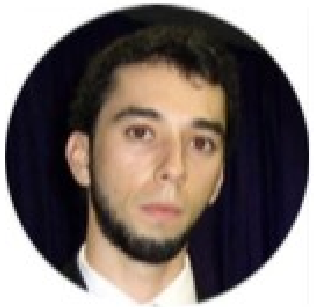
A Variable Neighborhood Heuristic for Facility Locations in Fog Computing

THE 8TH INTERNATIONAL CONFERENCE ON VARIABLE NEIGHBORHOOD SEARCH



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New Challenges

- New paradigm: Smart cities large scale sensing applications
- Several fields of application:
  - Urban applications
  - Industrial
  - Automotive
  - Healthcare
  - ...
- New scenarios: Cyber-physical systems
  - Geographically distributed sensors
  - Huge amount of information produced

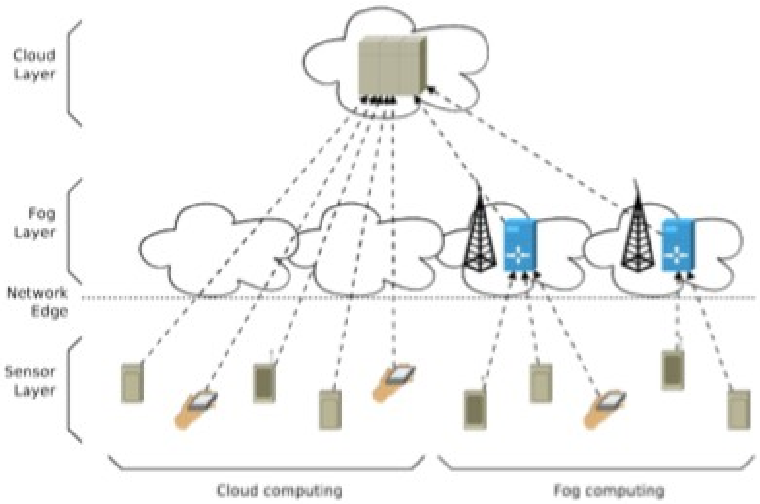
New Challenges

→ New requirements for the infrastructure

- Scalability challenge
  - Huge amount of data to transfer and process
  - Geographically distributed systems
  - Example: CPU- and bandwidth-bound applications
- Low latency challenge
  - Support for real time applications
  - Example: latency-bound applications
- Cloud computing is not enough
- *(5G alone is not an answer)*

Pros and Cons of Fog

- Benefits of Fog computing
- Scalability:
  - Pre-processing offloaded to fog nodes
  - Less strain on Cloud network links
- Latency:
  - Latency-critical tasks offloaded to Fog
  - Fog nodes are closer to the edge



- New open issues: → new Fog infrastructure
  - Fog node deployment
  - Sensors-to fog mapping
- Joint problem

Our Contribution

- Model for the design of Fog infrastructures
  - Based on location-allocation optimization problem
- Model decisions:
  - How many fog nodes do we need?
  - Which Fog nodes (among a set) turn on?
  - How to map sensors over fog nodes?
- Double optimization goal
  - Reduce infrastructure cost
  - Optimize performance
- Use of SLA constraints

Mathematical Model

Model parameters	
$\mathcal{S}$	Set of sensors
$\mathcal{F}$	Set of fog nodes
$\mathcal{C}$	Set of cloud data centers
λ_i	Outgoing data rate from sensor i
λ_j	Incoming data rate at fog node j
$1/\mu_j$	Processing time at fog node j
δ_{ij}	Communication latency between sensor i and fog j
δ_{jk}	Communication latency between fog j and cloud k
c_j	Cost for locating a fog node at position j (or for keeping the fog node turned on)
Model indices	
i	Index for a sensor
j	Index for a fog node
k	Index for a cloud data center
Decision variables	
E_j	Location of fog node j
x_{ij}	Allocation of sensor i to fog j
y_{jk}	Allocation of fog node j to cloud k

Mathematical Model

- Objective function
  - → Cost for fog nodes
  - → Response time
- Contributions to response time:
  - Sensor → Fog avg net delay
  - Fog → Cloud avg net delay
  - Fog processing time
- Caveat: definition of λ_j
- Main constraints:
  - Response time < SLA
  - Load on nodes

$$C = \sum_{j \in \mathcal{F}} c_j E_j$$

$$T_R = T_{netSF} + T_{netFC} + T_{proc}$$

$$T_{netsf} = \frac{1}{\sum_{i \in \mathcal{S}} \lambda_i} \sum_{i \in \mathcal{S}} \sum_{j \in \mathcal{F}} \lambda_i x_{i,j} \delta_{i,j}$$

$$T_{netfc} = \frac{1}{\sum_{j \in \mathcal{F}} \lambda_j} \sum_{j \in \mathcal{F}} \sum_{k \in \mathcal{C}} \lambda_j y_{j,k} \delta_{j,k}$$

$$T_{proc} = \frac{1}{\sum_{j \in \mathcal{F}} \lambda_j} \sum_{j \in \mathcal{F}} \frac{\lambda_j}{\mu_j - \lambda_j}$$

$$\lambda_j = \sum_{i \in \mathcal{S}} x_{i,j} \cdot \lambda_i$$

$$T_R \le T_{SLA}$$

$$\lambda_j < E_j \mu_j, \quad \forall j \in \mathcal{F}$$

$$\sum_{j \in \mathcal{F}} x_{ij} = 1, \qquad \forall i \in \mathcal{S}$$

$$\sum_{k \in \mathcal{C}} y_{jk} = E_j, \qquad \forall j \in \mathcal{F}$$

Variable Neighborhood Search

$x \leftarrow$ an initial solution generated by a random constructive heuristic;
while *the stopping criteria are not reached* **do**
  $k \leftarrow 1$;
  while $k \leq K_{max}$ **do**
    $x' \leftarrow$ random solution in the neighborhood structure $N_k(x)$;
    $x'' \leftarrow$ apply the local search on x';
    if $f(x'') < f(x)$ **then**
      $x \leftarrow x''$;
      $k \leftarrow 1$;
    end
    else $k \leftarrow k + 1$;
  end
end
return x;

Local Search: Best improvement
M1: All possible “insertion” of sensors in fog nodes
M2: All possible “swap” of sensors in fog nodes

Solution Representation

Solution representation:

X = [F1 | F2 | F3 | F4 | F5]

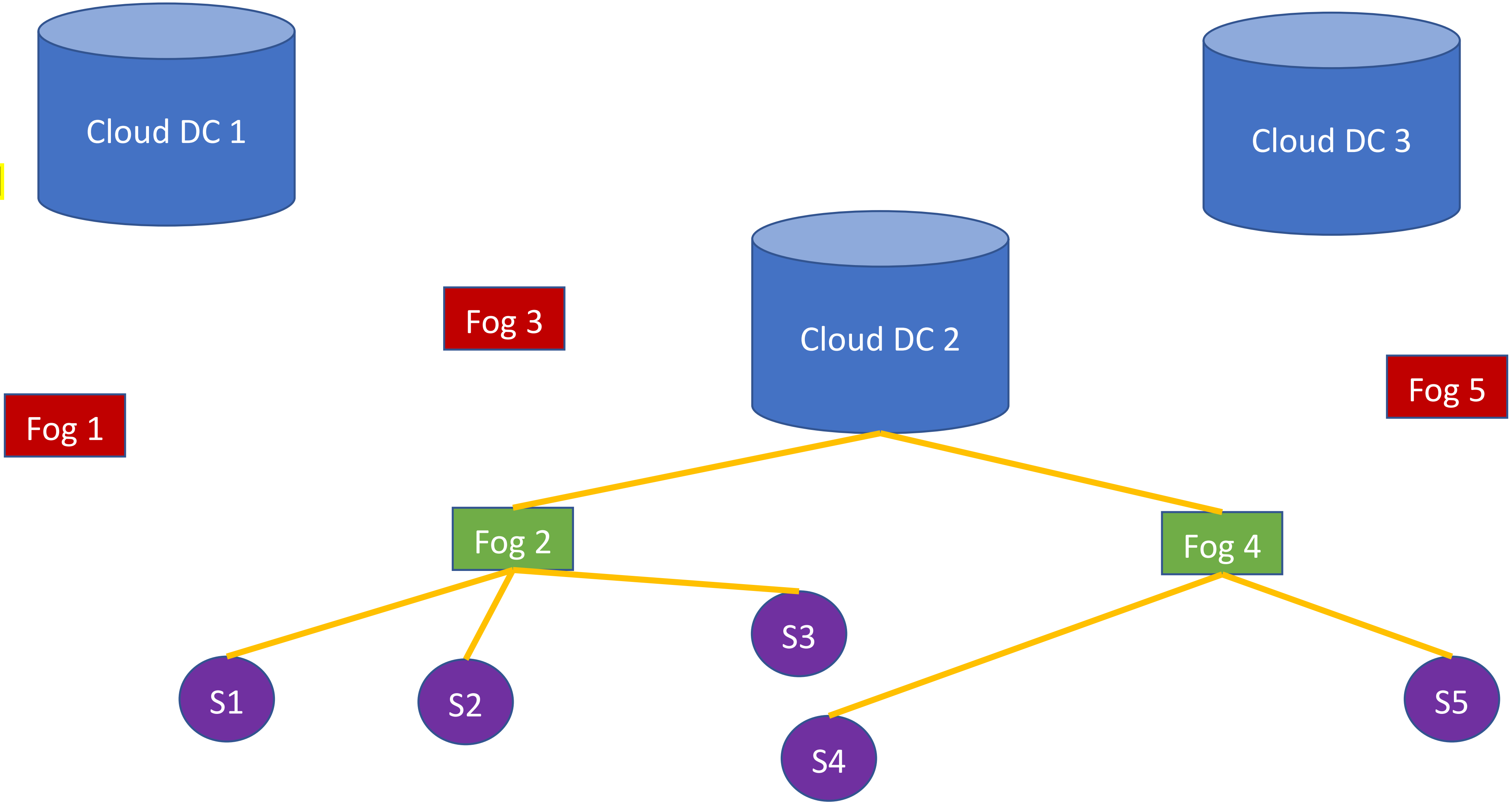
F1 = []

F2 = [DC2, S1, S2, S3]

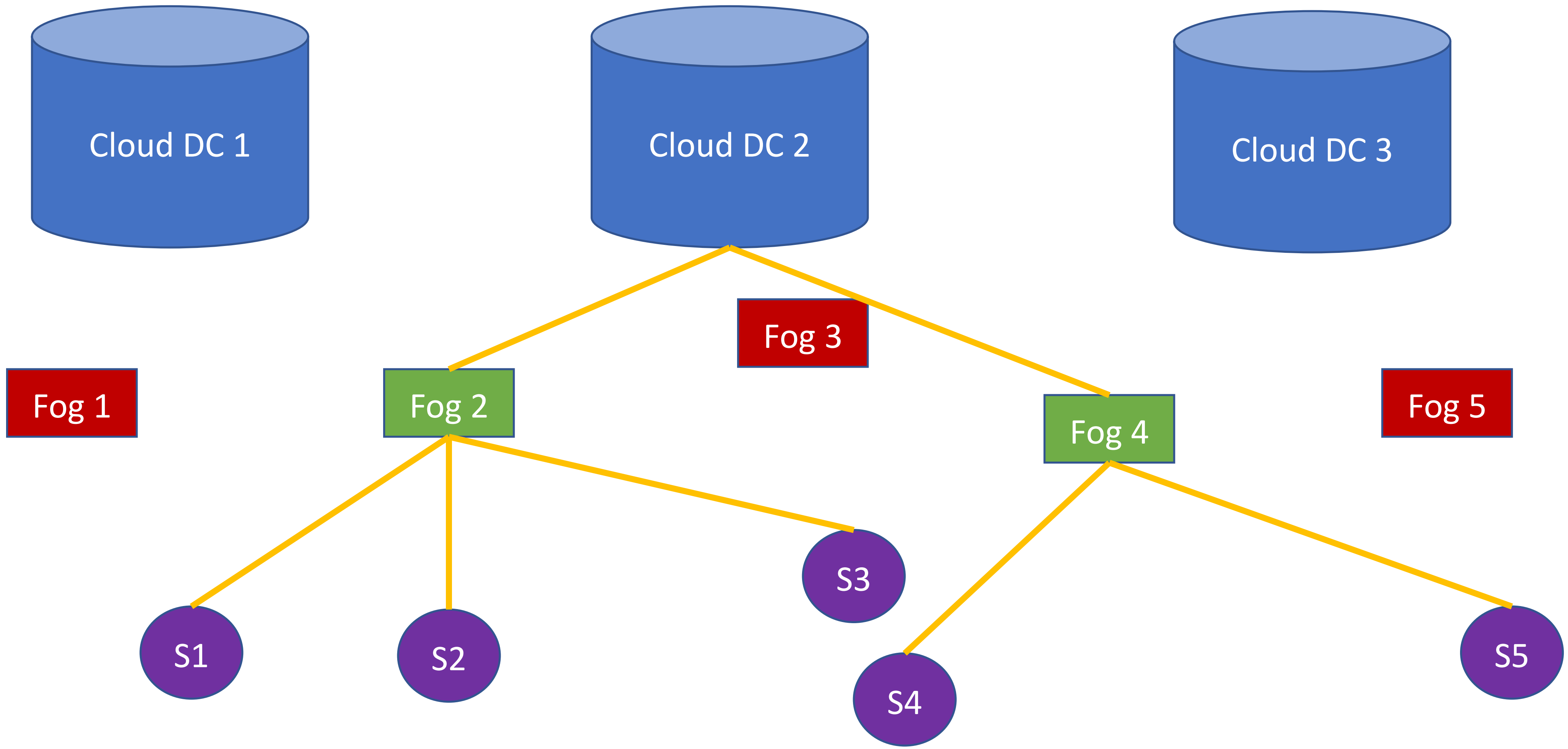
F3 = []

F4 = [DC2, S4, S5]

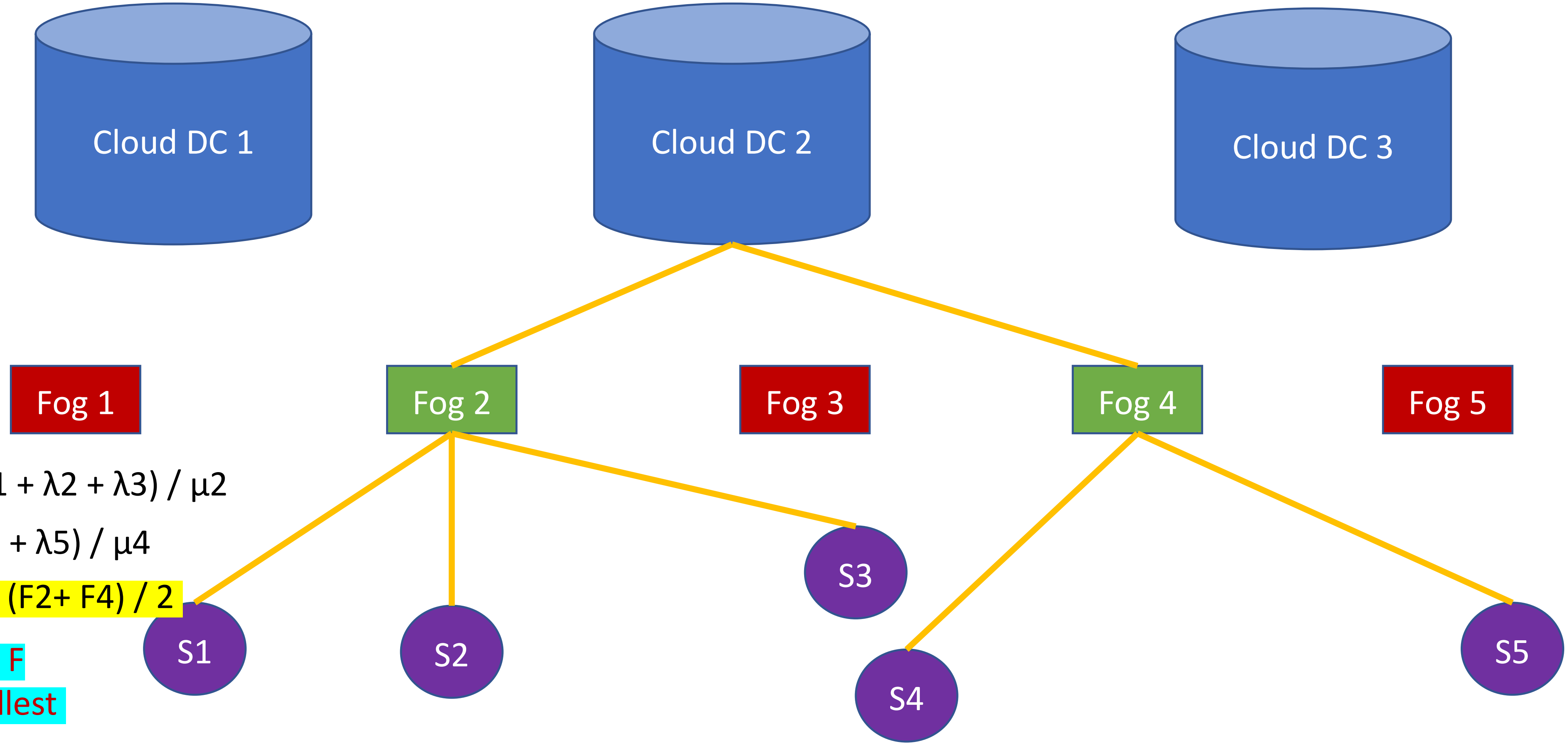
F5 = []



Neighborhood N1



Neighborhood N2



Load F2 = $(\lambda 1 + \lambda 2 + \lambda 3) / \mu 2$

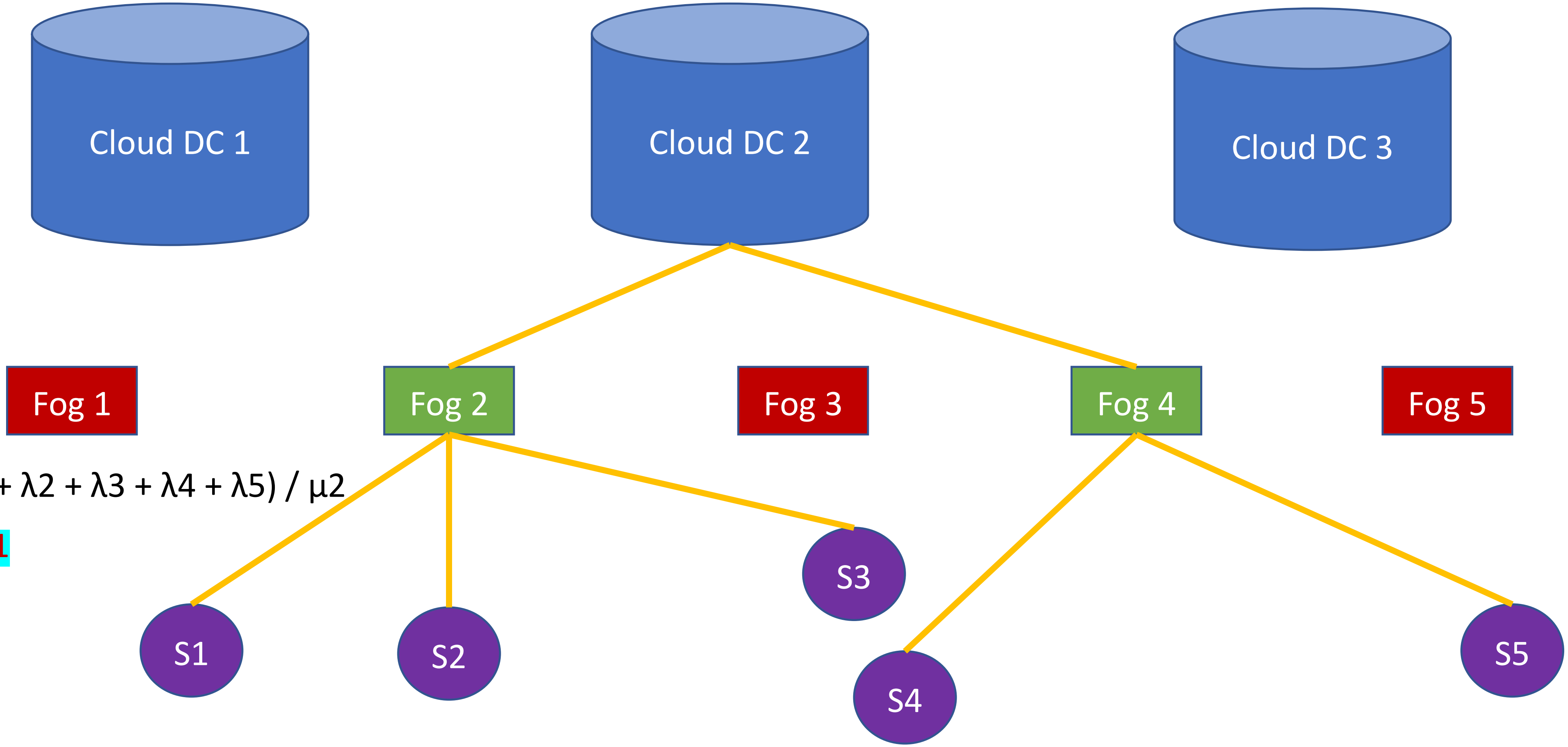
Load F4 = $(\lambda 4 + \lambda 5) / \mu 4$

Avg. Load F = (F2+ F4) / 2

Suppose F2 > F

F4 is the smallest

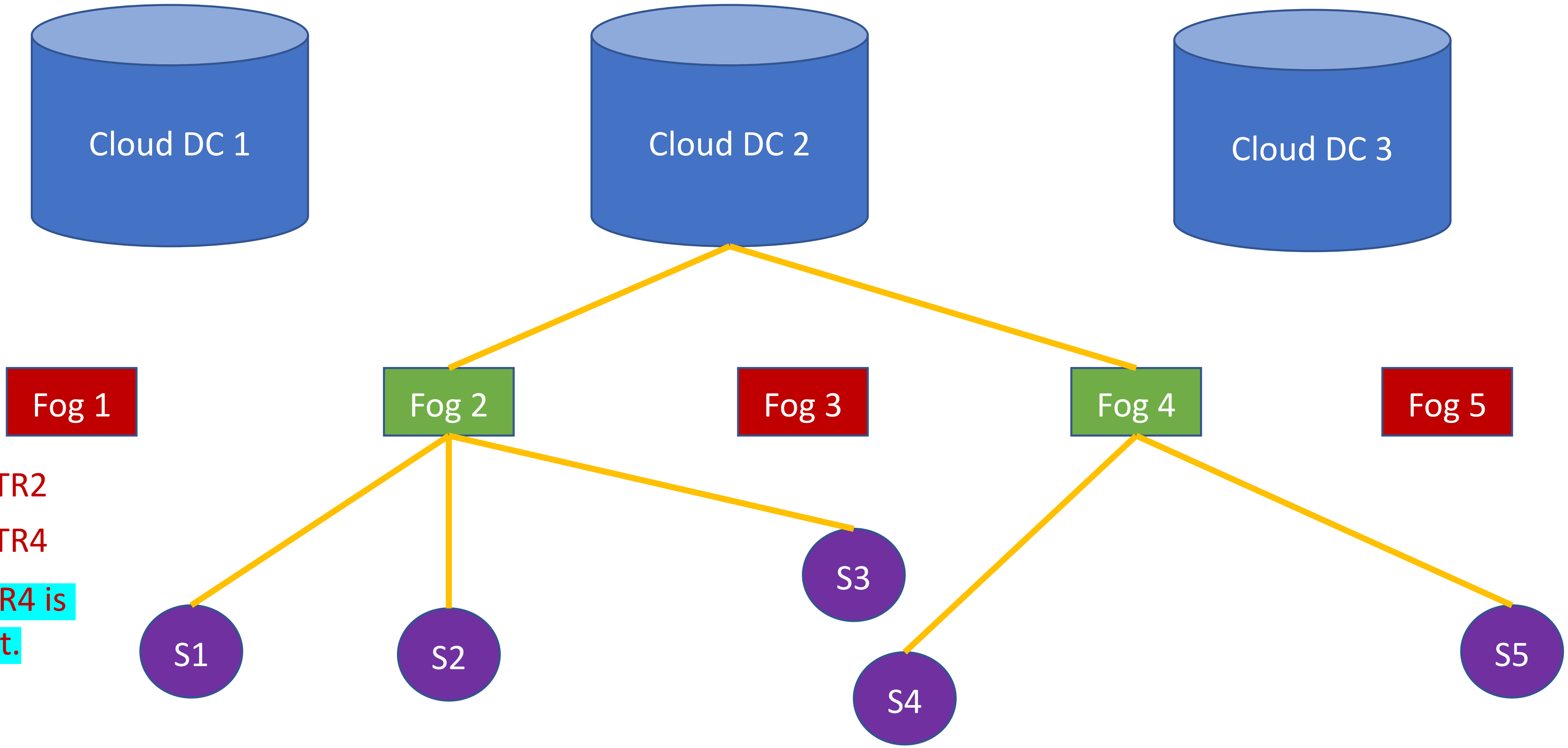
Neighborhood N3



Load R = $(\lambda 1 + \lambda 2 + \lambda 3 + \lambda 4 + \lambda 5) / \mu 2$

Suppose $R < 1$

Neighborhood N4

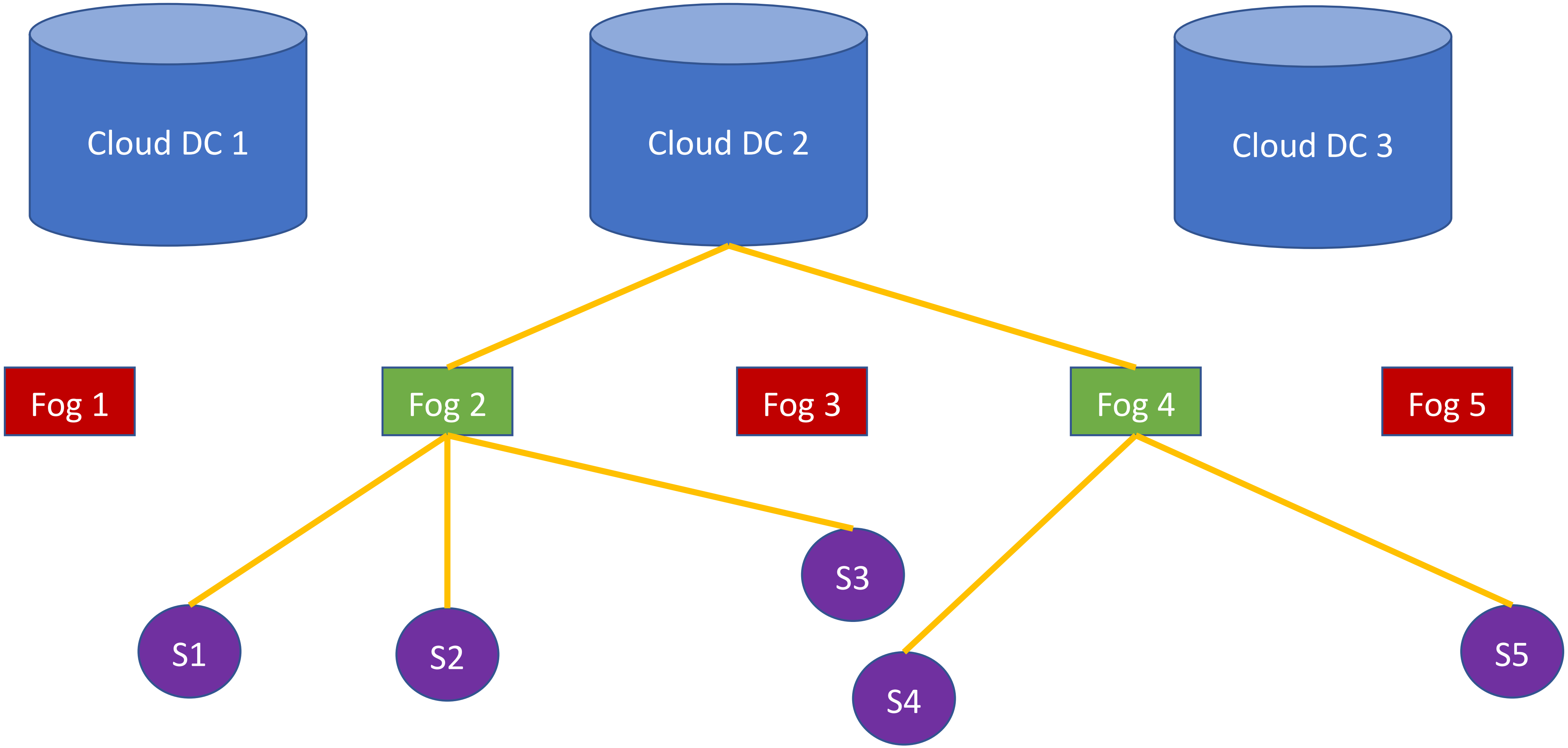


Response TR2

Response TR4

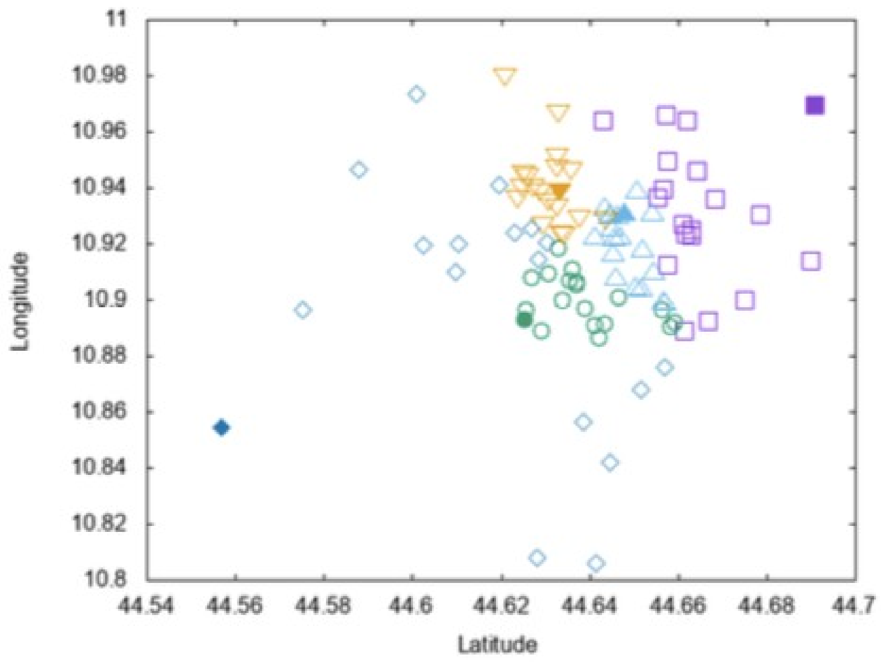
Suppose TR4 is the highest.

Neighborhood N5



Experimental Scenario

- Smart City scenario based on real example
  - Italian city (Modena),
  - ~180,000 inhabitants
- Traffic monitoring case
  - Sensors on streets
  - Fog nodes in public buildings
  - LoRa connections
- Evaluation using solver
- Comparison with:
  - Complex model (CM)
  - Simplified model ($E_i = 1$) (SM)



LocalSolver

Scenario Definition

- Parameters to describe scenarios
- Average network delay δ
  - Typically set to ~10ms
- Network delay / Processing time balance $\delta\mu$
  - Scenario CPU bound or Network bound
- System load ρ
  - Average load of fog nodes

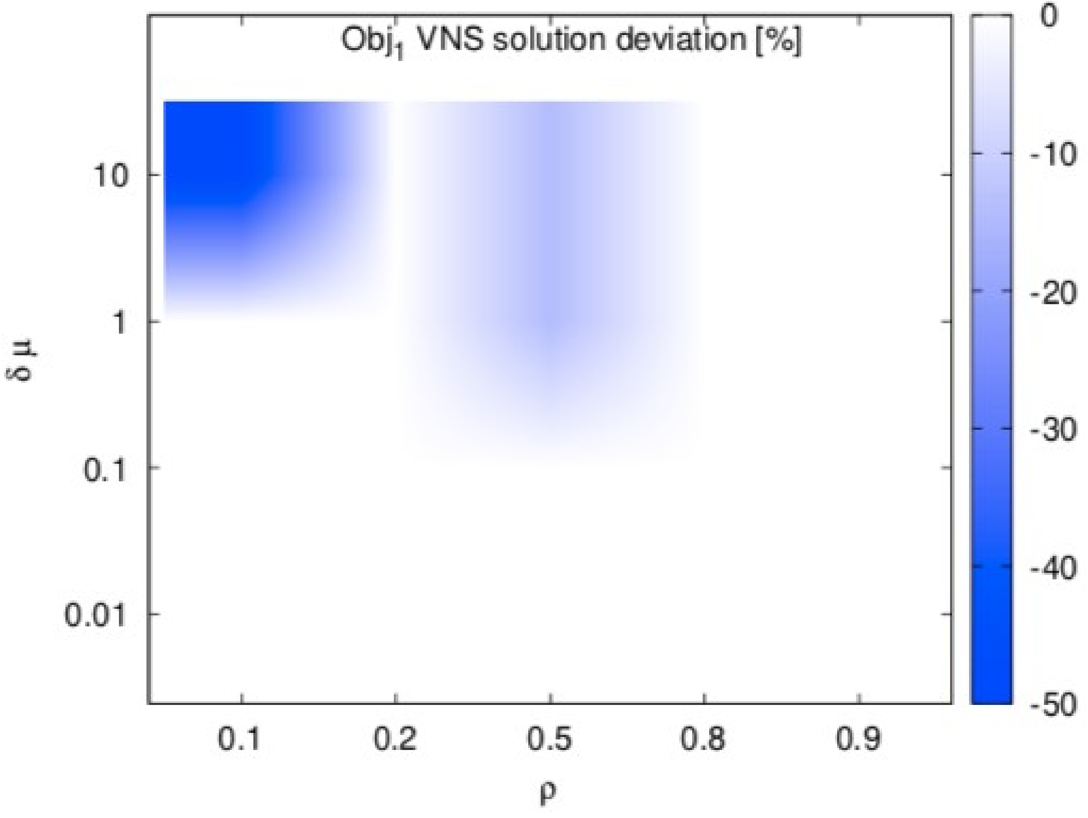
$$
\begin{aligned}
\delta &= \frac{\sum_{i\in\mathcal{S}}\sum_{j\in\mathcal{F}}\delta_{i,j}+\sum_{j\in\mathcal{F}}\sum_{k\in\mathcal{C}}\delta_{j,k}}{|\mathcal{S}|\cdot|\mathcal{F}|+|\mathcal{F}|\cdot|\mathcal{C}|}\\
\delta\mu &= \delta\cdot\frac{\sum_{j\in\mathcal{F}}\mu_j}{|\mathcal{F}|}\\
\rho &= \frac{\sum_{i\in\mathcal{S}}\lambda_i}{\sum_{j\in\mathcal{F}}\mu_j}
\end{aligned}
$$

Experimental Results

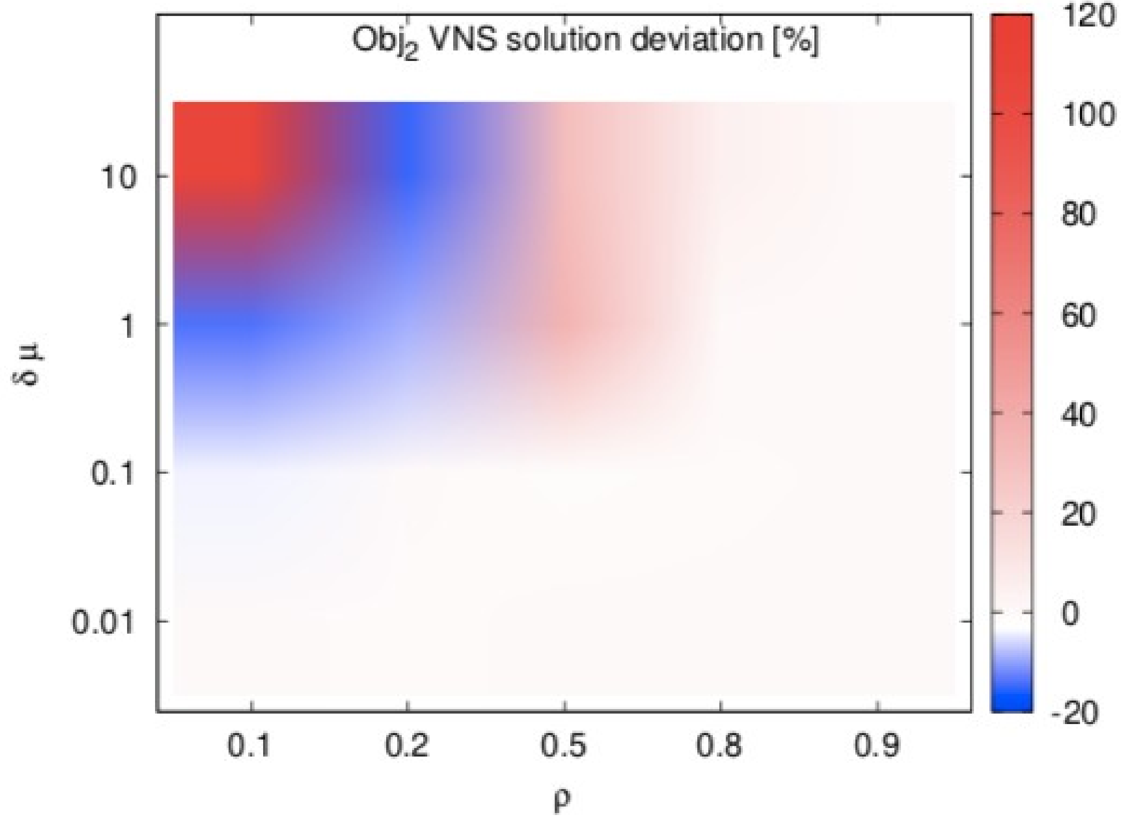
Instances	Simplified Model			Complex Model (Dev. CM vs. SM)					VNS (Dev. VNS vs. CM)				
	Iter.	Obj_1	Obj_2	Iter.	Obj_1	Dev. (%)	Obj_2	Dev. (%)	Iter.	Obj_1	Dev. (%)	Obj_2	Dev. (%)
ins-0.1-0.01	23655	10	0,1163	52421	2	-80,00	0,2337	100,96	1	2	0,00	0,2332	-0,23
ins-0.1-0.1	31809	10	0,1544	50876	2	-80,00	0,5520	257,45	1	2	0,00	0,5305	-3,90
ins-0.1-1	29173	10	0,5219	61189	2	-80,00	3,7795	624,22	1	2	0,00	3,2555	-13,86
ins-0.1-10	36088	10	4,1912	31853	6	-40,00	8,6976	107,52	1	3	-50,00	17,9568	106,46
ins-0.2-0.01	26833	10	0,2613	25242	3	-70,00	0,6482	148,07	1	3	0,00	0,6443	-0,61
ins-0.2-0.1	19049	10	0,3429	30661	3	-70,00	1,0125	195,30	6	3	0,00	1,0125	0,00
ins-0.2-1	28671	10	1,0829	33141	3	-70,00	4,9492	357,05	4	3	0,00	4,5140	-8,79
ins-0.2-10	38641	10	8,4215	46185	3	-70,00	45,6711	442,31	1	3	0,00	38,9263	-14,77
ins-0.5-0.01	39481	10	1,0300	13903	6	-40,00	3,1153	202,46	1	6	0,00	3,1148	-0,01
ins-0.5-0.1	24610	10	1,2825	15566	6	-40,00	3,5829	179,37	176	6	0,00	3,5344	-1,35
ins-0.5-1	21598	10	3,3132	7802	7	-30,00	5,9867	80,70	86	6	-14,29	8,1437	36,03
ins-0.5-10	25093	10	21,9581	10851	7	-30,00	34,4636	56,95	315	6	-14,29	44,9171	30,33
ins-0.8-0.01	52087	10	4,0480	11032	9	-10,00	8,3199	105,53	40	9	0,00	8,3160	-0,05
ins-0.8-0.1	51989	10	4,4799	14790	9	-10,00	8,8266	97,03	295	9	0,00	8,7628	-0,72
ins-0.8-1	38901	10	8,7654	14729	9	-10,00	13,1785	50,35	305	9	0,00	13,2132	0,26
ins-0.8-10	32297	10	44,1912	7335	9	-10,00	60,2917	36,43	455	9	0,00	63,1833	4,80
ins-0.9-0.01	57507	10	9,0540	11832	10	0,00	9,0540	0,00	16	10	0,00	9,0540	0,00
ins-0.9-0.1	45581	10	9,5399	15801	10	0,00	9,5399	0,00	20	10	0,00	9,5399	0,00
ins-0.9-1	54009	10	14,3987	10055	10	0,00	14,3987	0,00	16	10	0,00	14,3987	0,00
ins-0.9-10	50609	10	62,9869	12502	10	0,00	62,9869	0,00	50	10	0,00	62,9869	0,00

Experimental Results

Deviation between the VNS and CM model



(a) $\epsilon(Obj_1^{VNS})$



(b) $\epsilon(Obj_2^{VNS})$

Concluding Remarks

- Challenges of Fog computing
  - Selection of fog nodes and mapping of sensors
- Contribution: proposal of a model
  - Based on location-allocation optimization problem
  - Dual objective function
  - Non linear problem
- Validation of the model
  - Focus on a realistic scenario
  - Wide range of parameters considered
- Open issues
  - Heuristics (GA, Variable Neighborhood Search)
  - Dynamic scenarios

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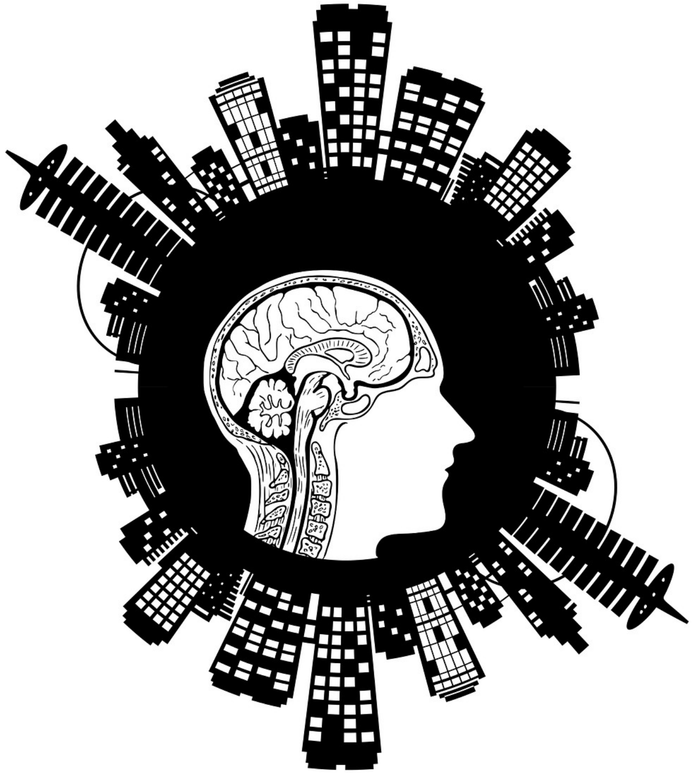
Questions?



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