Universidad Carlos III de Madrid

NFV Orchestration in Edge and Fog Scenarios

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"Service orchestration is the process of designing, creating, delivering, and monitoring service offerings in an automated way." – Ericsson

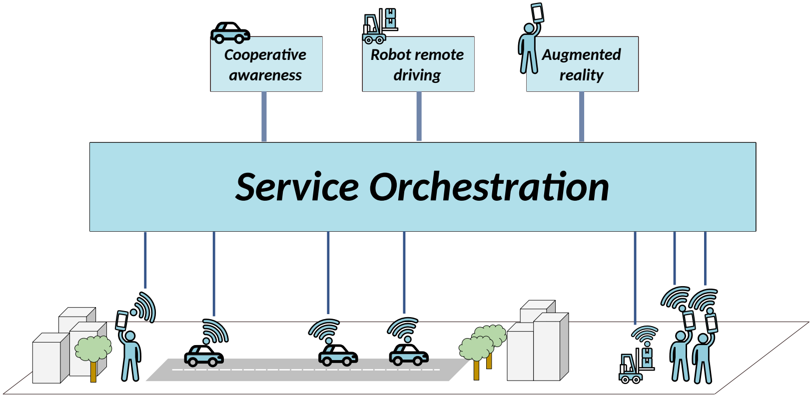

Figure 1: Orchestration of three services.

Service Orchestration:

- design network
- where services run?
- deliver to users
- monitor/scale service

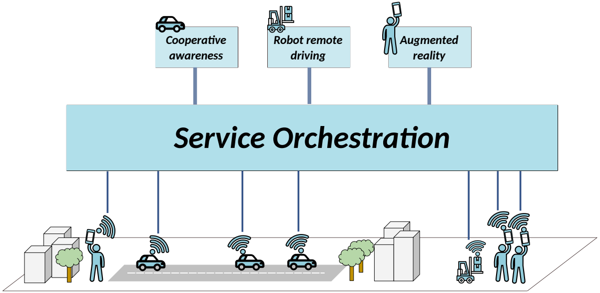

Figure 1: Orchestration of three services.

1 Generation of 5G infrastructure graphs

Outline

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2 NFV Orchestration in federated environments

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2. NFV Orchestration in federated environments
3. NFV orchestration for 5G networks: OKpi

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4 Scaling of V2N services: a study case

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- Thesis contribution
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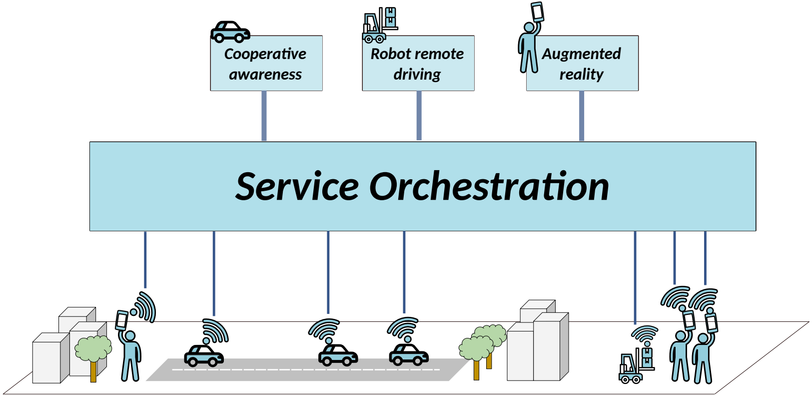

Figure 2: Orchestration of three services.

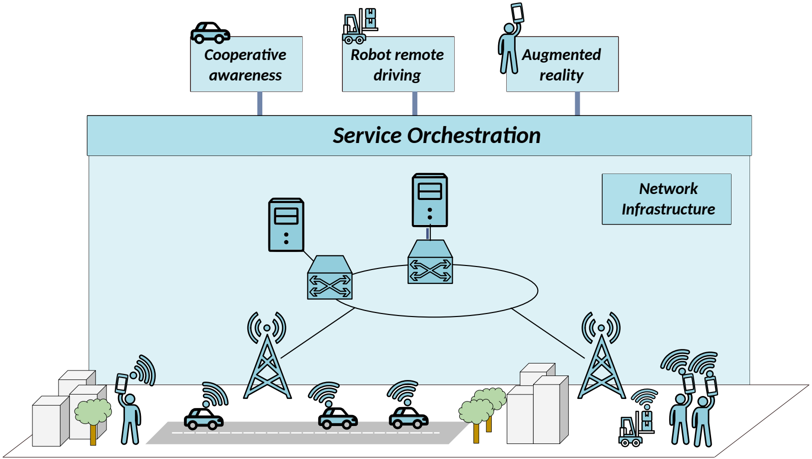

Figure 2: Network infrastructure for service providing.

This part derives **location** of:

1. **BSs** for user coverage
2. **servers** to process traffic

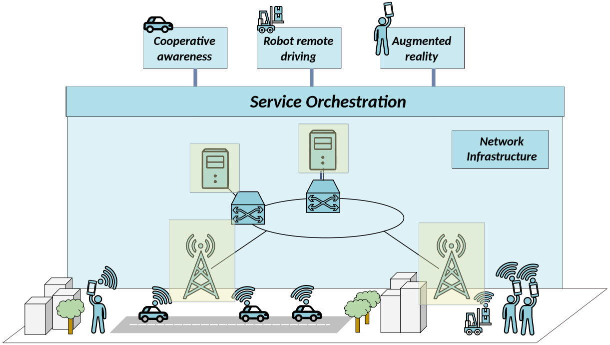

Figure 3: Network infrastructure for service providing.

This part derives **location** of:

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2. **servers** to process traffic

for **augmented reality**:

- tactile latency 1ms

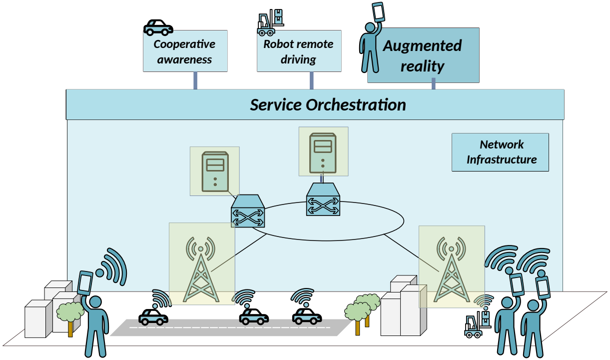

Figure 3: Network infrastructure for service providing.

uc3m

New methodology in the SoA

- **BS** location:
  - inhomogeneous Mattérn II PPP
- **Server** location:
  - population census
  - access & aggregation rings
  - satisfy RTT

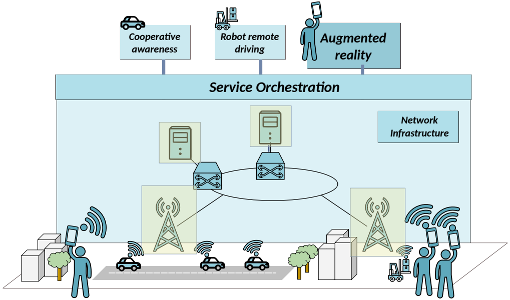

Figure 4: Network infrastructure for service providing.

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Higher gentrification $\implies$ more BSs

- R – region of interest
- C_i – area

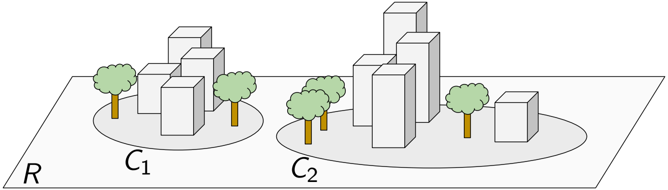
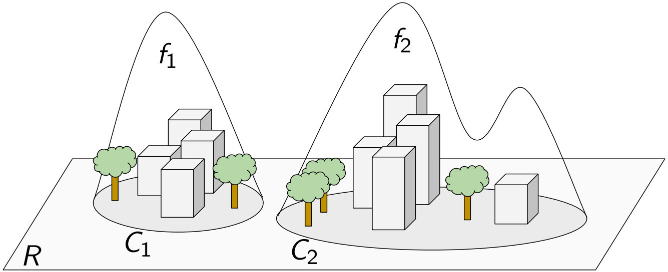


Figure 5: *Revolution functions* of a region with two building areas.

Higher gentrification $\implies$ more BSs

- R – region of interest
- C_i – area
- $f_i(x)$ – revolution func.



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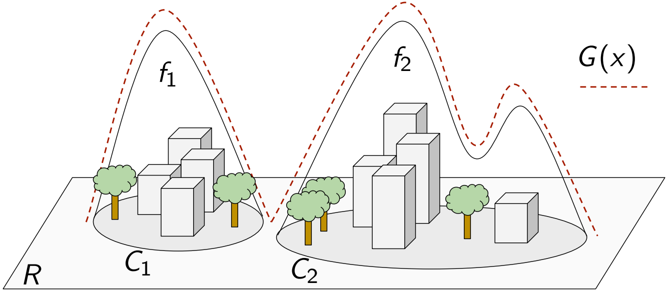
Higher gentrification $\implies$ more BSs

- 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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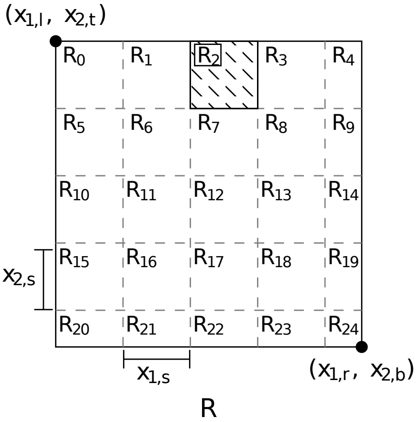
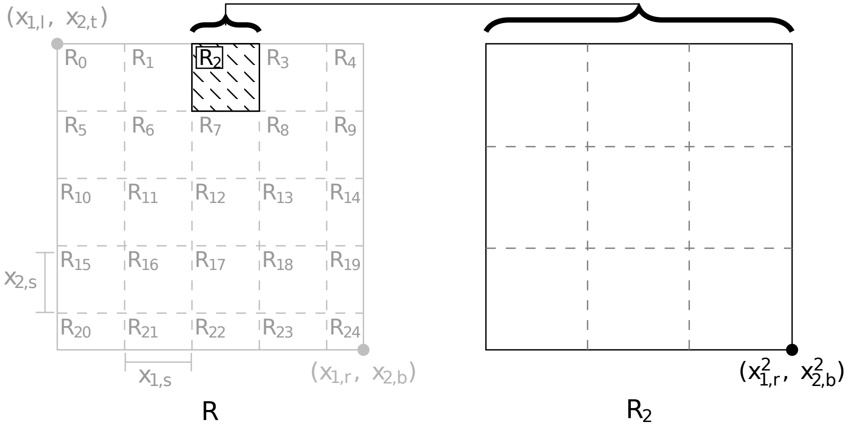


Figure 6: BS location – inhomogeneous Mattérn II process.



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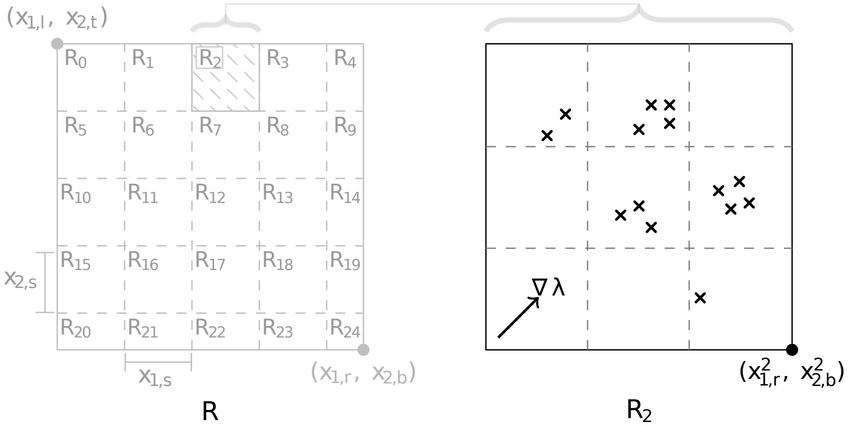
$\lambda(x) \sim G(x)$ probability of BS at x.



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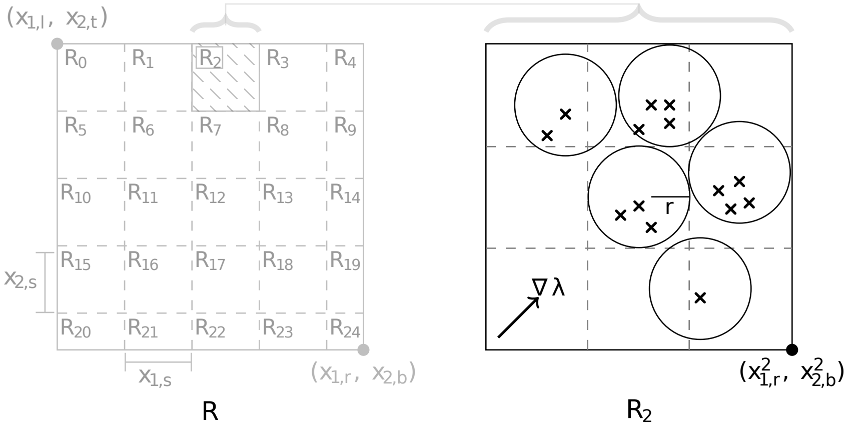

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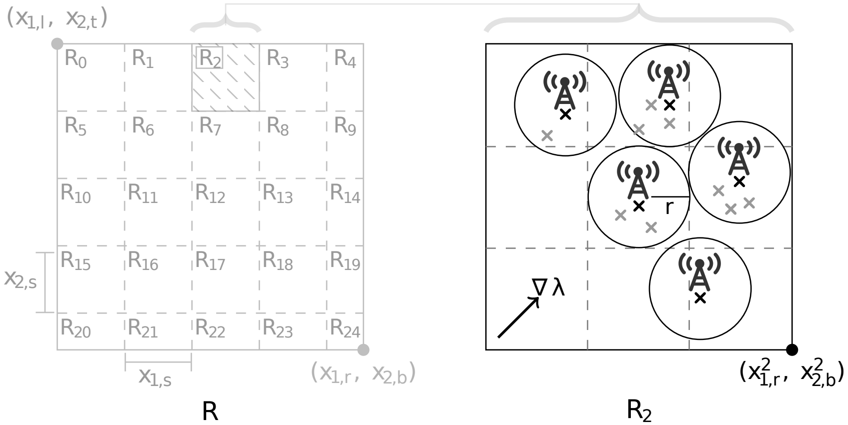

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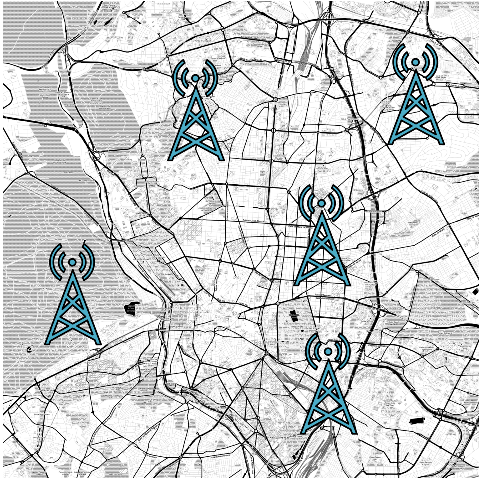
Inhomogeneous Mattérn II PPs applied on:

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



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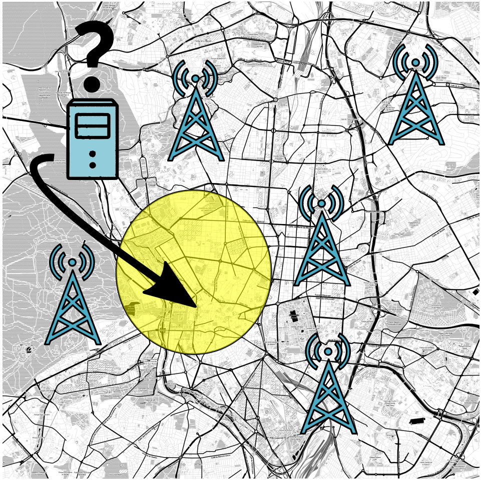

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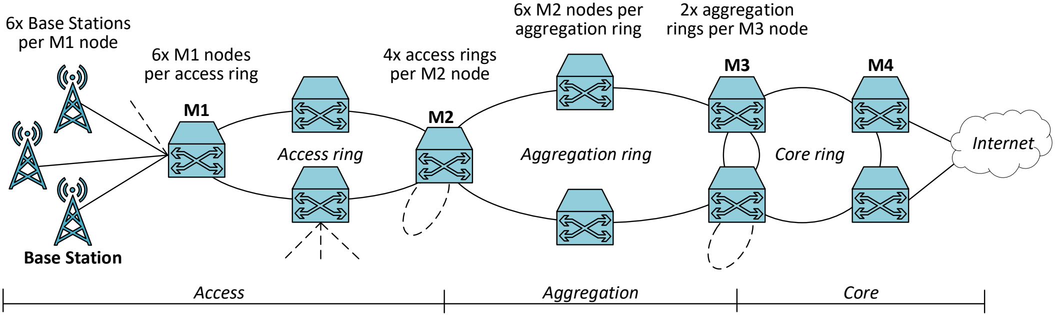
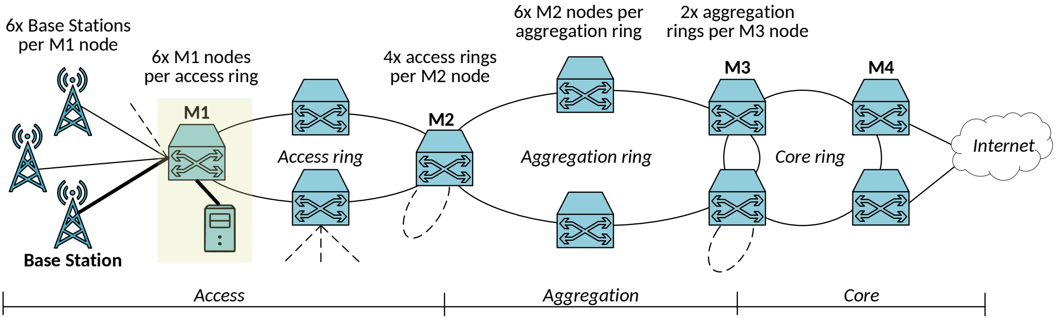


Figure 8: Reference network infrastructure as illustrated[1] in [6] and based on [10].

[1] Author: Dr. Luca Cominardi.



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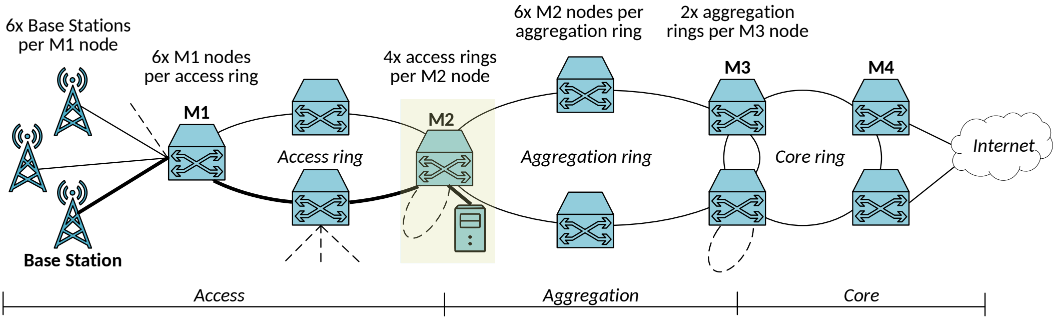

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Derive server location considering:

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

- d: distance between BS and server
- M: #traversed rings (e.g., $1, 2, \ldots$)
- UL: Uplink propagation latency
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Derive server location considering:

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Derive server location considering:

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

- d: distance between BS and server
- M: #traversed rings (e.g., $1, 2, \ldots$)
- UL: Uplink propagation latency
- DL: Downlink propagation latency

m_M: maximum distance between server at ring M and BS

Figure 9: How to select MEC PoP location.

m_2: maximum distance between server at ring 2 and BS

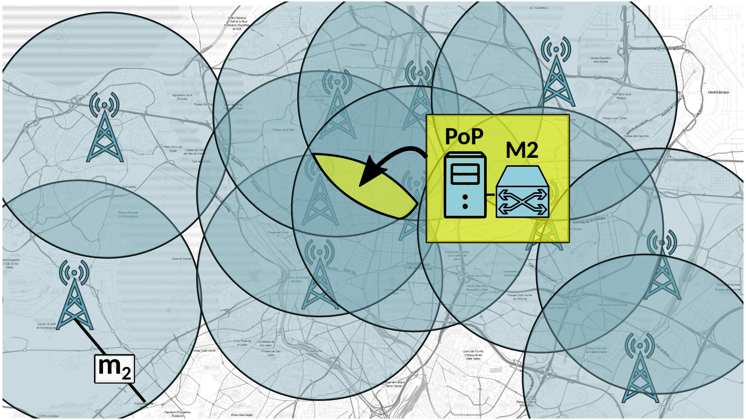
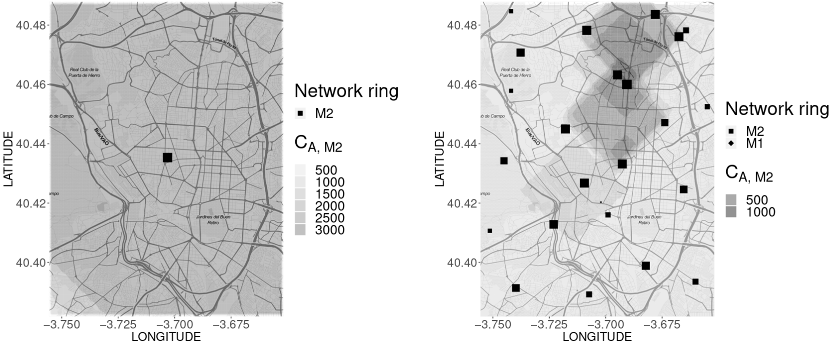


Figure 9: How to select MEC PoP location.

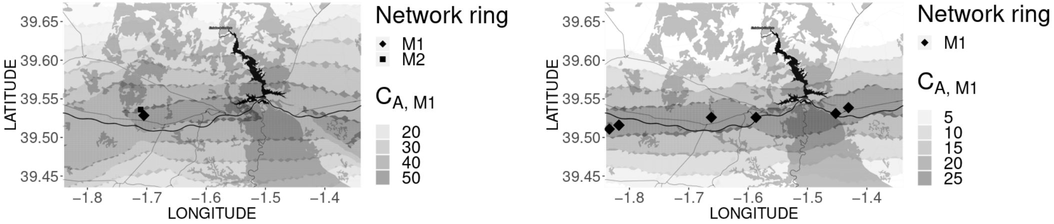
Experiments

- Urban, highway, industrial **scenarios**
- NR **BSs**:
  - FDD 120 kHz 7s
  - TDD 120 kHz 7s
  - FDD 30 kHz 2s
- **Servers**:
  - M1 network ring
  - M2 network ring



(a) FDD 120 kHz 7s (b) TDD 120 kHz 7s

Figure 10: **Urban scenario** (Madrid city center) – $C_{A,M2}$ =covered BSs by server at M2.



(a) FDD 120 kHz 7s

(b) TDD 120 kHz 7s

Figure 11: **Highway scenario** (Hoces del Cabriel A3) – $C_{A,M1}$ =covered BSs by server at M1.

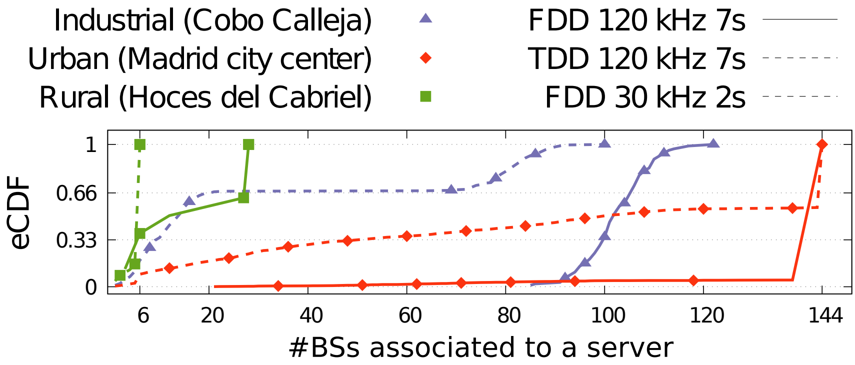


Figure 12: eCDF of the number of BSs assigned to a server in the studied scenarios.

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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**: http://github.com/MartinPJorge/mec-generator/
- **5GEN**: https://github.com/MartinPJorge/mec-generator/tree/5g-infra-gen/

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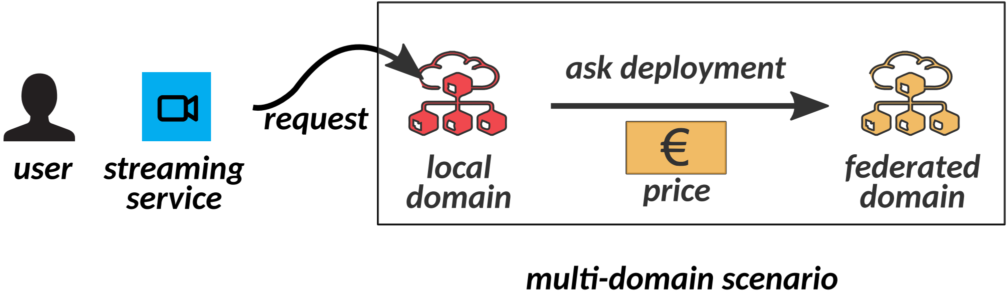

Figure 13: Service federation.

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

- Alternating Direction Method of Multipliers (ADMM) [23]
- branching heuristic [11]
- graph-based message passing [34]
- greedy with backtracking [20]

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- **Telefónica scenario**

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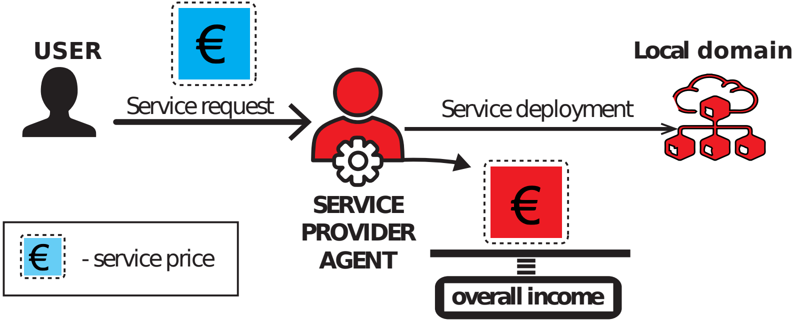

Figure 14: Business model - local deployment[2].

[2]Based on Kiril Antevski illustration

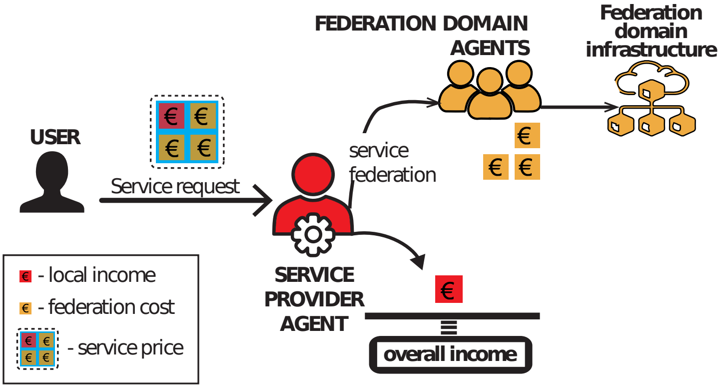

Figure 15: Business model - federate deployment[3].

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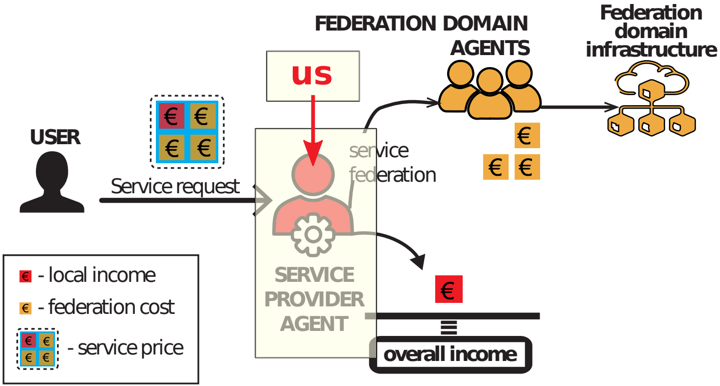

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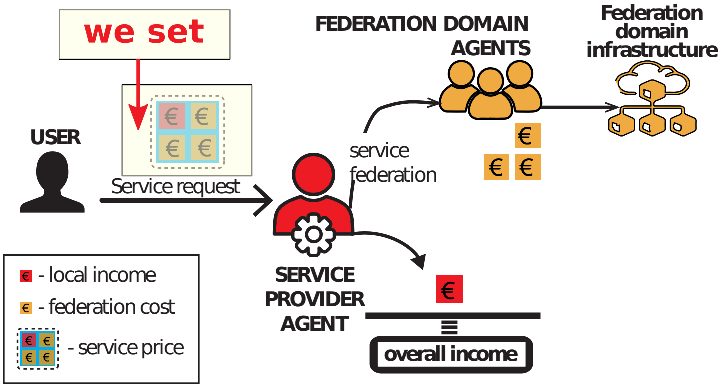

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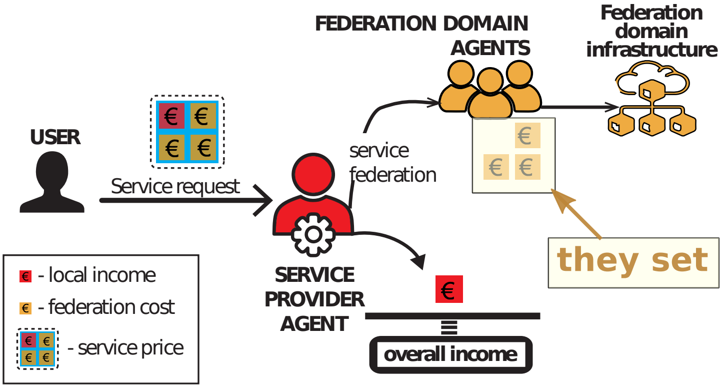

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t3a.small:

- 2 CPUs
- memory 2 GB
- storage 100 GB

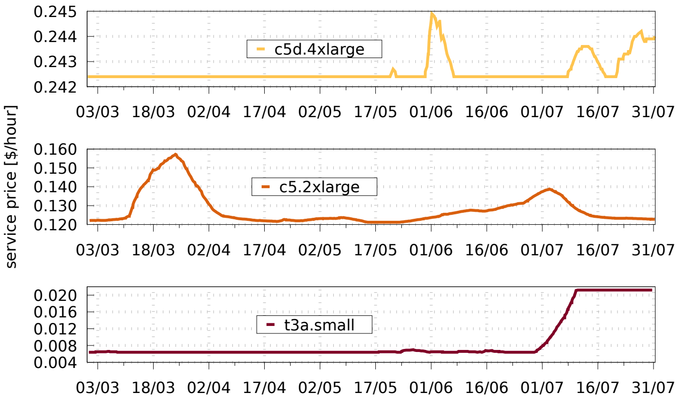

Figure 16: AWS service prices during 2020 in west Europe.

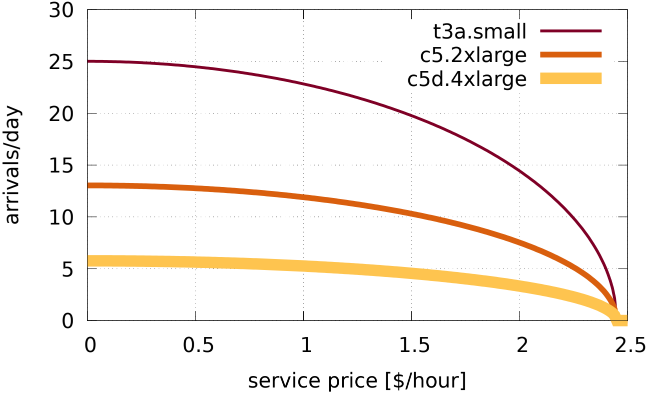

Figure 17: Impact of prices on arriving users – based on tid study [27] and [32].

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**

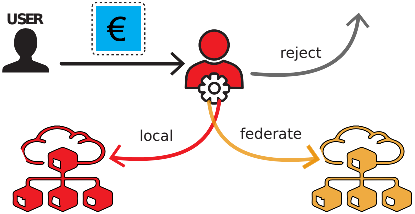

Figure 18: Possible actions.

Obtained **reward**:

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

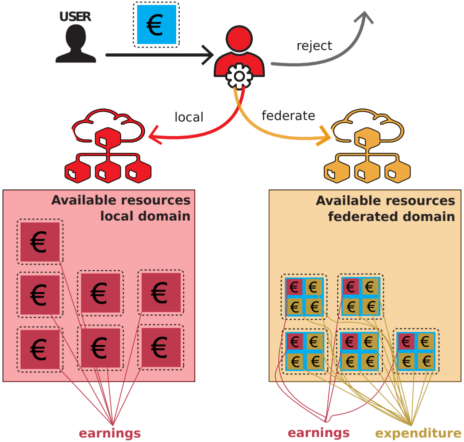

Figure 19: Environment snapshot at time t.

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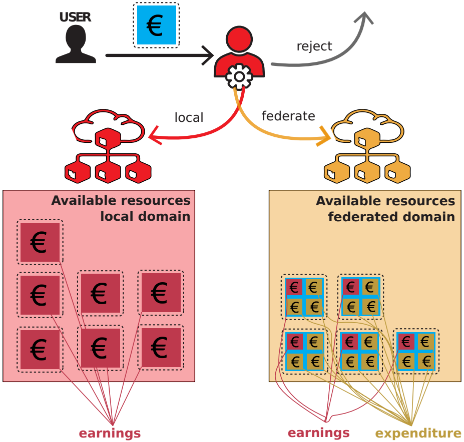

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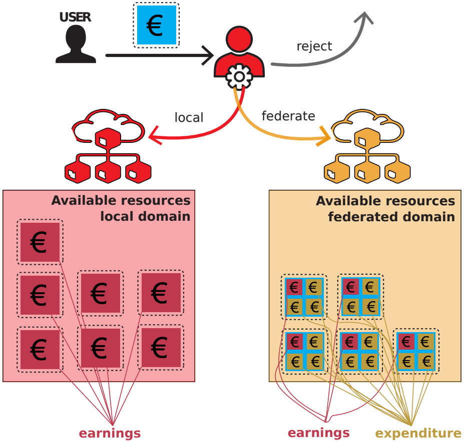

Figure 19: Environment snapshot at time t.

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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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 $r^{(t)}(\pi)$

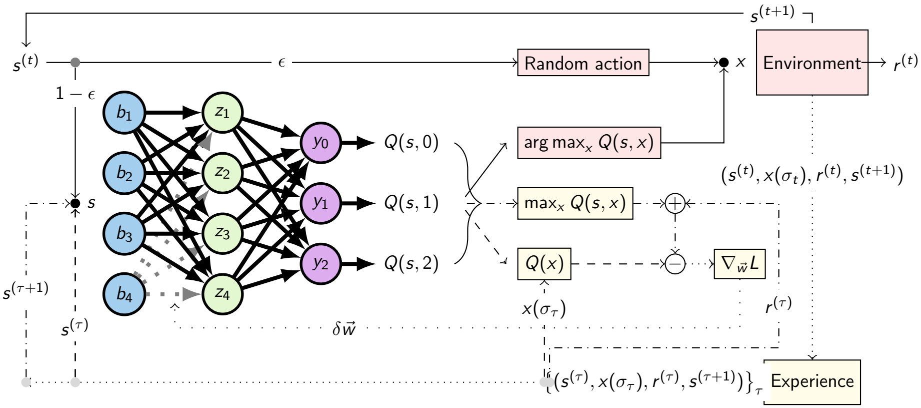

Figure 20: DQN architecture to decide rejection/local/federate.

Experimentation:

- Telefónica infrastructure & resources [27]

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- AWS prices dataset:
  - training 29/02/2020 – 02/05/2020
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- AWS prices dataset:
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- Poissonian arrival of users

Comparison of:

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

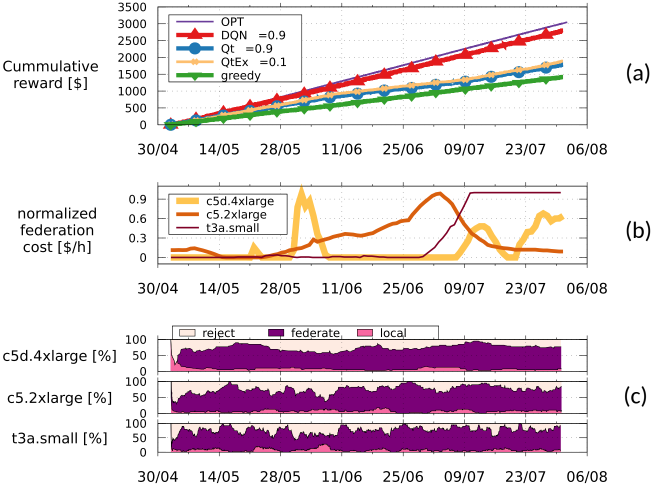

Figure 21: Federation agents' performance.

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

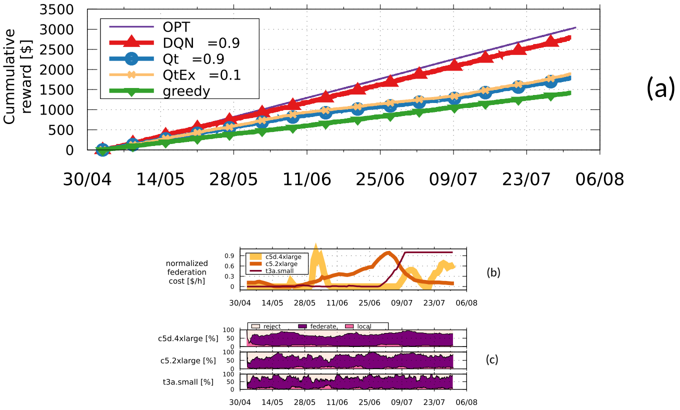


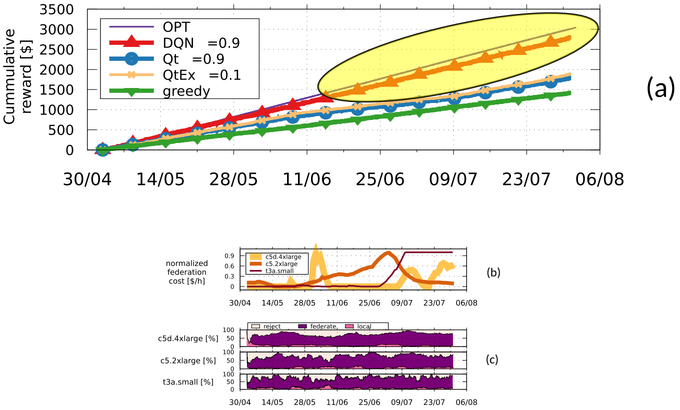
Figure 21: Federation agents' performance.

Comparison of:

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

Results:

- near-optimal



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Comparison of:

- Optimal
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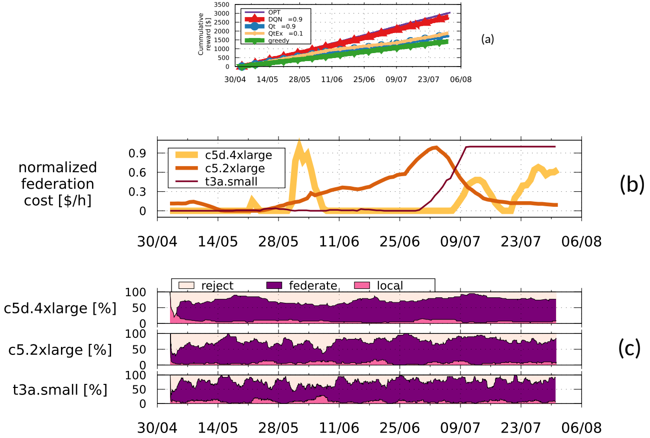


Figure 21: Federation agents' performance.

Comparison of:

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

Results:

- near-optimal
- react upon peaks

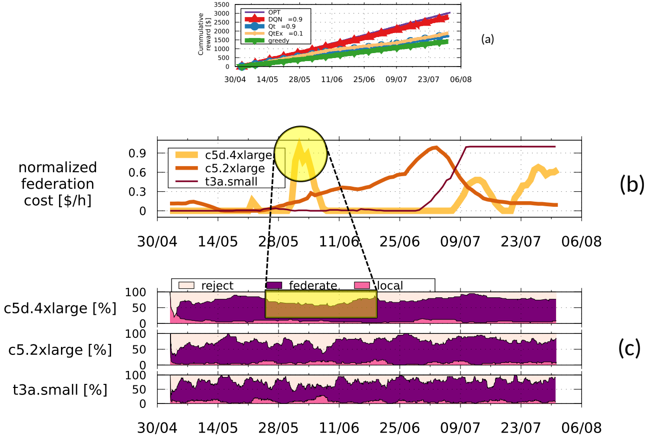
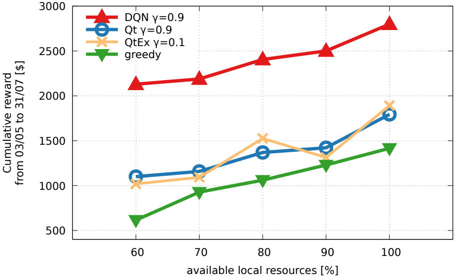
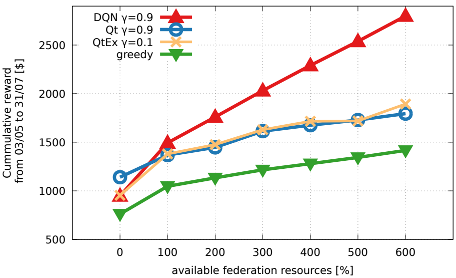


Figure 21: Federation agents' performance.



(a) Increasing local resources.



(b) Increasing resources in federation.

Figure 22: Cumulative reward vs. available resources.

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5 Conclusions & future work

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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/`

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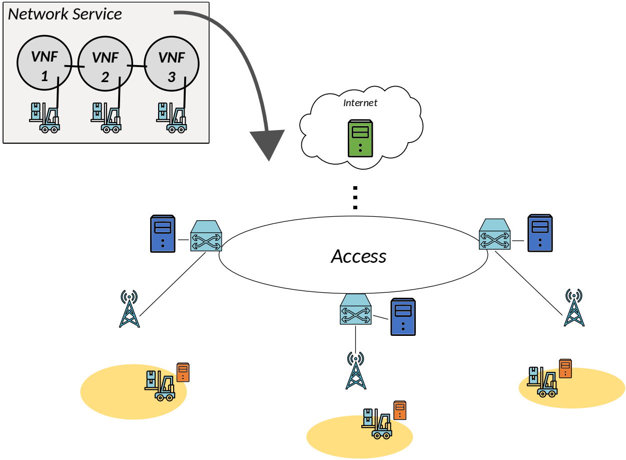
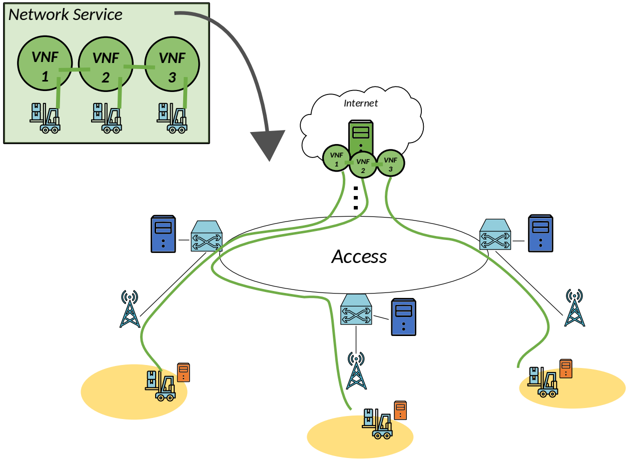


Figure 23: Virtual Network Function Embedding (VNE).



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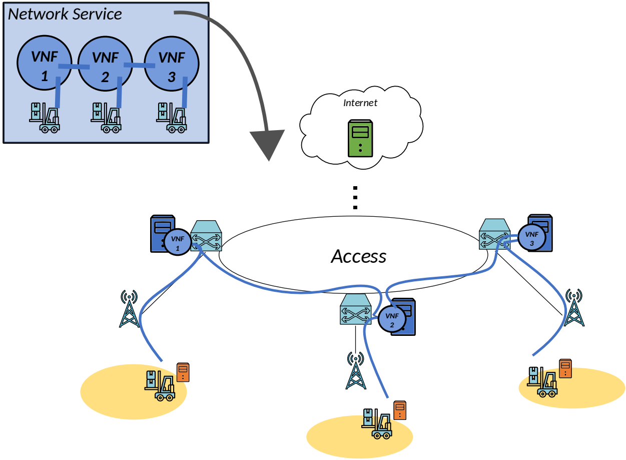

Figure 23: Virtual Network Function Embedding (VNE).

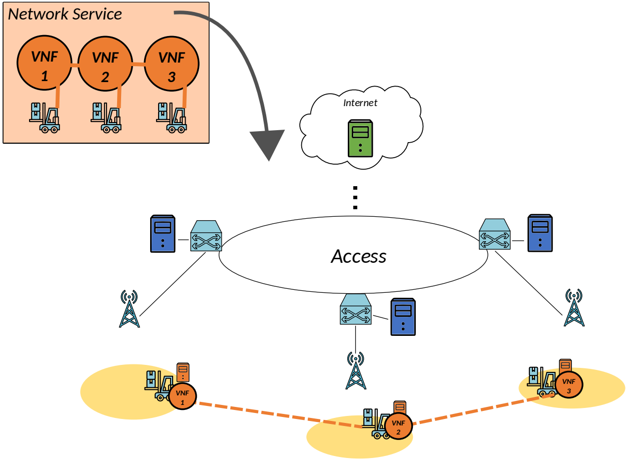

Figure 23: Virtual Network Function Embedding (VNE).

Existing Virtual Network Embedding (VNE) solutions:

- latency-aware, bipartite graph & Hungarian [12]
- maxZ: latency-aware, relaxed ILP [2]
- z-TORCH: KPI monitoring, k-means VNF assign [26]
- AIA: meet latency and throughput [33]

Existing Virtual Network Embedding (VNE) solutions:

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- AIA: meet latency and throughput [33]

OKpi accounts for:

- latency constraints
- **radio coverage**
- **geographical availability**
- **reliability**

Outline

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Latency constraint $D(s)$:

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

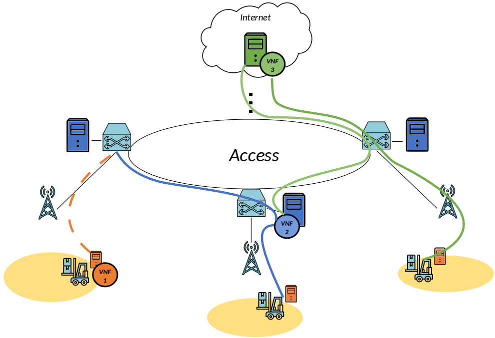


Figure 24: Service s delay.

Latency constraint $D(s)$:

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

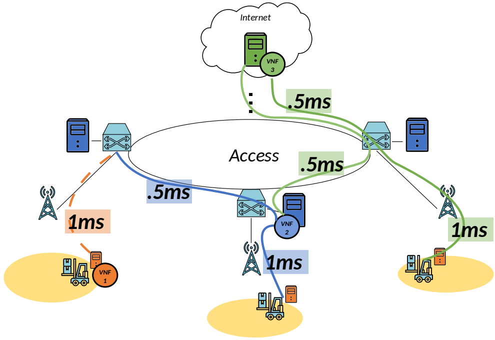


Figure 24: Service s delay.

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

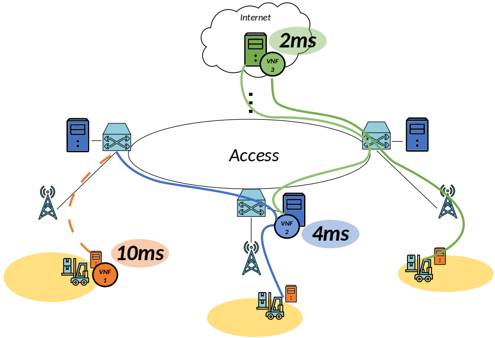


Figure 24: Service s delay.

Radio technology i constraint:

$$\rho(v,c)r_i(v) \leq R_i(c) \qquad (4)$$

- $\rho(v,c)$: 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

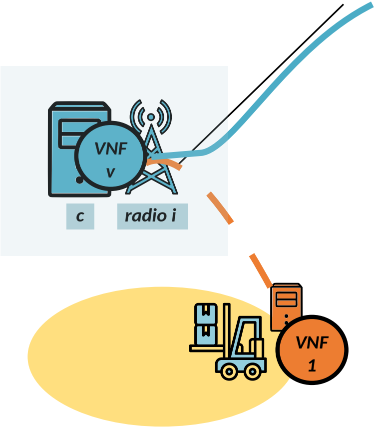


Figure 25: Radio VNF.

Geographical availability:

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

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

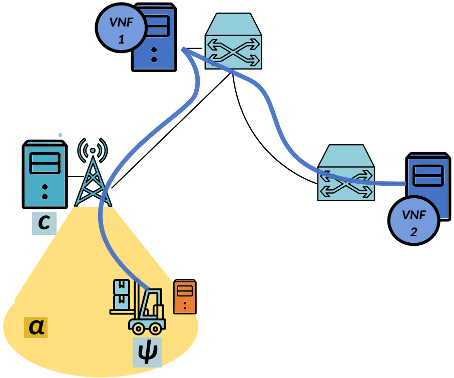


Figure 26: coverage of region α.

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

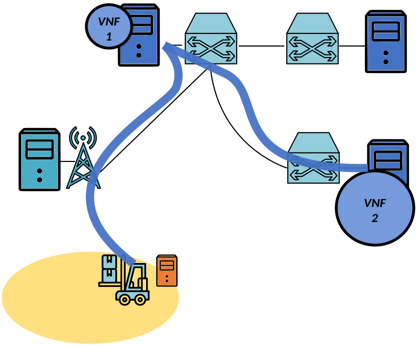


Figure 27: Traffic path.

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

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

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

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

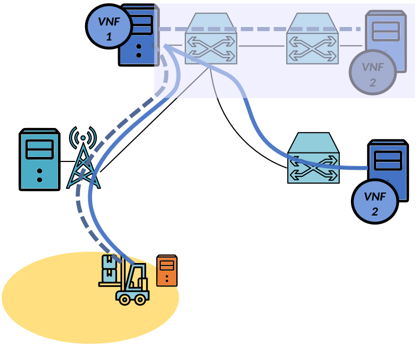


Figure 27: Fractioned traffic path.

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:

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

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

Formulate an optimization problem:

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

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

Formulate an optimization problem:

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

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

NP-hard: bin-packing problem equivalence.

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

- infrastructure as a graph
- edges with:
  - delay
  - reliability

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

- infrastructure as a graph
- edges with:
  - delay
  - reliability

Solve in two steps:

1. Create a decision graph
2. Create an expanded graph

Decision graph $\tilde{G} = (\tilde{N}, \tilde{E})$.

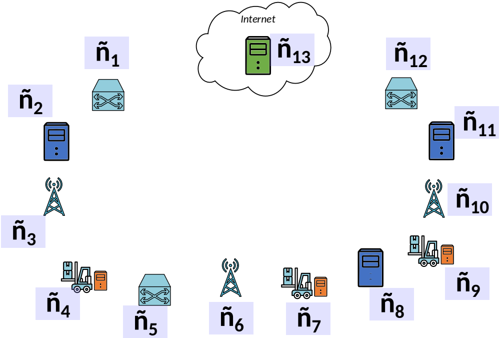


Figure 28: OKpi decision graph.

Decision graph $\tilde{G} = (\tilde{N}, \tilde{E})$.

Nodes $\tilde{N} = \{\tilde{n}_1, \tilde{n}_2, \dots\}$:

- $|\mathcal{V}| - 1$ replicas

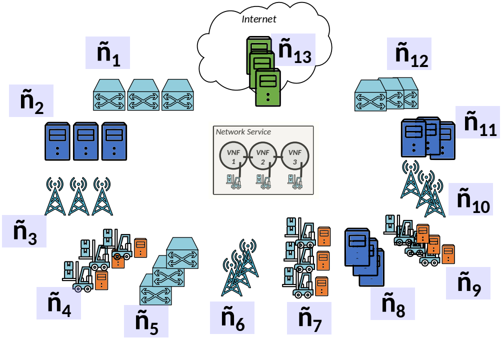


Figure 28: OKpi decision graph.

Decision graph $\tilde{G} = (\tilde{N}, \tilde{E})$.

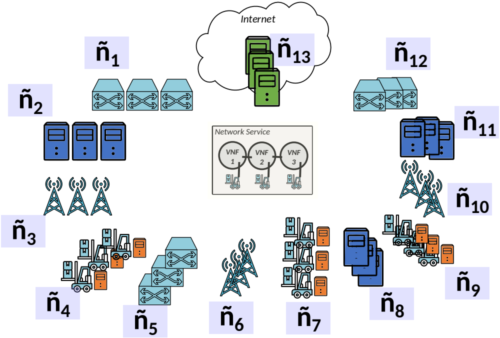
Nodes $\tilde{N} = \{\tilde{n}_1, \tilde{n}_2, \dots\}$:

- $|\mathcal{V}| - 1$ replicas

Edges $\tilde{E} = \{(\tilde{n}_1, \tilde{n}_2), \dots\}$:

- two weights:

$$\left(\frac{\tilde{D}_{\tilde{n}_1, \tilde{n}_2}}{D(s)}, \frac{\log \tilde{\eta}_{\tilde{n}_1, \tilde{n}_2}}{\log H(s)} \right) \tag{9}$$



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Decision graph $\tilde{G} = (\tilde{N}, \tilde{E})$.

Nodes $\tilde{N} = \{\tilde{n}_1, \tilde{n}_2, \dots\}$:

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$$\left(\frac{\tilde{D}_{\tilde{n}_1,\tilde{n}_2}}{D(s)}, \frac{\log \tilde{\eta}_{\tilde{n}_1,\tilde{n}_2}}{\log H(s)} \right) \tag{9}$$

delay fraction

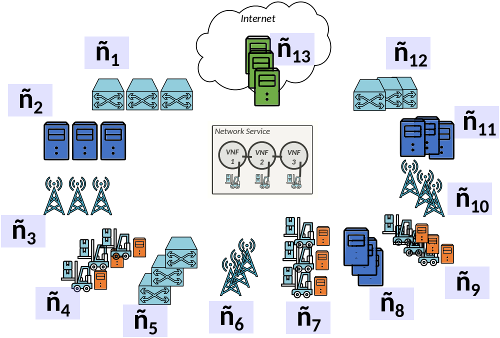


Figure 28: OKpi decision graph.

Decision graph $\tilde{G} = (\tilde{N}, \tilde{E})$.

Nodes $\tilde{N} = \{\tilde{n}_1, \tilde{n}_2, \dots\}$:

- $|\mathcal{V}| - 1$ replicas

Edges $\tilde{E} = \{(\tilde{n}_1, \tilde{n}_2), \dots\}$:

- two weights:

$$\left(\frac{\tilde{D}_{\tilde{n}_1,\tilde{n}_2}}{D(s)}, \underbrace{\frac{\log \tilde{\eta}_{\tilde{n}_1,\tilde{n}_2}}{\log H(s)}}_{\text{reliability fraction}} \right) \tag{9}$$

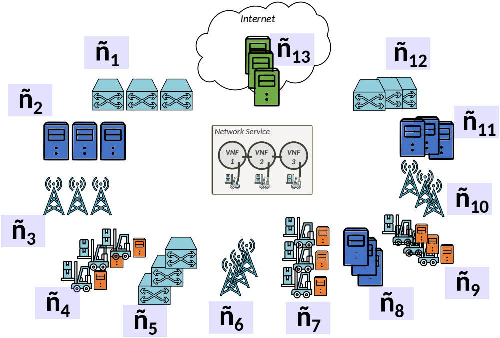


Figure 28: OKpi decision graph.

Decision graph $\tilde{G} = (\tilde{N}, \tilde{E})$.

Nodes $\tilde{N} = \{\tilde{n}_1, \tilde{n}_2, \ldots\}$:

- $|\mathcal{V}| - 1$ replicas

Edges $\tilde{E} = \{(\tilde{n}_1, \tilde{n}_2), \ldots\}$:

- two weights:

$$\left(\frac{\tilde{D}_{\tilde{n}_1,\tilde{n}_2}}{D(s)}, \frac{\log \tilde{\eta}_{\tilde{n}_1,\tilde{n}_2}}{\log H(s)}\right) \quad (9)$$

- create links $(\tilde{n}_1, \tilde{n}_2)$

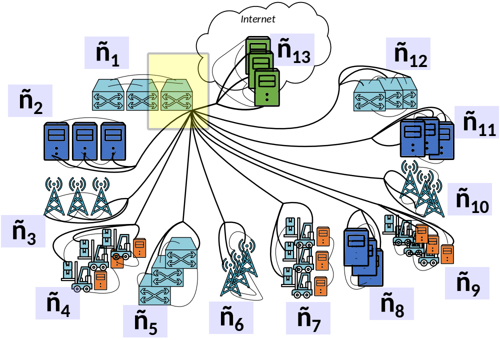


Figure 28: OKpi decision graph.

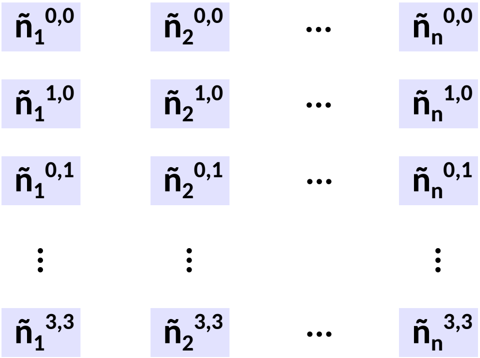
Expanded graph:

1. add superscripts $\tilde{n}^{d,r}$
   - d: delay to reach it
   - r: reliab. to reach it

Figure 29: OKpi expanded graph $\gamma = 3$.

Expanded graph:

1. add superscripts $\tilde{n}^{d,r}$
   - d: delay to reach it
   - r: reliab. to reach it
2. add $(\gamma+1)^2$ replicas



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Expanded graph:

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   - d: delay to reach it
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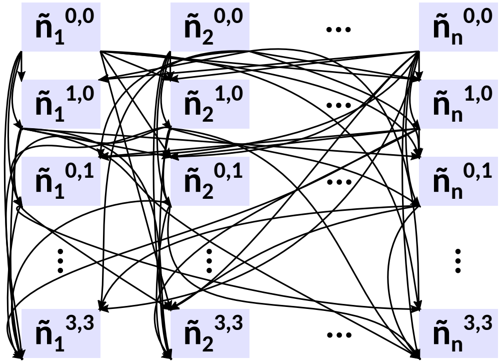
2. add $(\gamma+1)^2$ replicas
3. connect $\tilde{n_1}^{d_1,r_2}$ with $\tilde{n_2}^{d_2,r_2}$



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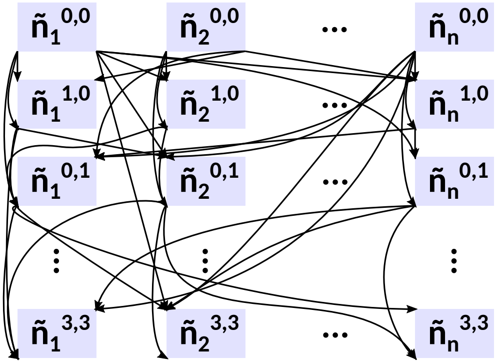
3. connect $\tilde{n}_1{}^{d_1,r_2}$ with $\tilde{n}_2{}^{d_2,r_2}$
   - link $(\tilde{n}_1, \tilde{n}_2) \in \tilde{E}$
   - $d_1 + \gamma \cdot d(\tilde{n}_1, \tilde{n}_2) \leq d_2$
   - $r_1 + \gamma \cdot r(\tilde{n}_1, \tilde{n}_2) \leq r_2$



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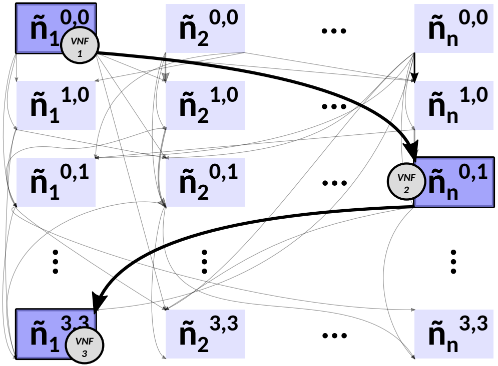
   - link $(\tilde{n}_1,\tilde{n}_2)\in\tilde{E}$
   - $d_1+\gamma\cdot d(\tilde{n}_1,\tilde{n}_2)\leq d_2$
   - $r_1+\gamma\cdot r(\tilde{n}_1,\tilde{n}_2)\leq r_2$
4. one hop per VNF



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   - link $(\tilde{n}_1, \tilde{n}_2) \in \tilde{E}$
   - $d_1 + \gamma \cdot d(\tilde{n}_1, \tilde{n}_2) \leq d_2$
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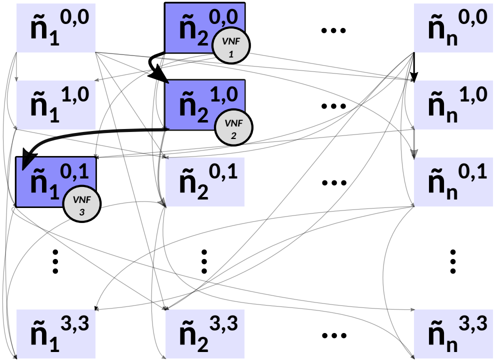
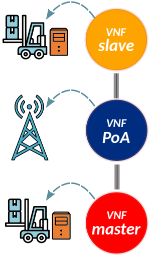
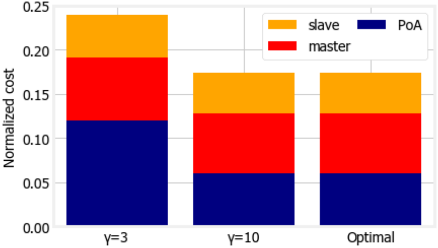


Figure 29: OKpi expanded graph $\gamma = 3$.

Simulations using realistic ITU+3GPP 5G scenarios [16]:



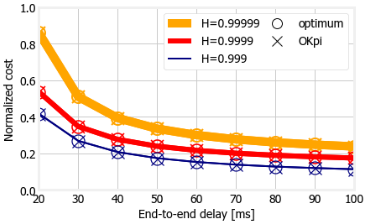
(a)



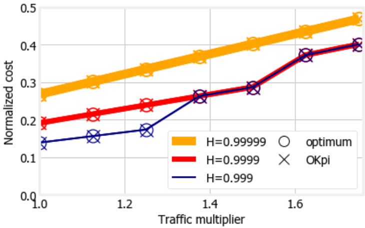
(b)

Figure 30: (a) master-slave robotic VS illustration, and (b) optimality comparison of the VNFs' deployment costs using OKpi with $\gamma = 3, 10$.

Simulations using realistic ITU+3GPP 5G scenarios [16]:



(a)



(b)

Figure 31: (a) end-to-end delay, and (b) traffic impact on deployment cost of master-slave robotic VS.

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Publications:

- **Martín-Peréz, Jorge**, F. Malandrino, C. F. Chiasserini, and C. J. Bernardos. "OKpi: All-KPI Network Slicing Through Efficient Resource Allocation". In: *IEEE INFOCOM 2020 - IEEE Conference on Computer Communications*. 2020, pp. 804–813. DOI: `10.1109/INFOCOM41043.2020.9155263`
- **Martín-Peréz, Jorge**, F. Malandrino, C. F. Chiasserini, M. Groshev, and C. J. Bernardos. "KPI Guarantees in Network Slicing". In: *IEEE/ACM Transactions on Networking* (2021). Accepted
- B. Nemeth, N. Molner, **Martín-Pérez, J.**, C. J. Bernardos, A. de la Oliva, and B. Sonkoly. "Delay and reliability-constrained VNF placement on mobile and volatile 5G infrastructure". In: *IEEE Transactions on Mobile Computing* (2021), pp. 1–1. DOI: `10.1109/TMC.2021.3055426`

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/`

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- Thesis contribution
- Output

5 Conclusions & future work

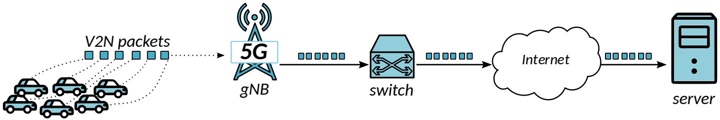

Figure 32: V2N service scaling.

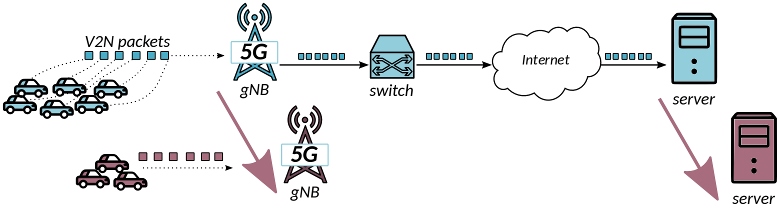

Figure 32: V2N service scaling.

V2N scaling solutions:

- asign radio resource blocks [22]
- computing resources scaling:
  - threshold-based [5, 25]
  - LSTM-based [7]

V2N scaling solutions:

- asign radio resource blocks [22]
- computing resources scaling:
  - threshold-based [5, 25]
  - LSTM-based [7]
  - **compare**:
    - DES, TES
    - HTM
    - GRU
    - LSTM
    - TCN
    - TCNLSTM

1 Generation of 5G infrastructure graphs

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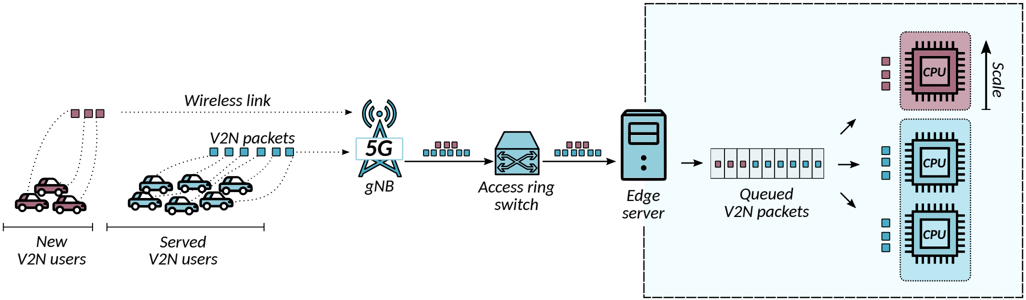


Figure 33: V2N service vertical scaling.

Edge server – $M/M/c$ queue:

- $\lambda(t)$: cars' arrival rate
- μ: CPU service rate
- $c(t)$: number of CPUs

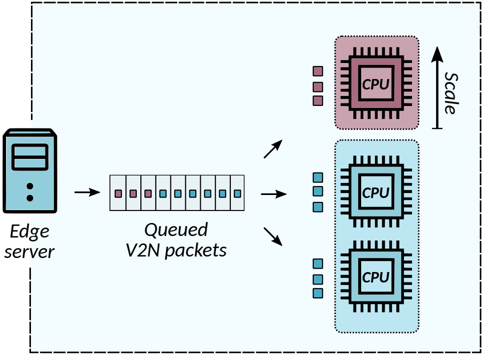


Figure 34: Server as $M/M/c$ queue.

Edge server – $M/M/c$ queue:

- $\lambda(t)$: cars' arrival rate
- μ: CPU service rate
- $c(t)$: number of CPUs

Scale to meet avg. latency:

$$\frac{1}{\mu} + \frac{P_Q}{c(t)\mu - \lambda(t)} \tag{10}$$

with P_Q the prob. of all servers bussy (Earlang C).

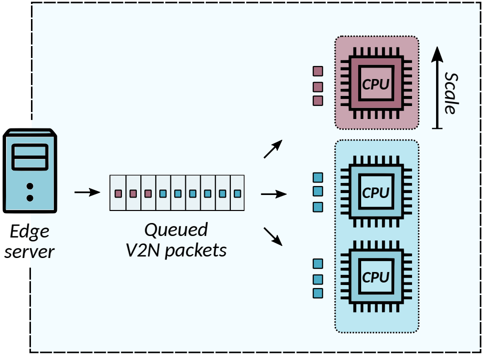


Figure 34: Server as $M/M/c$ queue.

Dataset to derive $\lambda(t)$:

- 116 roads in Torino
- (lat,lng) of roads
- traffic [vehicles/hour] each 5 min.
- avg. speed [vehicles/hour] each 5 min.
- from 28/01/2020 – now

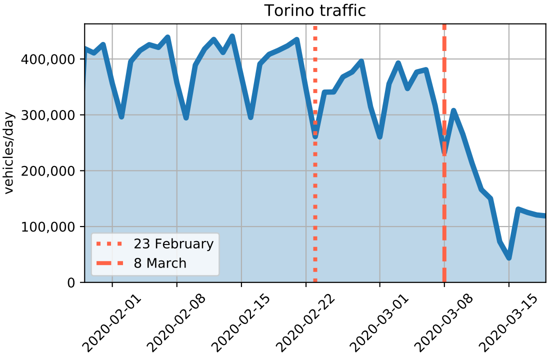


Figure 35: Traffic after COVID-19 lockdowns – 8 March.

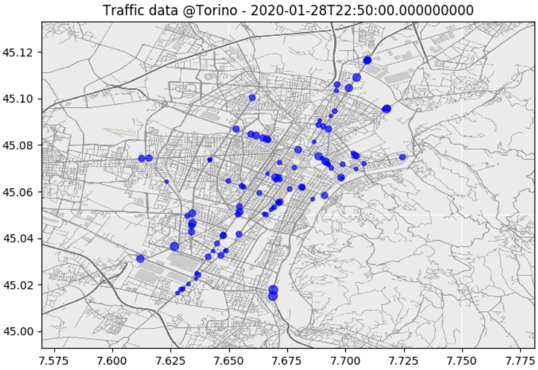


Figure 36: Vehicular traffic – wee hours @Torino.

Predict future traffic $\lambda(t+n)$

- **time-series techniques**: DES, TES
- **proprietary**: HTM
- **neural networks**: GRU, LSTM, TCN, TCNLSTM

Patterns:

- strong **seasonality**.

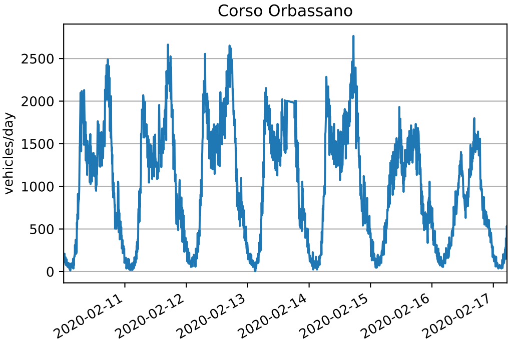


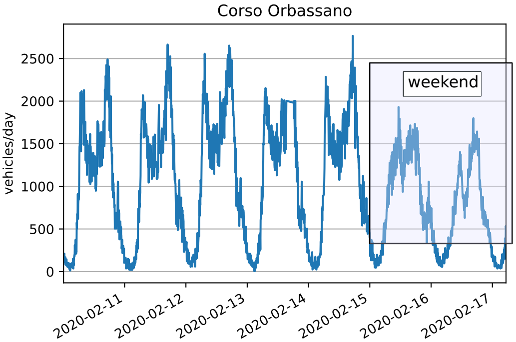
Figure 37: Weekly traffic at Corso Orbassano road.

Predict future traffic $\lambda(t+n)$

- **time-series techniques**: DES, TES
- **proprietary**: HTM
- **neural networks**: GRU, LSTM, TCN, TCNLSTM

Patterns:

- strong **seasonality**.
- week & weekend flows



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Predict future traffic $\lambda(t+n)$

- **time-series techniques**: DES, TES
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- **neural networks**: GRU, LSTM, TCN, TCNLSTM

Patterns:

- strong **seasonality**.
- week & weekend flows
- night hours,

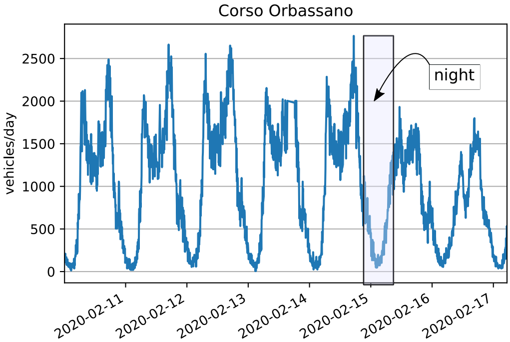

Figure 37: Weekly traffic at Corso Orbassano road.

Predict future traffic $\lambda(t+n)$

- **time-series techniques**: DES, TES
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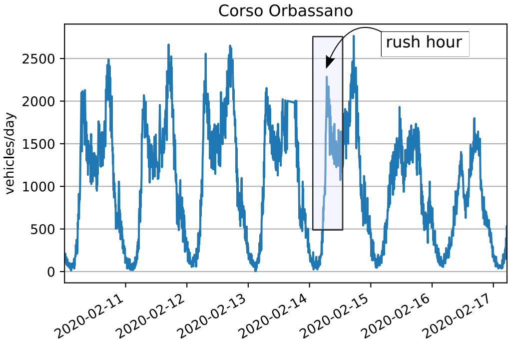
Patterns:

- strong **seasonality**.
- week & weekend flows
- night hours, rush hours,



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Predict future traffic $\lambda(t+n)$

- **time-series techniques**: DES, TES
- **proprietary**: HTM
- **neural networks**: GRU, LSTM, TCN, TCNLSTM

Patterns:

- strong **seasonality**.
- week & weekend flows
- night hours, rush hours, schools' out

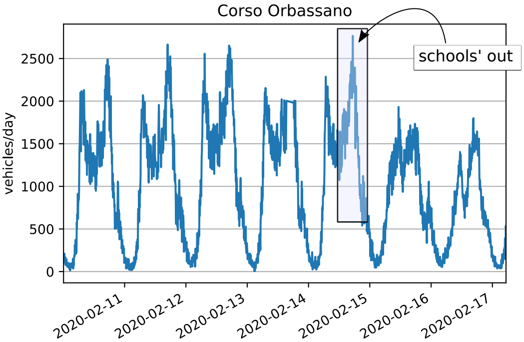


Figure 37: Weekly traffic at Corso Orbassano road.

non-COVID-19 (2020)

- training: 28thFeb - 28thMar
- testing: 29thFeb - 07thMar

COVID-19 (2020)

- training: 06thFeb - 07thMar
- testing: 08thMar - 15thMar

non-COVID-19 (2020)

- training: 28thFeb - 28thMar
- testing: 29thFeb - 07thMar

COVID-19 (2020)

- training: 06thFeb - 07thMar
- testing: 08thMar - 15thMar

Train:

- offline training
- online training

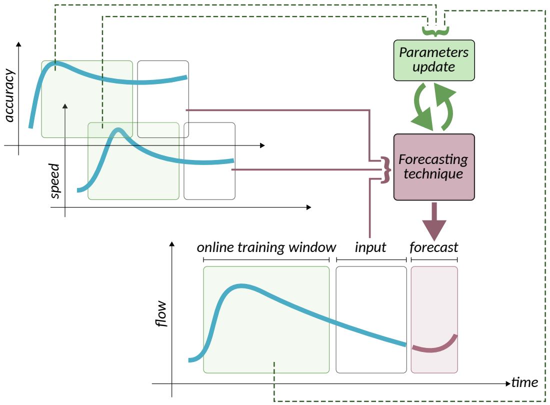


Figure 38: Online training.

Vertical scaling:

1. $\lambda(t+n)$: traffic prediction

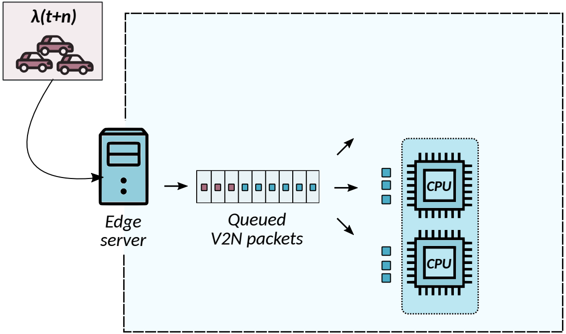


Figure 39: $M/M/c$-based scaling.

Vertical scaling:

1. $\lambda(t+n)$: traffic prediction
2. derive $c(t+n)$ s.t.:

$$\frac{1}{\mu}+\frac{P_Q}{c(t+n)\mu-\lambda(t+n)} \leq D(s) \tag{11}$$

with $D(s)$ the target delay

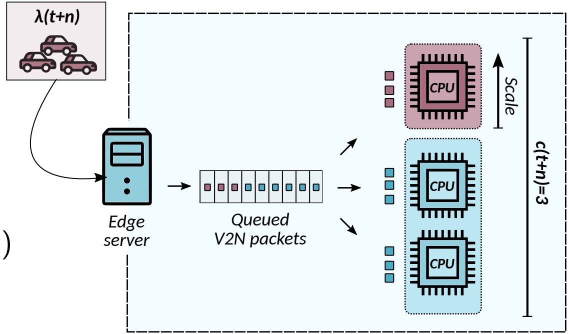
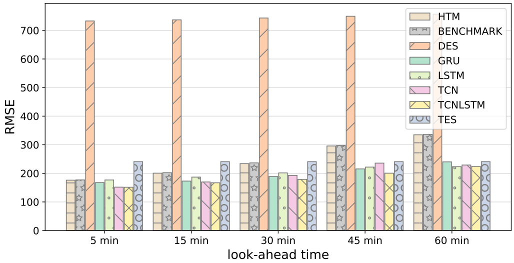
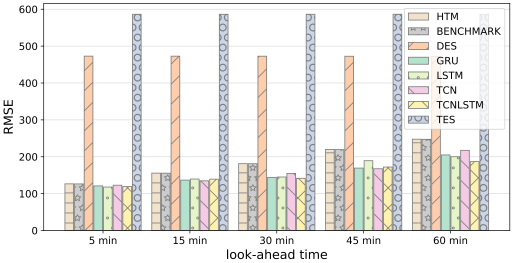


Figure 39: $M/M/c$-based scaling.



(a) non-COVID-19



(b) COVID-19

Figure 40: Prediction accuracy (offline training).

Most accurate: **Neural Networks**

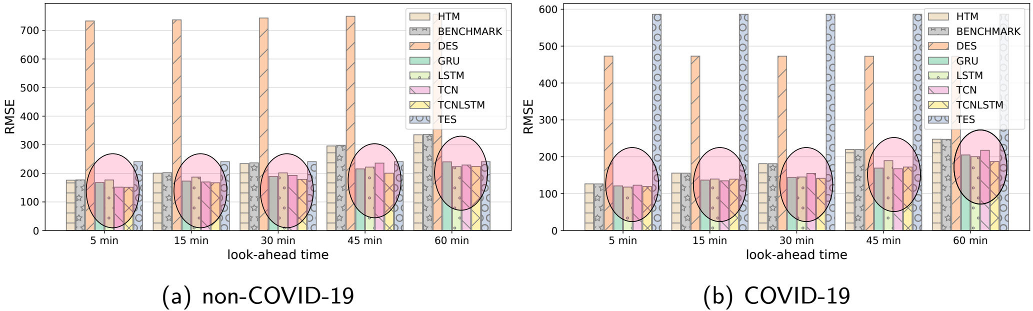
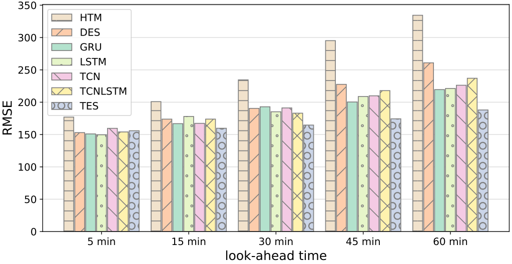
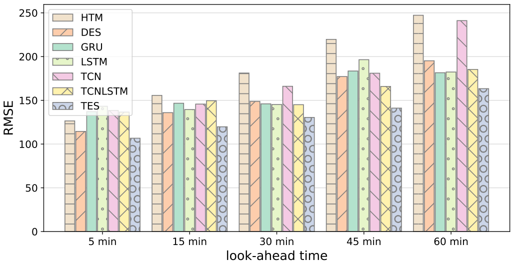


Figure 40: Prediction accuracy (offline training).



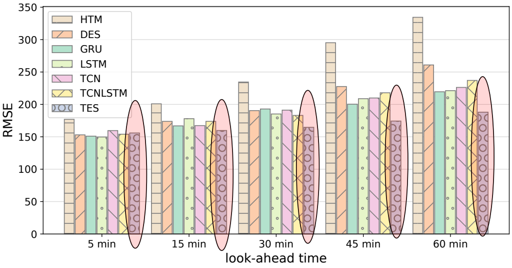
(a) non-COVID-19



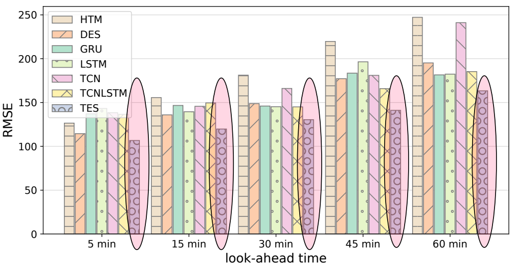
(b) COVID-19

Figure 41: Prediction accuracy (online training).

Most accurate: **TES**

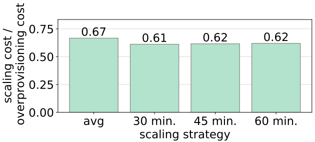


(a) non-COVID-19

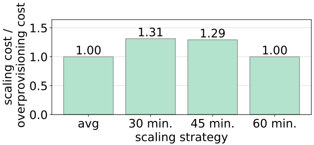


(b) COVID-19

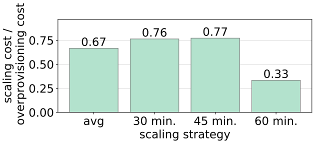
Figure 41: Prediction accuracy (online training).



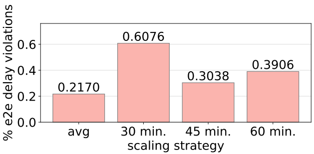
(a) Remote driving savings



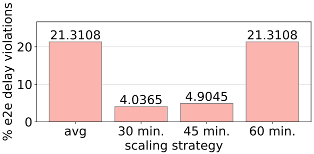
(b) Coop. aware. savings



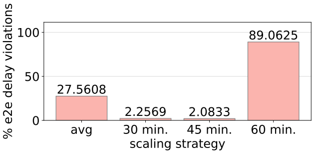
(c) Hazard warn. savings



(d) Remote driving delay violate



(e) Coop. aware. delay violate

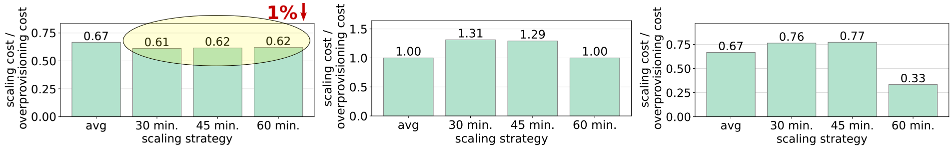


(f) Hazard warn. violate

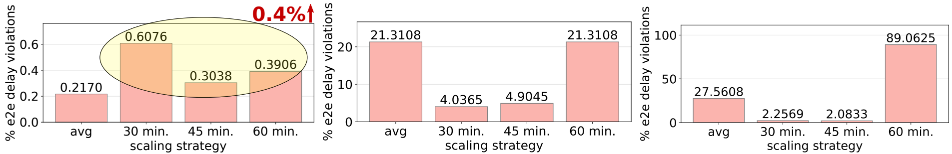
Figure 42: Cost savings and delay violations due to scaling – TES with online training was used.

Scaling of V2N services: a study case
Thesis contribution

uc3m

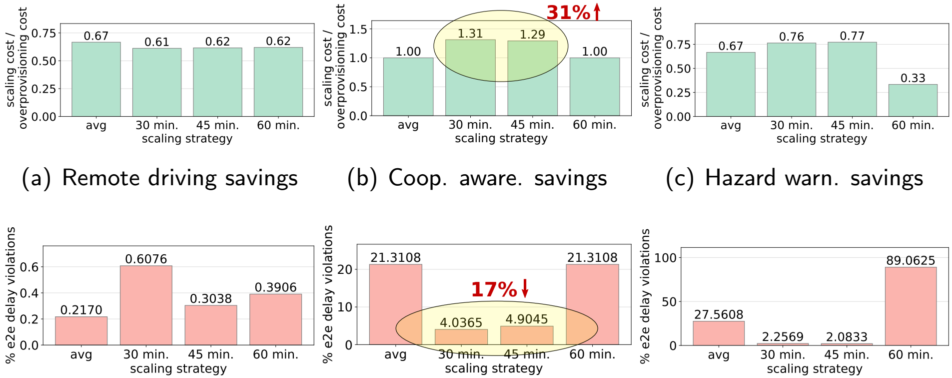


(a) Remote driving savings (b) Coop. aware. savings (c) Hazard warn. savings



(d) Remote driving delay violate (e) Coop. aware. delay violate (f) Hazard warn. violate

Figure 42: Cost savings and delay violations due to scaling – TES with online training was used.



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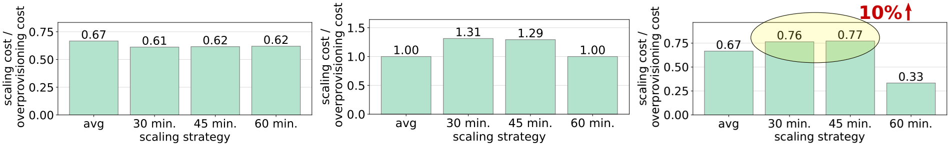
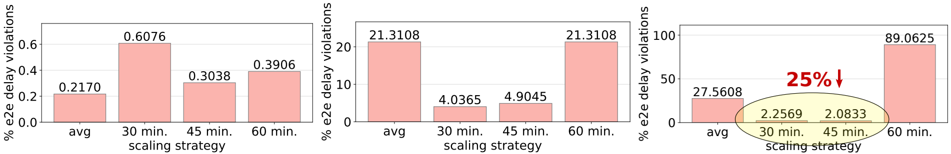
uc3m



(a) Remote driving savings (b) Coop. aware. savings (c) Hazard warn. savings



(d) Remote driving delay violate (e) Coop. aware. delay violate (f) Hazard warn. violate

Figure 42: Cost savings and delay violations due to scaling – TES with online training was used.

Outline

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1 Generation of 5G infrastructure graphs

2 NFV Orchestration in federated environments

3 NFV orchestration for 5G networks: OKpi

4 Scaling of V2N services: a study case
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5 Conclusions & future work

Publications:

- D. de Vleeschauwer, J. Baranda, J. Mangues-Bafalluy, C. F. Chiasserini, M. Malinverno, C. Puligheddu, L. Magoula, **Martín-Pérez, J.**, S. Barmpounakis, K. Kondepu, L. Valcarenzhi, X. Li, C. Papagianni, and A. Garcia-Saavedra. "5Growth Data-Driven AI-Based Scaling". In: *2021 EuCNC/6G Summit*. 2021, pp. 383–388. DOI: 10.1109/EuCNC/6GSummit51104.2021.9482476
- **Martín-Pérez, Jorge**, K. Kondepu, D. de Vleeschauwer, V. Reddy, C. Guimarães, A. Sgambelluri, L. Valcarenghi, C. Papagianni, and C. J. Bernardos. "Dimensioning of V2N Services in 5G Networks through Forecast-based Scaling". In: *IEEE Access* (2021). Under review

Open-source (to be released):

- https://github.com/MartinPJorge/5growth-scaling/
- https://github.com/MartinPJorge/5growth-forecasting/

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In the **NFV orchestration** process, this thesis contributes to:

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1. generate **5G graphs** meeting standard requirements
2. maximize revenue under **federation** and dynamic pricing
3. minimize **VNE** cost meeting: latency, reliability, and availability constraints
4. reduce the E2E latency violations with the proposed **scaling**

1. **generate federated** scenarios BSs, PoPs & datacenters, all at once

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2. **DQN** agent +**LSTM** layer to **predict**

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3. **OKpi** study on γ/runtime/optimality
4. **V2N scaling** to meet **99.9999%** latency quantile & use **ST-GCN**

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- **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
- **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
- **Martín-Peréz, Jorge**, F. Malandrino, C. F. Chiasserini, and C. J. Bernardos. "OKpi: All-KPI Network Slicing Through Efficient Resource Allocation". In: *IEEE INFOCOM 2020 - IEEE Conference on Computer Communications*. 2020, pp. 804–813. DOI: 10.1109/INFOCOM41043.2020.9155263

- 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
- D. de Vleeschauwer, J. Baranda, J. Mangues-Bafalluy, C. F. Chiasserini, M. Malinverno, C. Puligheddu, L. Magoula, **Martín-Pérez, J.**, S. Barmpounakis, K. Kondepu, L. Valcarenzhi, X. Li, C. Papagianni, and A. Garcia-Saavedra. "5Growth Data-Driven AI-Based Scaling". In: *2021 EuCNC/6G Summit*. 2021, pp. 383–388. DOI: 10.1109/EuCNC/6GSummit51104.2021.9482476

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- B. Nemeth, N. Molner, **Martín-Pérez, J.**, C. J. Bernardos, A. de la Oliva, and B. Sonkoly. "Delay and reliability-constrained VNF placement on mobile and volatile 5G infrastructure". In: *IEEE Transactions on Mobile Computing* (2021), pp. 1–1. DOI: 10.1109/TMC.2021.3055426
- **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

- **Martín-Peréz, Jorge**, F. Malandrino, C. F. Chiasserini, M. Groshev, and C. J. Bernardos. "KPI Guarantees in Network Slicing". In: *IEEE/ACM Transactions on Networking* (2021). Accepted

Thanks for your attention!

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Location of BSs:

- Neyman-Scott Poisson Cluster Process [28]
- Poisson Point Processes (PPPs) [4]
  - homogeneous [29, 1]
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Location of MEC PoPs:

- along highways [30]
- within stadiums [8]
- population census
- access & aggregation rings

Lemma

Given an inhomogeneous marked PPP X with intensity function λ, the thinning function l_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:

$$\mathbb{E}\left[N(C)\right] := \int_C e^{-\int_{B(x,r)} \mathbb{1}(\lambda(u)>\lambda(x))\lambda(u)du} \lambda(x)\ dx \tag{12}$$

where r is the thinning radius of l_2.

with

$$l_2(x, m, X, M_X) := \begin{cases} 1 & \text{if } m = \min_{m' \in M_X} \left\{(x', m') : x' \in B(x, r)\right\} \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

The RTT considered is computed as

$$RTT := 2l\left(\|x - m\|_1\right) + 2p(M) + UL + DL \tag{14}$$

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

$$\|x - m\|_1 \leq l^{-1}\left(\frac{RTT - 2p(M) - t_r}{2}\right) = m_M \tag{15}$$

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

Table 1: NR profiles satisfying the tactile interaction latency

Profile	DL	UL	M1 distance	M2 distance
FDD 30 kHz 2s	0.39 ms	0.39 ms	12 km	2 km
FDD 120 kHZ 7s	0.33 ms	0.33 ms	24 km	14 km
TDD 120 kHz 7s	0.39 ms	0.39 ms	12 km	2 km

- *Note*: FDD 30 kHz 2s stands for Frequency Division Duplex scheme with a subcarrier of 30 kHz and 2 symbols.
- *Note*: DL and UL values are the worst case transmission latency presented in [24].

User pays $p^{(t)}$ for the service σ

$$p^{(t)}(\sigma) = (1 + P)I^{(t)}(\sigma) \tag{16}$$

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

User pays $p^{(t)}$ for the service σ

$$p^{(t)}(\sigma) = (1+P)l^{(t)}(\sigma) \tag{16}$$

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:

$$r^{(t)}(X_t) := \sum_{\substack{\sigma:\ x(\sigma)=0\\ a(\sigma)\leq t\leq d(\sigma)}} p^{a(\sigma)}(\sigma) + \sum_{\substack{\sigma:\ x(\sigma)=1\\ a(\sigma)\leq t\leq d(\sigma)}} \left[p^{a(\sigma)}(\sigma) - f^{(t)}(\sigma)\right] \tag{17}$$

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

$$f(p^{(t)}(\sigma)) := \begin{cases} k\left(1-\left(\frac{p^{(t)}(\sigma)}{K\cdot M}\right)^{a}\right)^{b}, & p^{(t)}(\sigma) \leq K\cdot M \\ 0, & p^{(t)}(\sigma) > K\cdot M \end{cases} \tag{18}$$

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.

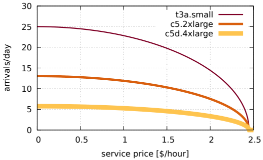

Figure 43: Impact of prices on arriving users.

Increase of P leads to:

- less user arrivals
- larger reward

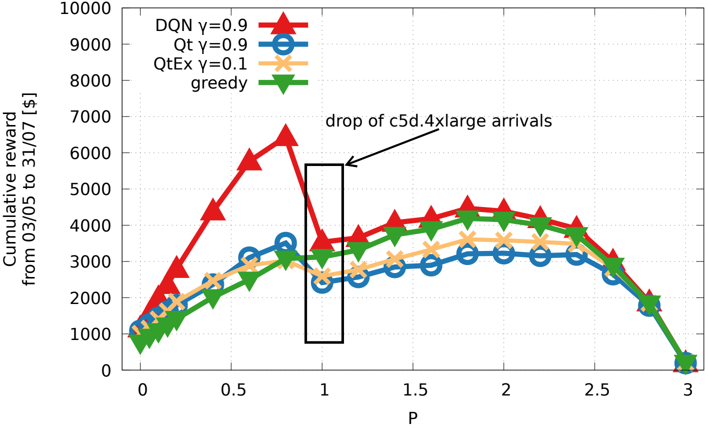

Figure 44: Impact of the marginal benefit P in the commutative reward achieved by each solution.