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NFV Orchestration in Edge and Fog Scenarios

26th October, 2021

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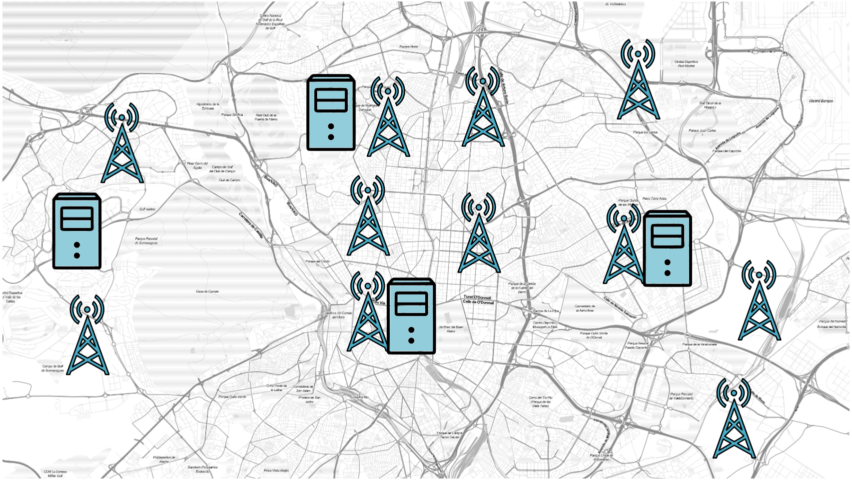

Figure 1: Illustration of BS and PoPs in Madrid

Location of BSs:

- Neyman-Scott Poisson Cluster Process [19]
- Poisson Point Processes (PPPs) [4]
  - homogeneous [20, 1]
  - hard-core [7]

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Location of MEC PoPs:

- along highways [21]
- within stadiums [6]

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Location of MEC PoPs:

- along highways [21]
- within stadiums [6]
- **population census**
- **access & aggregation rings**

Derive:

- BS location
- MEC PoP location

Meet:

- Tactile RTT of **1 ms**

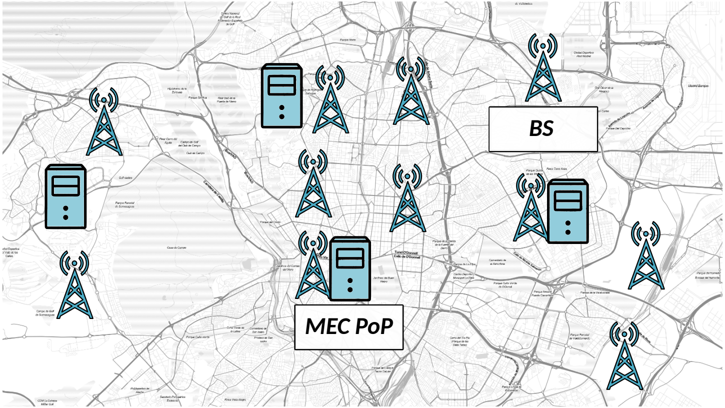

Figure 2: BS and MEC PoP locations

Higher gentrification $\implies$ more BSs

- R – region of interest
- C_i – area

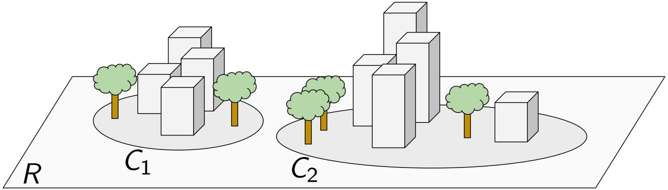

Figure 3: *Revolution functions* of a region with two building areas.

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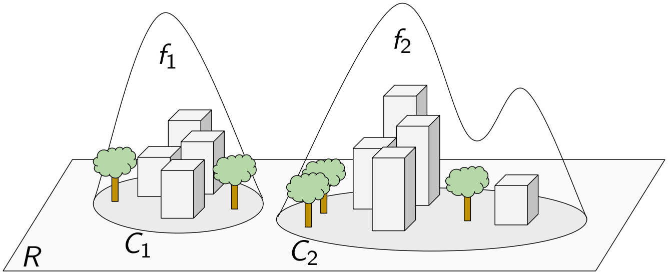

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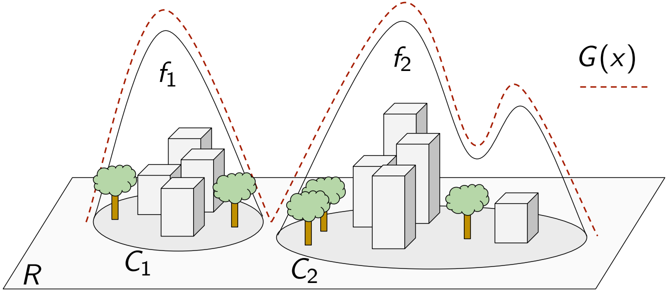
Higher gentrification $\implies$ more BSs

- R – region of interest
- C_i – area
- $f_i(x)$ – revolution func.
- $G(x)$ – gentrification
  - $G(x) = \sum_i f_i(x)$



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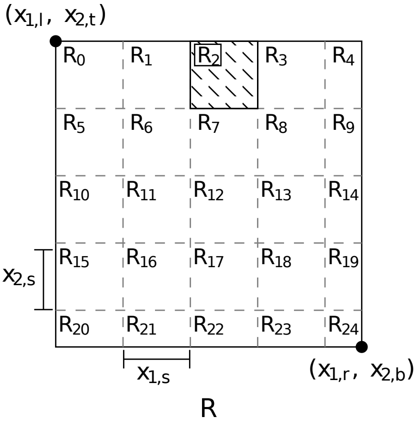


Figure 4: Gridded region

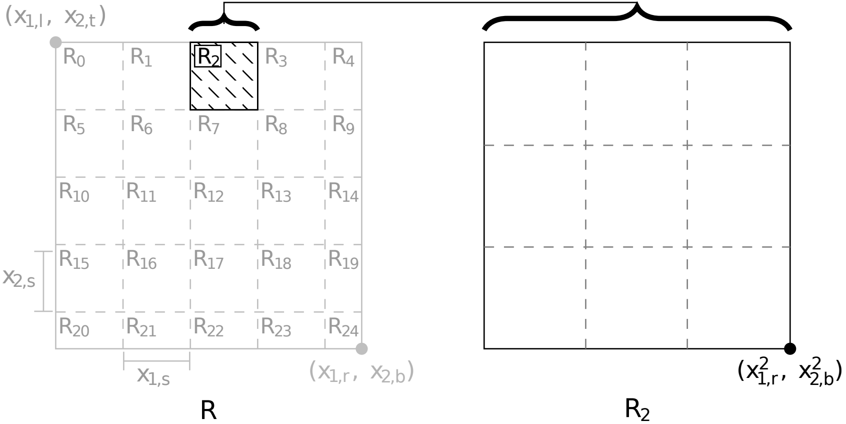
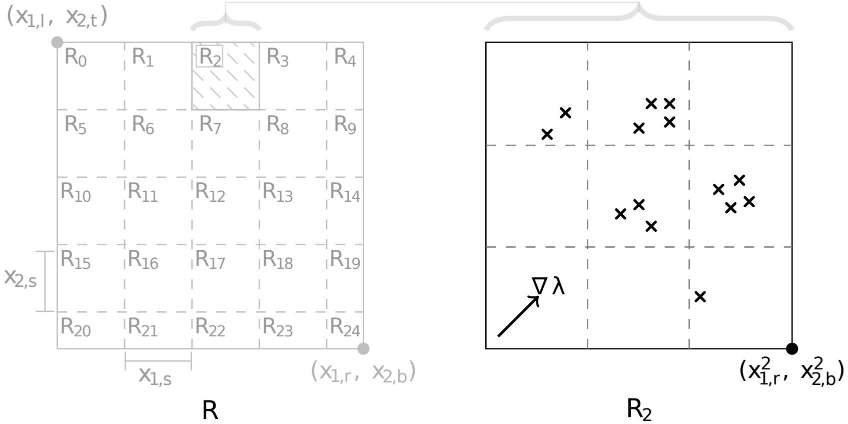


Figure 4: Gridded region (left), and inhomogeneous Mattérn II process of BSs (right).

BS intensity function $\lambda(x) \sim G(x)$ proportional to gentrification.



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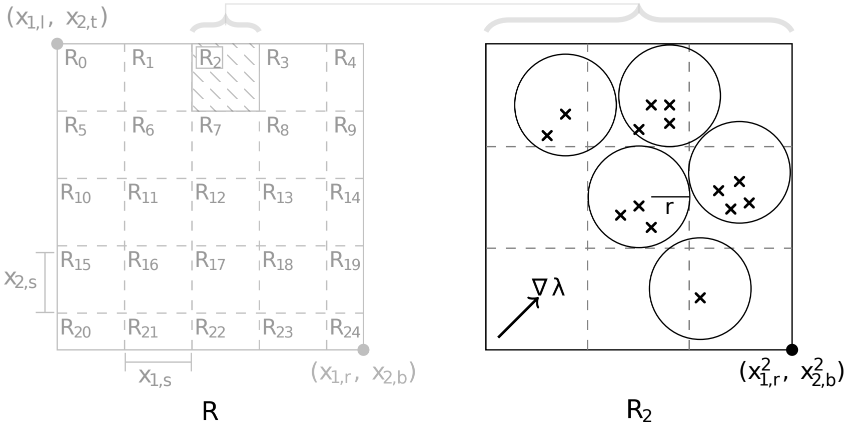

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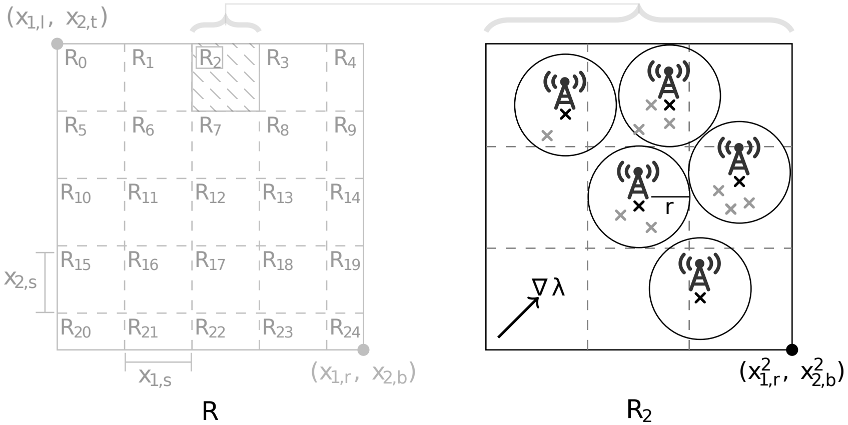

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Inhomogeneous Mattérn II PPs applied on:

- R: Madrid city
- $G(x)$: Madrid census

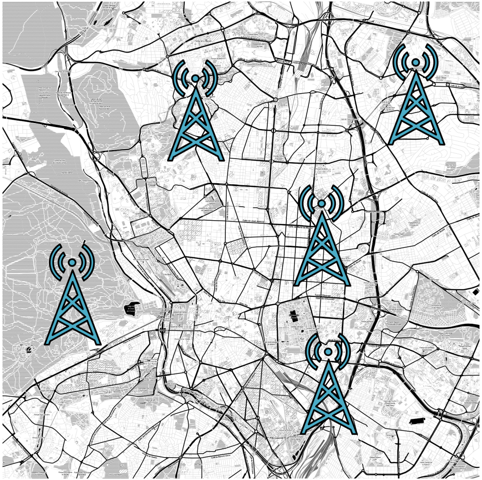

Figure 5: Location of BSs

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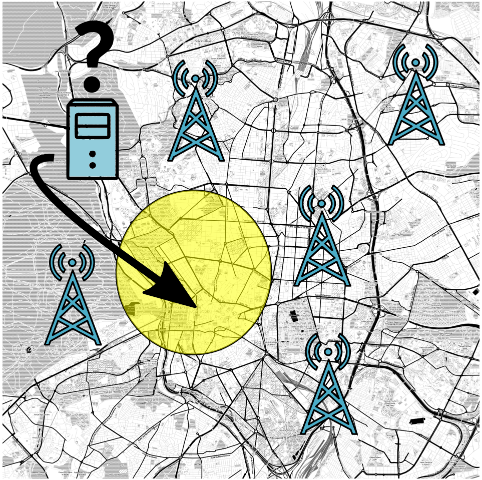


Figure 5: Location of BSs

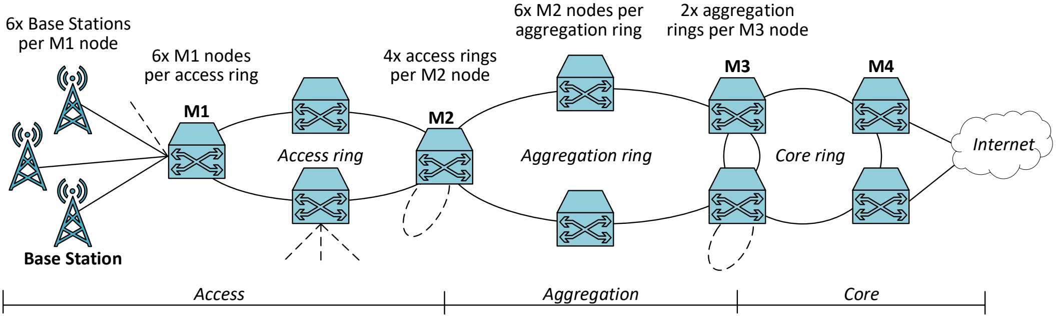
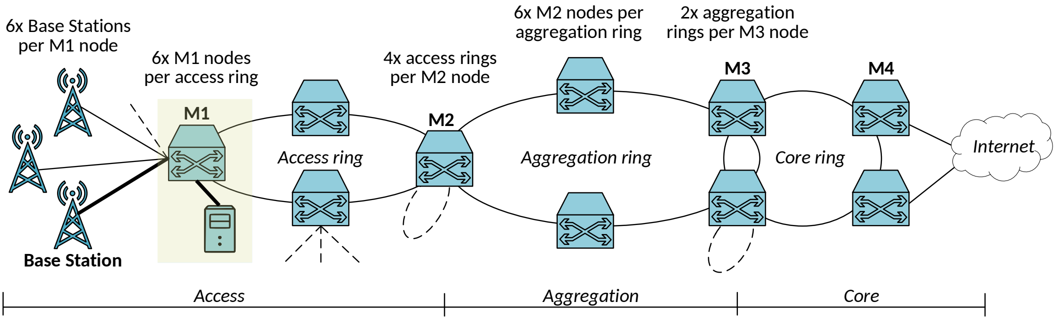


Figure 6: Reference network infrastructure as illustrated[1] in [5] and based on [8].

[1]Author: Dr. Luca Cominardi.



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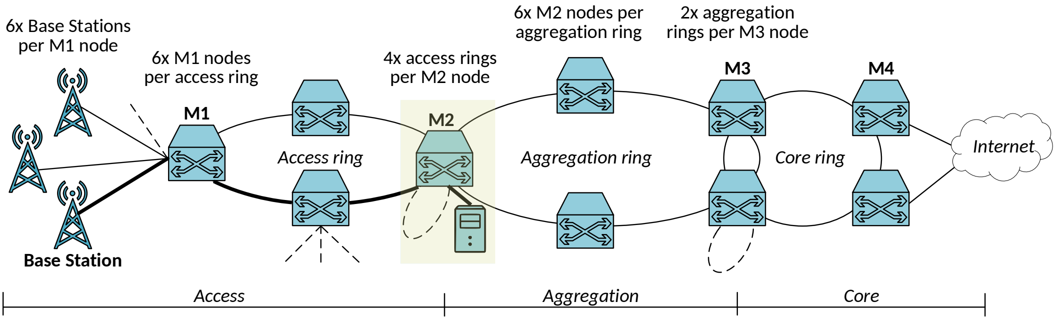

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Derive MEC PoP location considering:

$$RTT = \underbrace{2d \cdot 5\frac{\mu s}{km}}_{\text{fiber propagation}} + 2M \cdot 50\mu s + UL + DL \tag{1}$$

- d: distance between BS and MEC PoP
- M: network ring (M1,M2,M3,M4)
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$$RTT = 2d \cdot 5\frac{\mu s}{km} + 2M \cdot 50\mu s + \underbrace{UL + DL}_{\text{radio propagation}} \quad (1)$$

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- M: network ring (M1,M2,M3,M4)
- UL: Uplink propagation latency
- DL: Downlink propagation latency

m_M: maximum distance between MEC PoP at ring M and BS

Figure 7: How to select MEC PoP location

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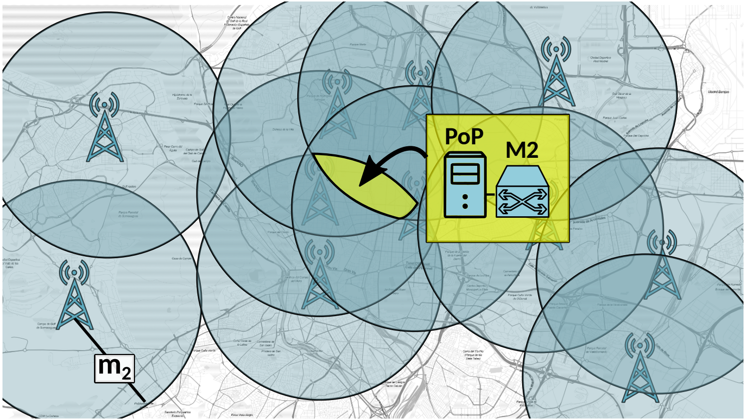
m_2: maximum distance between MEC PoP at ring 2 and BS



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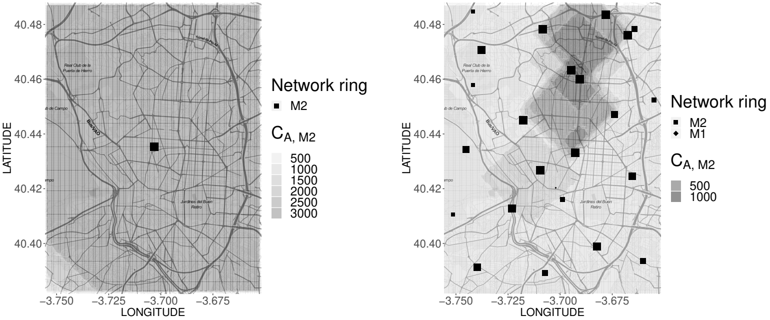
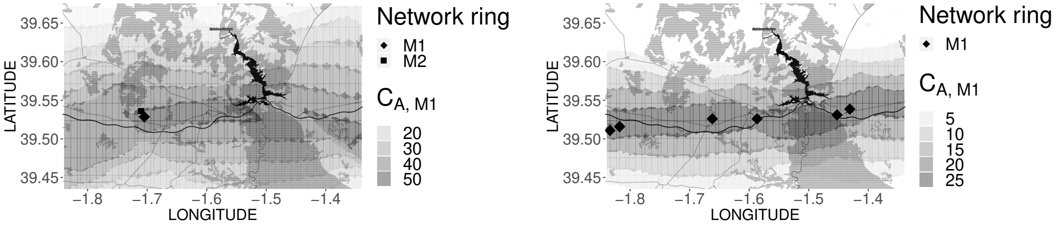


(a) FDD 120 kHz 7s

(b) TDD 120 kHz 7s

Figure 8: **Urban scenario** (Madrid city center) – $C_{A,M2}$ =covered BSs



(a) FDD 120 kHz 7s

(b) TDD 120 kHz 7s

Figure 9: **Highway scenario** (Hoces del Cabriel A3) – $C_{A,M1}$ =covered BSs by M1 MEC PoP

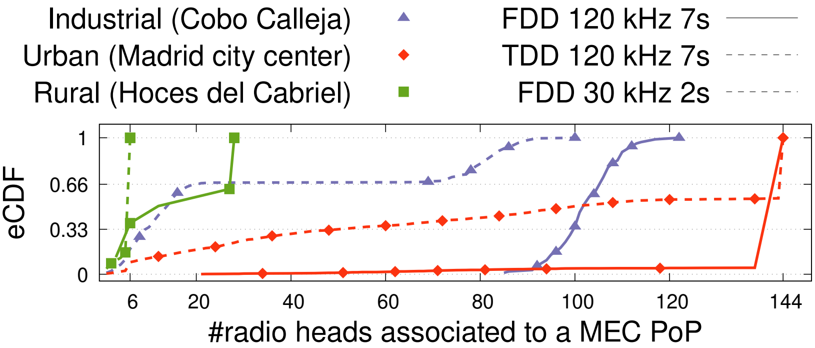


Figure 10: eCDF of the number of BSs assigned to a MEC PoP in the studied scenarios.

Publications:

- **Martín-Pérez, Jorge**, L. Cominardi, C. J. Bernardos, A. de la Oliva, and A. Azcorra. "Modeling Mobile Edge Computing Deployments for Low Latency Multimedia Services". In: *IEEE Transactions on Broadcasting* 65.2 (2019), pp. 464–474. DOI: 10.1109/TBC.2019.2901406
- **Martín-Pérez, Jorge**, L. Cominardi, C. J. Bernardos, and A. Mourad. "5GEN: A tool to generate 5G infrastructure graphs". In: *2019 IEEE Conference on Standards for Communications and Networking (CSCN)*. 2019, pp. 1–4. DOI: 10.1109/CSCN.2019.8931334

Open-source:

- **BS & MEC PoP generation**: `github.com/MartinPJorge/mec-generator`
- **5GEN**: 5GEN R package

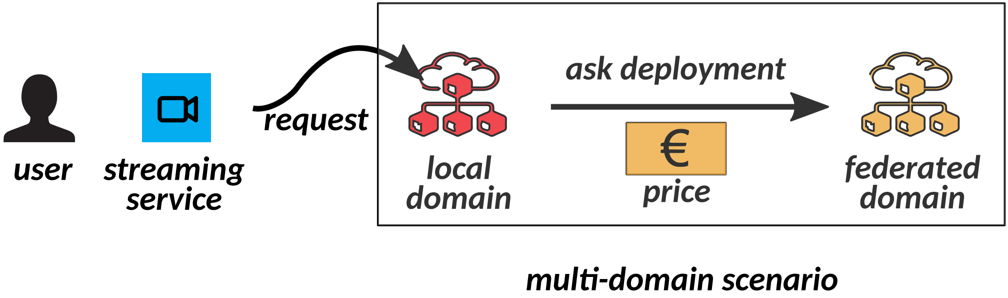


Figure 11: Service federation

Orchestration and **fixed pricing** in multi-domain:

- Alternating Direction Method of Multipliers (ADMM) [16]
- branching heuristic [9]
- graph-based message passing [24]
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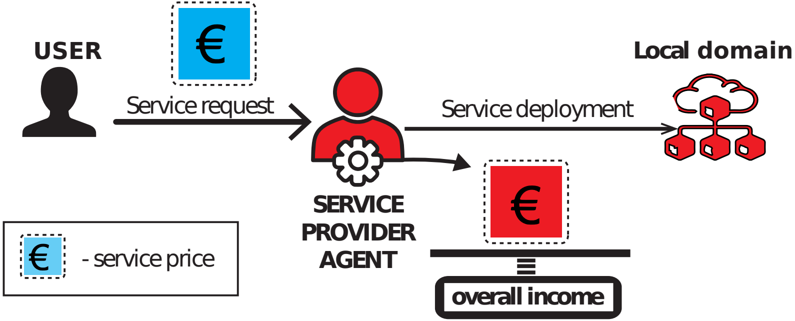

Figure 12: Business model - local deployment[2].

[2] Based on Kiril Antevski illustration

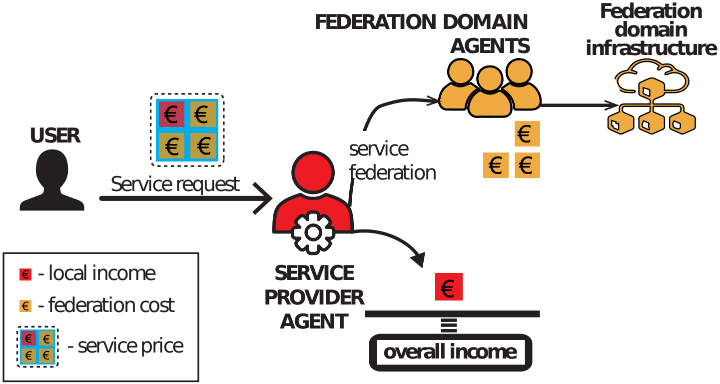

Figure 13: Business model - federate deployment[3].

[3] Based on Kiril Antevski illustration

t3a.small:

- 2 CPUs
- memory 2 GB
- storage 100 GB

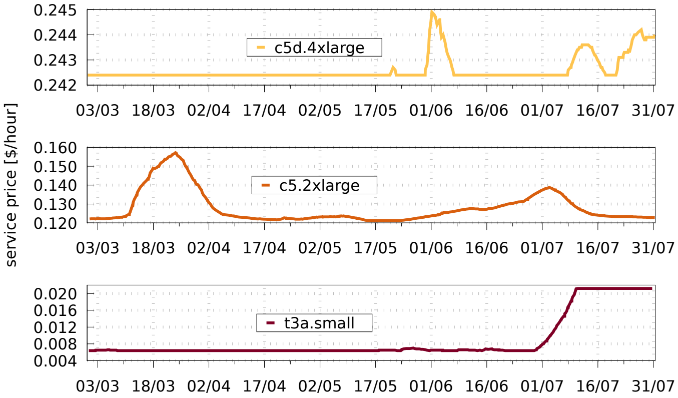

Figure 14: AWS service prices during 2020 in west Europe.

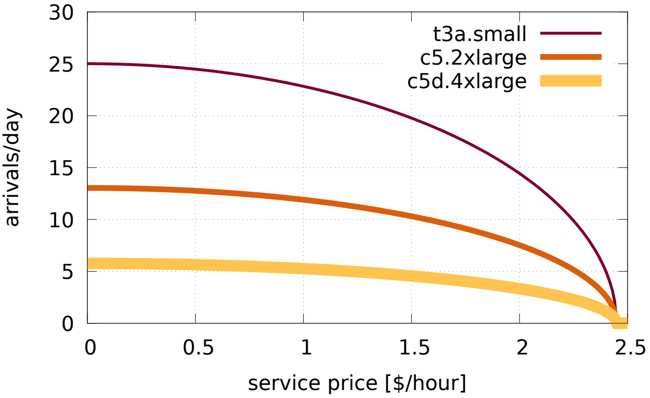

Figure 15: Impact of prices on arriving users – based on tid study [18] and [22].

Considering:

- Price changes
- Available resources (CPU, memory, disk)
- Service lifetime (e.g., 2 days)

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For each service σ, decide / take an **action**:

- $x(\sigma) = 0$: **reject**
- $x(\sigma) = 1$: **local**
- $x(\sigma) = 2$: **federate**

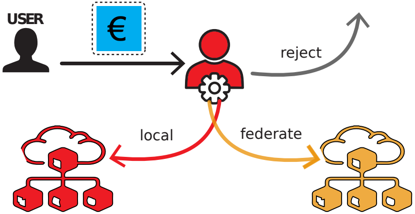

Figure 16: Possible actions.

Obtained **reward**:

$$r^{(t)}(X_t) := \sum_{\substack{\sigma:\ x(\sigma)=0 \\ a(\sigma)\leq t\leq d(\sigma)}} p^{a(\sigma)}(\sigma) + \sum_{\substack{\sigma:\ x(\sigma)=1 \\ a(\sigma)\leq t\leq d(\sigma)}} \left[p^{a(\sigma)}(\sigma) - f^{(t)}(\sigma)\right] \quad (2)$$

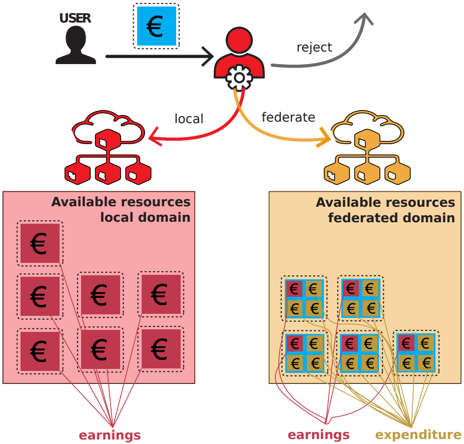

Figure 17: Environment snapshot at time t.

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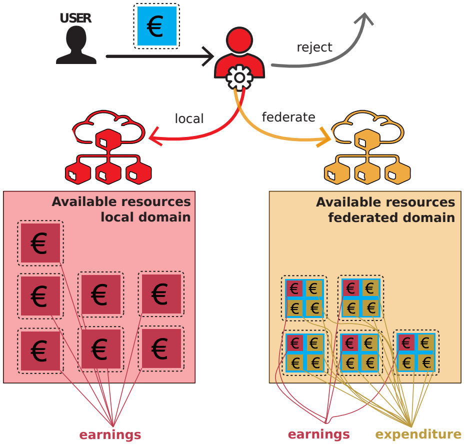
local



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federation

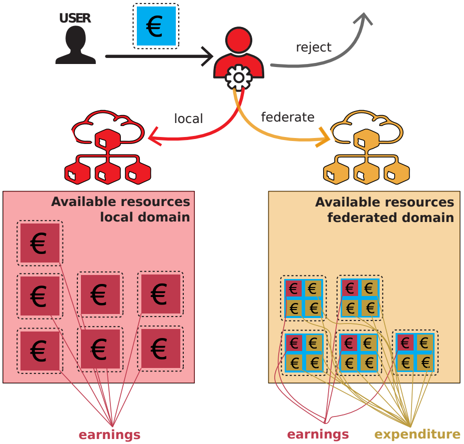

Figure 17: Environment snapshot at time t.

Online optimization problem:

- objective: $\max_{X_t} \frac{1}{T} \sum_t r^{(t)}(X_t)$
- constraints:
  - CPU
  - memory
  - disk

NP-hard: knapsack problem equivalence

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  - CPU
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NP-hard: knapsack problem equivalence

Markov Decision Problem (MDP):

- find policy π to:
  $\max_\pi \mathbb{E}_{x(\sigma)\sim\pi} \left[\sum_t \gamma^t \; r^{(t)}(\pi)\right]$
- action space $\mathcal{A} = \{0, 1, 2\}$
- state space $\mathcal{S}$:
  - available & requested resources
  - current prices
  - service lifetime
- instant reward $r^{(t)}(\pi)$

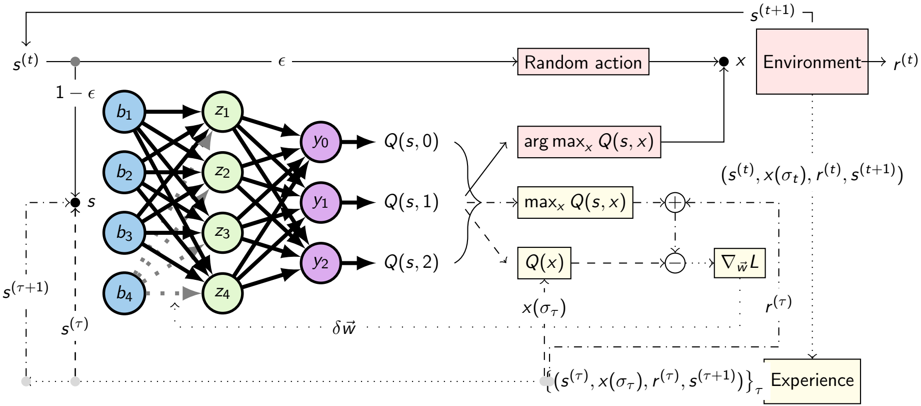

Figure 18: DQN architecture to decide rejection/local/federate.

Experimentation:

- TID infrastructure & resources [18]

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  - training 29/02/2020 – 02/05/2020
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Comparison of:

- Optimal
- DQN
- Q-table
- Q-table explore
- greedy

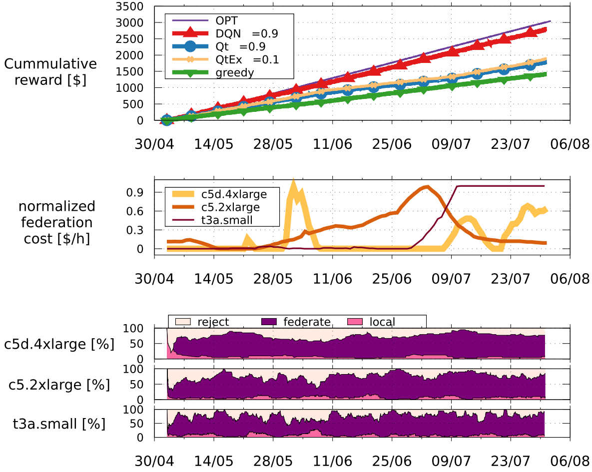

Figure 19: federation agents' performance.

Comparison of:

- Optimal
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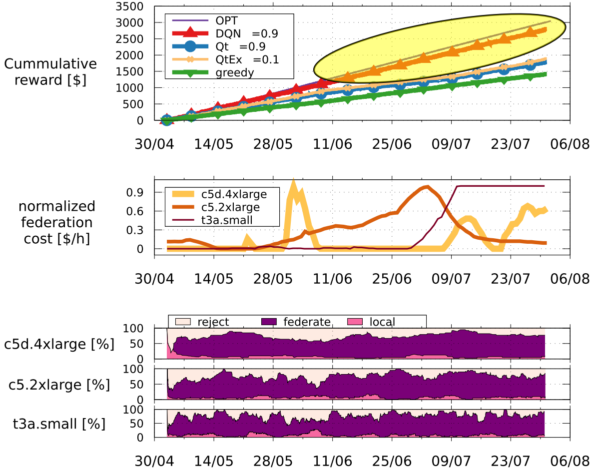
Results:

- near-optimal



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Comparison of:

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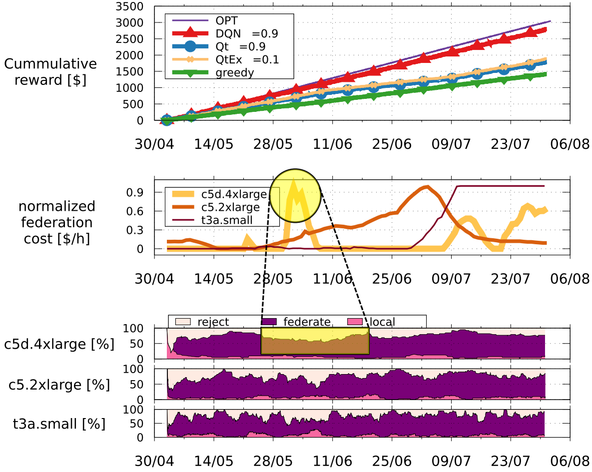
Results:

- near-optimal
- react upon peaks



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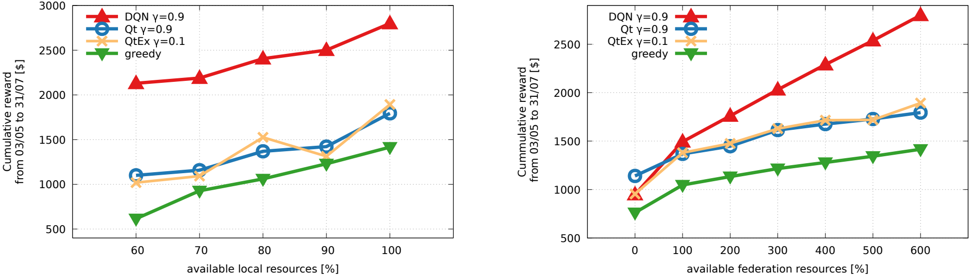


(a) Increasing local resources. (b) Increasing resources in federation.

Figure 20: Cumulative reward vs. available resources

Publications:

- **Martín-Pérez, Jorge** and C. J. Bernardos. "Multi-Domain VNF Mapping Algorithms". In: *2018 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. 2018, pp. 1–6. DOI: 10.1109/BMSB.2018.8436765
- K. Antevski, **J. Martín-Pérez**, A. Garcia-Saavedra, C. J. Bernardos, X. Li, J. Baranda, J. Mangues-Bafalluy, R. Martnez, and L. Vettori. "A Q-learning strategy for federation of 5G services". In: *ICC 2020 - 2020 IEEE International Conference on Communications (ICC)*. 2020, pp. 1–6. DOI: 10.1109/ICC40277.2020.9149082
- **Martín-Pérez, Jorge**, K. Antevski, A. Garcia-Saavedra, X. Li, and C. J. Bernardos. "DQN Dynamic Pricing and Revenue driven Service Federation Strategy". In: *IEEE Transactions on Network and Service Management* (2021), pp. 1–1. DOI: 10.1109/TNSM.2021.3117589

Open-source:

- **DFS, BFS w/ cutoffs**: `https://github.com/MartinPJorge/placement`
- **Q-table**: `https://github.com/MartinPJorge/5gt-federation`
- **DQN & environment**: `https://github.com/MartinPJorge/5gt-federation/tree/extensionICC/utils/aws`

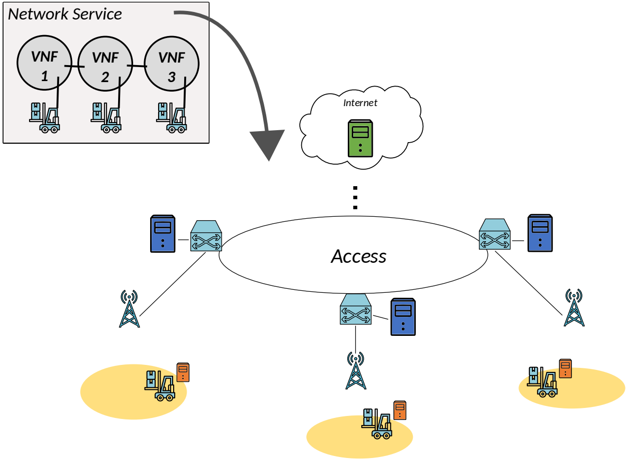
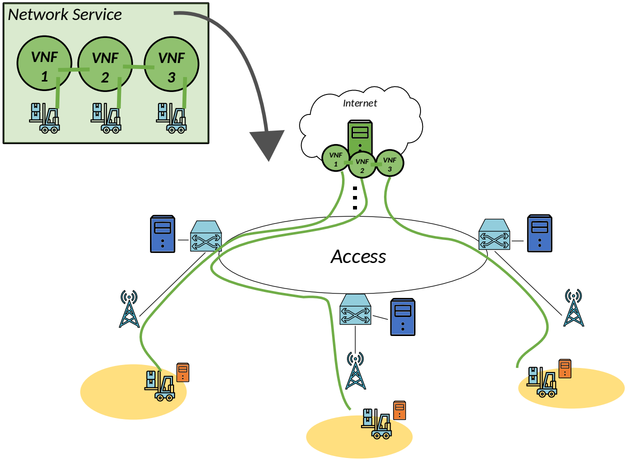


Figure 21: Virtual Network Function Embedding (VNE).



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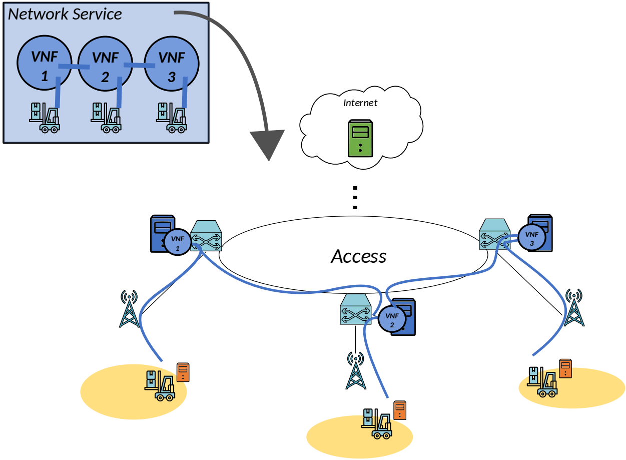

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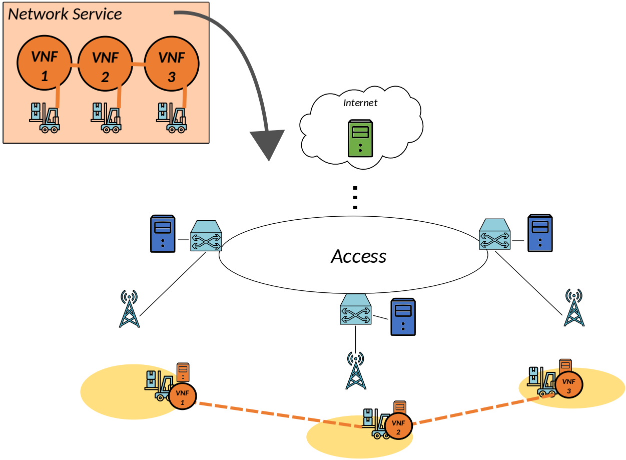

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Existing Virtual Network Embedding (VNE) solutions:

- latency-aware, bipartite graph & Hungarian [10]
- maxZ: latency-aware, relaxed ILP [2]
- z-TORCH: KPI monitoring, k-means VNF assign [17]
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OKpi accounts for:

- latency constraints
- radio coverage
- geographical availability
- reliability

Latency constraint $D(s)$:

$$d_{\text{net}}(\psi) + d_{\text{proc}} \leq D(s) \qquad (3)$$

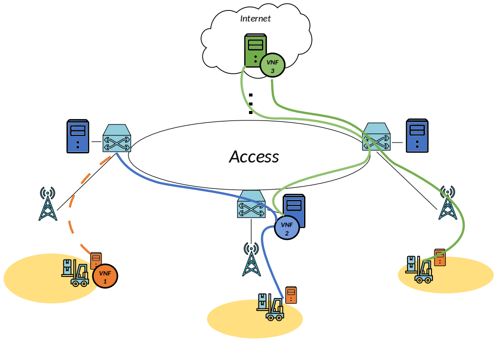

Figure 22: Service s delay.

Latency constraint $D(s)$:

$$\underbrace{d_{\text{net}}(\psi)}_{\text{propagation delay}} + d_{\text{proc}} \leq D(s) \quad (3)$$

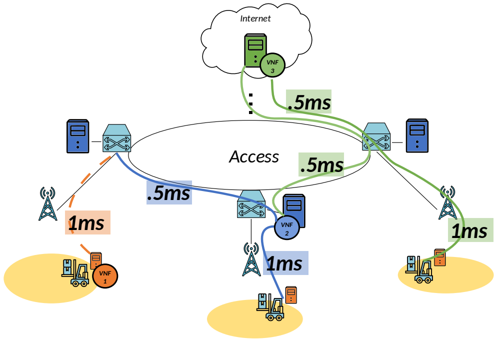

Figure 22: Service s delay.

Latency constraint $D(s)$:

$$d_{\text{net}}(\psi) + \underbrace{d_{\text{proc}}(\psi)}_{\text{processing delay}} \leq D(s) \quad (3)$$

d_{proc}: VNF as M/M/1-PS queue

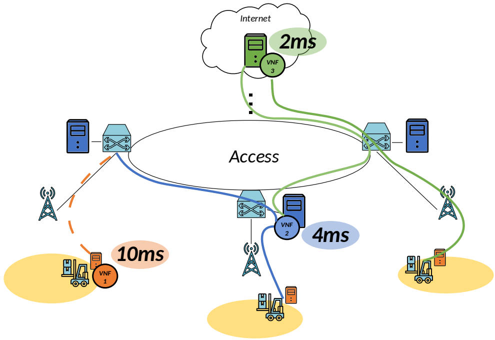

Figure 22: Service s delay.

Radio technology *i* constraint:

$$\rho(v,c) r_i(v) \leq R_i(c) \tag{4}$$

- $\rho(v,c)$: VNF v is deployed in c
- $R_i(c)$: radio point of access c has radio technology i
- $r_i(v)$: VNF v needs radio technology i

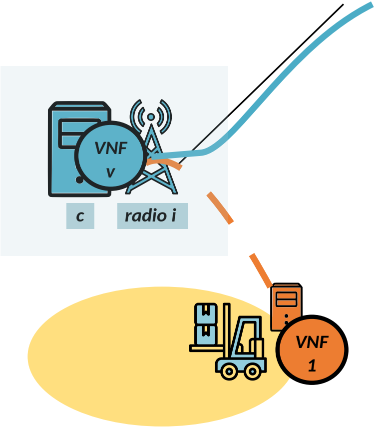

Figure 23: Radio VNF.

Geographical availability:

$$\forall \psi = (\alpha, s), \exists c, v_1, v_2 : \\ \tau_{\psi,c}(e, v_1, v_2) > 0 \quad (5)$$

- location α
- $\tau_{e,c}(e, v_1, v_2)$: flow (ψ, v_1, v_2) traverses link (ψ, c)

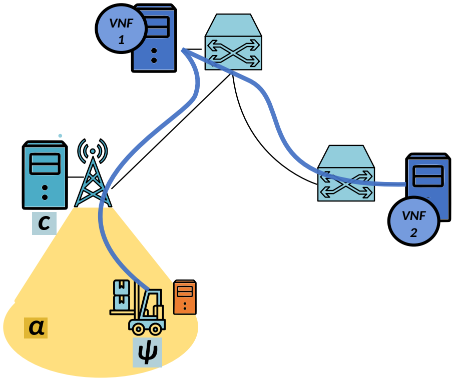

Figure 24: coverage of region α.

Service **reliability** $H(s)$:

$$\prod_{\substack{v_1, v_2 \in \mathcal{V} \\ (i,j) \in w}} \eta(j,t)\eta(i,j,t) \geq H(s) \quad (6)$$

- $\eta(j,t)$: node reliability at t
- $\eta(i,j,t)$: node reliability at t

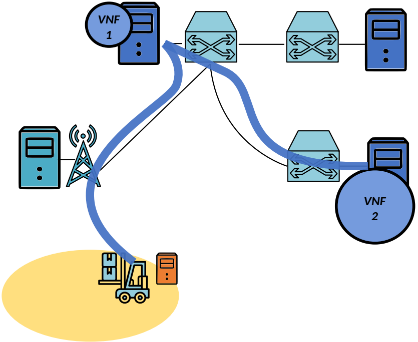

Figure 25: Traffic path.

Service **reliability** $H(s)$:

$$\prod_{v_1,v_2\in\mathcal{V}} \sum_{w\in\mathcal{W}} \underbrace{\boxed{f(\psi, v_1, v_2, w)}}_{\text{traffic fraction}}$$

$$\prod_{(i,j)\in w} \eta(j,t)\eta(i,j,t) \geq H(s) \quad (6)$$

- $\eta(j,t)$: node reliability at t
- $\eta(i,j,t)$: node reliability at t
- w: traffic path

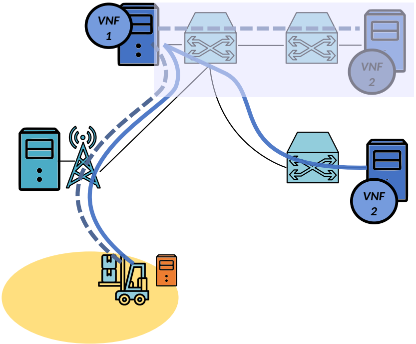

Figure 25: Fractioned traffic path.

Formulate an optimization problem:

$$\min \sum_{c} \sum_{v} \left[c_c(v) + \sum_{e} \sum_{\kappa} c_c(\kappa) a_c(\psi, v, \kappa) \right] + \sum_{(i,j)} \sum_{e} \sum_{v_1, v_2} c_{i,j} \tau_{i,j}(\psi, v_1, v_2) \tag{7}$$

$$s.t.(3) - (6) \tag{8}$$

Formulate an optimization problem:

$$\min \sum_{c} \sum_{v} \left[\underbrace{c_c(v)}_{\text{VNF cost}} + \sum_{e} \sum_{\kappa} c_c(\kappa) a_c(\psi, v, \kappa) \right] + \sum_{(i,j)} \sum_{e} \sum_{v_1, v_2} c_{i,j} \tau_{i,j}(\psi, v_1, v_2) \quad (7)$$

$$s.t. (3) - (6) \quad (8)$$

Formulate an optimization problem:

$$\min \sum_{c} \sum_{v} \left[c_c(v) + \sum_{e} \sum_{\kappa} \underbrace{c_c(\kappa) a_c(\psi, v, \kappa)}_{\text{assigned resource } \kappa \text{ cost}} \right] + \sum_{(i,j)} \sum_{e} \sum_{v_1, v_2} c_{i,j} \tau_{i,j}(\psi, v_1, v_2) \quad (7)$$

$$s.t. (3) - (6) \quad (8)$$

Formulate an optimization problem:

$$\min \sum_{c} \sum_{v} \left[c_c(v) + \sum_{e} \sum_{\kappa} c_c(\kappa) a_c(\psi, v, \kappa) \right] + \sum_{(i,j)} \sum_{e} \sum_{v_1, v_2} \underbrace{c_{i,j} \tau_{i,j}(\psi, v_1, v_2)}_{\text{traffic steering cost}} \tag{7}$$

$$s.t. (3) - (6) \tag{8}$$

Formulate an optimization problem:

$$\min \sum_{c} \sum_{v} \left[c_c(v) + \sum_{e} \sum_{\kappa} c_c(\kappa) a_c(\psi, v, \kappa) \right] + \sum_{(i,j)} \sum_{e} \sum_{v_1, v_2} c_{i,j} \tau_{i,j}(\psi, v_1, v_2) \quad (7)$$

$$s.t. (3) - (6) \quad (8)$$

NP-hard: bin-packing problem equivalence.

The **OKpi** (all KPI) solution:

1. Create a decision graph
2.

Open-source:

- **AMPLPY**: `https://github.com/ampl/amplpy`
- **networkx**: `https://github.com/networkx/networkx`
- **OKpi**: `https://github.com/MartinPJorge/placement`
- **FMC**: `https://github.com/MartinPJorge/placement`

Thanks for your attention!

OKpi is open-source, and it is implemented in python's placement module as FPTASMapper:

`https://github.com/MartinPJorge/placement`

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Lemma

Given an inhomogeneous marked PPP X with intensity function λ, the thinning function I_2, and marks $m \sim \frac{1}{\lambda(x)}$, the resulting thinned point process, called inhomogeneous Matérn II PP, has the following average number of points at C:

$$\mathbb{E}\left[N(C)\right] := \int_C e^{-\int_{B(x,r)} \mathbb{1}(\lambda(u) > \lambda(x))\lambda(u)du} \lambda(x)\ dx \tag{9}$$

where r is the thinning radius of I_2.

with

$$I_2(x, m, X, M_X) := \begin{cases} 1 & \text{if } m = \min_{m' \in M_X} \left\{(x', m') : x' \in B(x, r)\right\} \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

The RTT considered is computed as

$$RTT := 2l\left(\|x - m\|_1\right) + 2p(M) + UL + DL \tag{11}$$

We find m_M, the maximum distance from MEC PoP m to the BS at position x, as:

$$\|x - m\|_1 \leq l^{-1}\left(\frac{RTT - 2p(M) - t_r}{2}\right) = m_M \tag{12}$$

with $\|\cdot\|_1$ denoting the Manhattan distance.

User pays $p^{(t)}$ for the service σ

$$p^{(t)}(\sigma) = (1 + P)I^{(t)}(\sigma) \tag{13}$$

with P the profit margin, and $I^{(t)}$ the local deployment cost (based on uncertain phenomena).

User pays $p^{(t)}$ for the service σ

$$p^{(t)}(\sigma) = (1+P)l^{(t)}(\sigma) \tag{13}$$

with P the profit margin, and $l^{(t)}$ the local deployment cost (based on uncertain phenomena).

Given the federation fee $f(\sigma)$ the **reward** is:

$$r^{(t)}(X_t) := \sum_{\substack{\sigma:\ x(\sigma)=0\\ a(\sigma)\leq t\leq d(\sigma)}} p^{a(\sigma)}(\sigma) + \sum_{\substack{\sigma:\ x(\sigma)=1\\ a(\sigma)\leq t\leq d(\sigma)}} \left[p^{a(\sigma)}(\sigma) - f^{(t)}(\sigma)\right] \tag{14}$$

where $X_t := \{x(\sigma)\}_{\sigma:a(\sigma)\leq t}$.

$$f(p^{(t)}(\sigma)) := \begin{cases} k\left(1-\left(\frac{p^{(t)}(\sigma)}{K\cdot M}\right)^a\right)^b, & p^{(t)}(\sigma) \leq K\cdot M \\ 0, & p^{(t)}(\sigma) > K\cdot M \end{cases} \quad (15)$$

where $M = \max_{\sigma,t}\{l^{(t)}(\sigma)\}$ is the maximum local deployment cost over time across all services σ (e.g., *t3a.small*), and K is a normalization constant to control the decay of the arrival rate.

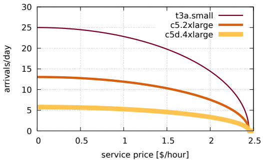

Figure 26: Impact of prices on arriving users.

Increase of P leads to:

- less user arrivals
- larger reward

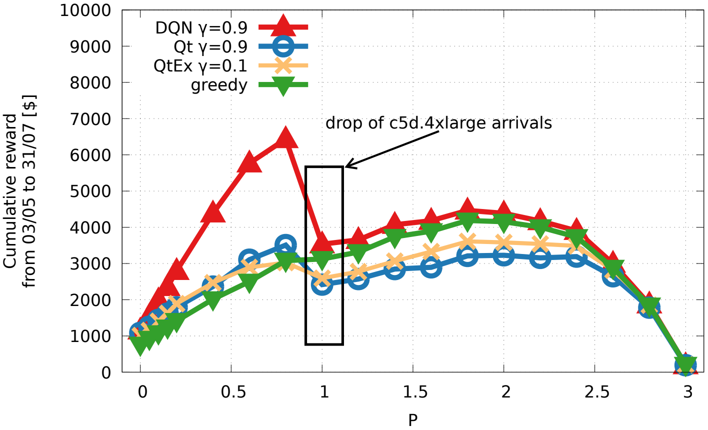

Figure 27: Impact of the marginal benefit P in the commutative reward achieved by each solution.