

NFV Orchestration in Edge and Fog Scenarios

26th October, 2021

student: J. Martín-Pérez

supervisor: C. J. Bernardos

contact: jmartinp@it.uc3m.es

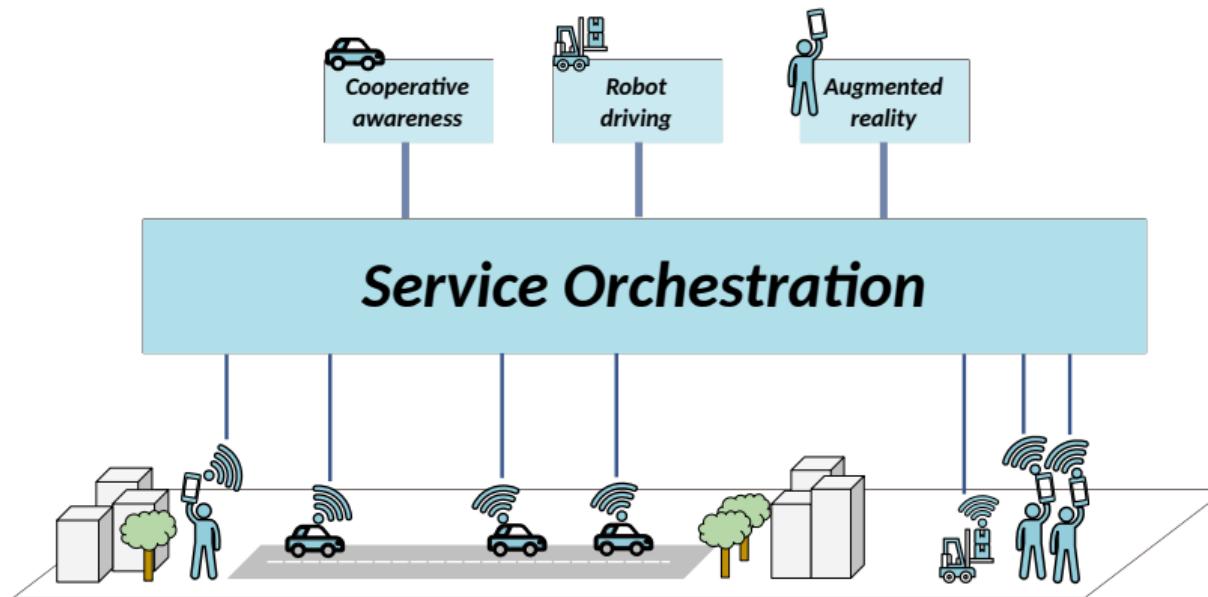


Figure 1: Orchestration of three services.

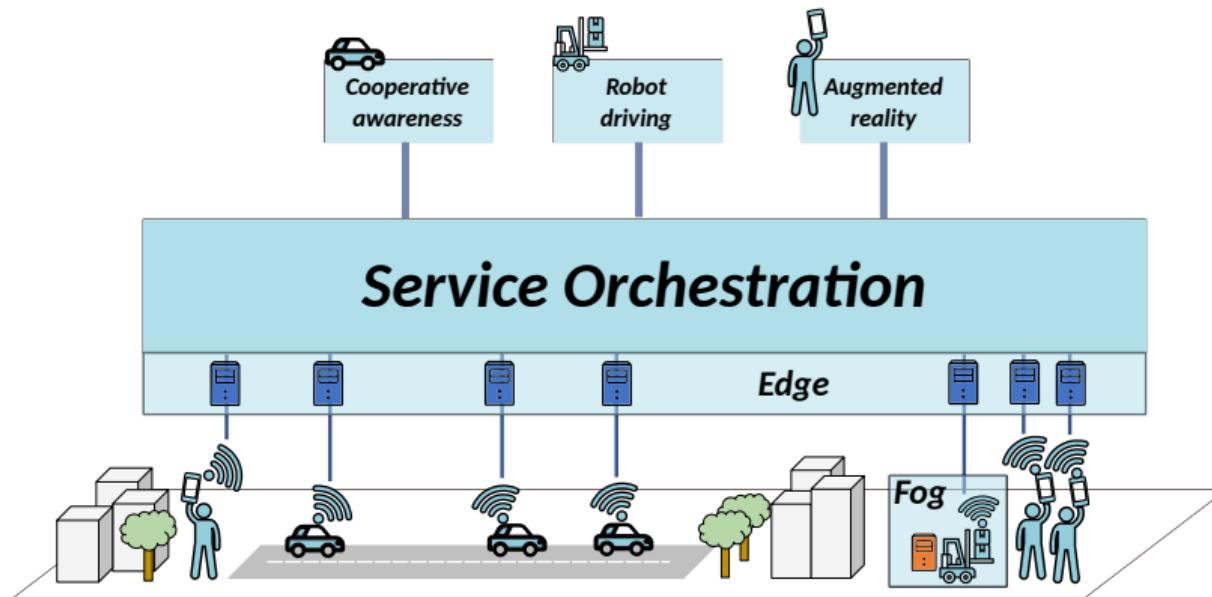


Figure 1: Orchestration of three services in Edge & Fog.

Service Orchestration:

- design network
- where services run?
- deliver to users

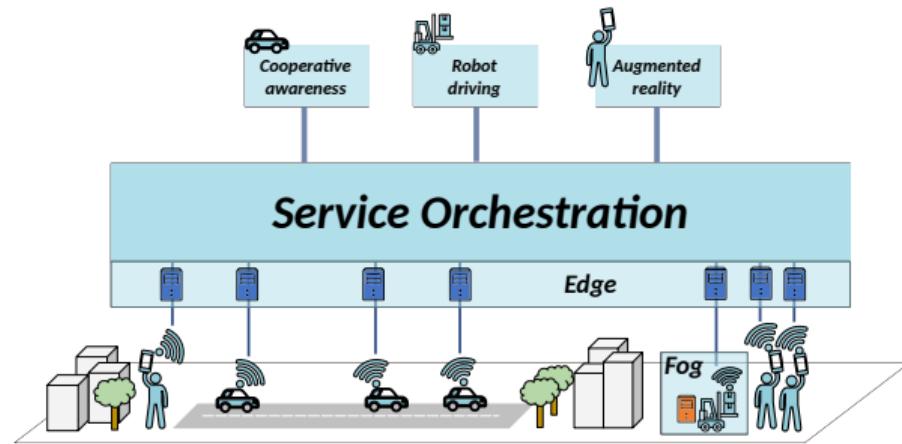


Figure 1: Orchestration of three services in Edge & Fog.

1 Generation of 5G infrastructure graphs

- 1 Generation of 5G infrastructure graphs**
- 2 NFV Orchestration in federated environments**

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- 4 Conclusions & future work

1 Generation of 5G infrastructure graphs

- Motivation

- Thesis contribution

- Output

2 NFV Orchestration in federated environments

3 NFV orchestration for 5G networks: OKpi

4 Conclusions & future work

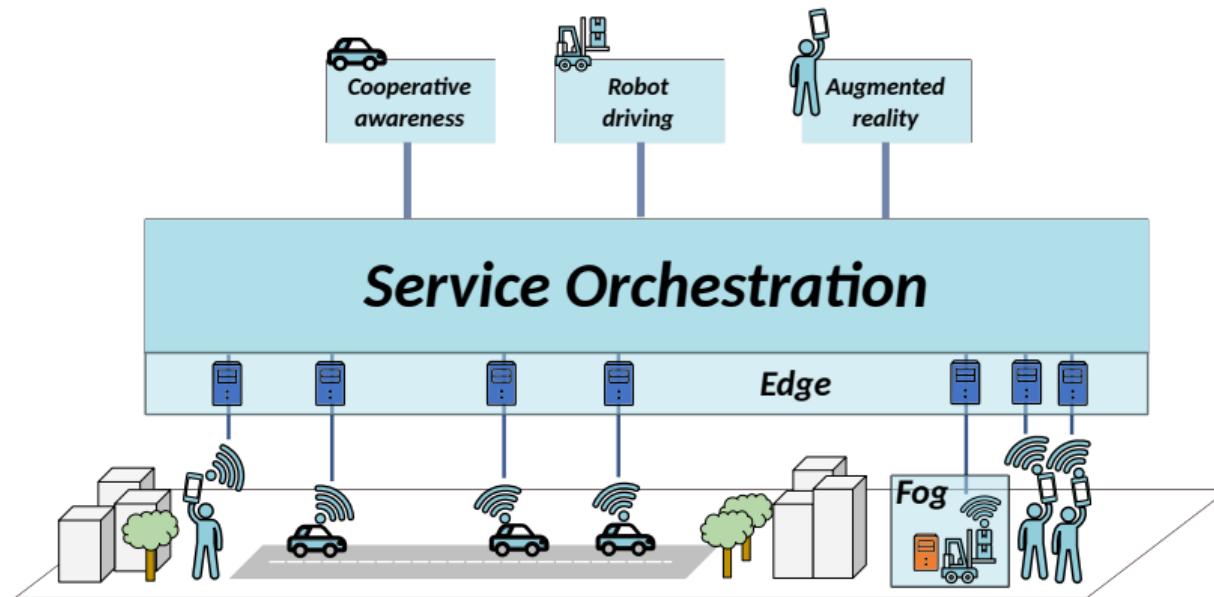


Figure 2: Orchestration of three services in Edge & Fog.

Generation of 5G infrastructure graphs

Motivation

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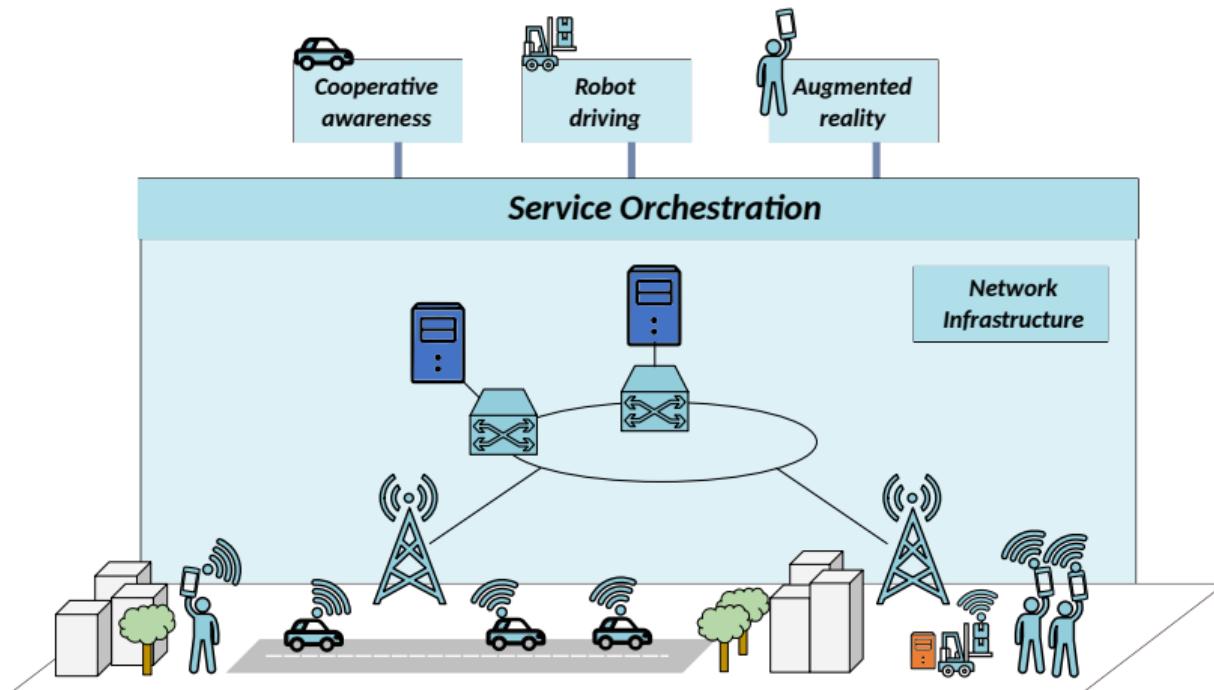


Figure 2: Network infrastructure for service providing.

This part derives **location** of:

- 1 BSs for user coverage
- 2 servers to process traffic

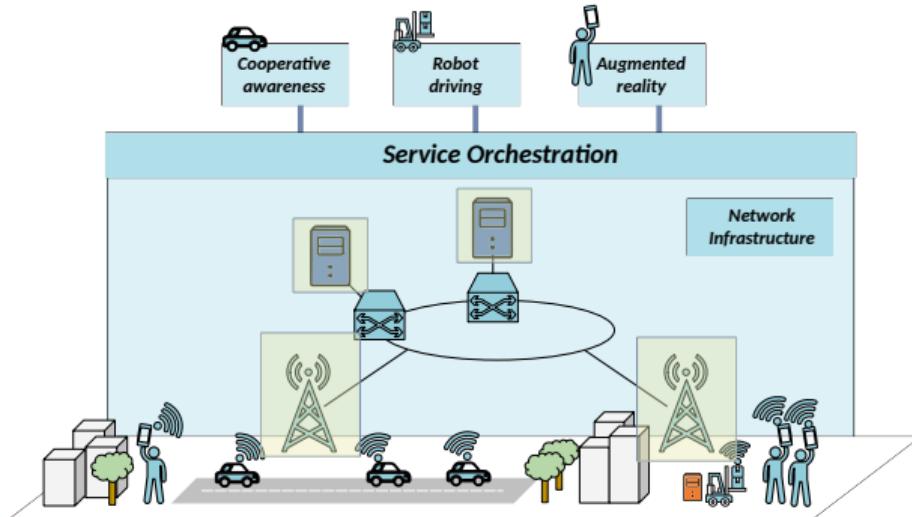


Figure 3: Network infrastructure for service providing.

Motivation

This part derives **location** of:

- 1 BSs for user coverage
- 2 servers to process traffic

for **augmented reality**:

- tactile latency 1ms

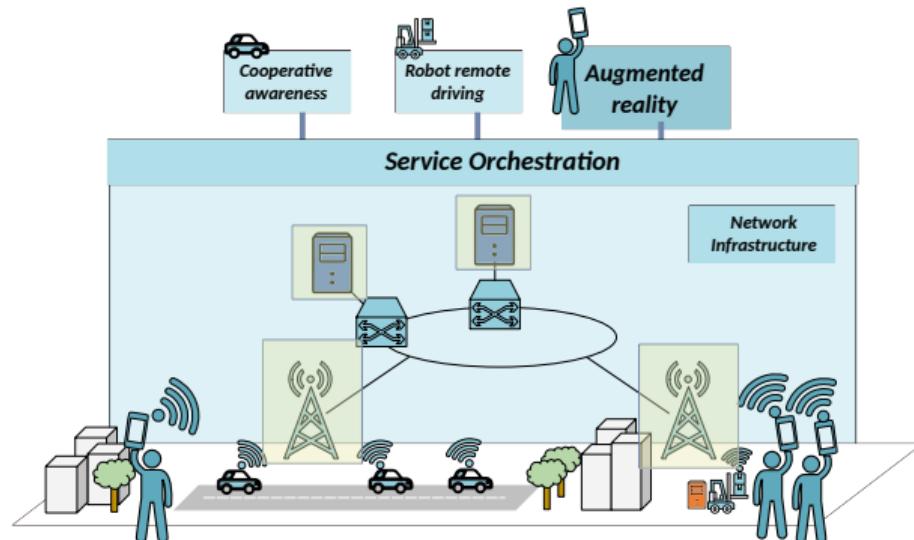


Figure 3: Network infrastructure for service providing.

New methodology in the SoA

- BS location:
 - inhomogeneous Matérn II PPP
- Server location:
 - population census
 - access & aggregation rings

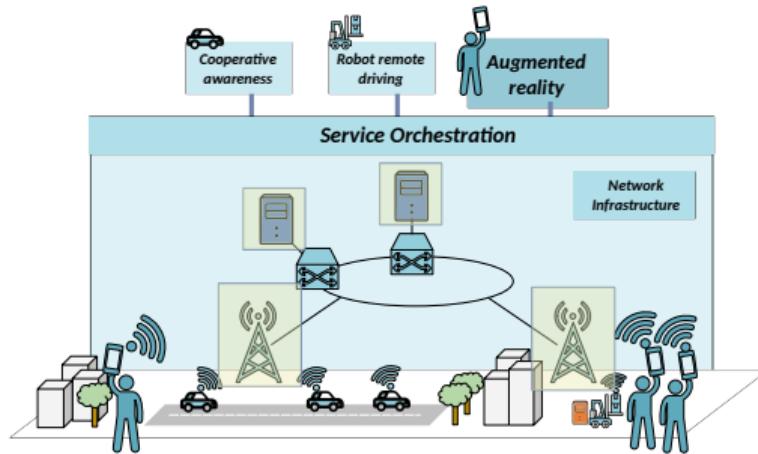


Figure 4: Network infrastructure for service providing.

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4 Conclusions & future work

Higher gentrification \implies more BSs

- R – region of interest
- C_i – area

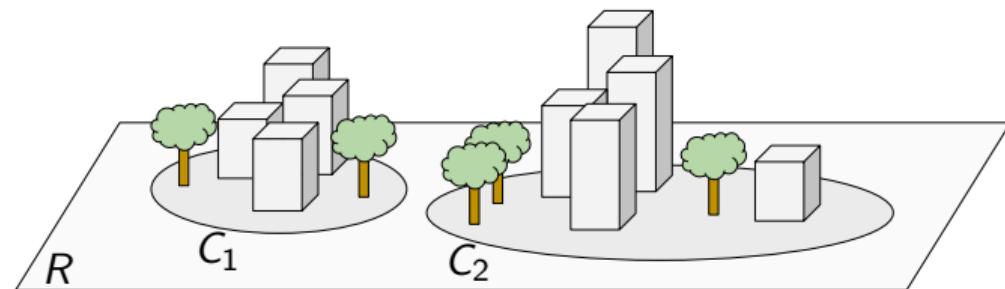


Figure 5: Revolution functions of a region with two building areas.

Higher gentrification \implies more BSs

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

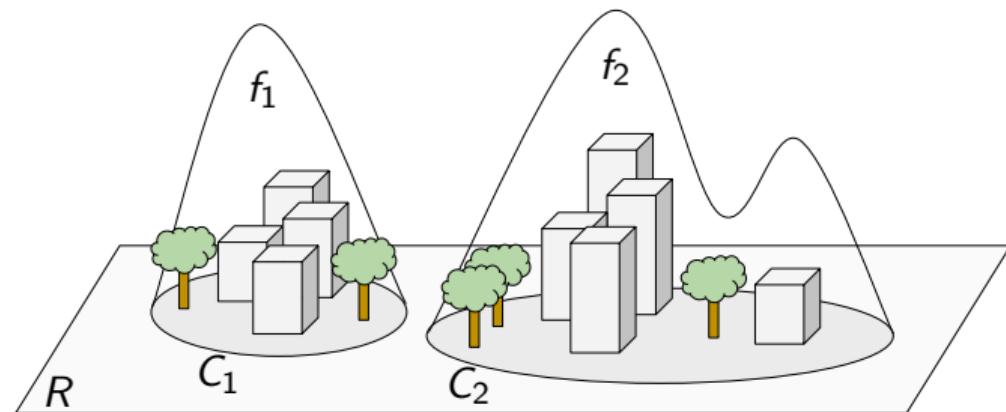


Figure 5: Revolution functions of a region with two building areas.

Higher gentrification \implies more BSs

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

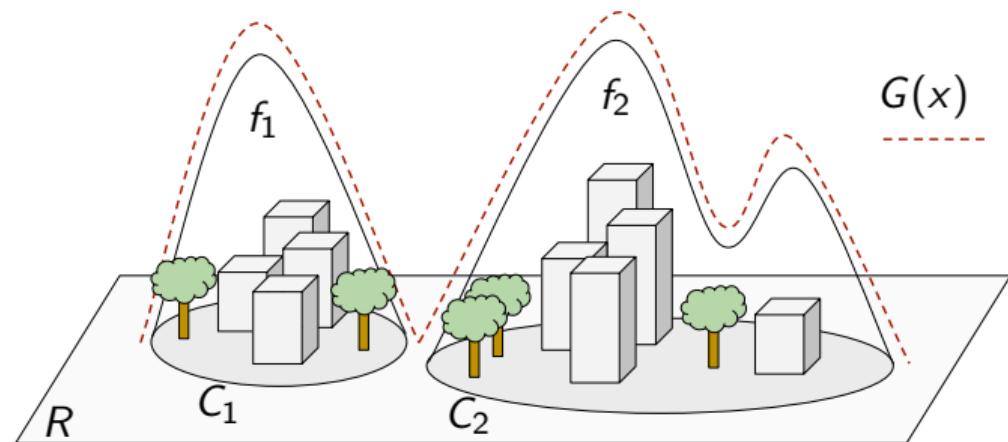


Figure 5: Revolution functions of a region with two building areas.

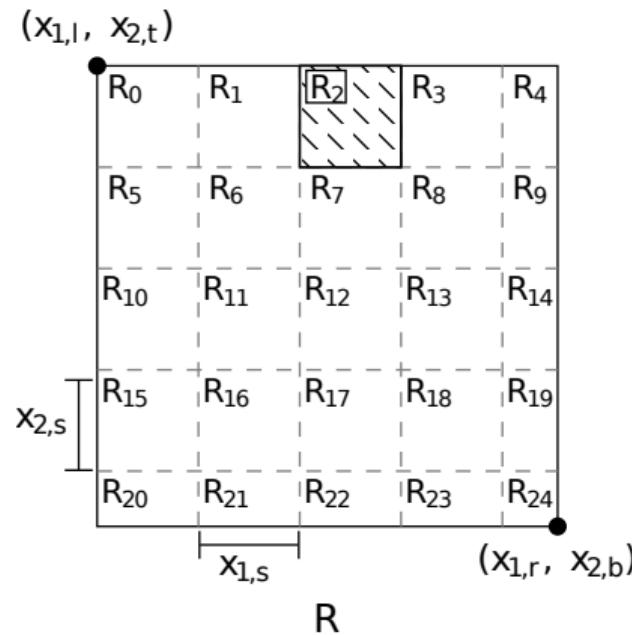


Figure 6: BS location – inhomogeneous Matérn II process.

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Thesis contribution

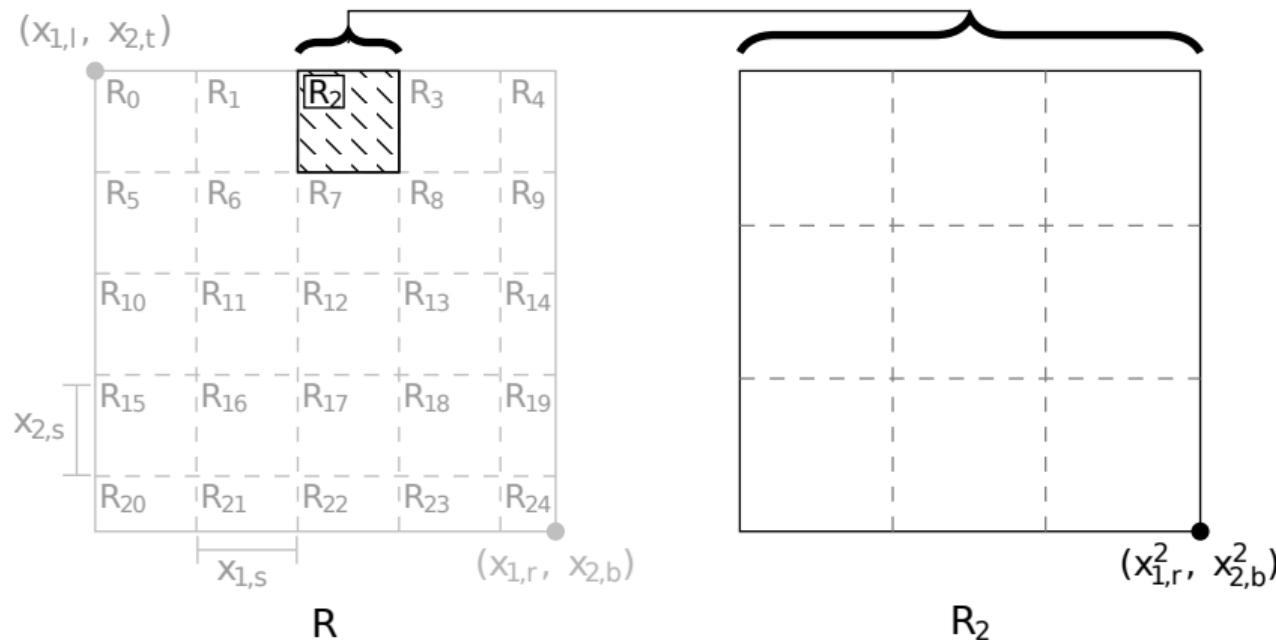


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Thesis contribution

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

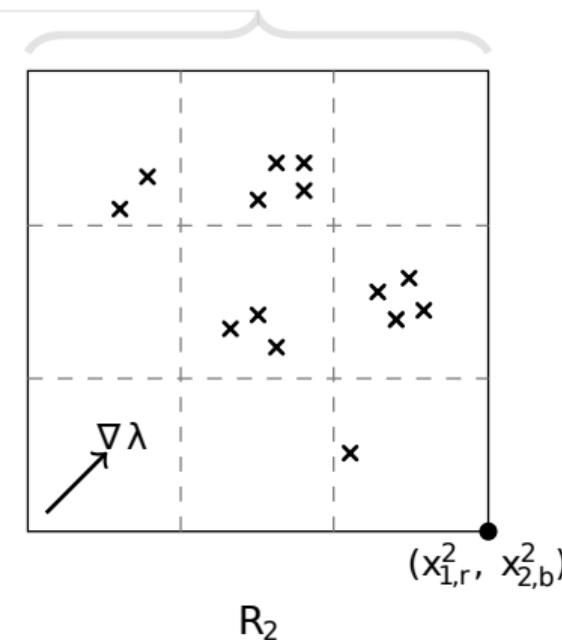
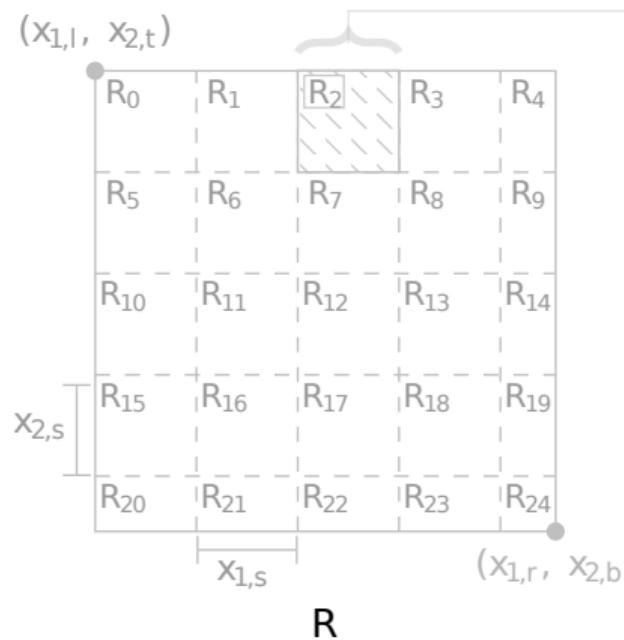


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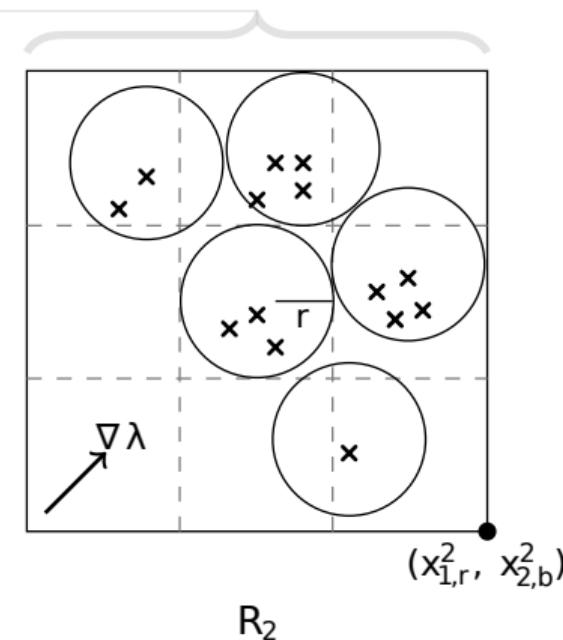
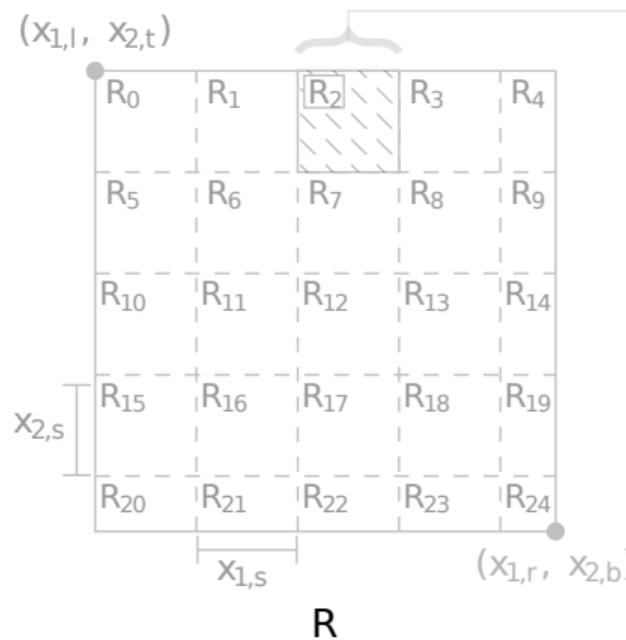


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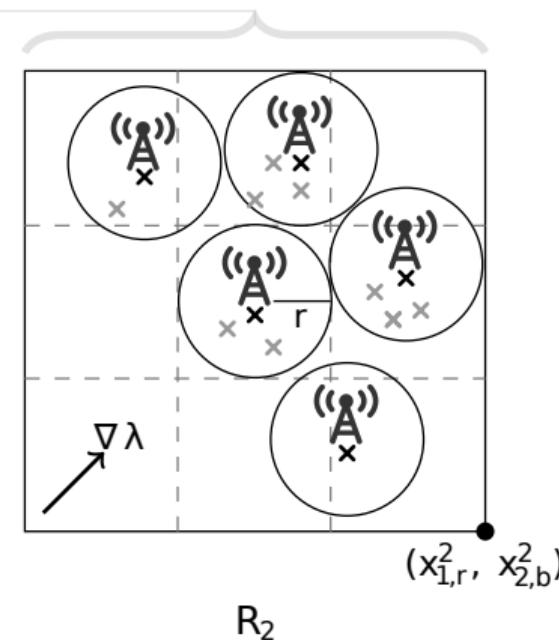
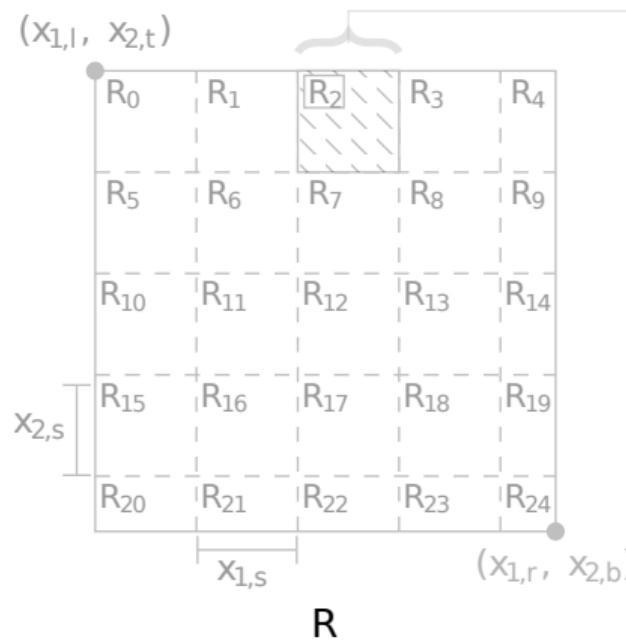


Figure 6: BS location – inhomogeneous Mattérn II process.

Inhomogeneous Mattérn II PPs applied on:

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



Figure 7: Location of BSs.

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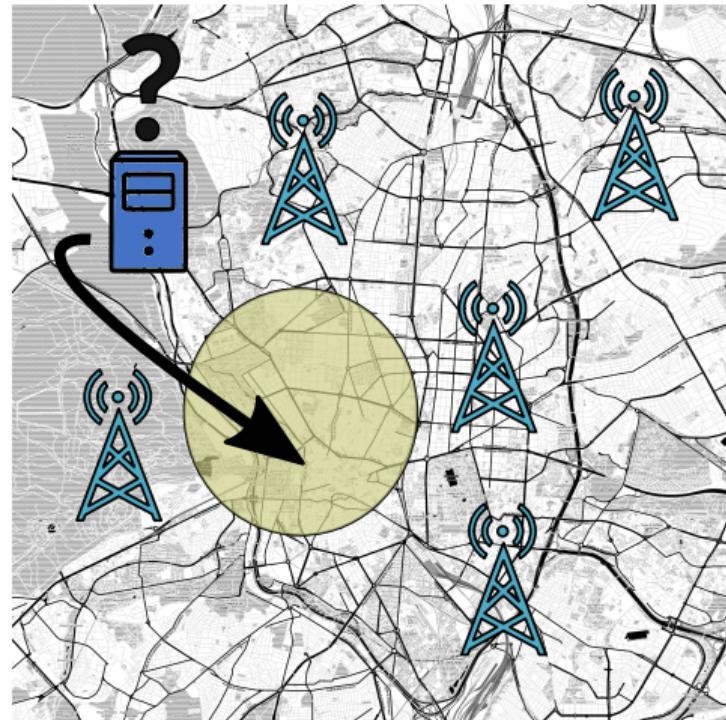


Figure 7: Location of BSs.

Generation of 5G infrastructure graphs

Thesis contribution

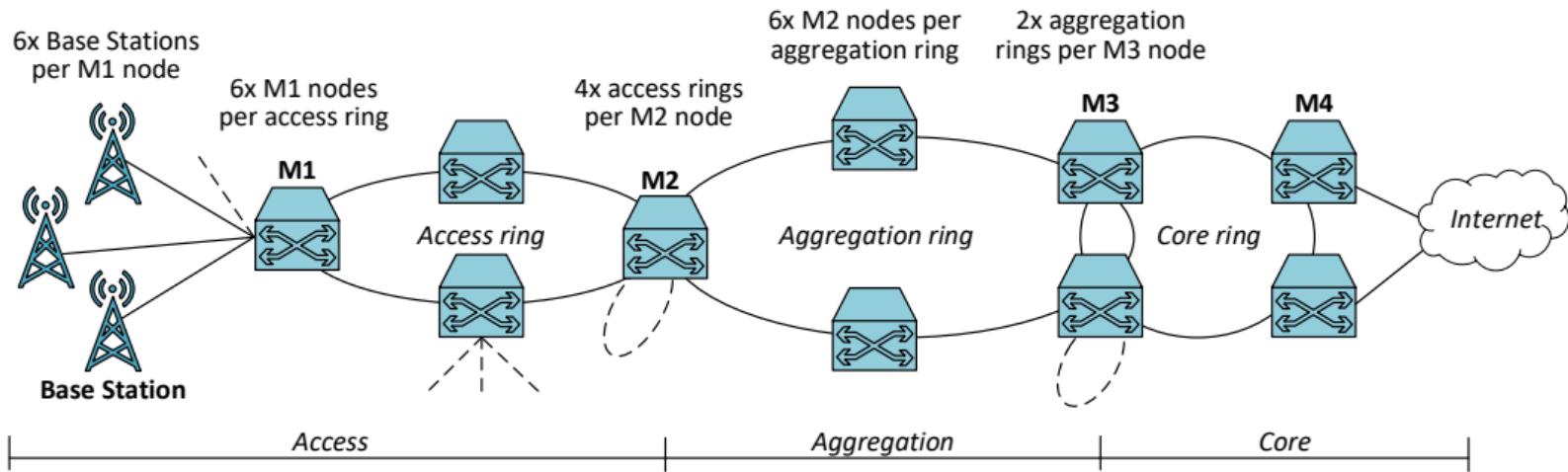


Figure 8: Reference network infrastructure as illustrated¹ in [5] and based on [8].

¹Author: Dr. Luca Cominardi.

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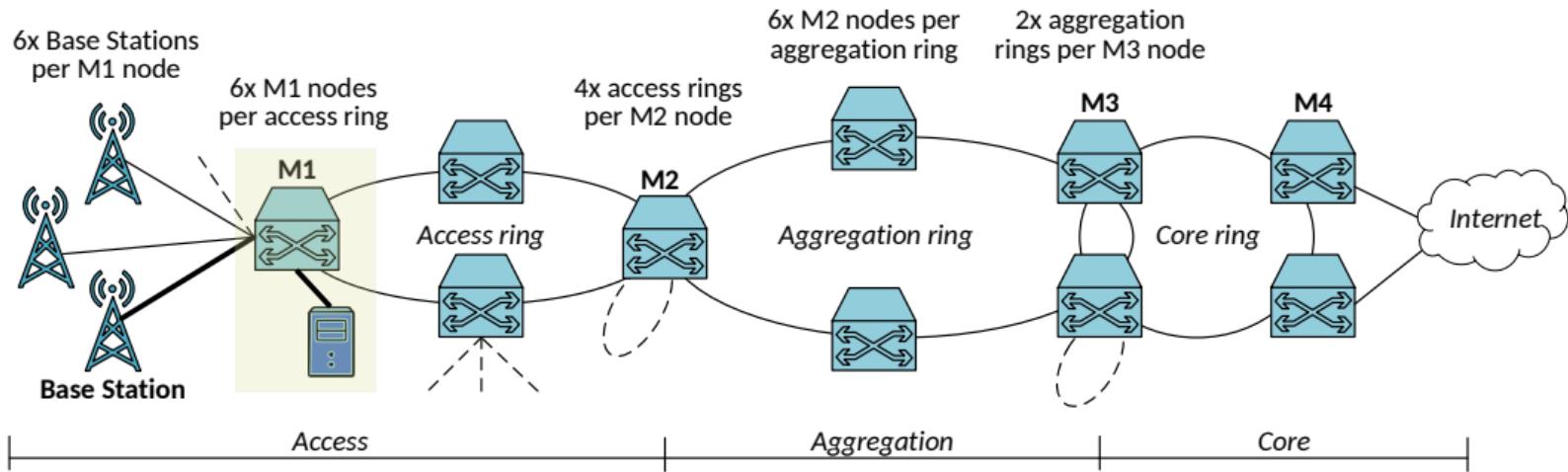


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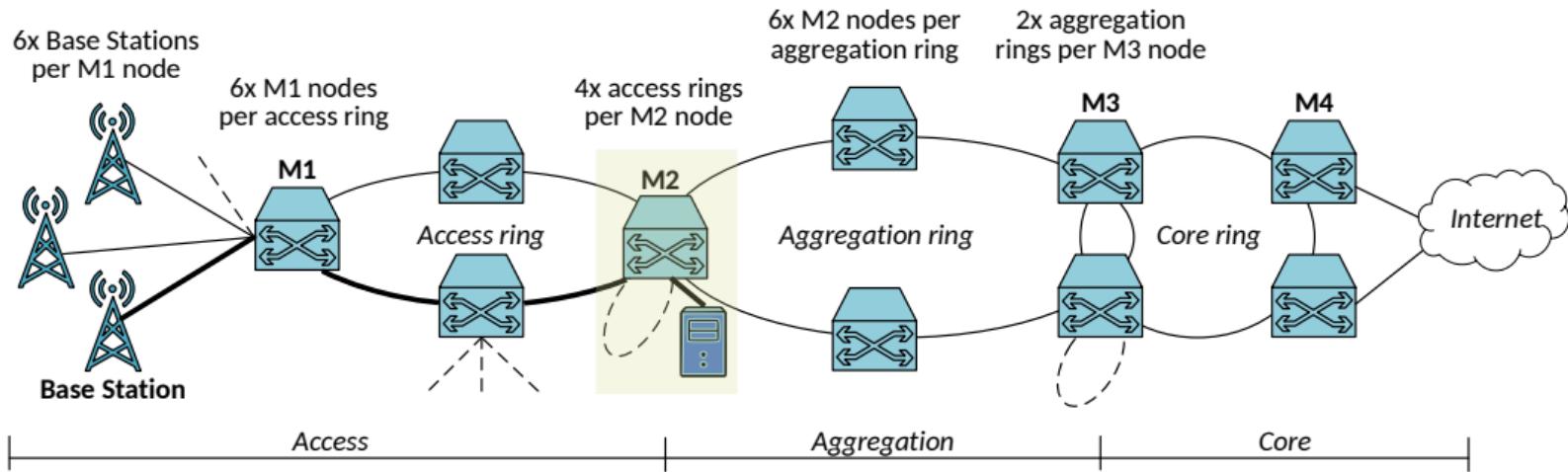


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Derive server location s.t. $RTT \leq 1\text{ms}$ (tactile latency – **augmented reality**):

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

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

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

fiber propagation

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

Derive server location s.t. $RTT \leq 1\text{ms}$ (tactile latency – **augmented reality**):

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ring propagation

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

Derive server location s.t. $RTT \leq 1\text{ms}$ (tactile latency – **augmented reality**):

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

radio propagation

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

Generation of 5G infrastructure graphs

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m_M : maximum distance between server at ring M and BS

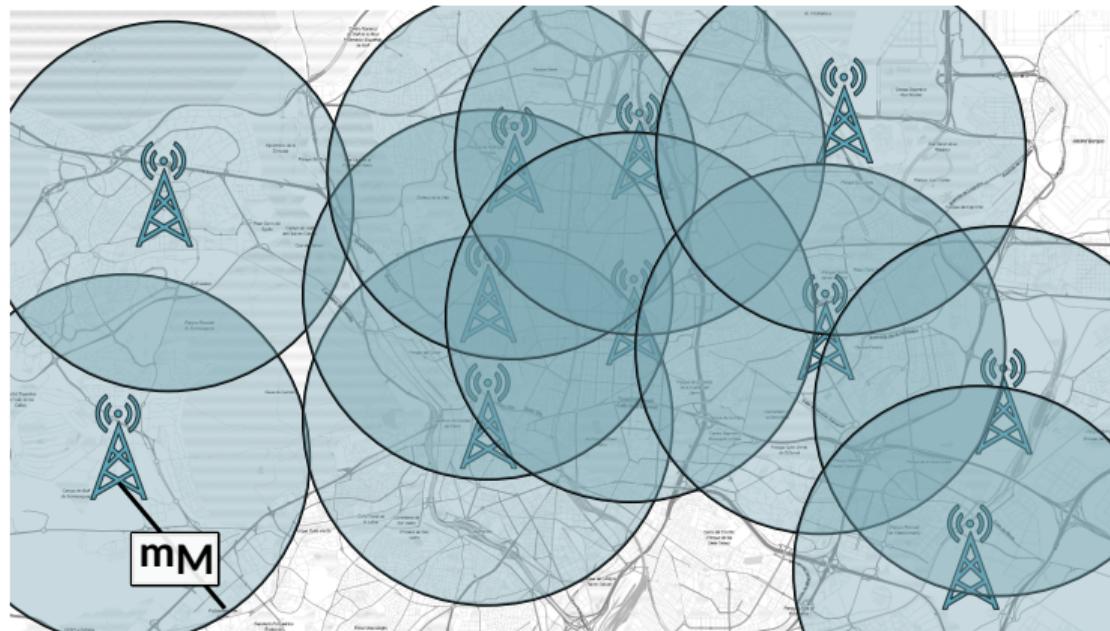


Figure 9: How to select MEC PoP location.

m_2 : maximum distance between server at ring 2 and BS

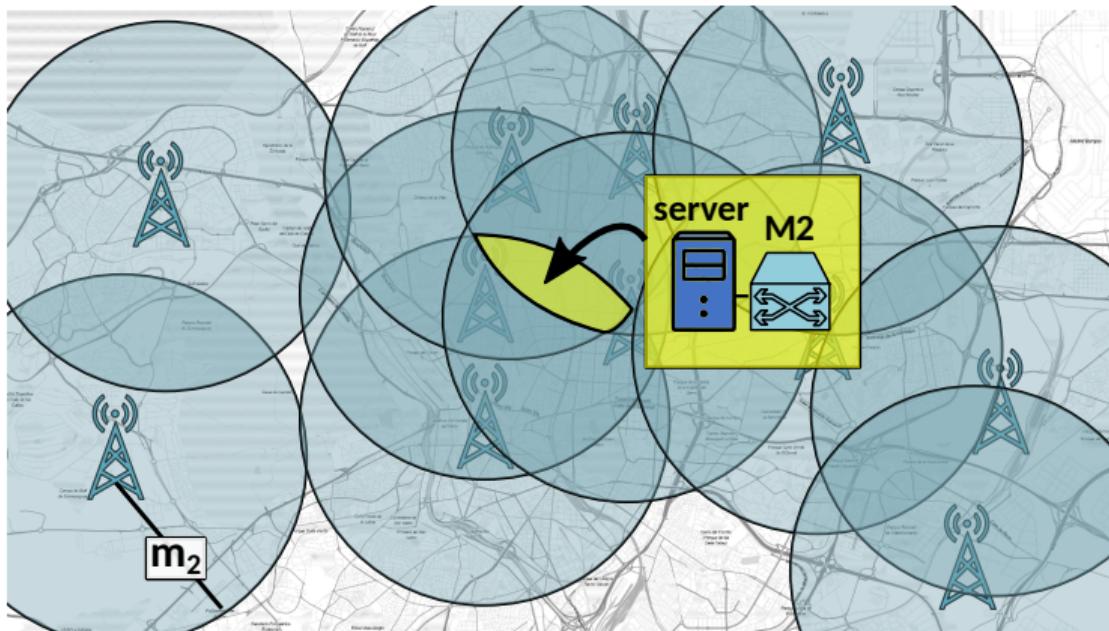


Figure 9: How to select MEC PoP location.

Experiments

- Urban, highway, industrial **scenarios**
- NR **BSs** (different UL+DL latencies):
 - FDD 120 kHz 7s
 - TDD 120 kHz 7s
 - FDD 30 kHz 2s
- **Servers:**
 - M1 switch – access ring
 - M2 switch – aggregation ring
- **Meet:** tactile latencies 1ms

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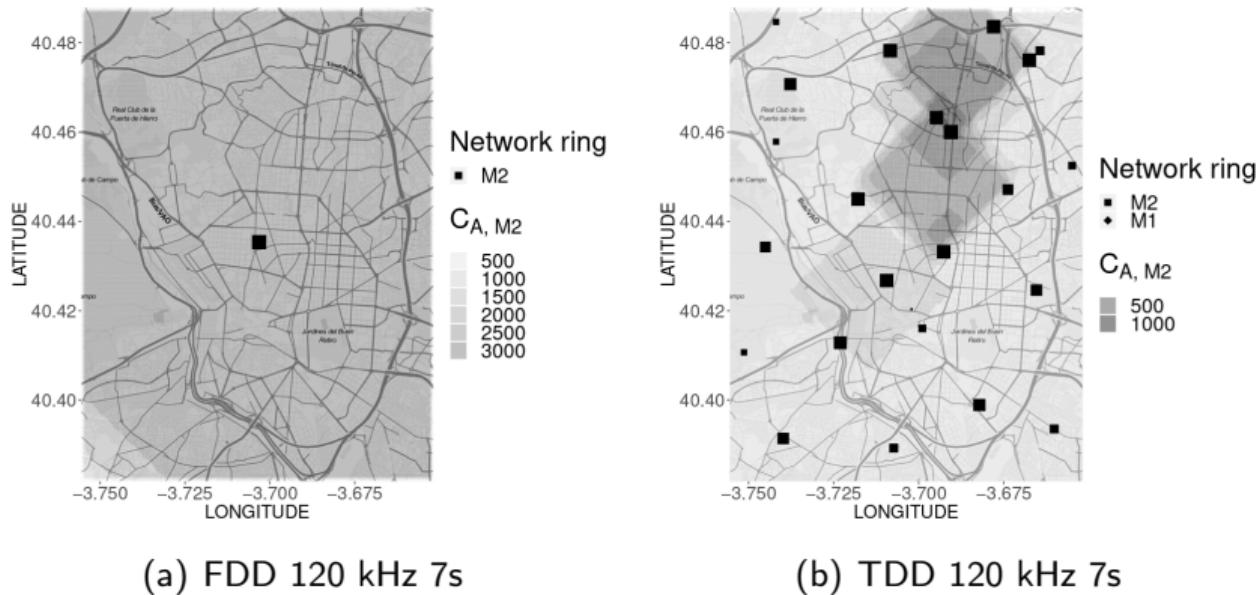
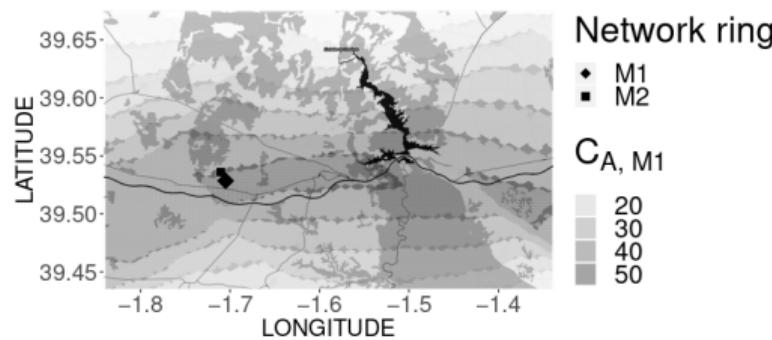


Figure 10: **Urban scenario** (Madrid city center) – $C_{A,M2}$ =covered BSs by server at M2.

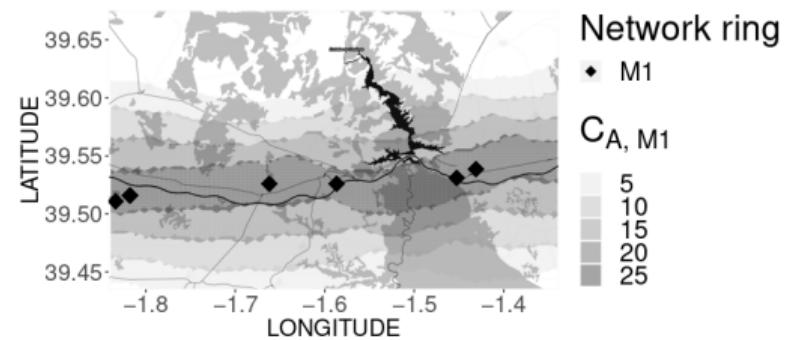
Generation of 5G infrastructure graphs

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(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.

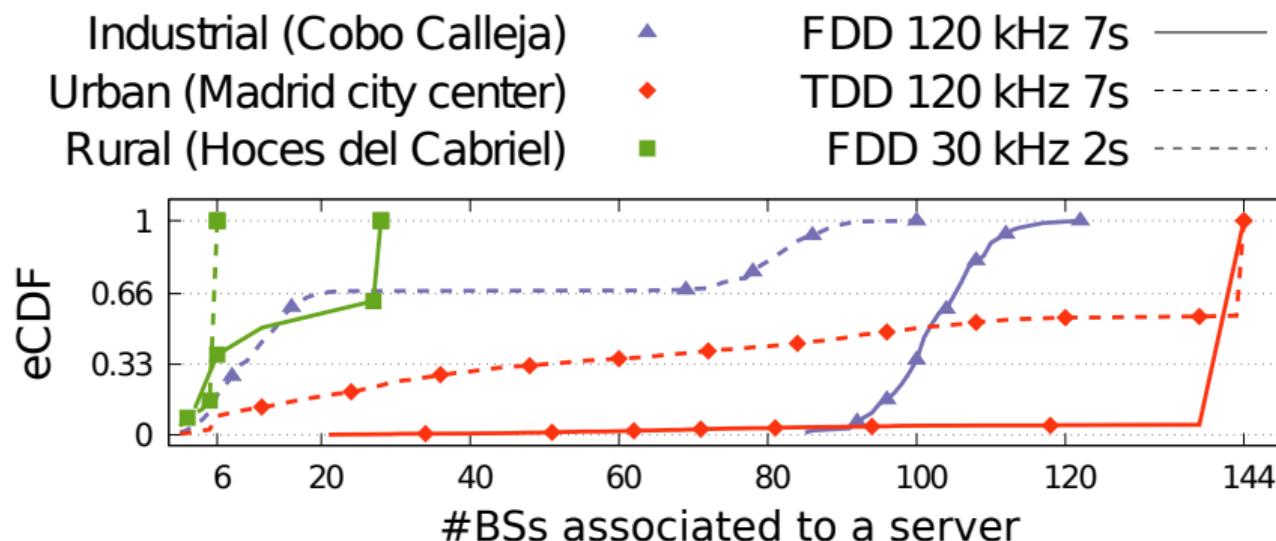


Figure 12: eCDF of the number of BSs assigned to a server in the studied scenarios.

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4 Conclusions & future work

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 & server generation:**
<https://github.com/MartinPJorge/mec-generator/>
- **5GEN:**
<https://github.com/MartinPJorge/mec-generator/tree/5g-infra-gen/>

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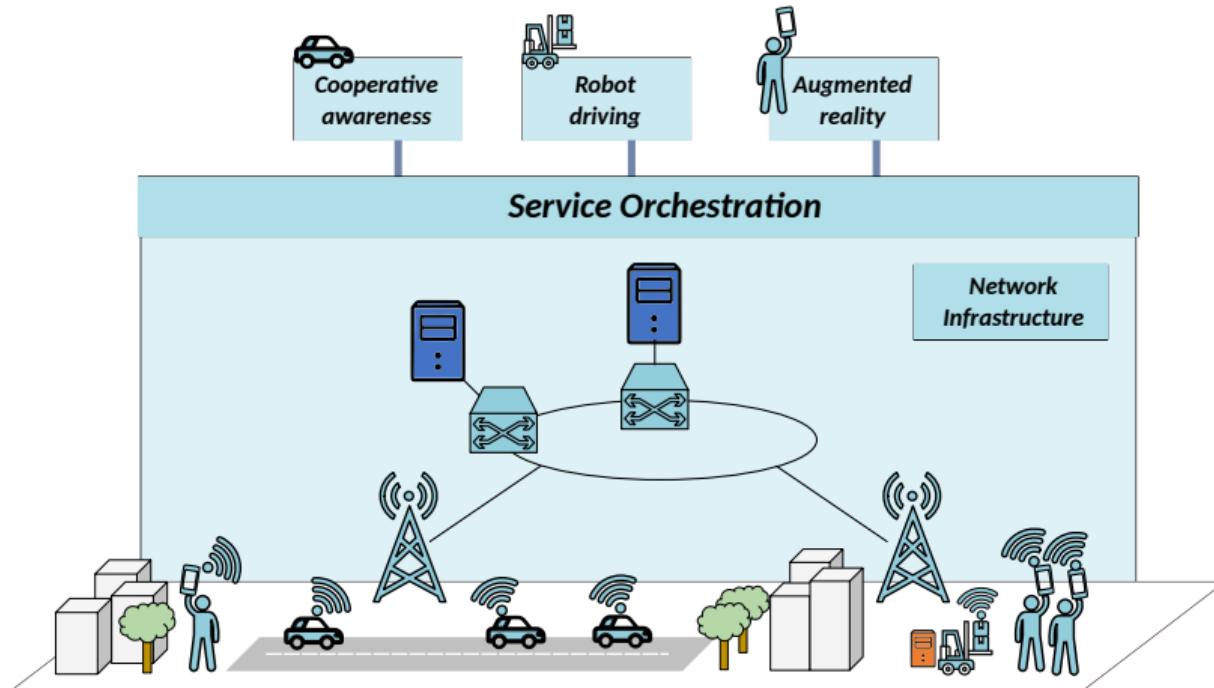


Figure 13: Infrastructure design.

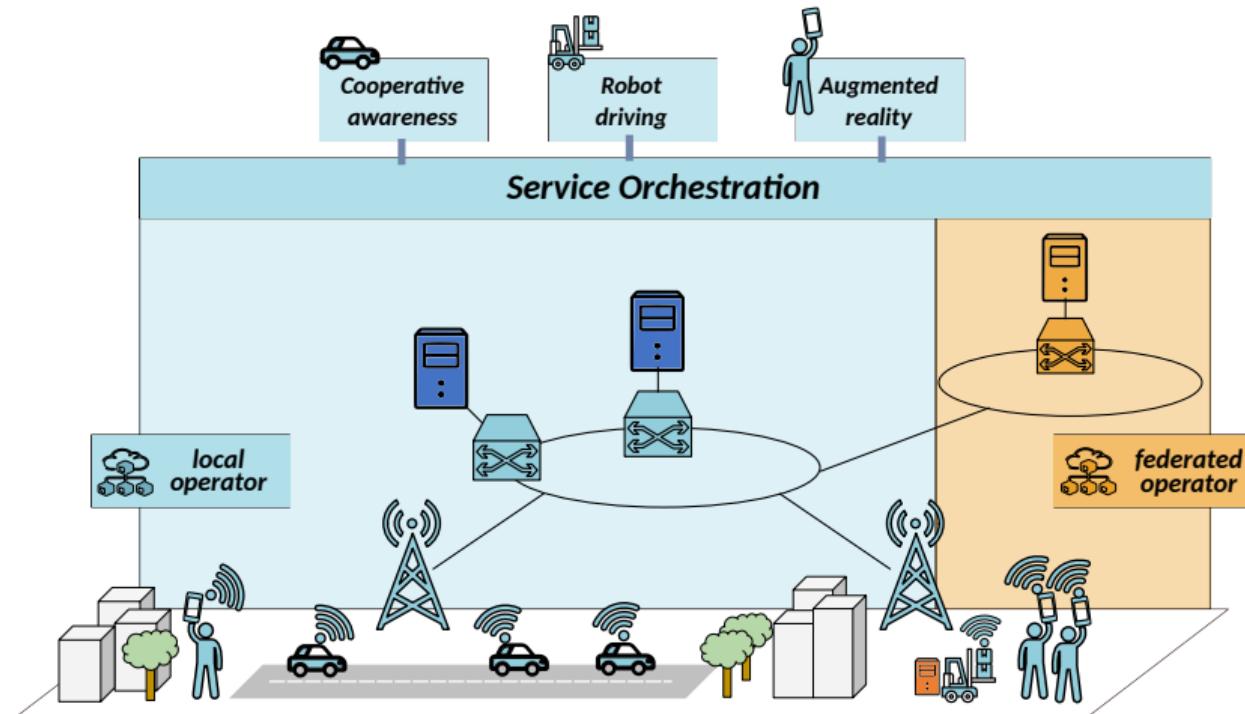


Figure 13: Local and federation operator.

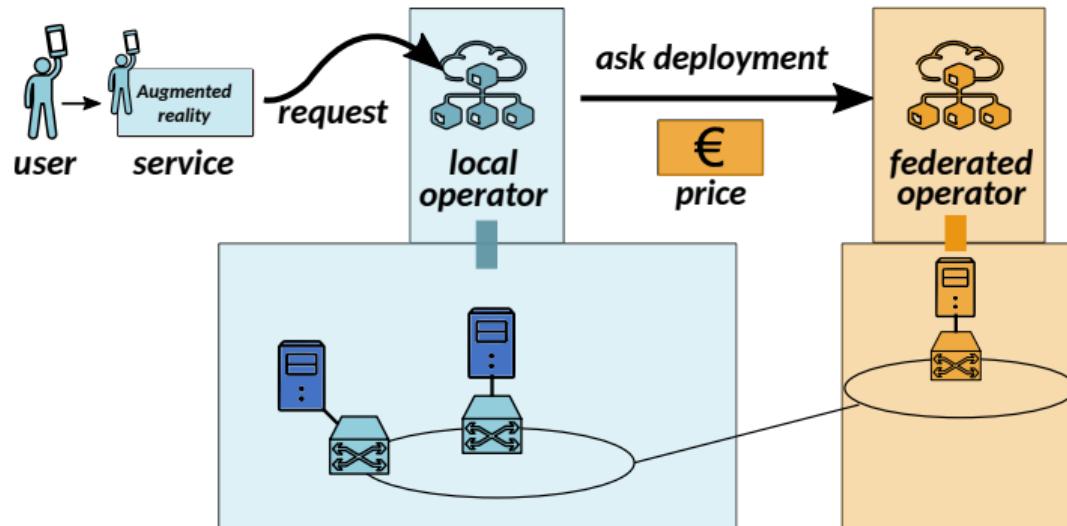


Figure 14: Service federation.

New in SoA:

- dynamic pricing
- real-price traces AWS
- Deep Q-learning
- Telefónica scenario

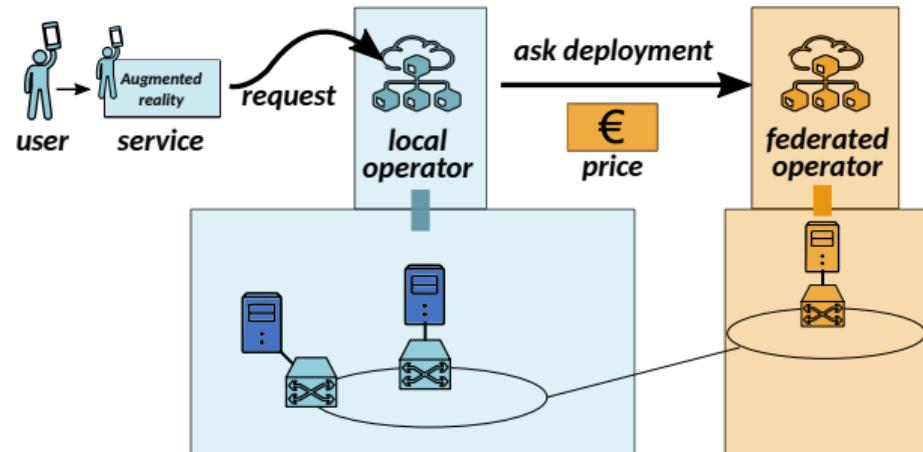


Figure 14: Service federation.

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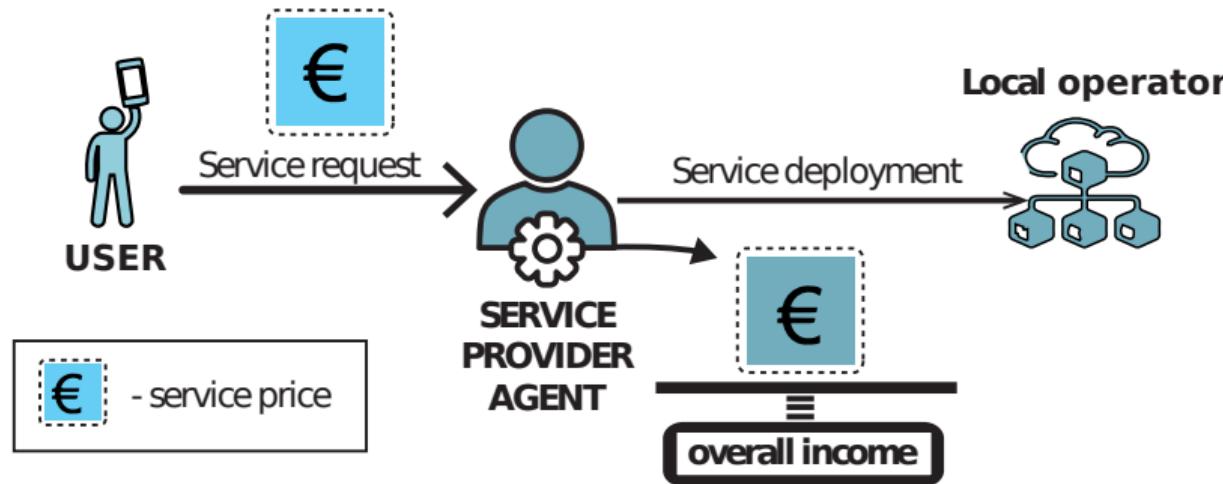


Figure 15: Business model - local deployment².

²Based on Kiril Antevski illustration

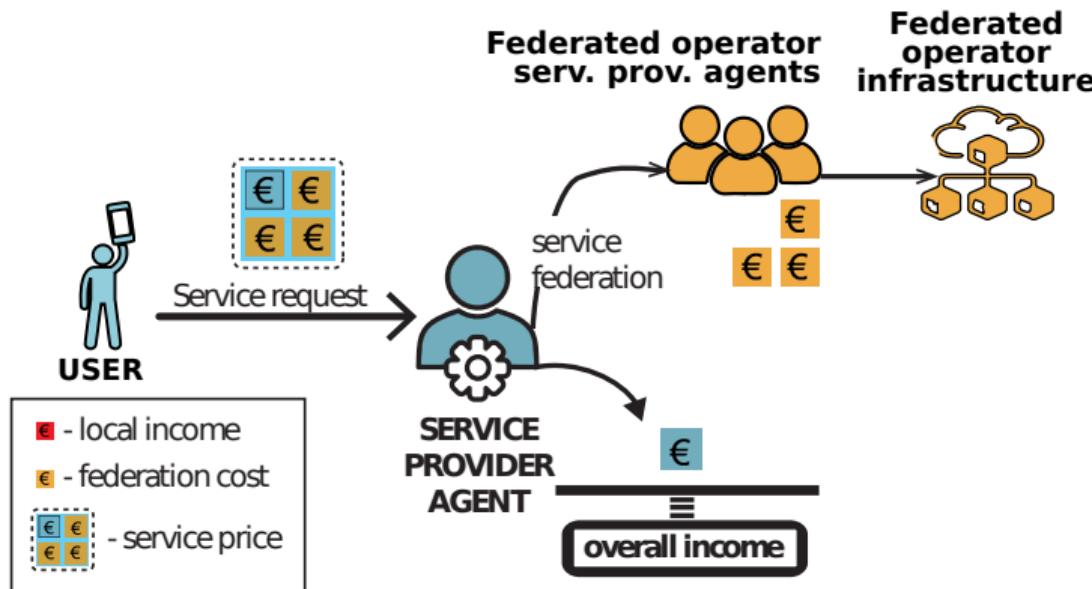


Figure 16: Business model - federate deployment³.

³Based on Kiril Antevski illustration

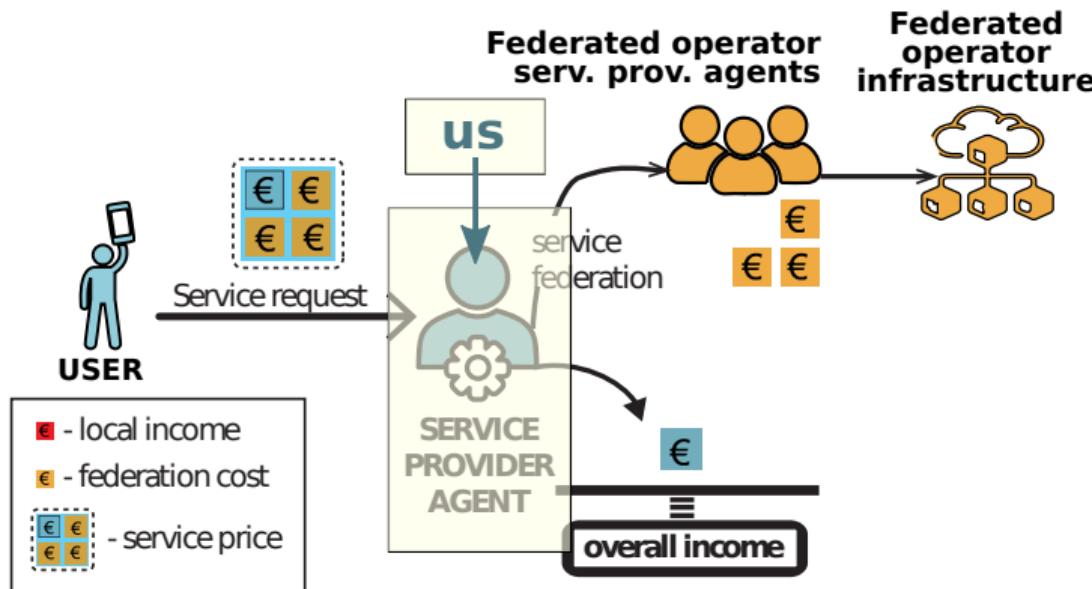


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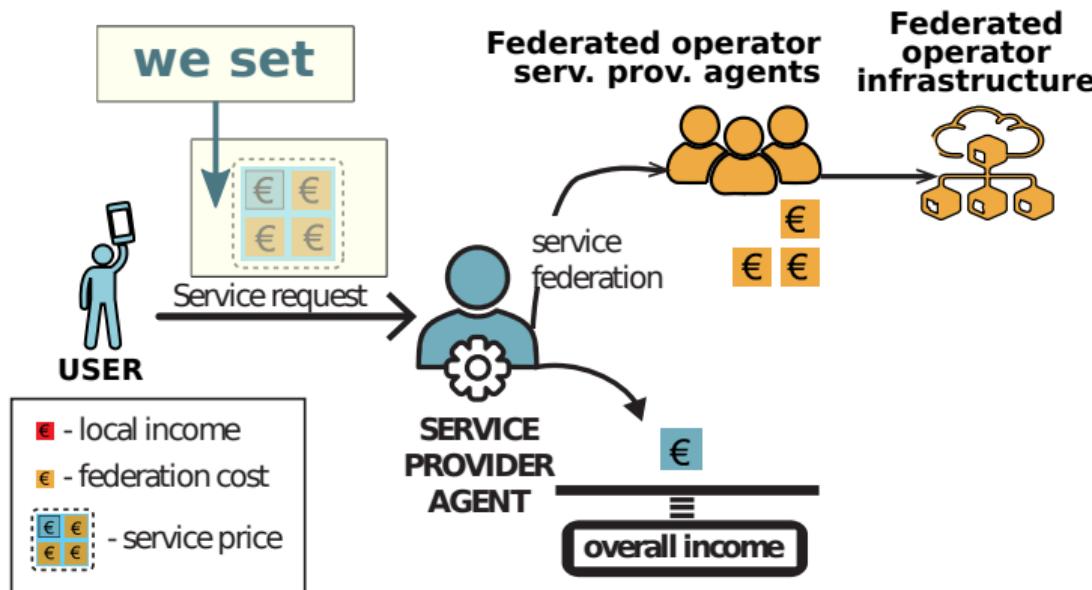


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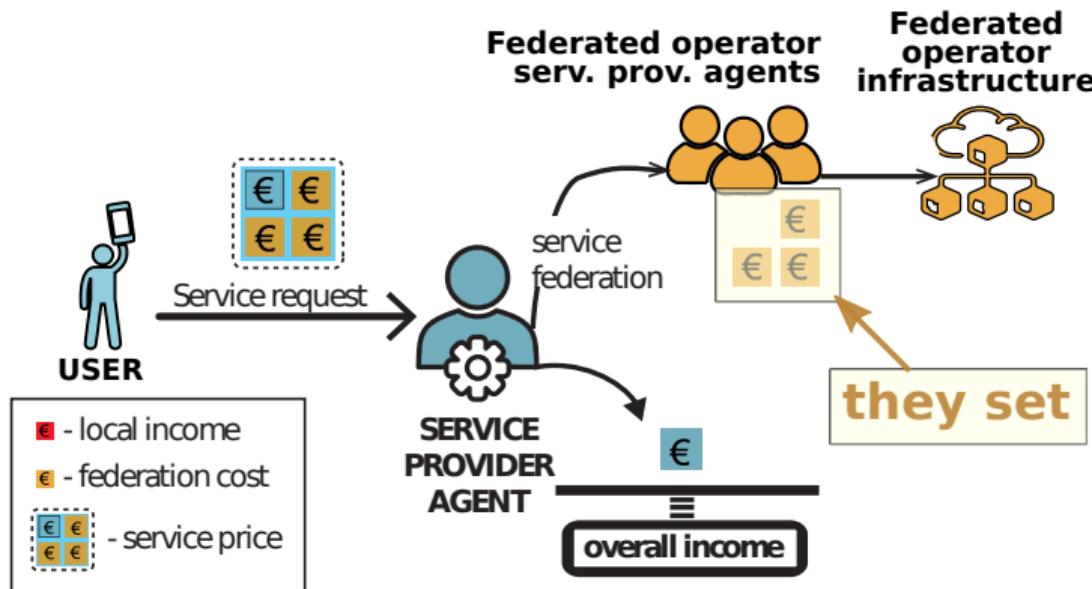


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t3a.small:

- 2 CPUs
- memory 2 GB
- storage 100 GB

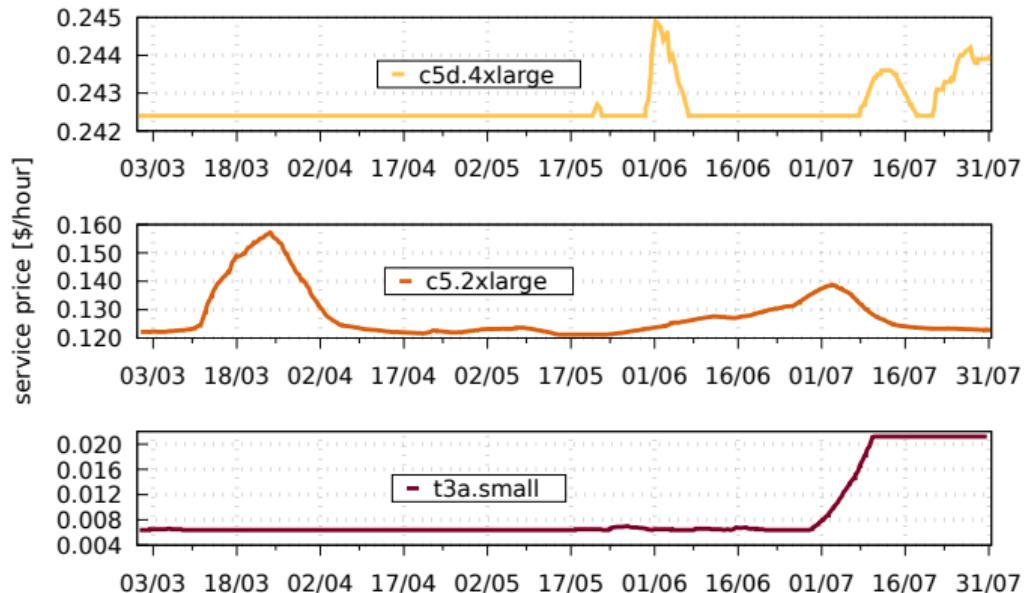


Figure 17: AWS service prices during 2020 in west Europe.

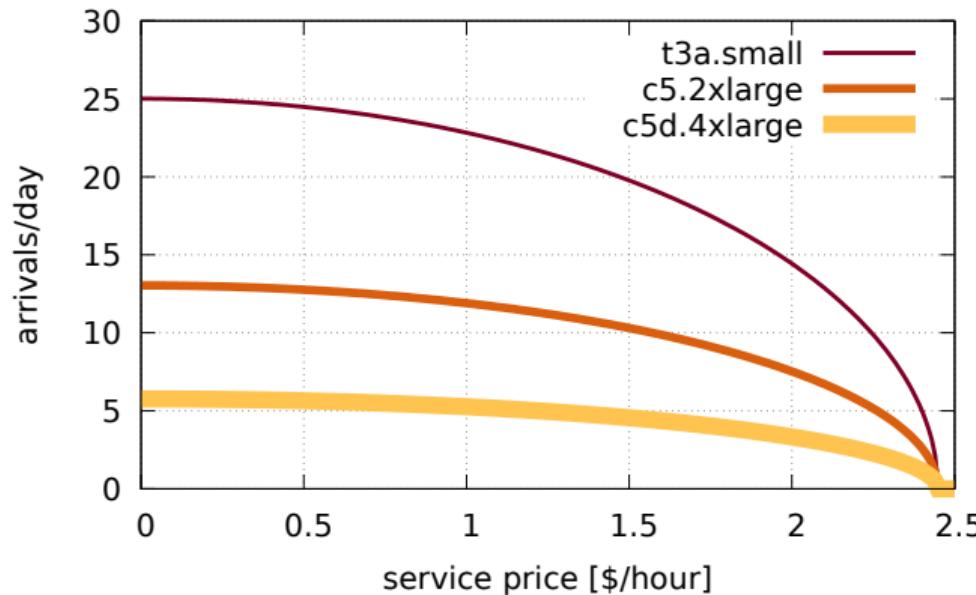


Figure 18: Impact of prices on arriving users – based on tid study [22] and [26].

Considering:

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

Considering:

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For each service σ , decide / take an action:

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

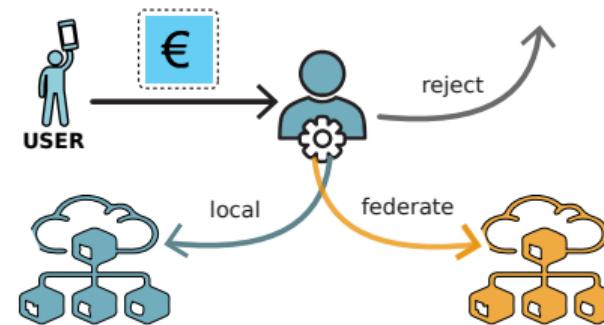


Figure 19: Possible actions.

Obtained **reward**:

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

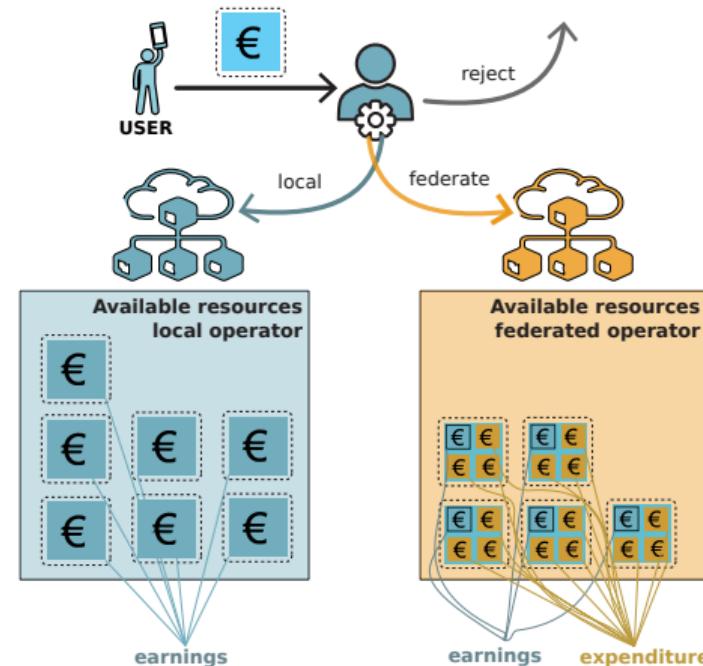


Figure 20: Environment snapshot at time t .

Obtained reward:

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local

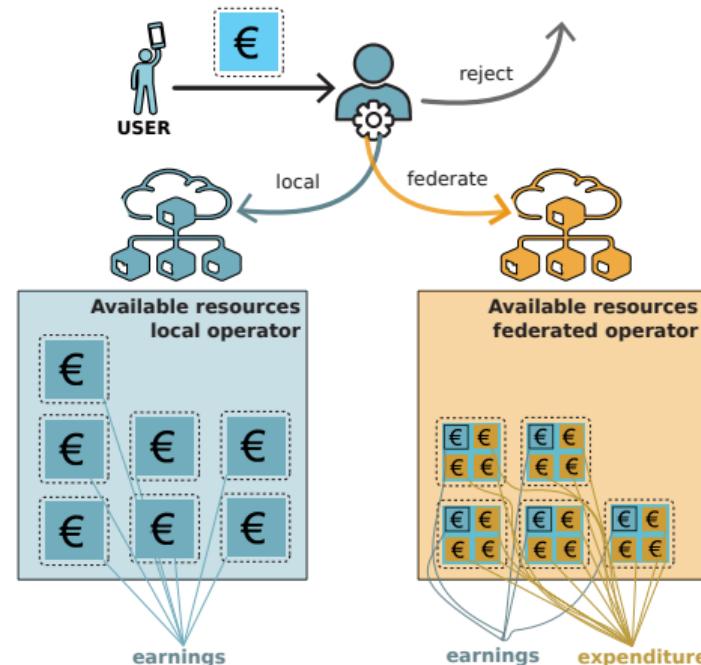


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federation

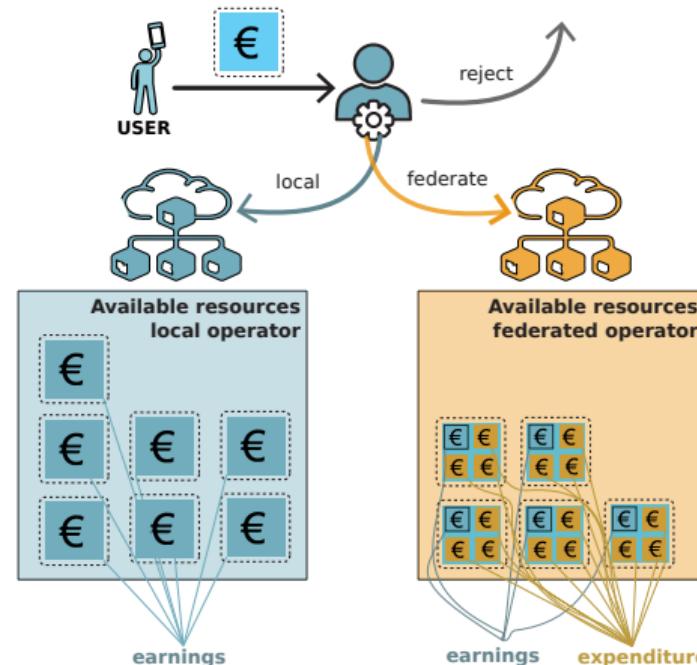


Figure 20: Environment snapshot at time t .

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

Online optimization problem:

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

NFV Orchestration in federated environments

Thesis contribution

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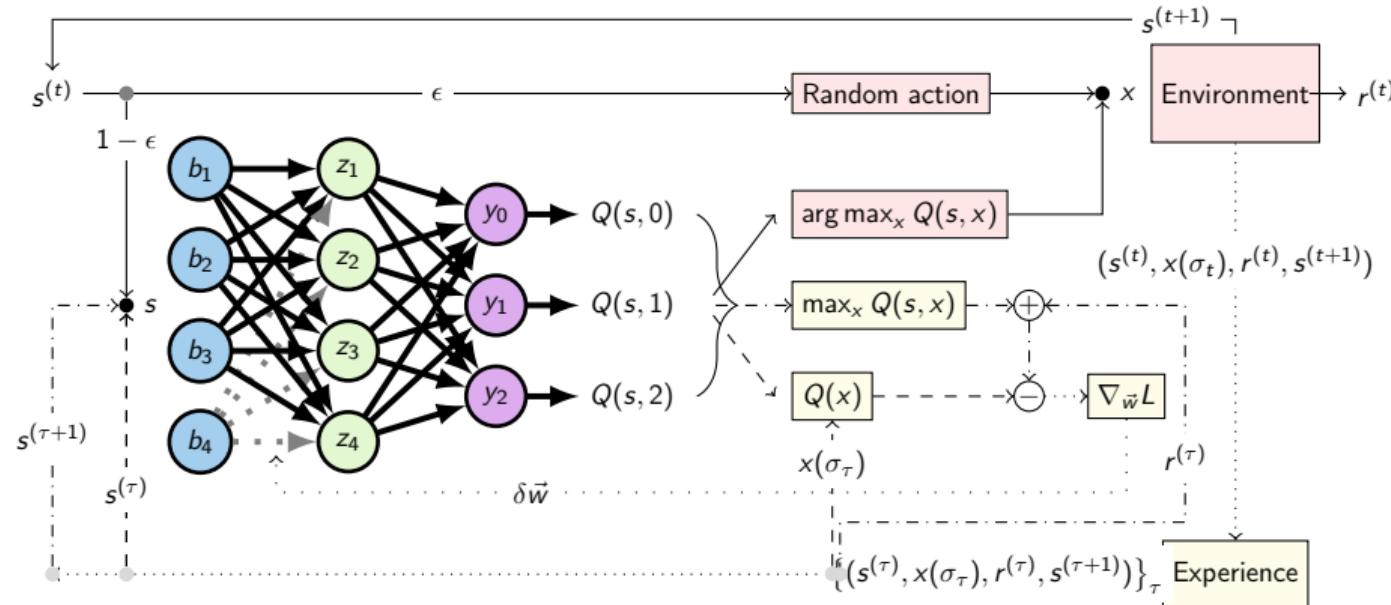


Figure 21: DQN architecture to decide rejection/local/federate.

Experiments

- Telefónica infrastructure & resources [22]
- AWS prices dataset:
 - training 29/02/2020 – 02/05/2020
 - testing 03/05/2020 – 31/07/2020
- Poissonian arrival of users

Comparison of:

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

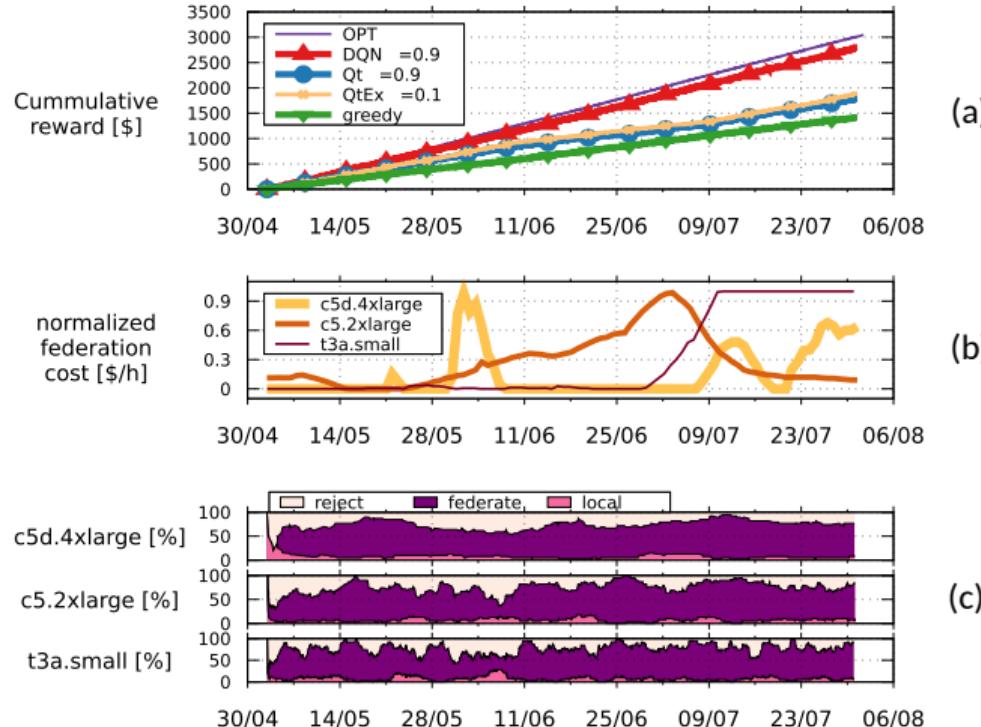


Figure 22: Federation agents' performance.

Comparison of:

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

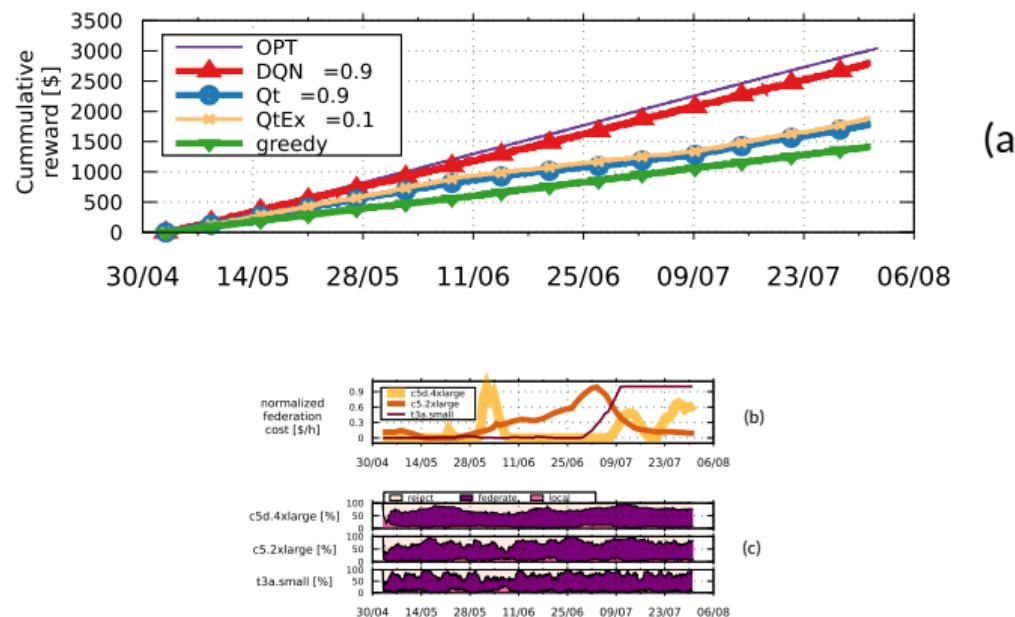


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Comparison of:

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Results:

- near-optimal

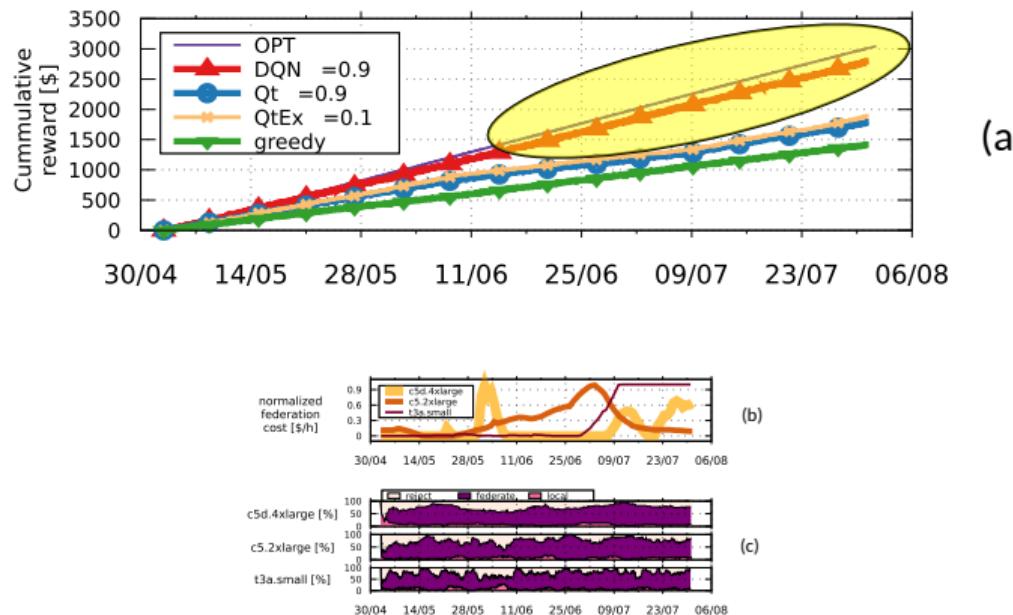


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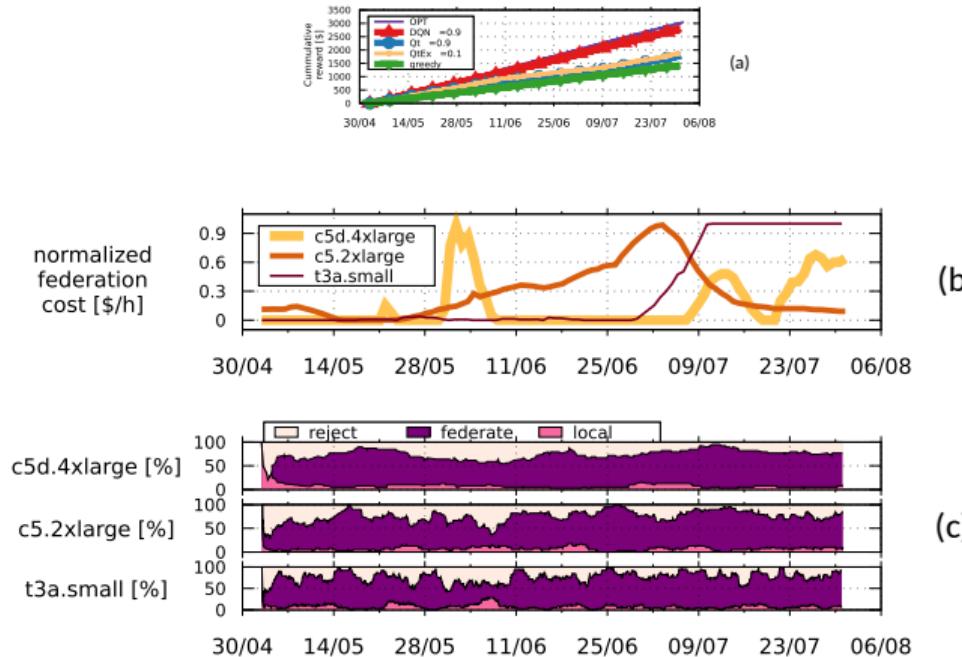


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Comparison of:

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Results:

- near-optimal
- react upon peaks

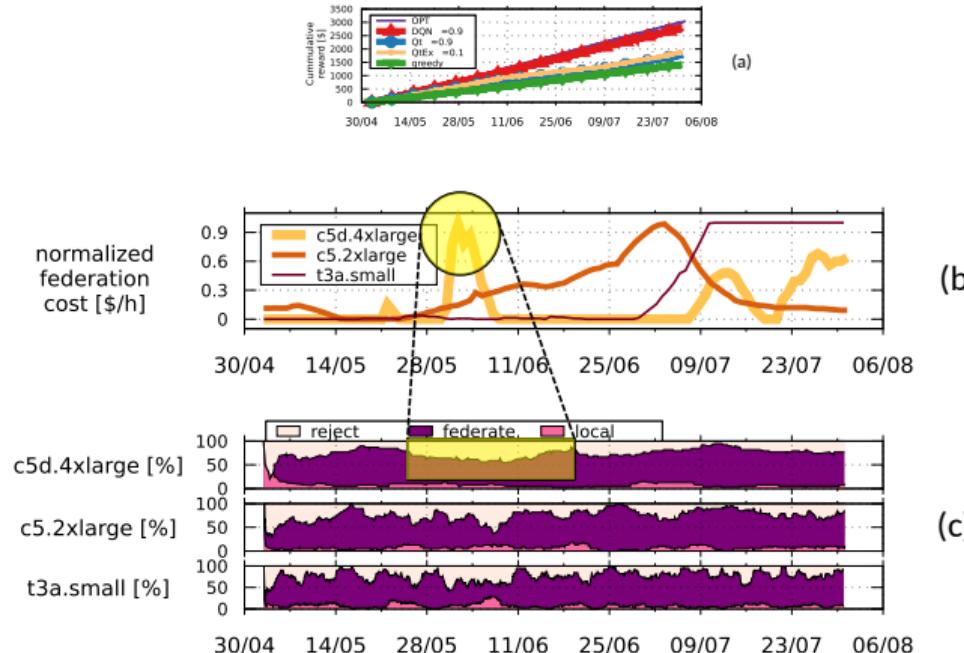
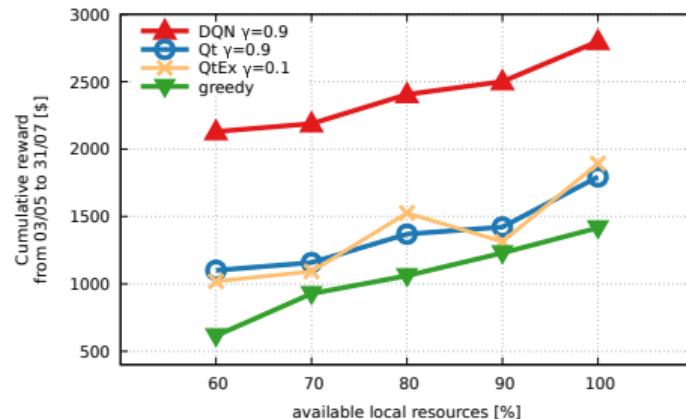


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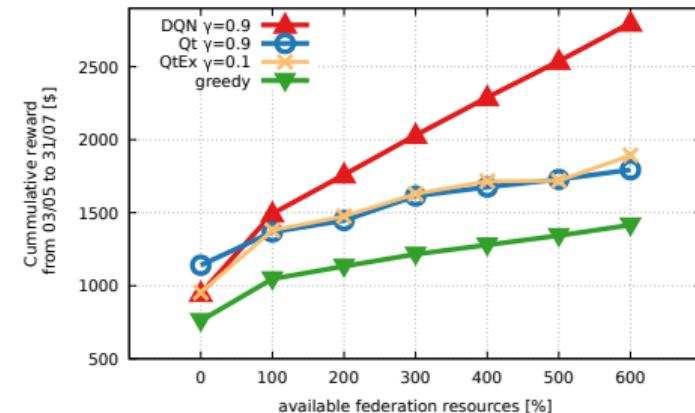
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Thesis contribution

uc3m



(a) Increasing local resources.



(b) Increasing resources in federation.

Figure 23: Cumulative reward vs. available resources.

1 Generation of 5G infrastructure graphs

2 NFV Orchestration in federated environments

- Motivation
- Thesis contribution
- Output

3 NFV orchestration for 5G networks: OKpi

4 Conclusions & future work

Publications:

- Martín-Pérez, Jorge and C. J. Bernados. “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](https://doi.org/10.1109/BMSB.2018.8436765)
- K. Antevski, J. Martín-Pérez, A. Garcia-Saavedra, C. J. Bernados, 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](https://doi.org/10.1109/ICC40277.2020.9149082)
- Martín-Pérez, Jorge, K. Antevski, A. Garcia-Saavedra, X. Li, and C. J. Bernados. “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](https://doi.org/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/>

- 1 Generation of 5G infrastructure graphs
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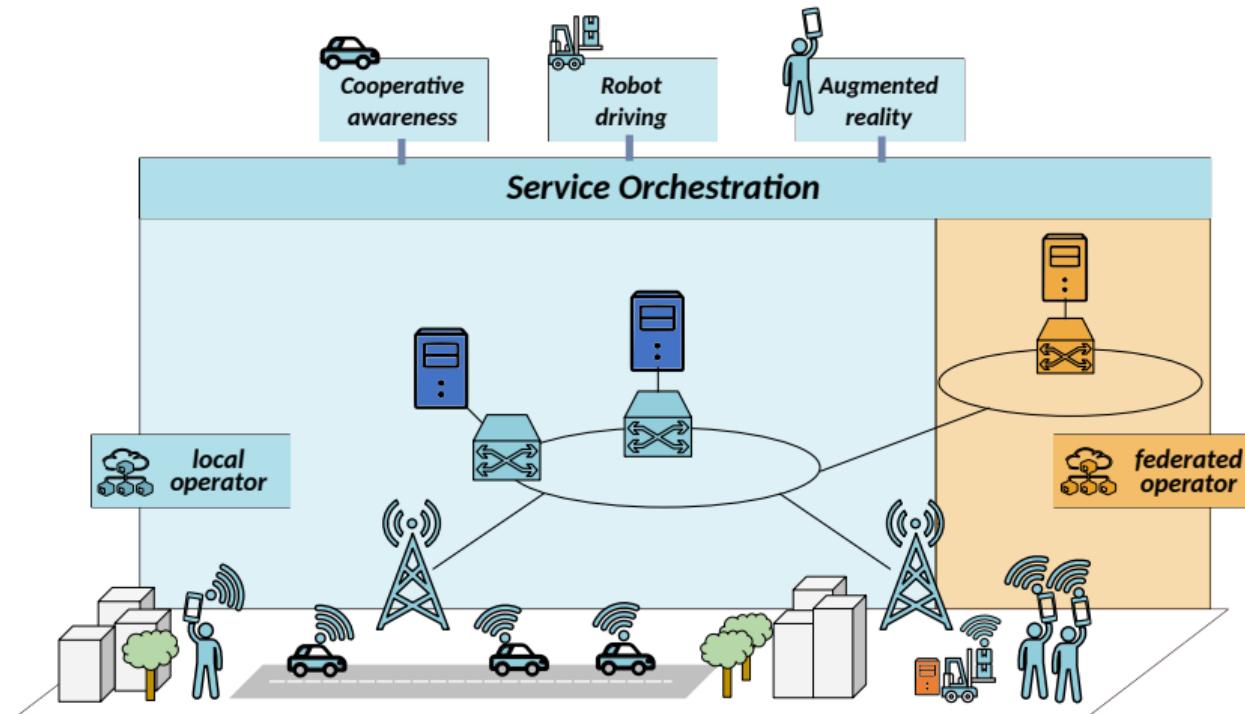


Figure 24: Local and federation operator

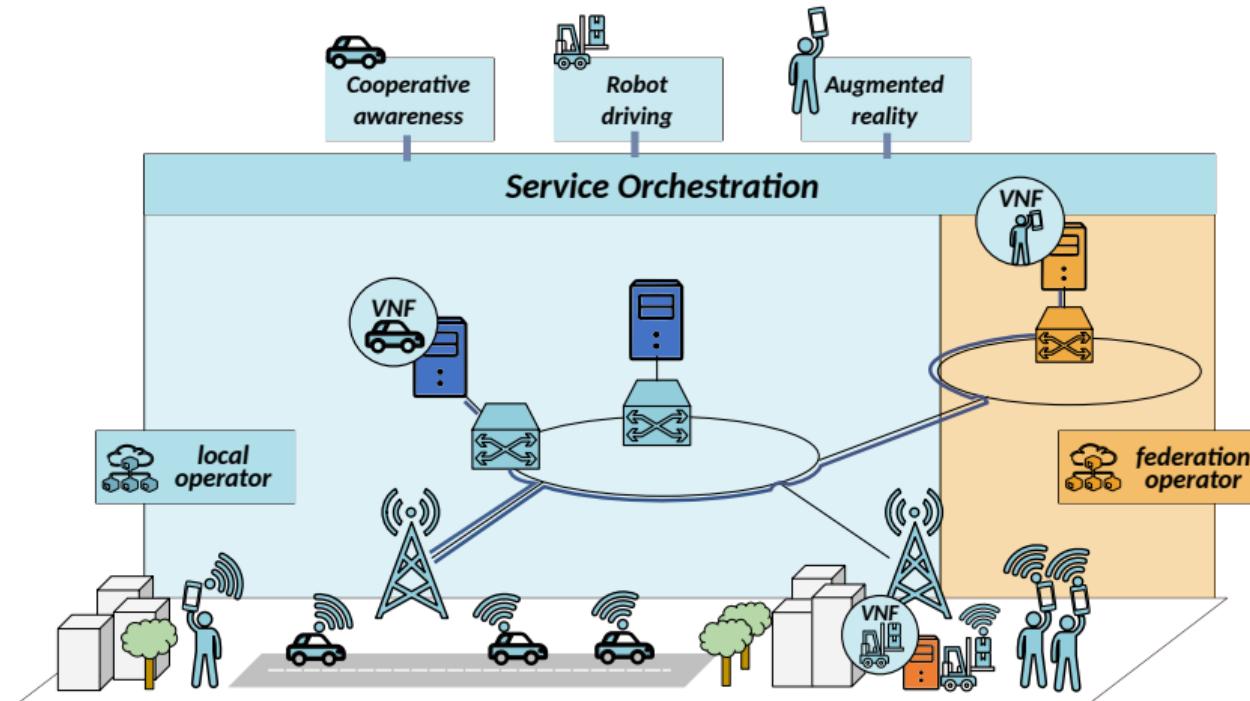


Figure 25: Services' embedding.

Motivation

OKpi **new** embedding algo. in SoA:

- latency constraints
- radio coverage
- geographical availability
- reliability

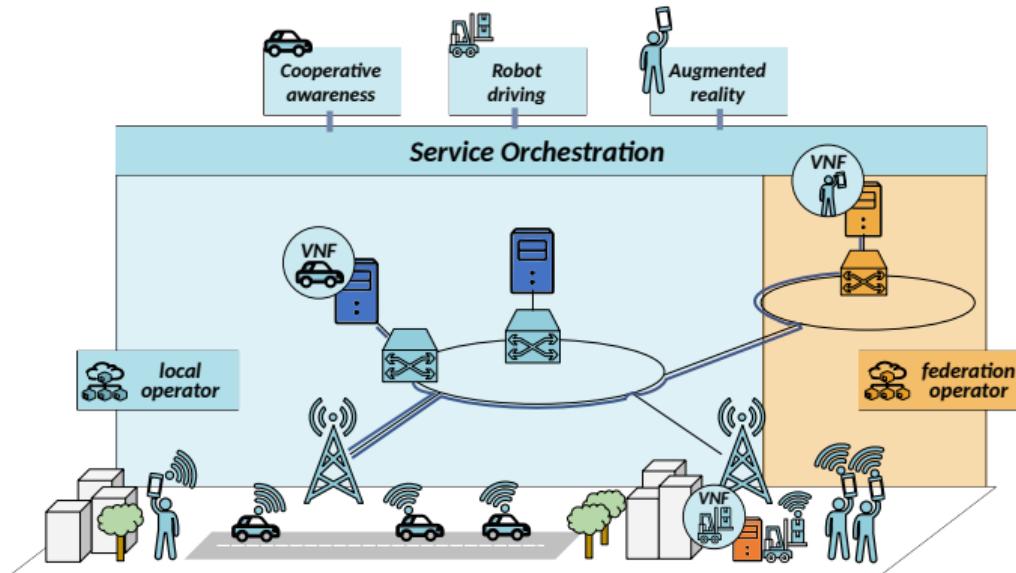


Figure 25: Services' embedding.

1 Generation of 5G infrastructure graphs

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- Motivation

- Thesis contribution**

- Output

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OKpi solves the VNE problem.

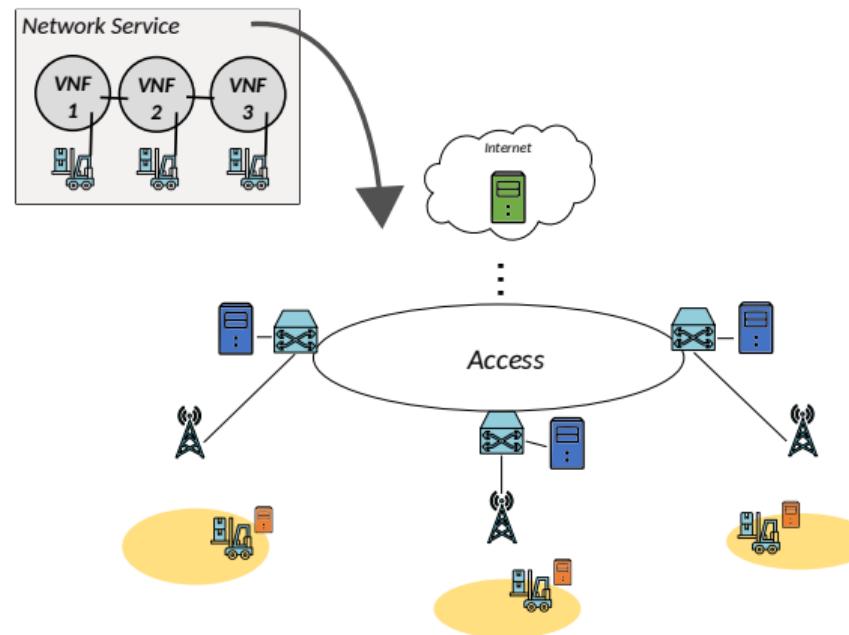


Figure 26: Virtual Network Function Embedding (VNE).

OKpi solves the VNE problem.

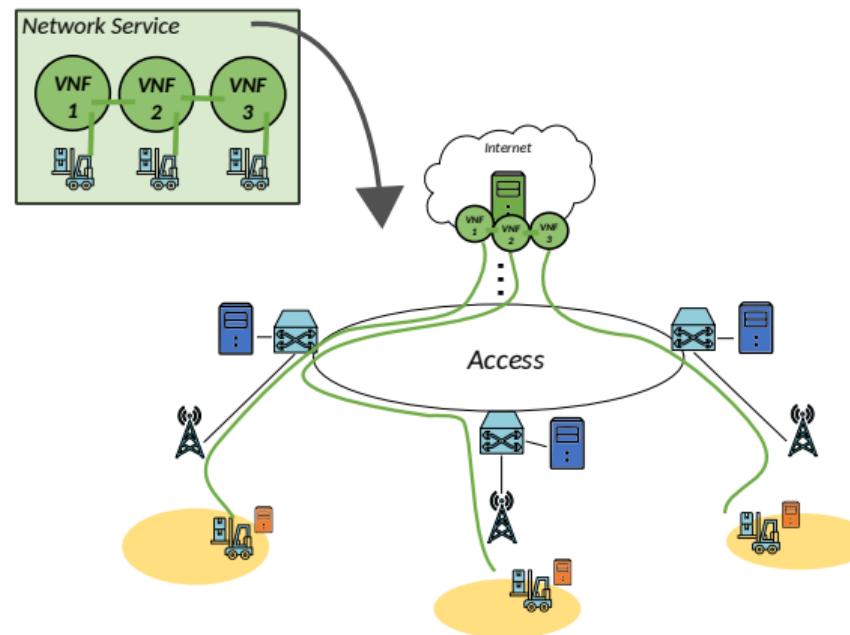


Figure 26: Virtual Network Function Embedding (VNE).

OKpi solves the VNE problem.

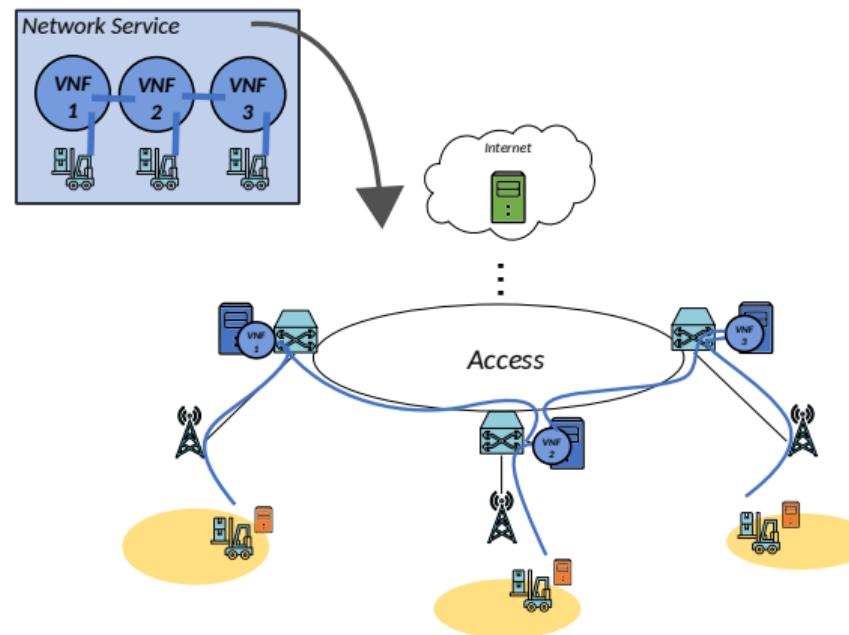


Figure 26: Virtual Network Function Embedding (VNE).

OKpi solves the VNE problem.

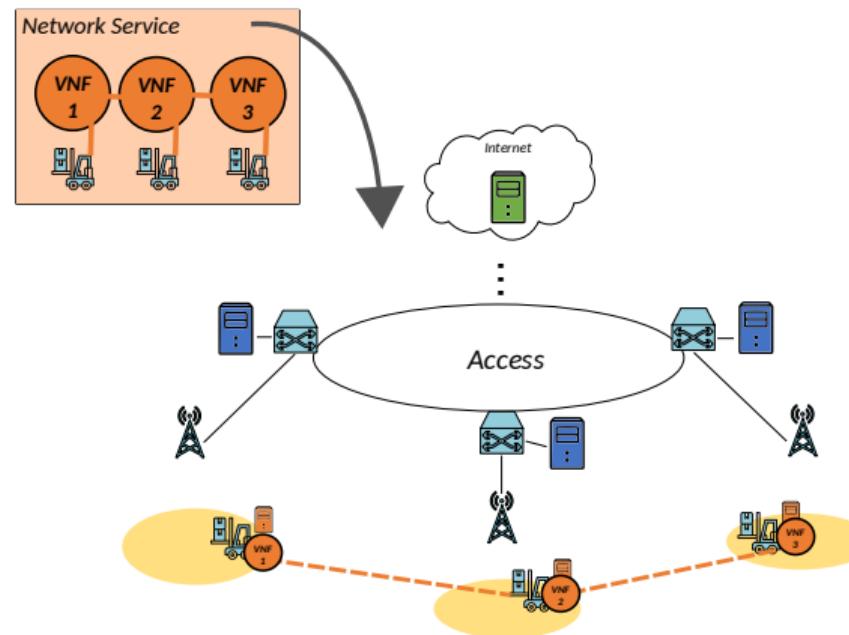


Figure 26: Virtual Network Function Embedding (VNE).

To solve the VNE problem **OKpi** imposes these constraints:

- latency constraint
- radio technology constraint
- geographical availability constraint
- reliability constraint

Latency constraint $D(s)$:

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

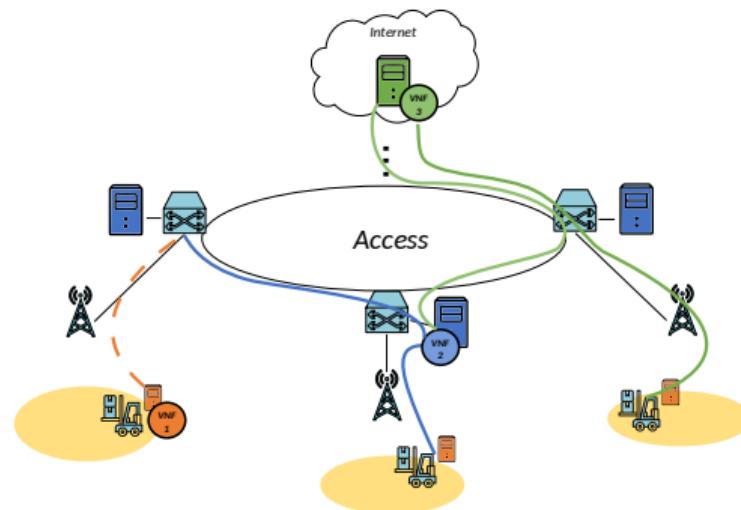


Figure 27: Service s delay.

Latency constraint $D(s)$:

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

propagation delay

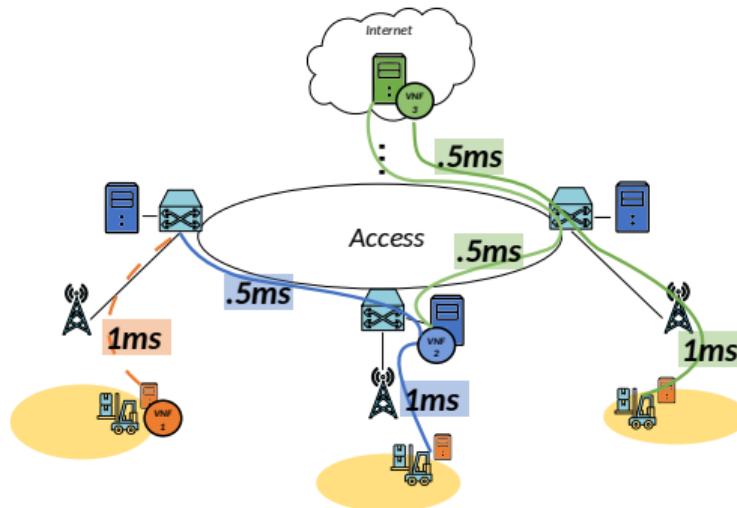


Figure 27: Service s delay.

Latency constraint $D(s)$:

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

processing delay

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

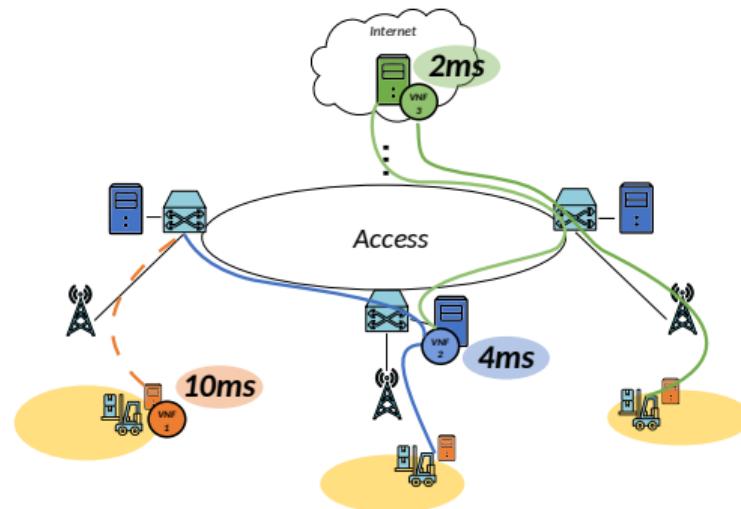


Figure 27: Service s delay.

Radio technology i constraint:

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

- $\rho(v, c)$: 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

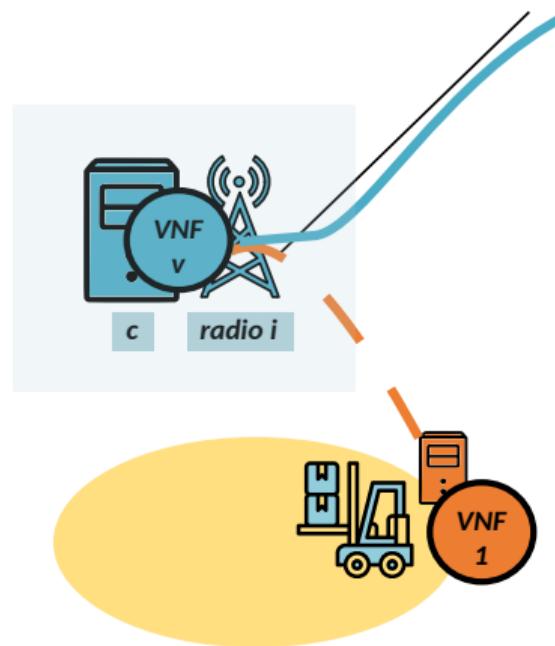


Figure 28: Radio VNF.

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)

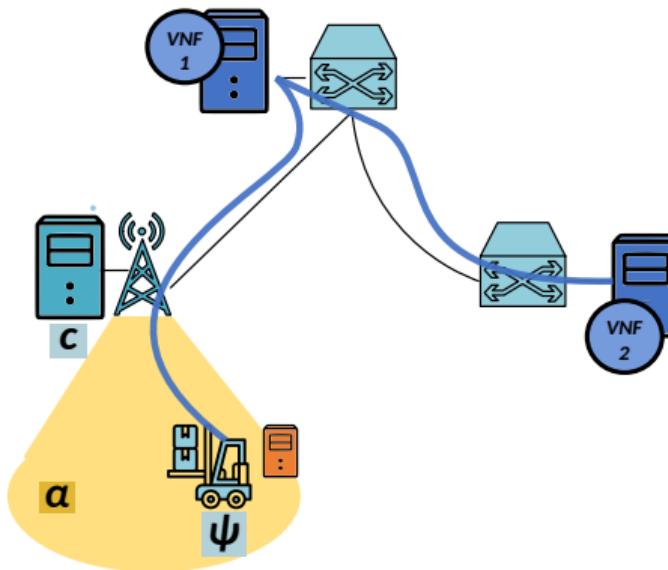


Figure 29: coverage of region α .

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

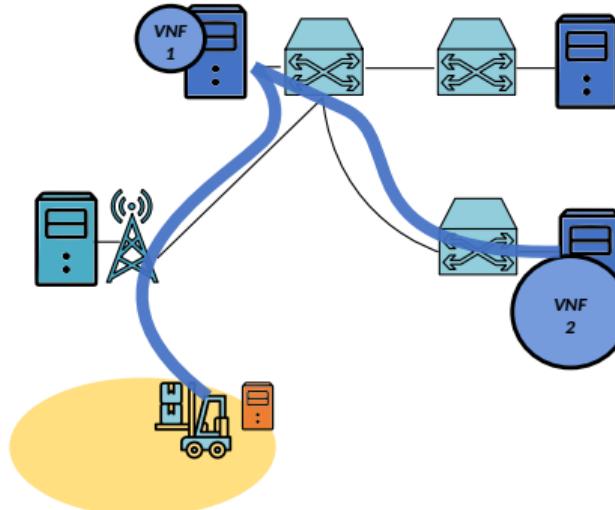


Figure 30: Traffic path.

Service reliability $H(s)$:

$$\prod_{v_1, v_2 \in \mathcal{V}} \sum_{w \in \mathcal{W}} f(\psi, v_1, v_2, w)$$

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

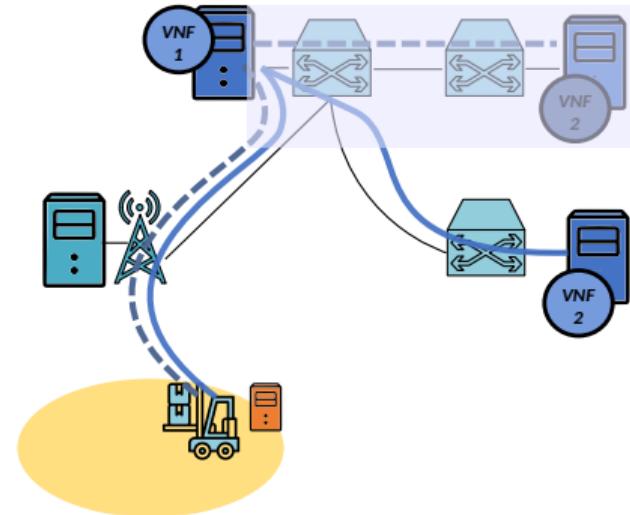


Figure 30: Fractioned traffic path.

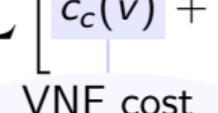
Formulate an optimization problem:

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

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

Formulate an optimization problem:

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


VNF cost

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

Formulate an optimization problem:

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

assigned resource κ cost

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

Formulate an optimization problem:

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

|
traffic steering cost

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

Formulate an optimization problem:

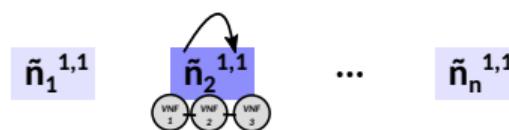
$$\min \sum_c \sum_v \left[c_c(v) + \sum_e \sum_\kappa c_c(\kappa) a_c(\psi, v, \kappa) \right] + \sum_{(i,j)} \sum_e \sum_{v_1, v_2} c_{i,j} \tau_{i,j}(\psi, v_1, v_2) \quad (7)$$

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

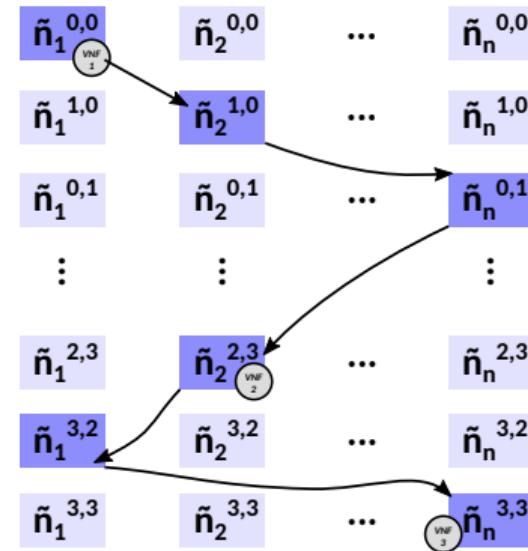
NP-hard: bin-packing problem equivalence.

OKpi VNE idea: high $\gamma \Rightarrow$ more hops

OKpi VNE idea: high $\gamma \implies$ more hops



(a) $\gamma = 0$



(b) $\gamma = 3$

Figure 31: Impact of resolution γ on OKpi embedding.

OKpi (all KPI) solve VNE in two steps:

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

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

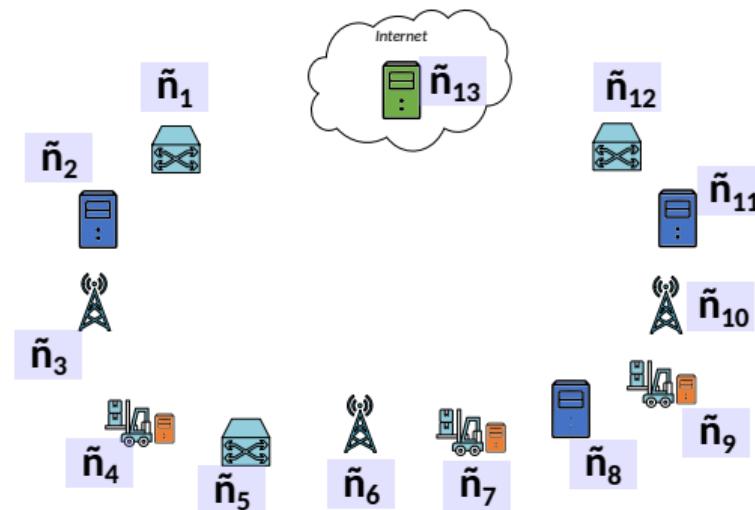


Figure 32: OKpi decision graph.

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

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

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

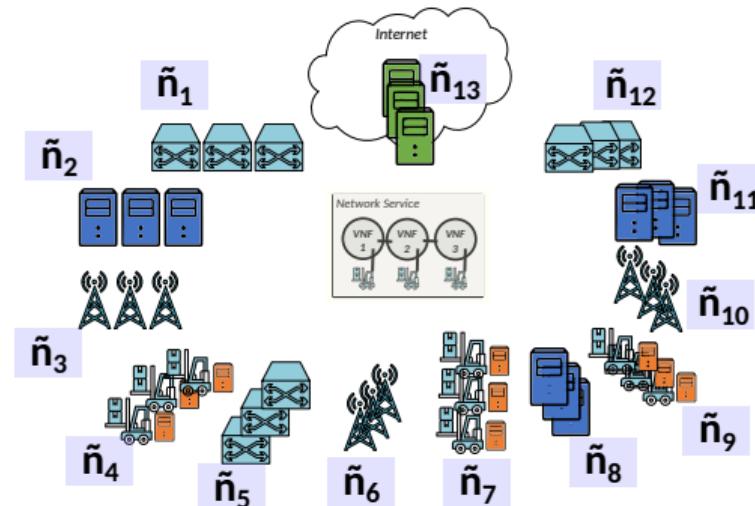


Figure 32: OKpi decision graph.

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:

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

(9)

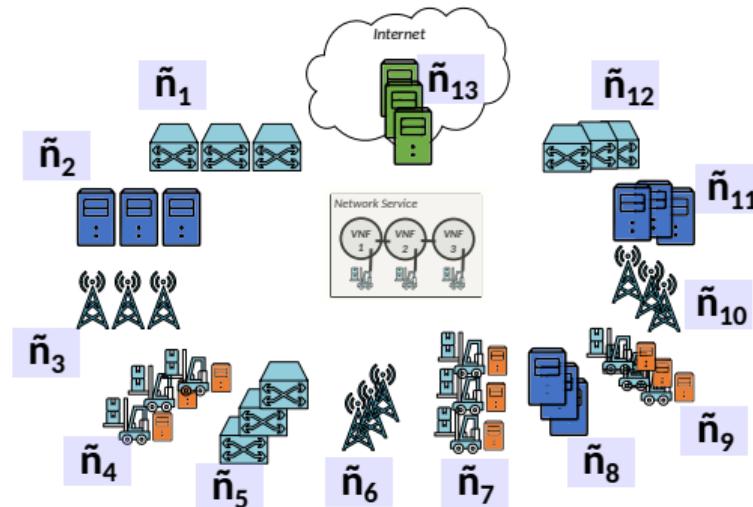


Figure 32: OKpi decision graph.

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:

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

delay fraction

(9)

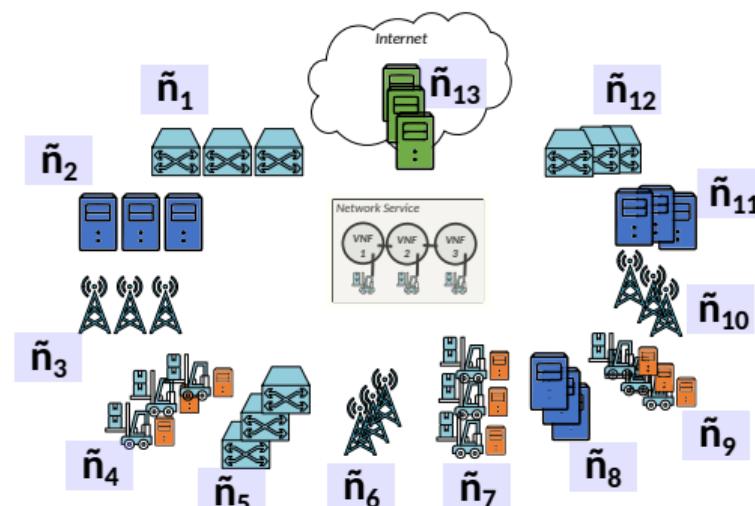


Figure 32: OKpi decision graph.

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:

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

reliability fraction

(9)

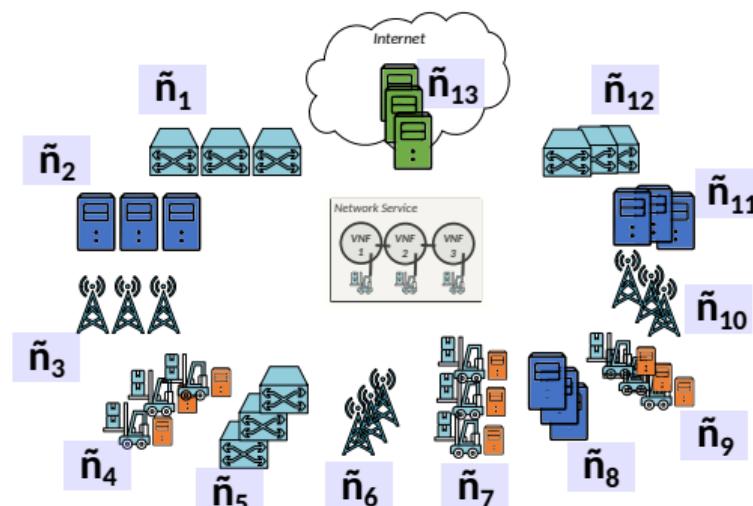


Figure 32: OKpi decision graph.

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:

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

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

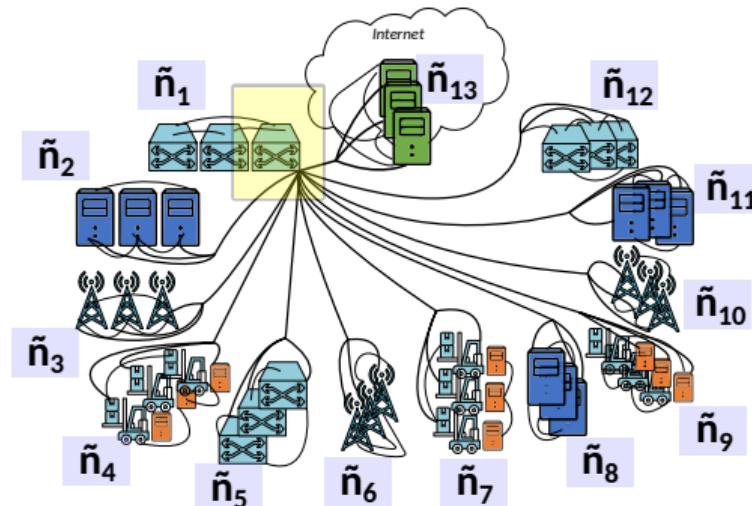


Figure 32: OKpi decision graph.

$$\tilde{n}_1^{0,0} \quad \tilde{n}_2^{0,0} \quad \dots \quad \tilde{n}_n^{0,0}$$

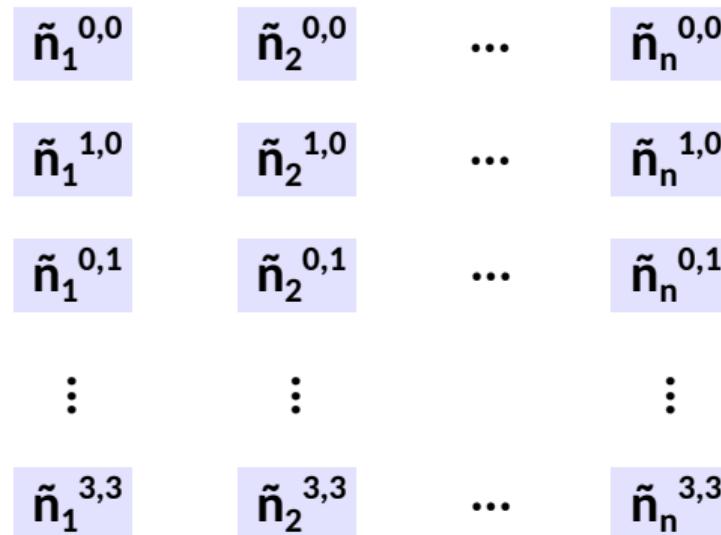
Expanded graph:

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

Figure 33: OKpi expanded graph $\gamma = 3$.

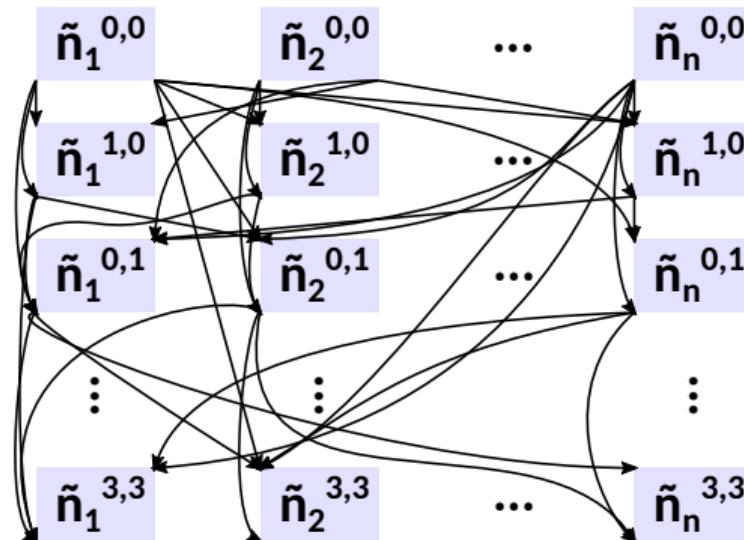
Expanded graph:

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

Figure 33: OKpi expanded graph $\gamma = 3$.

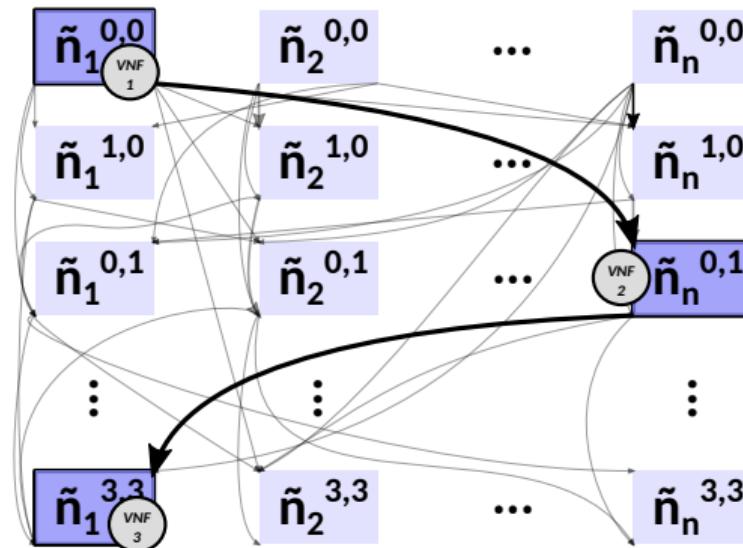
Expanded graph:

- 1 add superscripts $\tilde{n}^{d,r}$
 - d : delay to reach it
 - r : reliab. to reach it
- 2 do $(\gamma + 1)^2$ replicas
- 3 paths of up to $2 \cdot \gamma$ hops

Figure 33: OKpi expanded graph $\gamma = 3$.

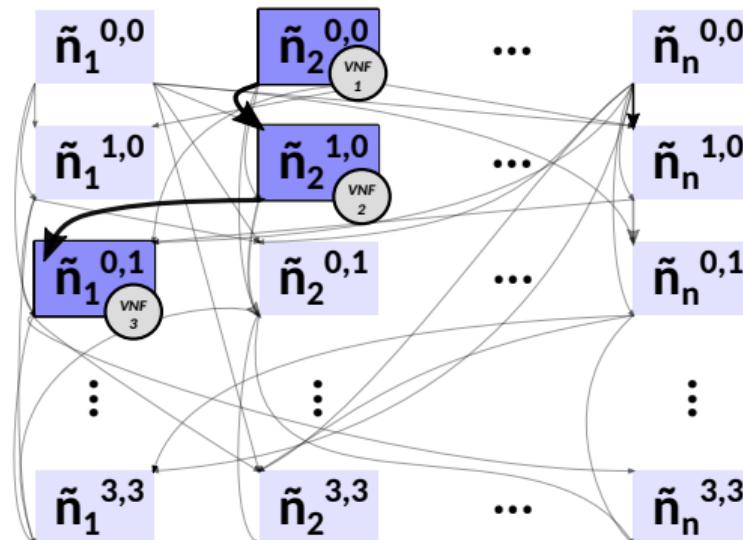
Expanded graph:

- 1 add superscripts $\tilde{n}^{d,r}$
 - d : delay to reach it
 - r : reliab. to reach it
- 2 do $(\gamma + 1)^2$ replicas
- 3 paths of up to $2 \cdot \gamma$ hops
- 4 embed across any path

Figure 33: OKpi expanded graph $\gamma = 3$.

Expanded graph:

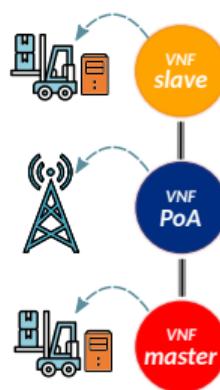
- 1 add superscripts $\tilde{n}^{d,r}$
 - d : delay to reach it
 - r : reliab. to reach it
- 2 do $(\gamma + 1)^2$ replicas
- 3 paths of up to $2 \cdot \gamma$ hops
- 4 embed across any path

Figure 33: OKpi expanded graph $\gamma = 3$.

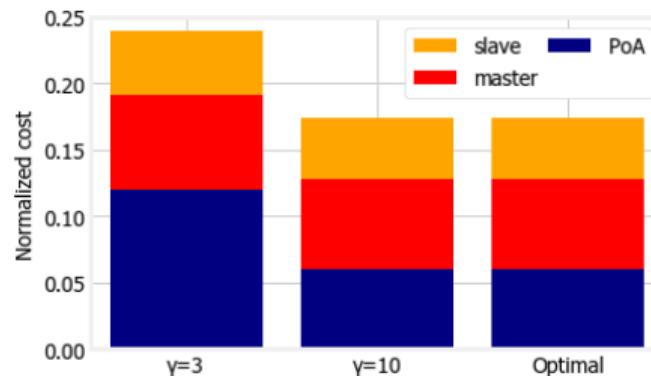
Experiments

- realistic 5G Edge & Fog scenarios
- how much to increase γ to achieve optimality
- relax delay constraint $D(s)$
- increase reliability constraint $H(s)$
- increase exchanged traffic

Simulations using realistic ITU+3GPP 5G scenarios [14]:



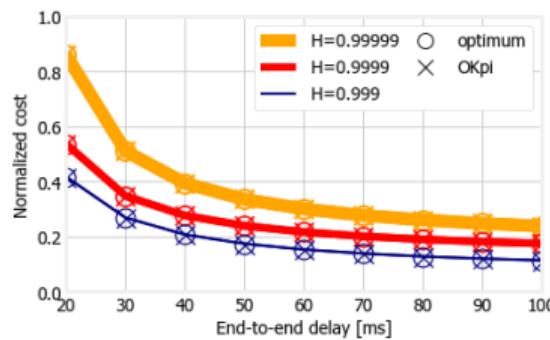
(a)



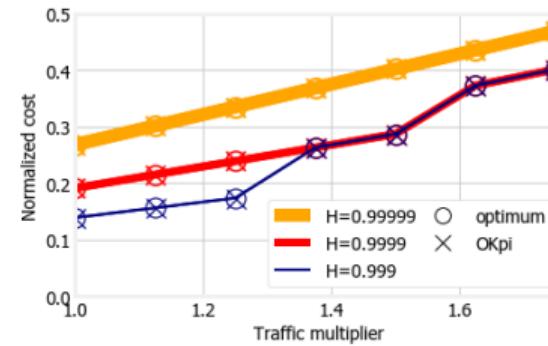
(b)

Figure 34: (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 [14]:



(a)



(b)

Figure 35: (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](https://doi.org/10.1109/INFOCOM41043.2020.9155263)
- J. Martín-Pérez, F. Malandrino, C. F. Chiasserini, M. Groshev, and C. J. Bernardos. "KPI Guarantees in Network Slicing". In: *IEEE/ACM Transactions on Networking* (2021), pp. 1–14. DOI: [10.1109/TNET.2021.3120318](https://doi.org/10.1109/TNET.2021.3120318)
- 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](https://doi.org/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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This thesis contributions:

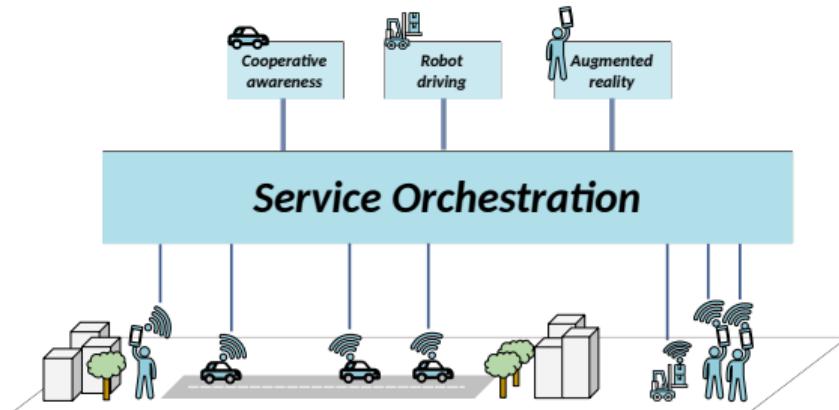


Figure 36: Service orchestration.

This thesis contributions:

- 1 generate **5G graphs** meeting
1ms RTT

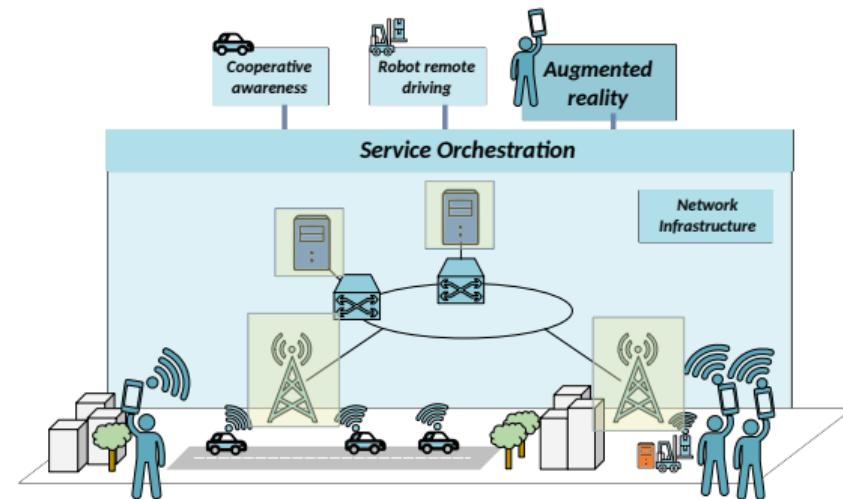


Figure 36: Service orchestration – infrastructure generation.

This thesis contributions:

- 1 generate **5G graphs** meeting 1ms RTT
- 2 DQN maximizes revenue under **federation** and dynamic pricing

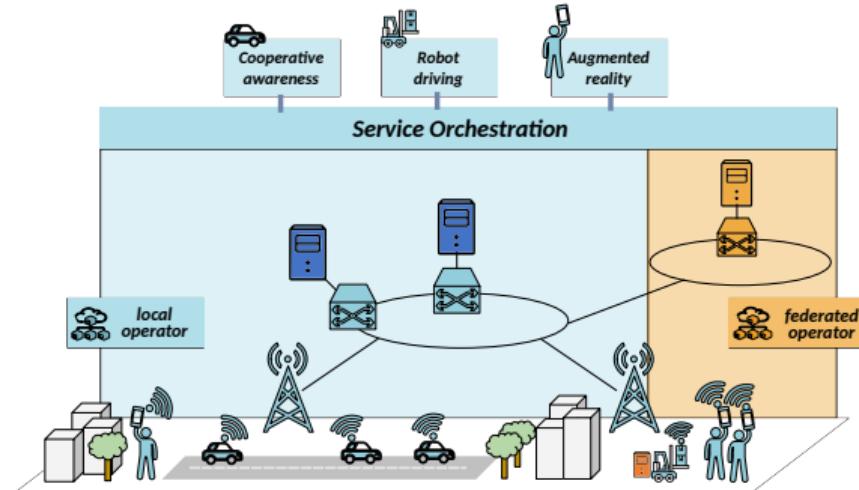


Figure 36: Service orchestration – federation.

This thesis contributions:

- 1 generate **5G graphs** meeting 1ms RTT
- 2 DQN maximizes revenue under **federation** and dynamic pricing
- 3 OKpi minimizes **VNE** cost meeting: latency, reliability, and availability constraints

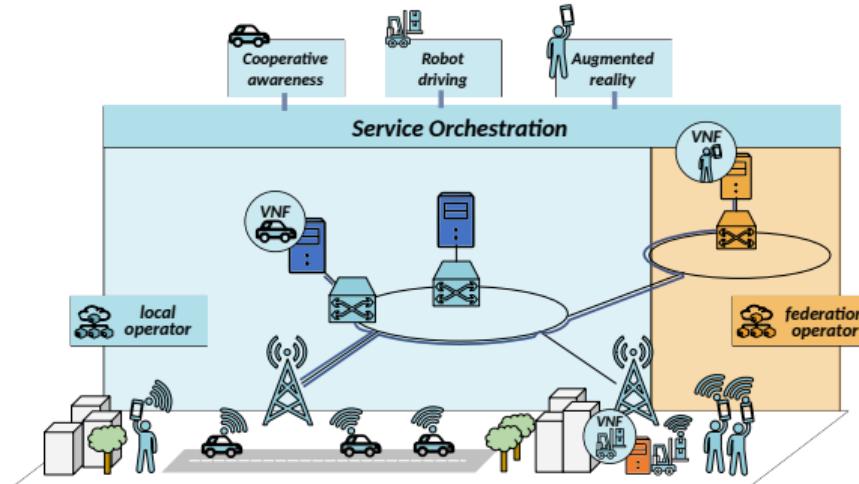


Figure 36: Service orchestration – VNE.

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

- 1 generate federated scenarios BSs, PoPs & datacenters, all at once**
- 2 DQN agent +LSTM layer to predict**

- 1 generate federated scenarios BSs, PoPs & datacenters, all at once
- 2 DQN agent +LSTM layer to predict
- 3 OKpi study on γ /runtime/optimality

Publications:

■ Conferences:

- 1 IEEE BMSB [3]
- 2 IEEE CSCN [13]
- 3 IEEE INFOCOM [15]
- 4 IEEE ICC [3]

■ Journals:

- 1 IEEE TB [14]
- 2 IEEE TMC [18]
- 3 IEEE TNSM [11]
- 4 IEEE TON [16]

Open-source – MartinPJorge@GitHub:

- 1 BS & server generation
- 2 5GEN R package
- 3 DFS, BFS w/ cutoffs
- 4 Q-table federation
- 5 DQN federation + AWS env.
- 6 AMPLPY
- 7 networkx
- 8 OKpi
- 9 FMC

Thanks for your attention!



- [1] M. Afshang and H. S. Dhillon. "Poisson Cluster Process Based Analysis of HetNets With Correlated User and Base Station Locations". In: *IEEE Transactions on Wireless Communications* 17.4 (Apr. 2018), pp. 2417–2431. ISSN: 1536-1276. DOI: 10.1109/TWC.2018.2794983.
- [2] S. Agarwal, F. Malandrino, C. F. Chiasserini, and S. De. "VNF Placement and Resource Allocation for the Support of Vertical Services in 5G Networks". In: *IEEE/ACM Trans. Netw.* 27.1 (Feb. 2019), pp. 433–446. ISSN: 1063-6692. DOI: 10.1109/TNET.2018.2890631. URL: <https://doi.org/10.1109/TNET.2018.2890631>.

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

Location of BSs:

- Neyman-Scott Poisson Cluster Process [23]
- Poisson Point Processes (PPPs) [4]
 - homogeneous [24, 1]
 - hard-core [7]
 - **inhomogeneous & Matérn II**

Location of MEC PoPs:

- along highways [25]
- within stadiums [6]
- **population census**
- **access & aggregation rings**

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 :

$$\mathbb{E}[N(C)] := \int_C e^{-\int_{B(x,r)} \mathbb{1}(\lambda(u) > \lambda(x)) \lambda(u) du} \lambda(x) dx \quad (10)$$

where r is the thinning radius of I_2 .

with

$$I_2(x, m, X, M_X) := \begin{cases} 1 & \text{if } m = \min_{m' \in M_X} \{(x', m') : x' \in B(x, r)\} \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

The RTT considered is computed as

$$RTT := 2I(\|x - m\|_1) + 2p(M) + UL + DL \quad (12)$$

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

$$\|x - m\|_1 \leq I^{-1} \left(\frac{RTT - 2p(M) - t_r}{2} \right) = m_M \quad (13)$$

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 [20].

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

- Alternating Direction Method of Multipliers (ADMM) [19]
- branching heuristic [9]
- graph-based message passing [28]
- greedy with backtracking [17]
- **cutoffs in Dijkstra, DFS and BFS [12]**
- **Q-learning federation [3]**

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

- **real-price traces AWS**
- **Deep Q-learning**
- **Telefónica scenario**

User pays $p^{(t)}$ for the service σ

$$p^{(t)}(\sigma) = (1 + P)l^{(t)}(\sigma) \quad (14)$$

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:

$$r^{(t)}(X_t) := \sum_{\substack{\sigma: x(\sigma)=0 \\ a(\sigma) \leq t \leq d(\sigma)}} p^{a(\sigma)}(\sigma) + \sum_{\substack{\sigma: x(\sigma)=1 \\ a(\sigma) \leq t \leq d(\sigma)}} \left[p^{a(\sigma)}(\sigma) - f^{(t)}(\sigma) \right] \quad (15)$$

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

$$f(p^{(t)}(\sigma)) := \begin{cases} k \left(1 - \left(\frac{p^{(t)}(\sigma)}{K \cdot M}\right)^a\right)^b, & p^{(t)}(\sigma) \leq K \cdot M \\ 0, & p^{(t)}(\sigma) > K \cdot M \end{cases} \quad (16)$$

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.

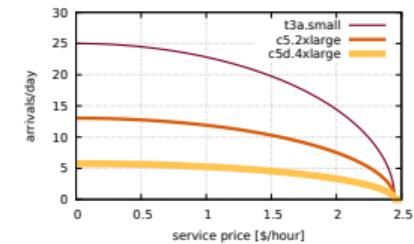


Figure 37: Impact of prices on arriving users.

Increase of P leads to:

- less user arrivals
- larger reward

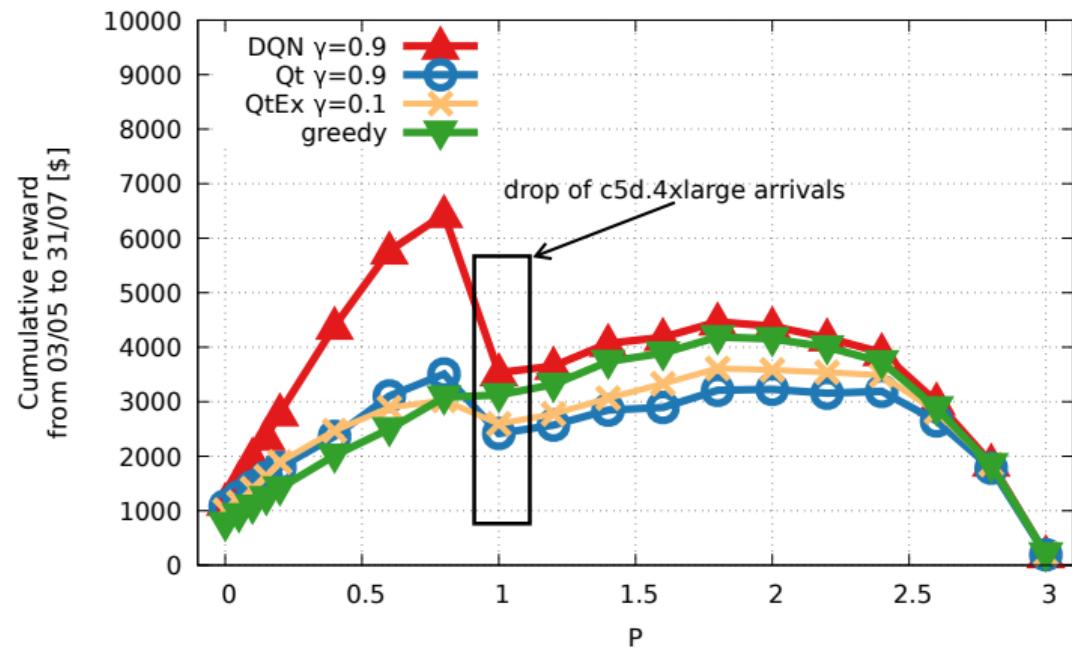


Figure 38: Impact of the marginal benefit P in the commutative reward achieved by each solution.

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 [21]
- AIA: meet latency and throughput [27]

OKpi accounts for:

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

Decision graph edges have weights: $w(\tilde{n}_1, \tilde{n}_2) = \left(\frac{\tilde{D}_{\tilde{n}_1, \tilde{n}_2}}{D(s)}, \frac{\log \tilde{\eta}_{\tilde{n}_1, \tilde{n}_2}}{\log H(s)} \right)$

The **expanded graph** has nodes: $\{\tilde{n}_1^{0,0}, \tilde{n}_2^{0,0}, \dots, \tilde{n}_1^{\gamma,\gamma}, \tilde{n}_2^{\gamma,\gamma}\}$

In the **expanded graph** OKpi creates **edges** as:

$$\tilde{n}_1^{d_1, r_1} \longrightarrow \tilde{n}_2^{d_1 + \lceil \gamma w_1(\tilde{n}_1, \tilde{n}_2) \rceil, r_1 + \lceil \gamma w_2(\tilde{n}_1, \tilde{n}_2) \rceil} \quad (17)$$

Property

The worst-case computational complexity of building the expanded graph is

$$O\left((\gamma + 1)^4 \cdot |\tilde{N}|^2 \cdot K\right) \quad (18)$$

- γ : resolution parameter
- \tilde{N} : decision graph nodes
- K : number of additive constraints (KPIs)