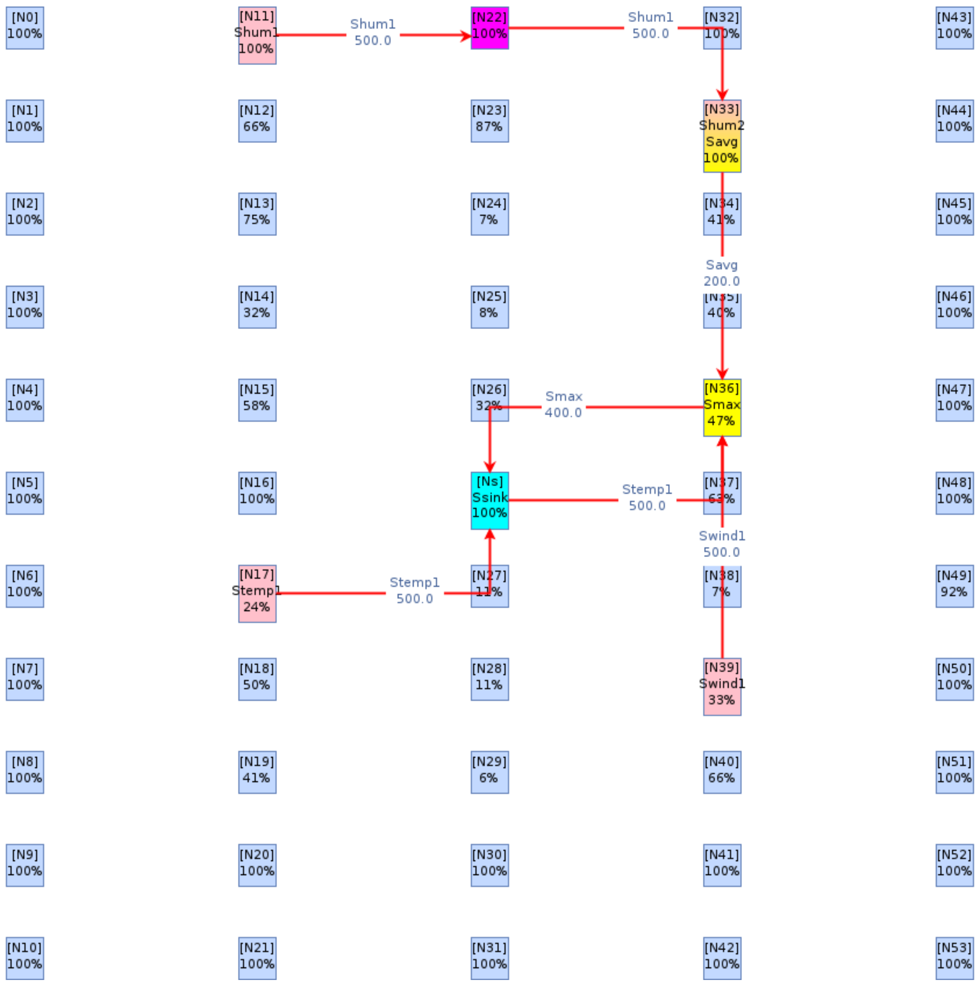
RESULTS

Optimal assignment – Run #1



RESULTS

Optimal assignment – Run #21



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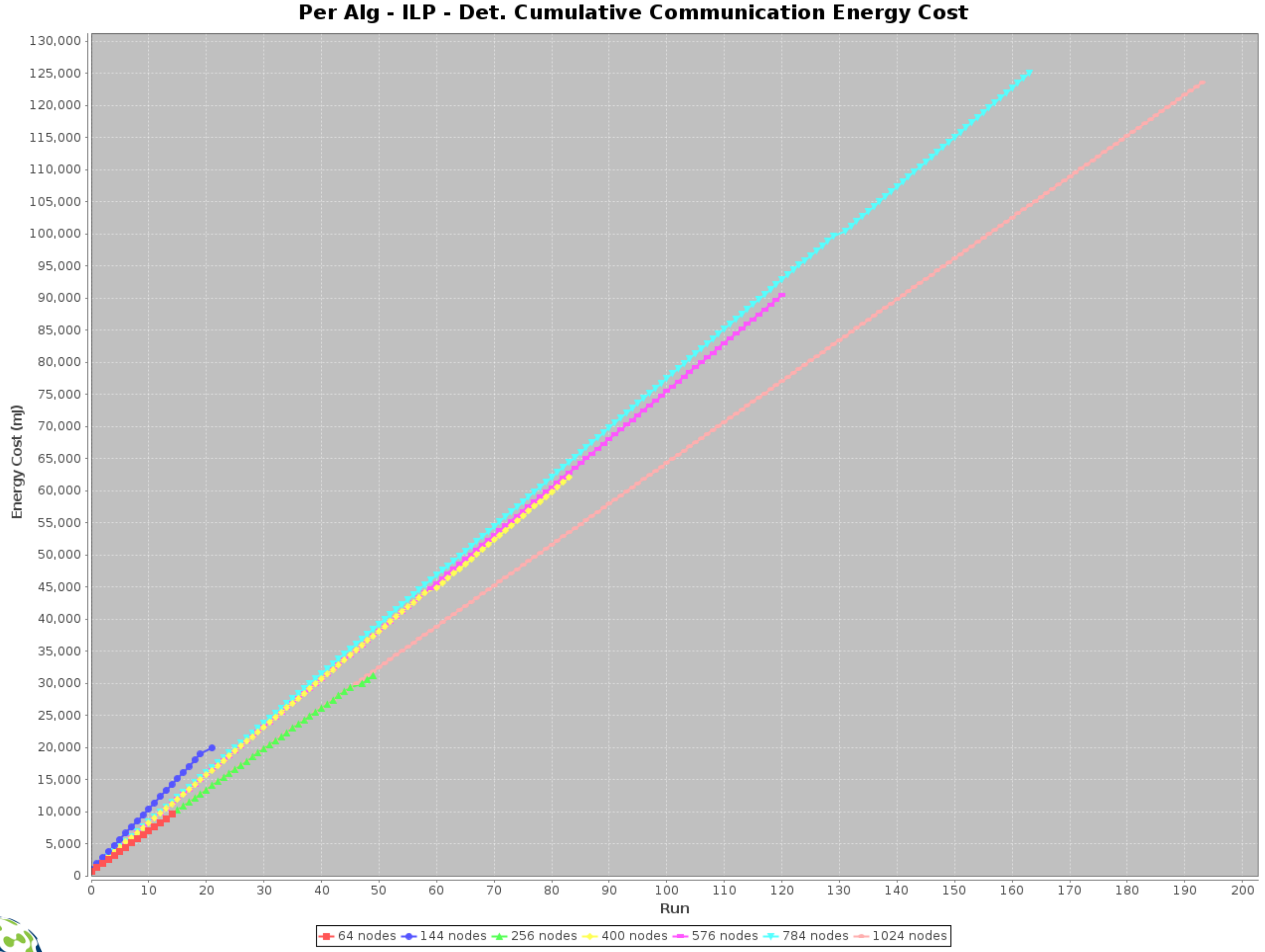
RESULTS

Mesh network



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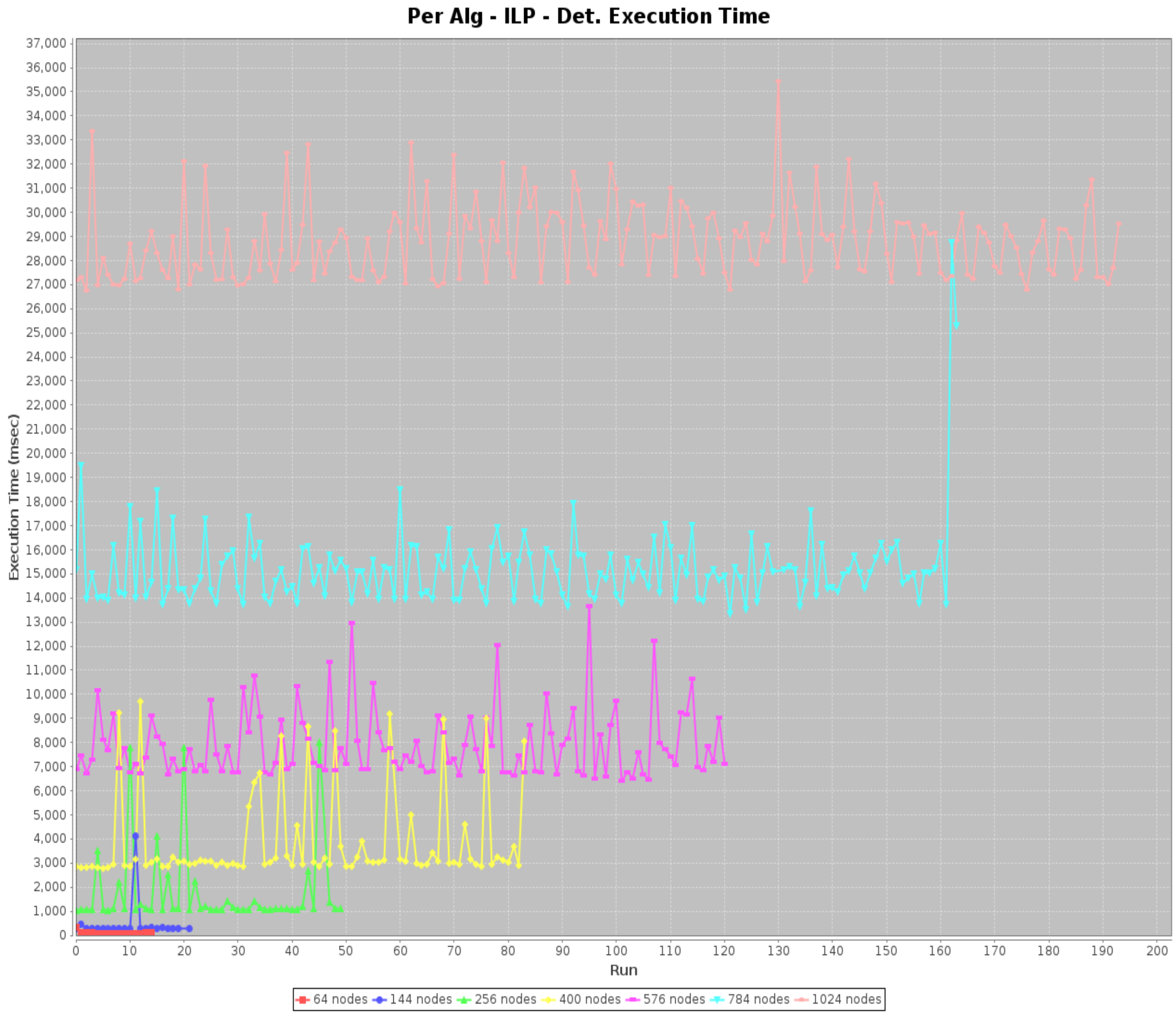
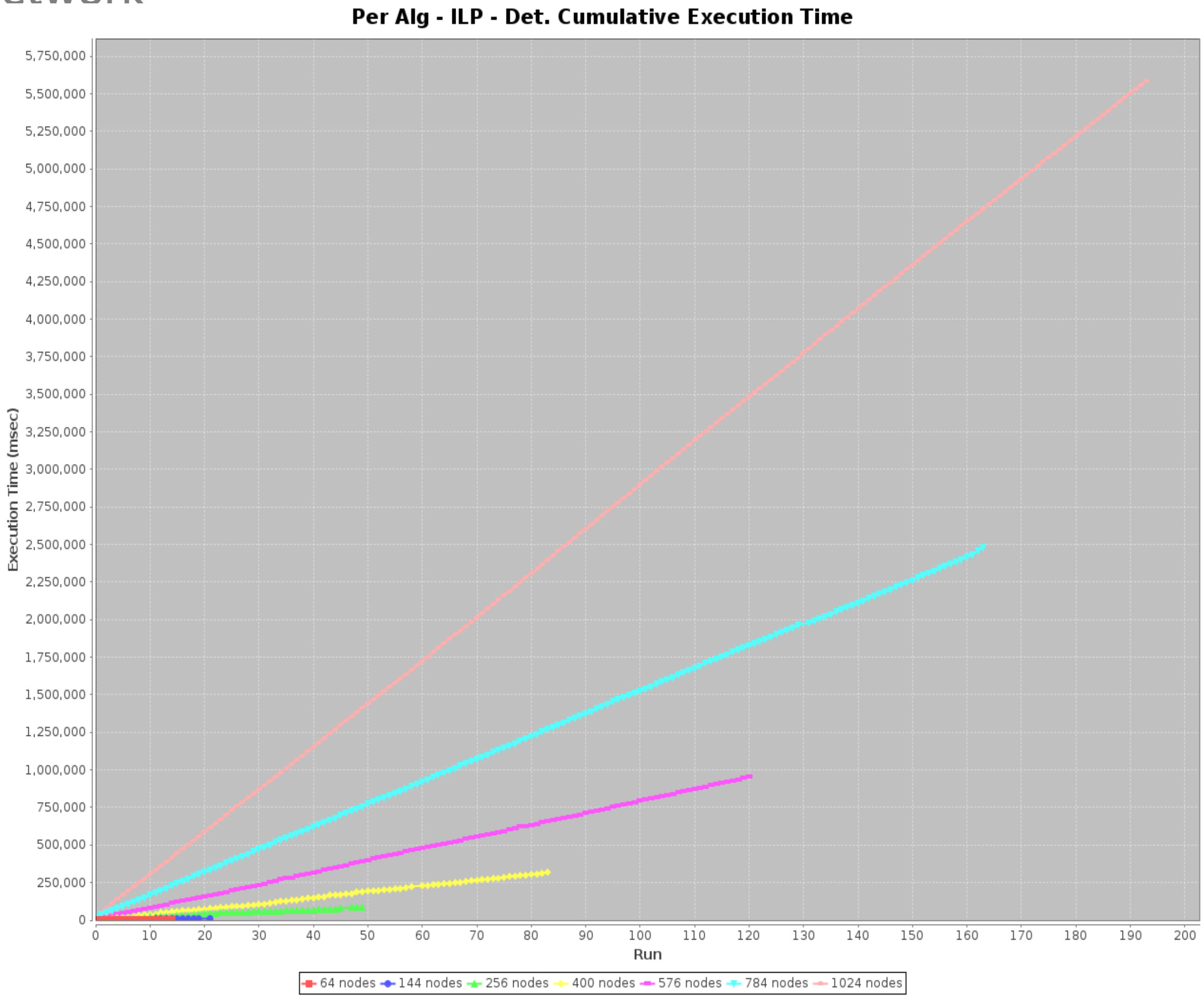
RESULTS

Mesh network



RESULTS

Mesh network



FUTURE WORK & EXTENSIONS

- Experimentation with non-optimal solutions that scale
- Maximize the network lifetime instead of minimizing the energy at each step separately
- Model the unreliability of wireless channels
- Insert the concept of ***mobility*** (Levy Walk model)
- Incremental assignment of tasks

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