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NFV Orchestration in Edge and Fog Scenarios

26th October, 2021

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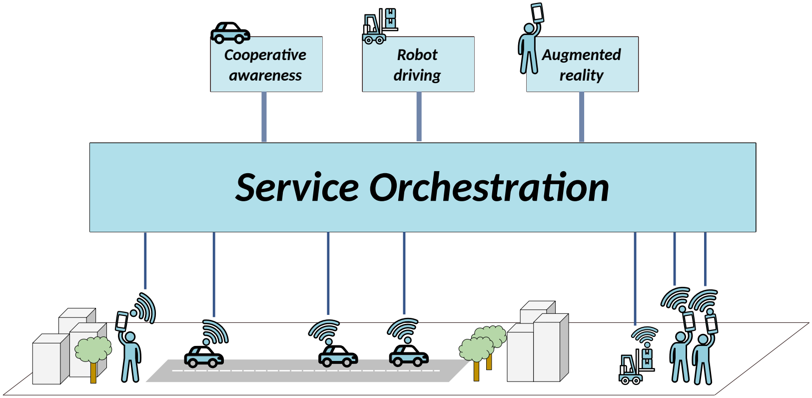


Figure 1: Orchestration of three services.

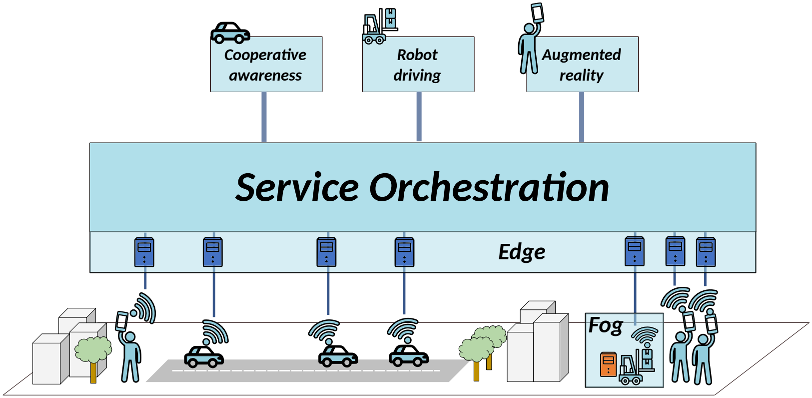


Figure 1: Orchestration of three services in Edge & Fog.

Service Orchestration:

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

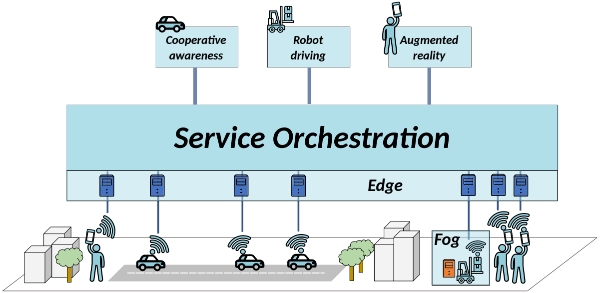


Figure 1: Orchestration of three services in Edge & Fog.

Outline

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

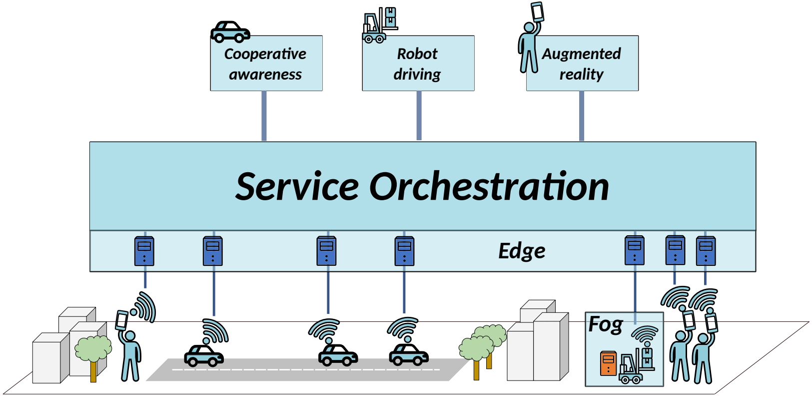


Figure 2: Orchestration of three services in Edge & Fog.

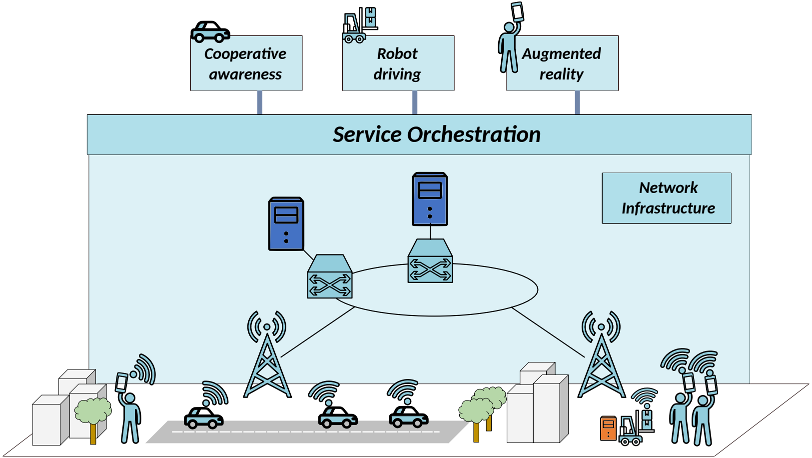


Figure 2: Network infrastructure for service providing.

This part derives **location** of:

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

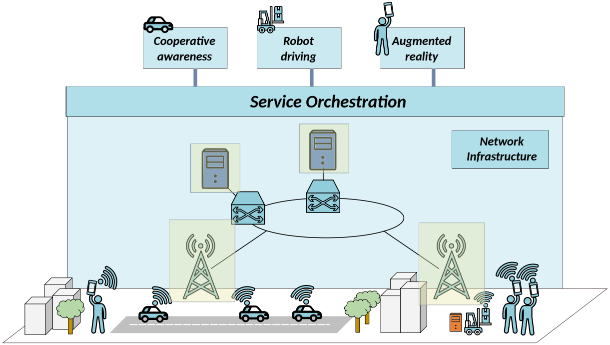


Figure 3: Network infrastructure for service providing.

This part derives **location** of:

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

for **augmented reality**:

- tactile latency 1ms

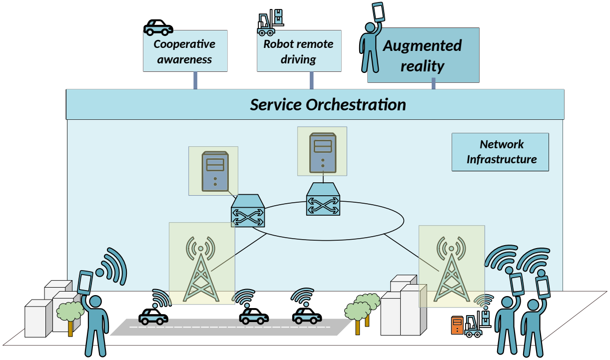


Figure 3: Network infrastructure for service providing.

New methodology in the SoA

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

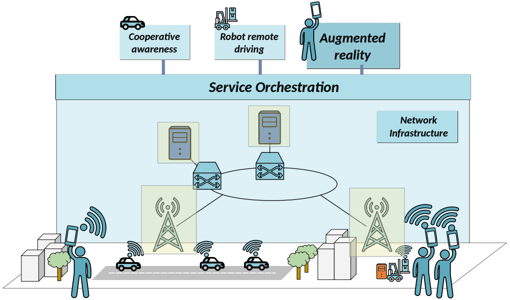


Figure 4: Network infrastructure for service providing.

Higher gentrification $\implies$ more BSs

- R – region of interest
- C_i – area

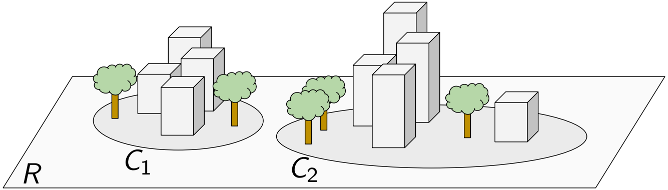
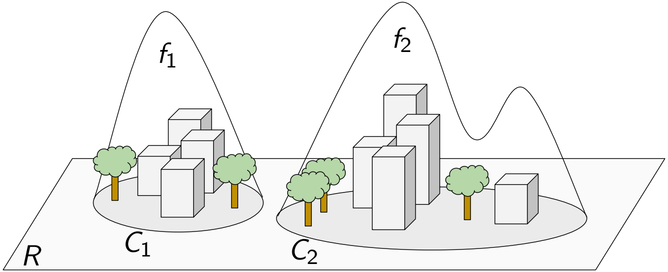


Figure 5: *Revolution functions* of a region with two building areas.

Higher gentrification $\implies$ more BSs

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



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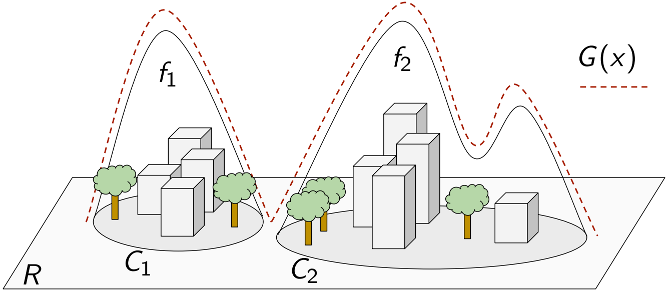
Higher gentrification $\implies$ more BSs

- 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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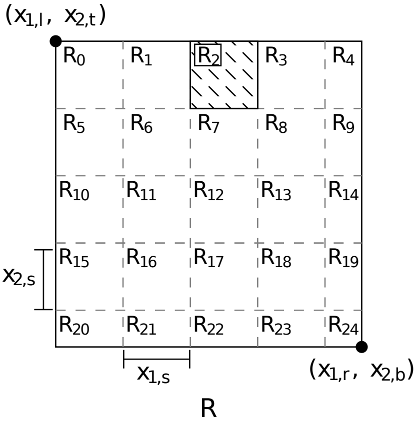
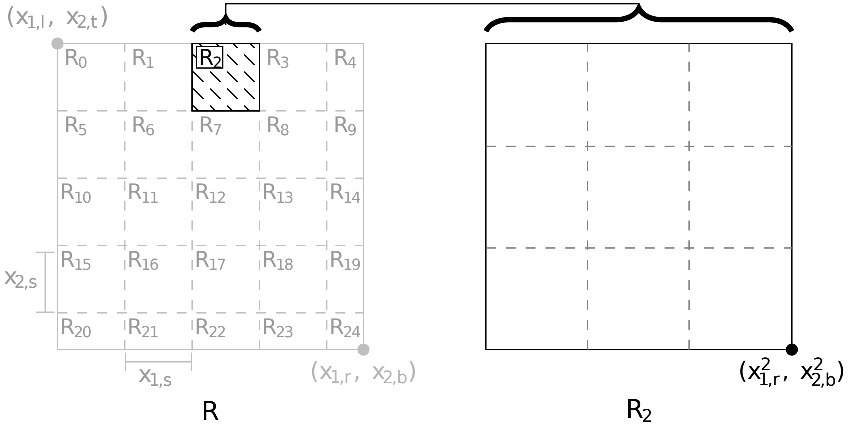


Figure 6: BS location – inhomogeneous Mattérn II process.



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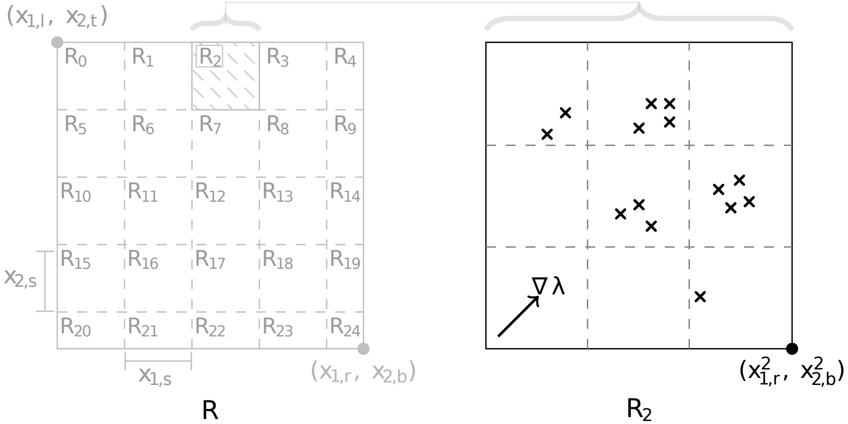
$\lambda(x) \sim G(x)$ probability of BS at x.



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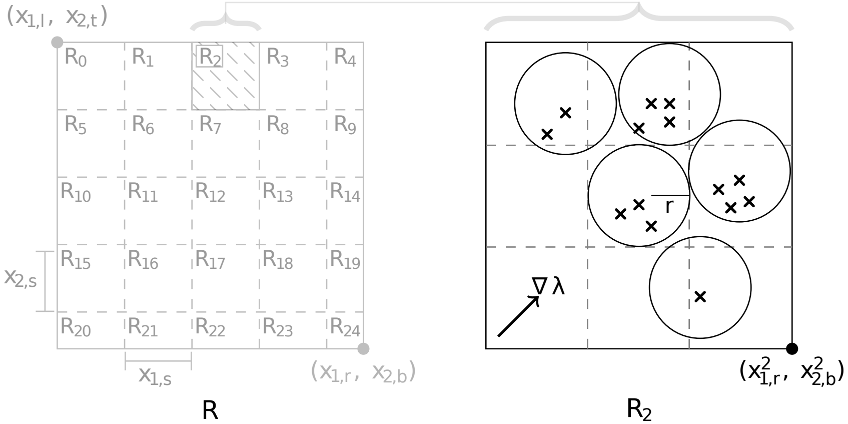

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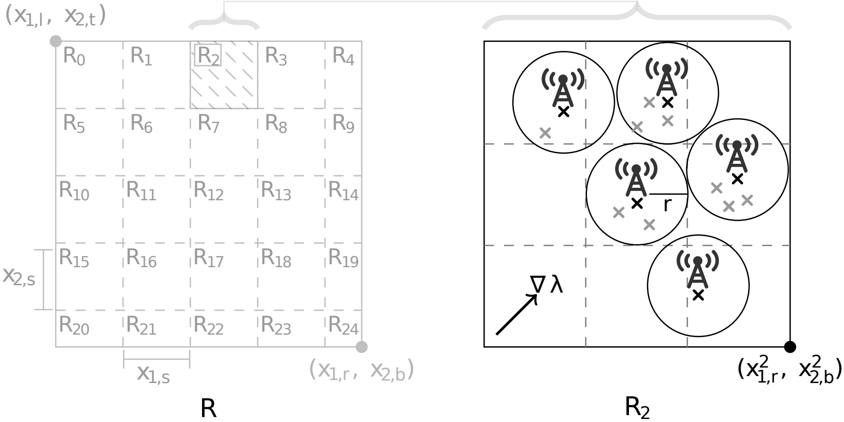

Figure 6: BS location – inhomogeneous Mattérn II process.

Inhomogeneous Mattérn II PPs applied on:

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

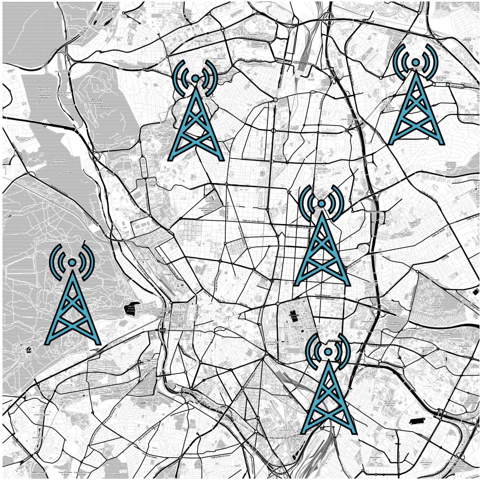

Figure 7: Location of BSs.

Inhomogeneous Mattérn II PPs applied on:

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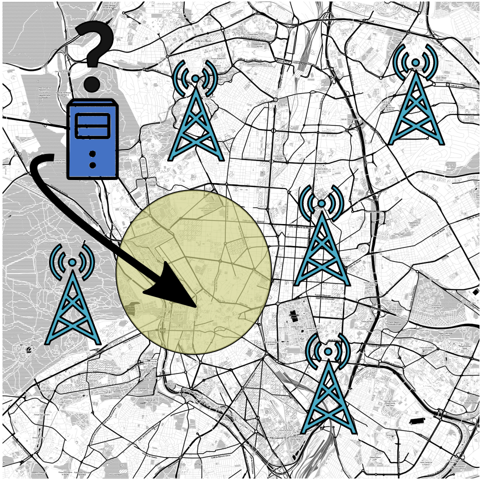

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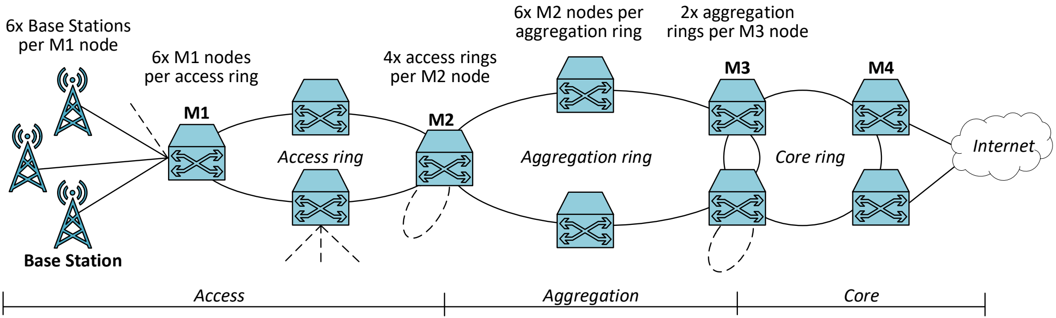
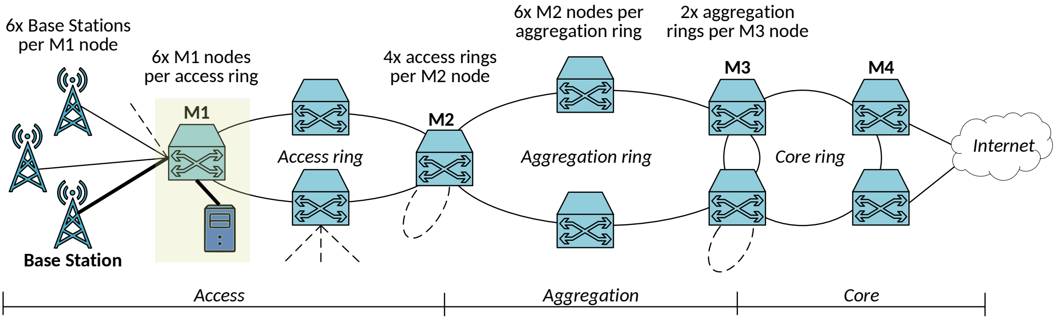


Figure 8: Reference network infrastructure as illustrated[1] in [5] and based on [8].

[1]Author: Dr. Luca Cominardi.



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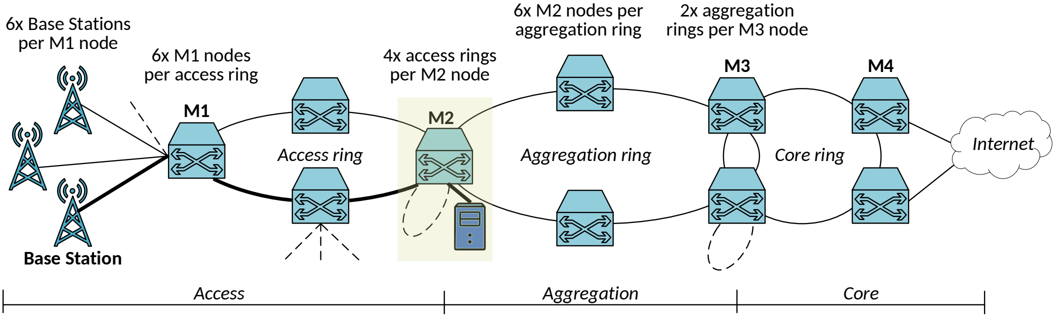

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Derive server location s.t. $RTT \leq 1\text{ms}$ (tactile latency – **augmented reality**):

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

- d: distance between BS and server
- M: #traversed rings (e.g., $1, 2, \ldots$)
- 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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Derive server location s.t. $RTT \leq 1$ms (tactile latency – **augmented reality**):

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- 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

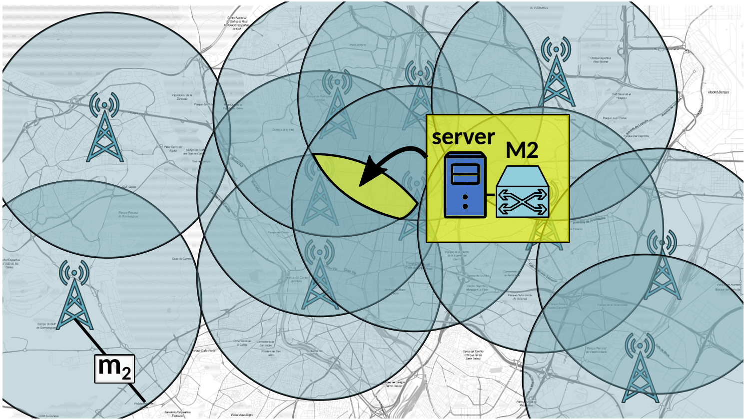
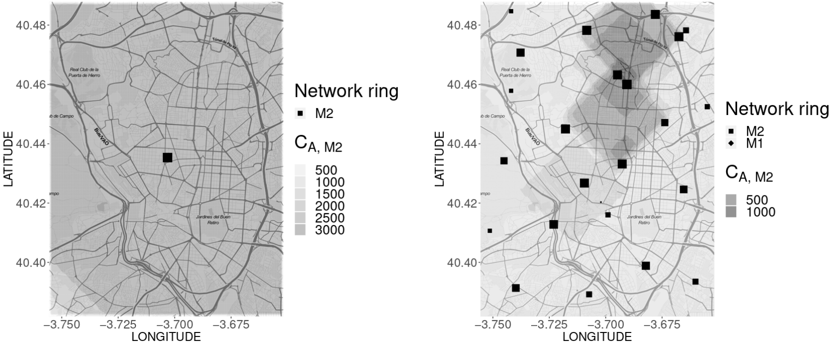


Figure 9: How to select MEC PoP location.

Experiments

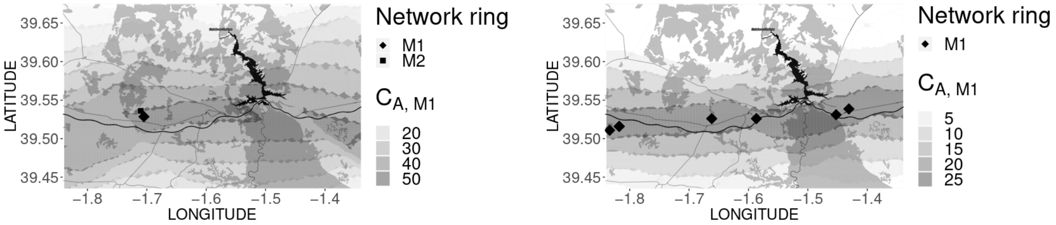
- Urban, highway, industrial **scenarios**
- NR **BSs** (different UL+DL):
  - FDD 120 kHz 7s
  - TDD 120 kHz 7s
  - FDD 30 kHz 2s
- **Servers**:
  - M1 switch – access ring
  - M2 switch – aggregation ring
- **Meet**: tactile latencies 1ms



(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.

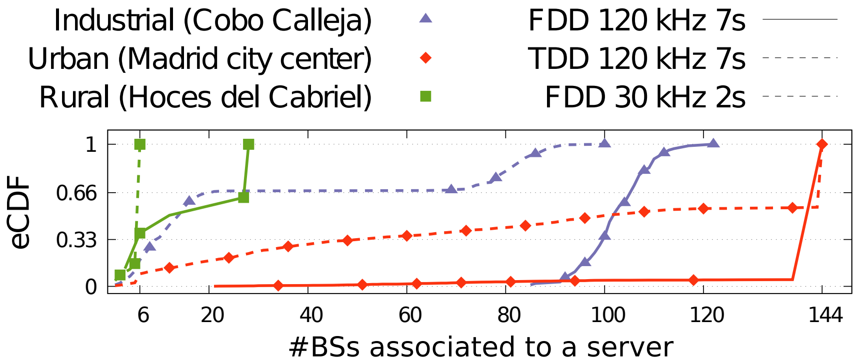


Figure 12: eCDF of the number of BSs assigned to a server in the studied scenarios.

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

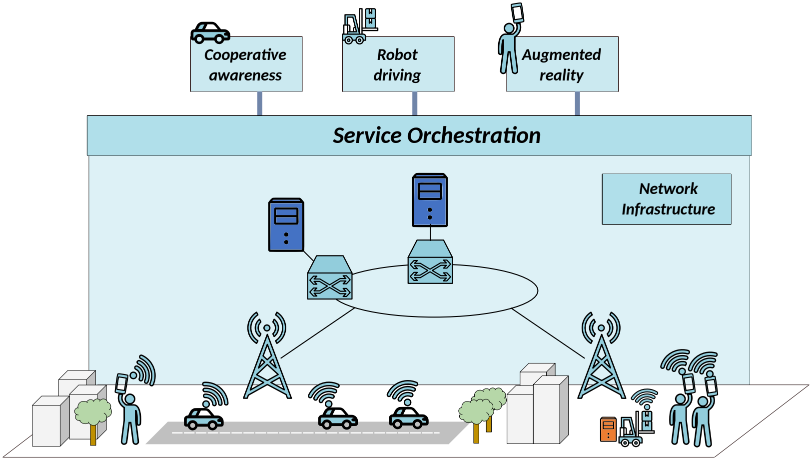


Figure 13: Infrastructure design.

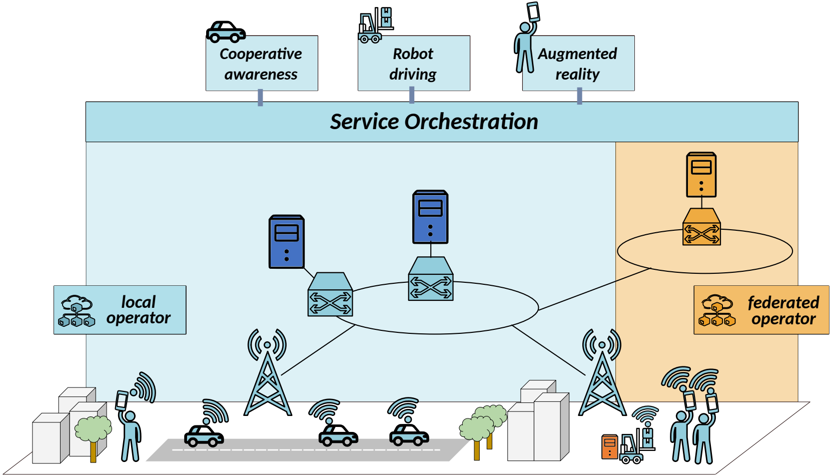


Figure 13: Local and federation operator.

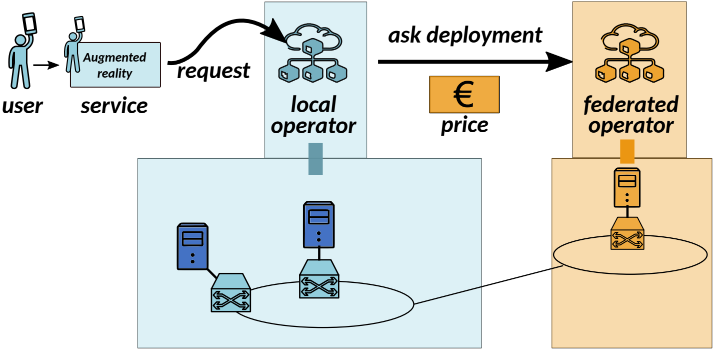
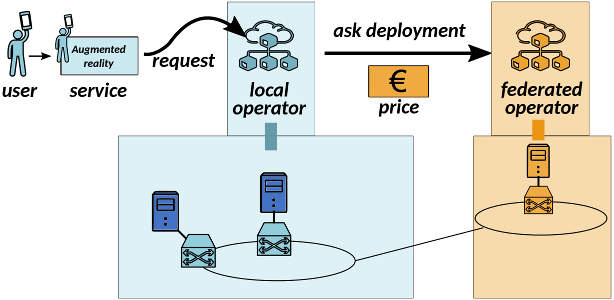


Figure 14: Service federation.

New in SoA:

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



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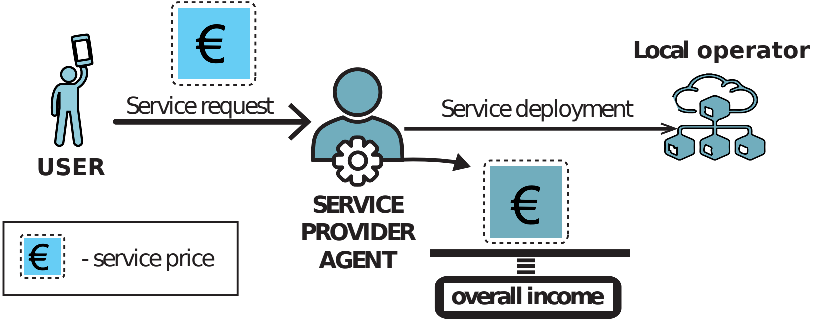


Figure 15: Business model - local deployment[2].

[2]Based on Kiril Antevski illustration

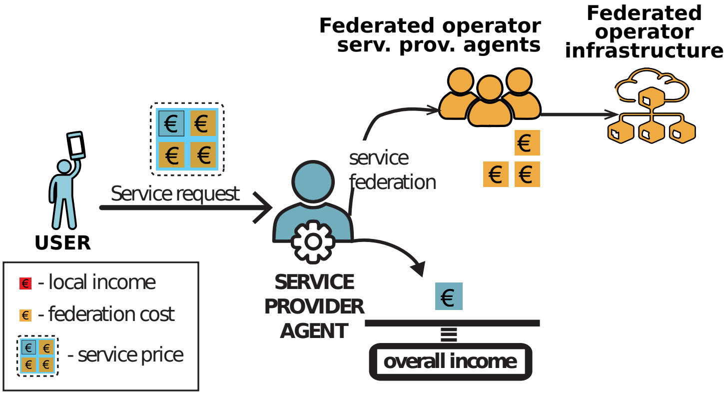
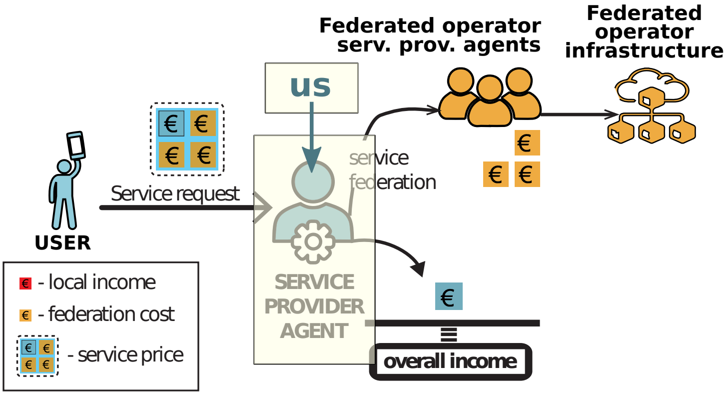


Figure 16: Business model - federate deployment[3].

[3] Based on Kiril Antevski illustration



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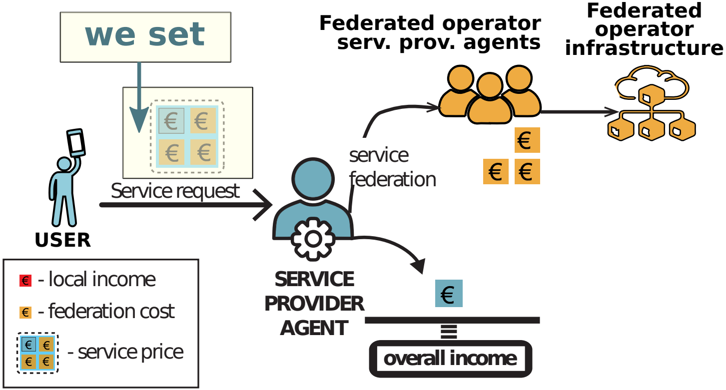

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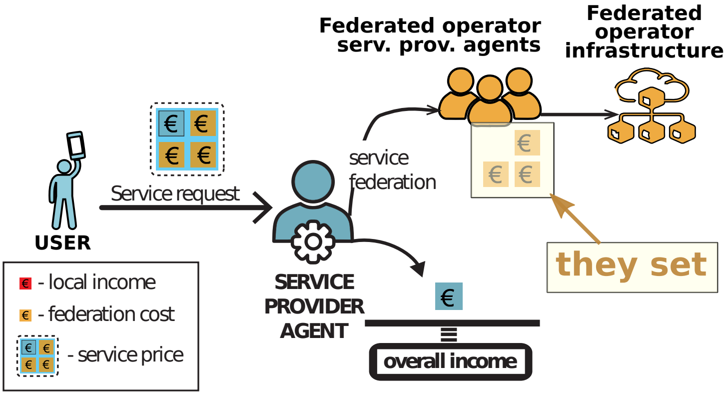

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t3a.small:

- 2 CPUs
- memory 2 GB
- storage 100 GB

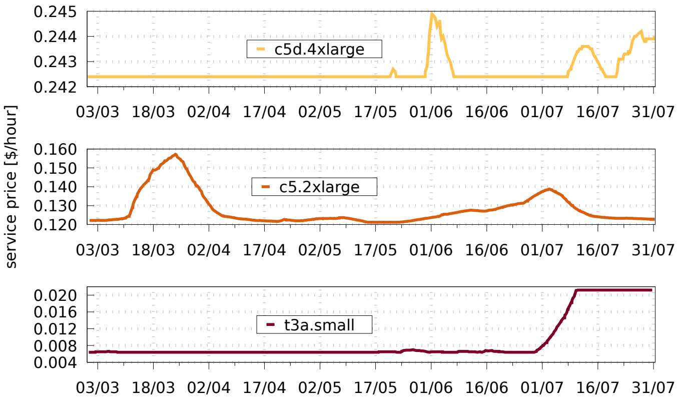

Figure 17: AWS service prices during 2020 in west Europe.

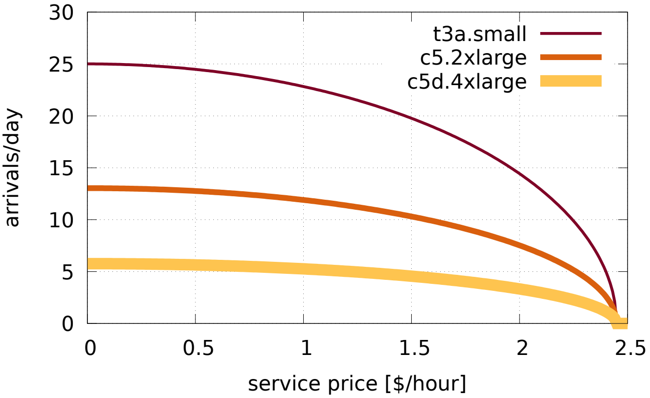

Figure 18: Impact of prices on arriving users – based on tid study [22] and [26].

Considering:

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

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

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

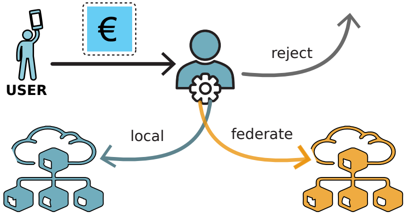

Figure 19: Possible actions.

Obtained **reward**:

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

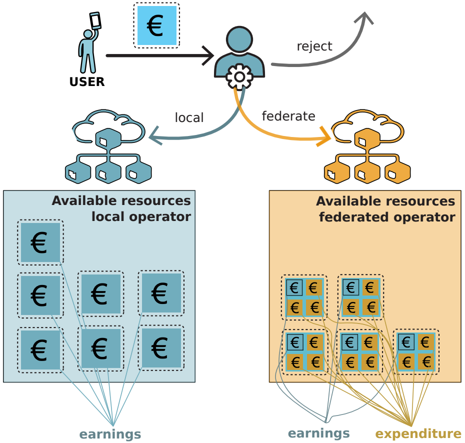

Figure 20: Environment snapshot at time t.

Obtained **reward**:

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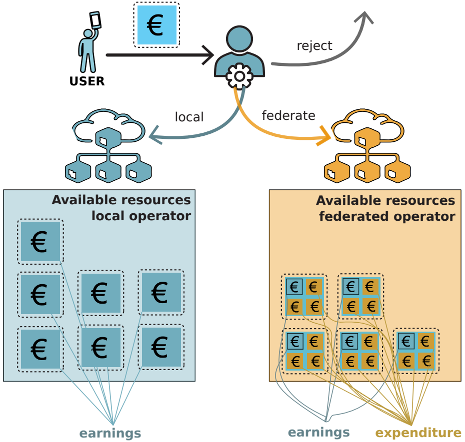

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federation

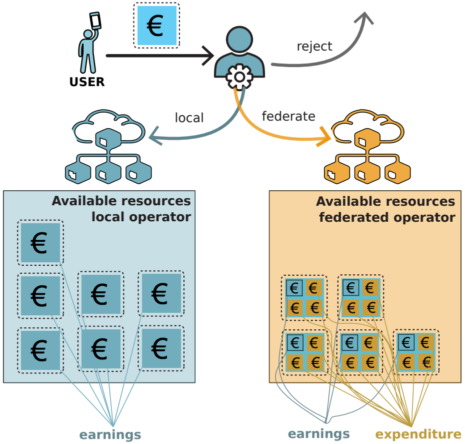

Figure 20: Environment snapshot at time t.

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

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

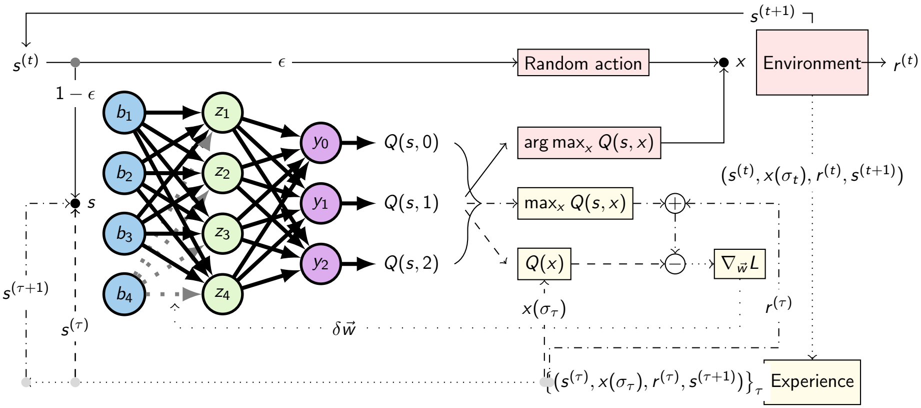

Figure 21: DQN architecture to decide rejection/local/federate.

Experimentation:

- Telefónica infrastructure & resources [22]

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- AWS prices dataset:
  - training 29/02/2020 – 02/05/2020
  - testing 03/05/2020 –31/07/2020

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- 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

NFV Orchestration in federated environments
Thesis contribution

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Comparison of:

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

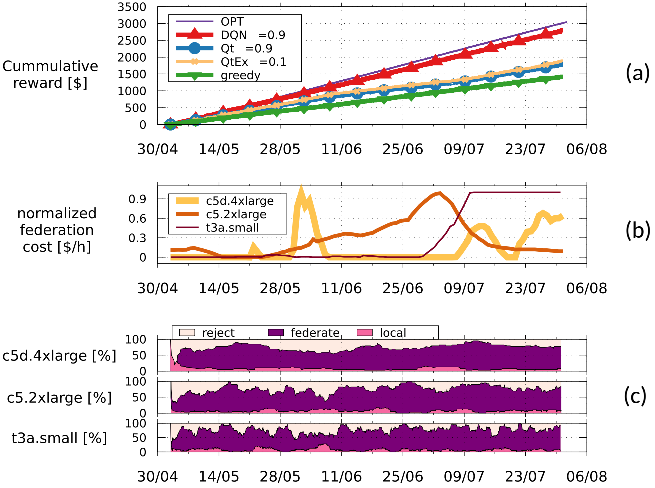

Figure 22: Federation agents' performance.

Comparison of:

- Optimal
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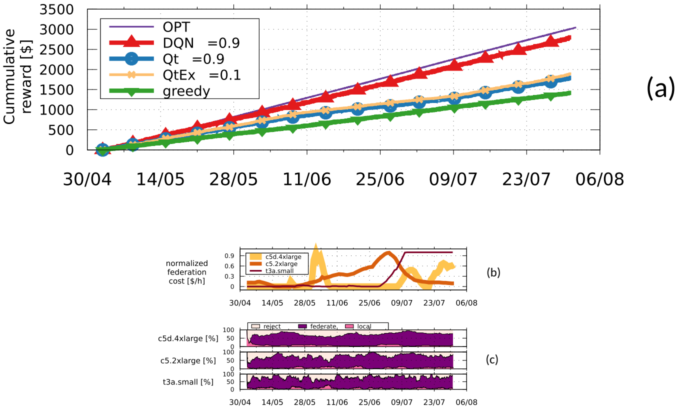

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Comparison of:

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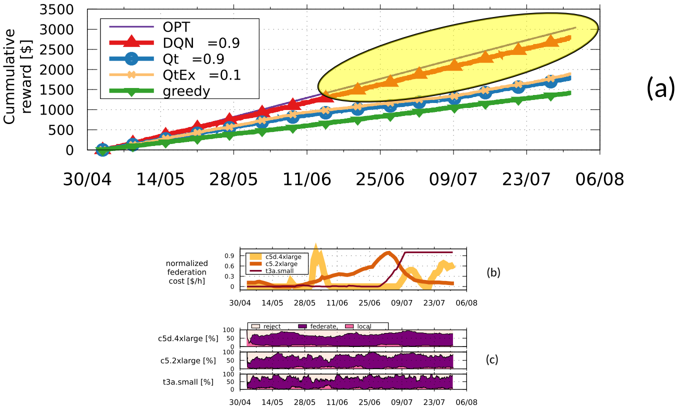
Results:

- near-optimal



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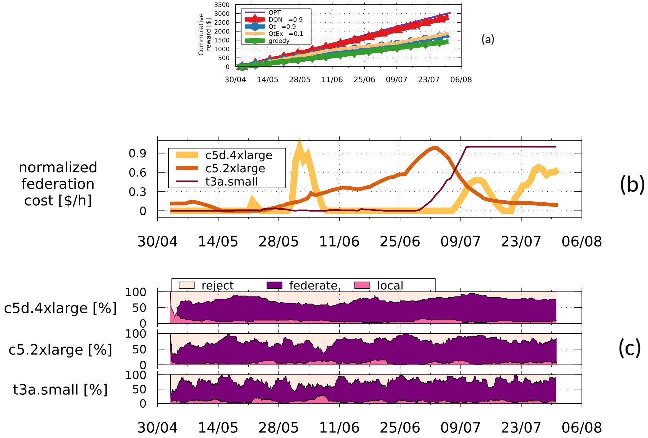


Figure 22: Federation agents' performance.

Comparison of:

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

Results:

- near-optimal
- react upon peaks

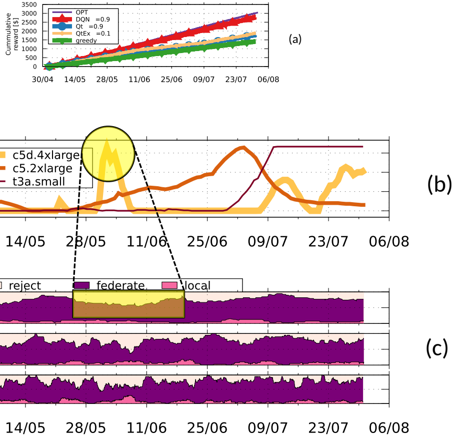
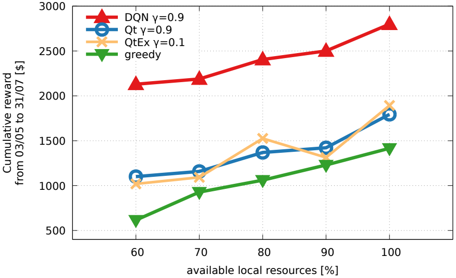
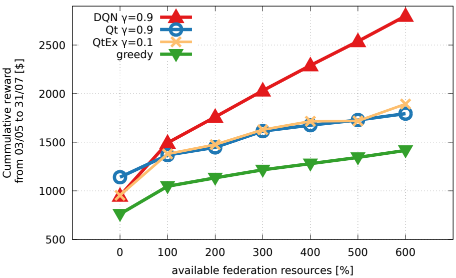


Figure 22: Federation agents' performance.



(a) Increasing local resources.



(b) Increasing resources in federation.

Figure 23: Cumulative reward vs. available resources.

Outline

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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/`

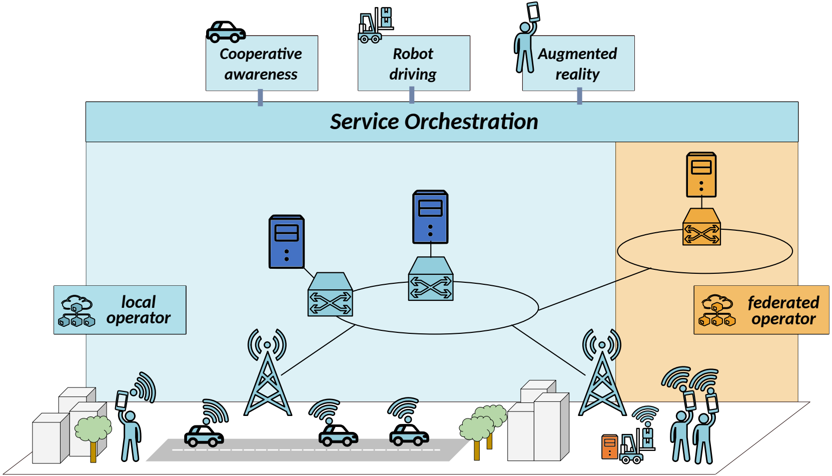

Figure 24: Local and federation operator

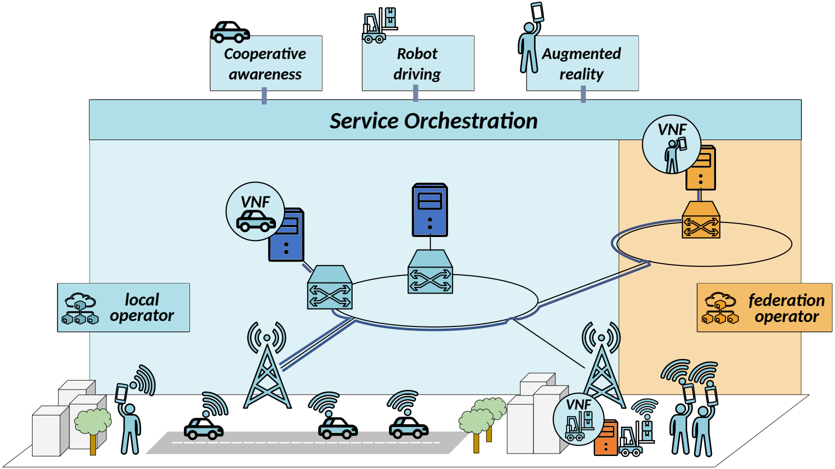

Figure 25: Services' embedding.

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

- latency constraints
- radio coverage
- geographical availability
- reliability

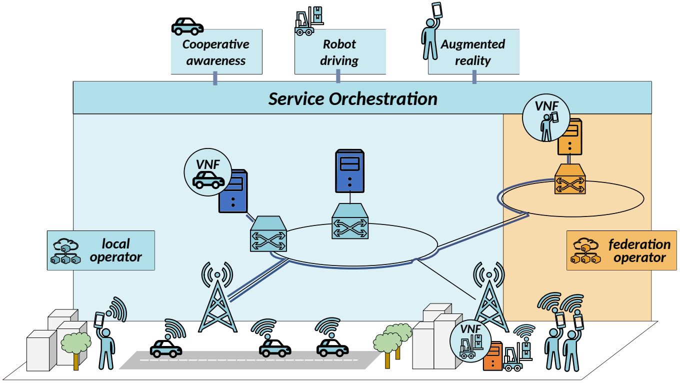

Figure 25: Services' embedding.

OKpi solves the VNE problem.

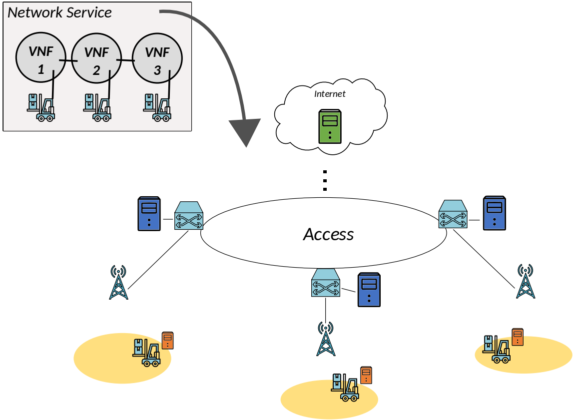

Figure 26: Virtual Network Function Embedding (VNE).

OKpi solves the VNE problem.

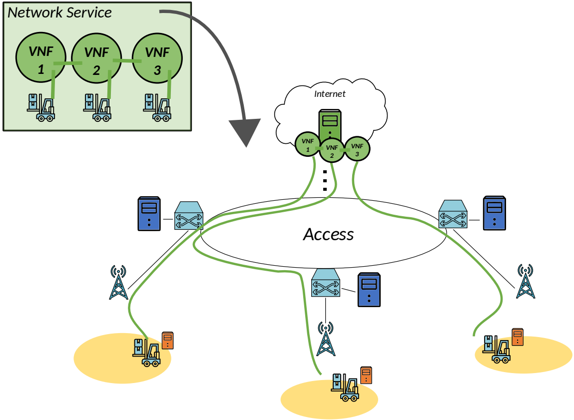

Figure 26: Virtual Network Function Embedding (VNE).

OKpi solves the VNE problem.

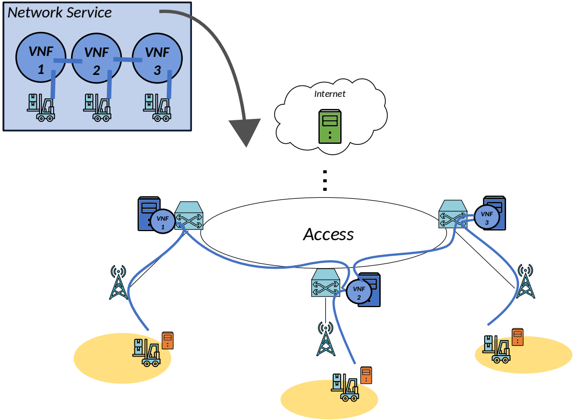

Figure 26: Virtual Network Function Embedding (VNE).

OKpi solves the VNE problem.

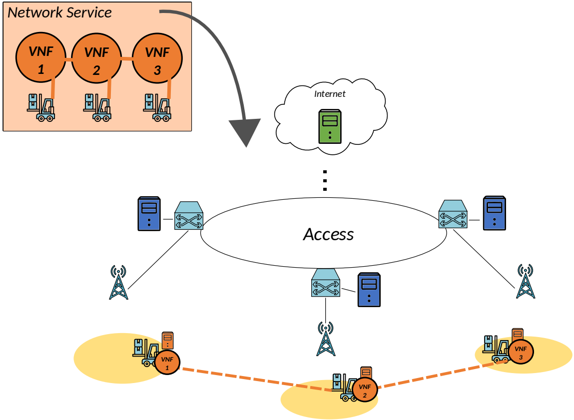

Figure 26: Virtual Network Function Embedding (VNE).

Latency constraint $D(s)$:

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

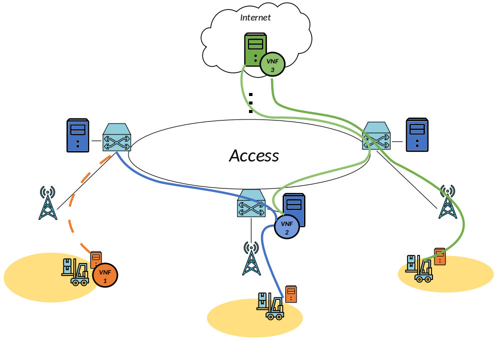

Figure 27: Service s delay.

Latency constraint $D(s)$:

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

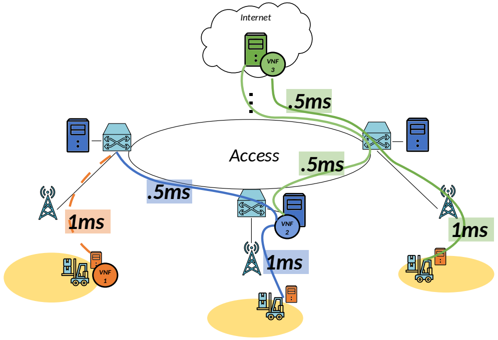

Figure 27: Service s delay.

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

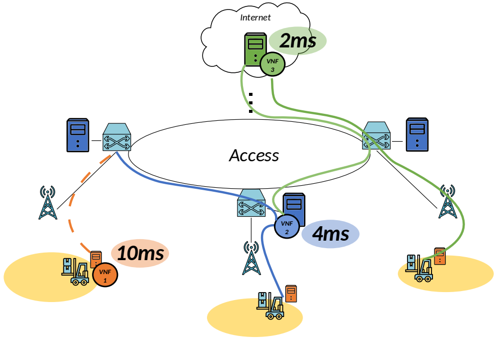

Figure 27: Service s delay.

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

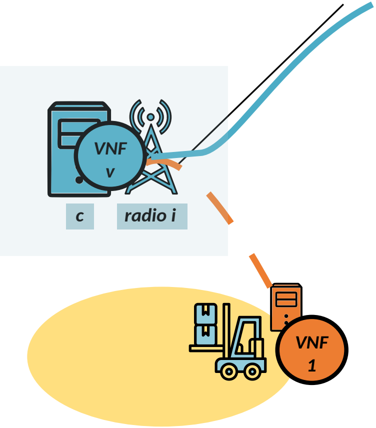

Figure 28: Radio VNF.

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)

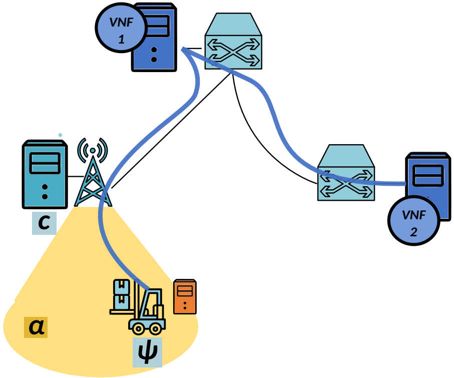

Figure 29: coverage of region α.

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

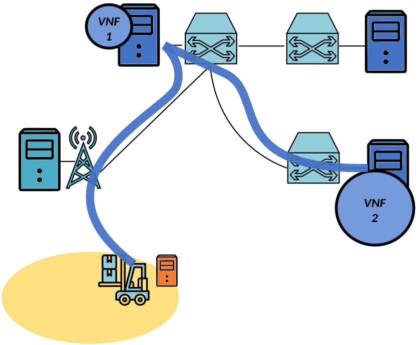

Figure 30: Traffic path.

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

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

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

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

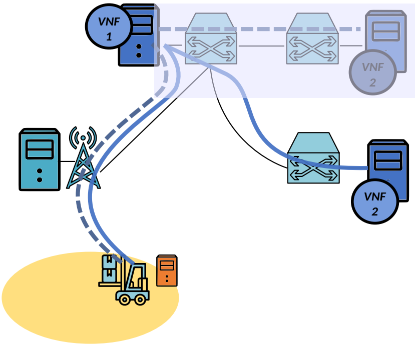

Figure 30: Fractioned traffic path.

Formulate an optimization problem:

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

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

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.

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

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

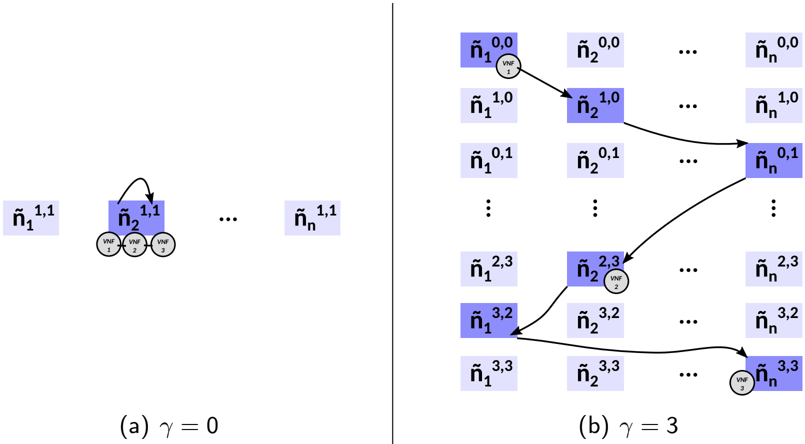

Figure 31: Impact of resolution γ on OKpi embedding.

OKpi (all KPI) solve VNE in two steps:

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

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

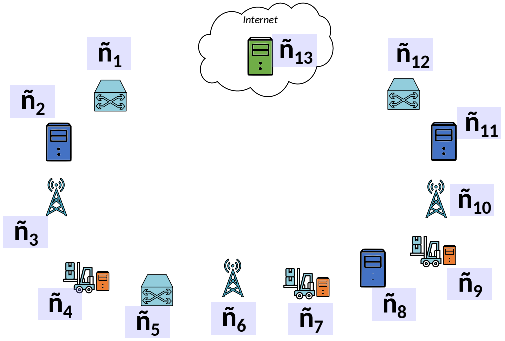

Figure 32: OKpi decision graph.

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

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

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

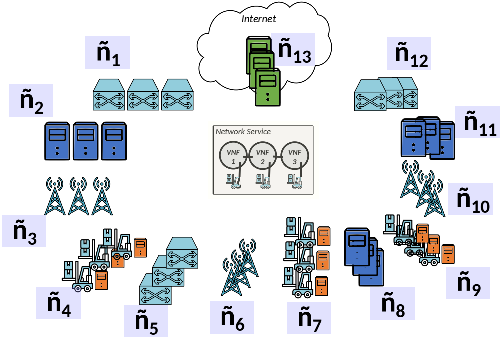

Figure 32: OKpi decision graph.

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:

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

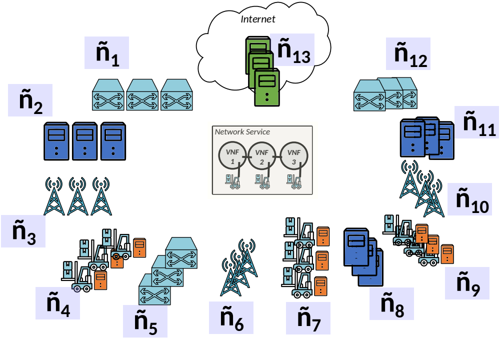

Figure 32: OKpi decision graph.

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:

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

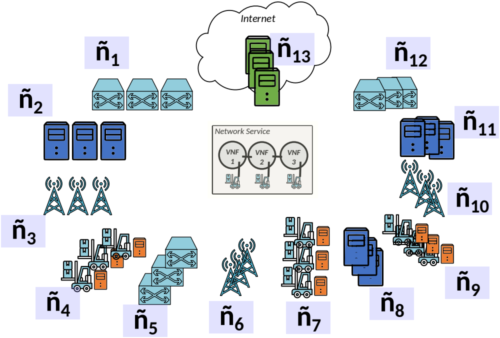

Figure 32: OKpi decision graph.

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:

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

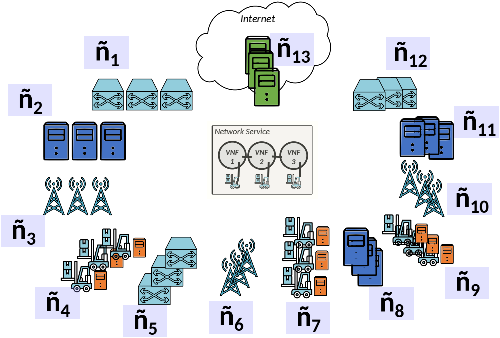

Figure 32: OKpi decision graph.

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 $(\tilde{n}_1, \tilde{n}_2)$

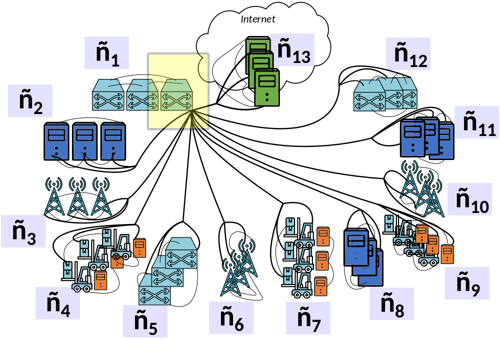

Figure 32: OKpi decision graph.

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

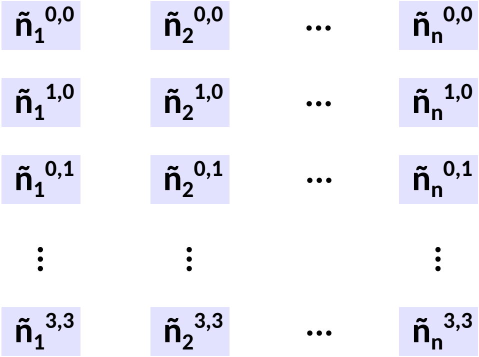

Figure 33: OKpi expanded graph $\gamma = 3$.

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

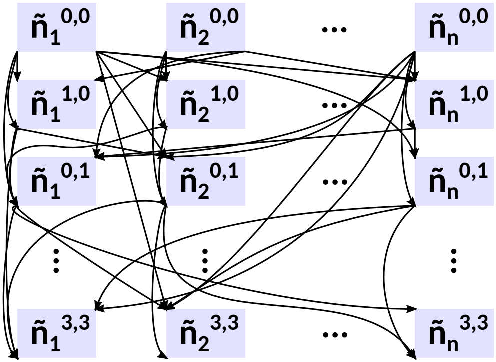

Figure 33: OKpi expanded graph $\gamma = 3$.

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

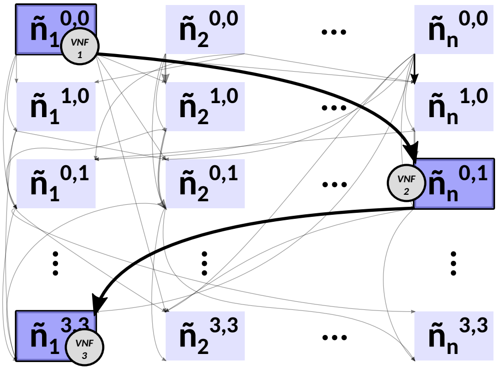

Figure 33: OKpi expanded graph $\gamma = 3$.

Expanded graph:

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3. paths of up to $2\cdot\gamma$ hops
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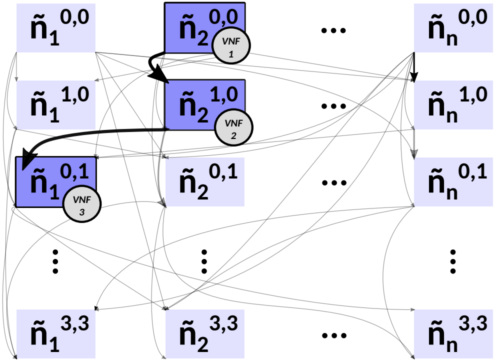

Figure 33: OKpi expanded graph $\gamma = 3$.

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

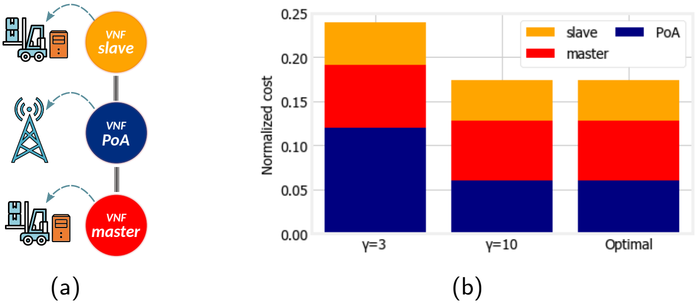

Figure 34: (a) master-slave robotic VS illustration, and (b) optimality comparison of the VNFs' deployment costs using OKpi with $\gamma = 3, 10$.

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

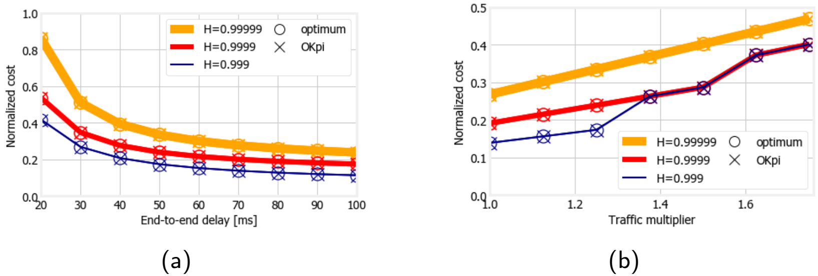

Figure 35: (a) end-to-end delay, and (b) traffic impact on deployment cost of master-slave robotic VS.

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`
- 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`
- 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`

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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:

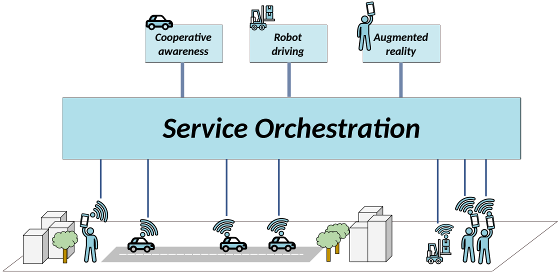

Figure 36: Service orchestration.

This thesis contributions:

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

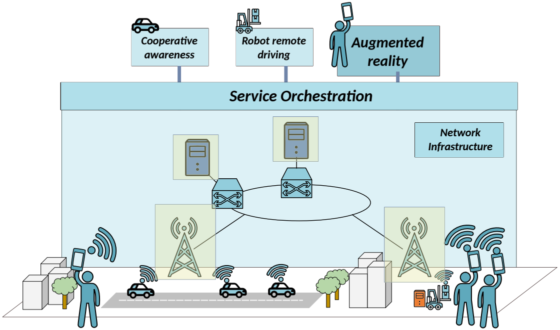

Figure 36: Service orchestration – infrastructure generation.

This thesis contributions:

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

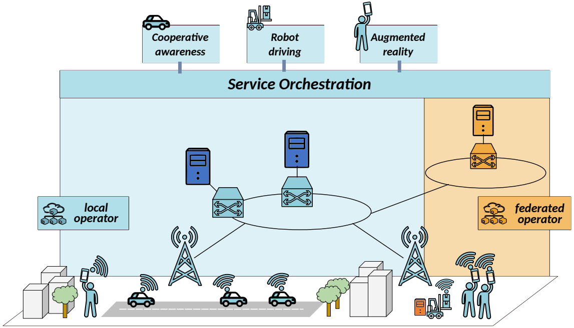

Figure 36: Service orchestration – federation.

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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

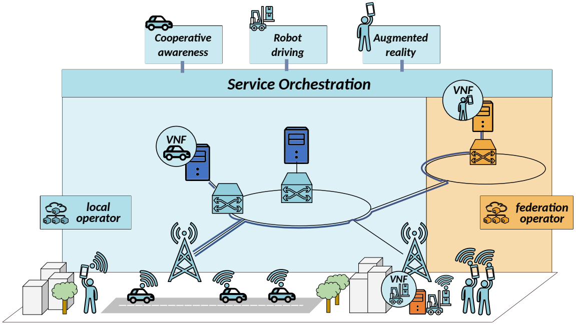

Figure 36: Service orchestration – VNE.

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

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

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

DOWNLOAD THE PDF

Presentation available at: `https://github.com/MartinPJorge/thesis-presentation/`

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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 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:

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

where r is the thinning radius of l_2.

with

$$l_2(x, m, X, M_X) := \begin{cases} 1 & \text{if } m = \min_{m' \in M_X} \left\{(x', m') : x' \in B(x, r)\right\} \\ 0 & \text{otherwise} \end{cases} \tag{11}$$

uc3m

The RTT considered is computed as

$$RTT := 2l\left(\|x - m\|_1\right) + 2p(M) + UL + DL \tag{12}$$

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

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

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

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

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:

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

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

uc3m

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

where $M = \max_{\sigma,t}\{I^{(t)}(\sigma)\}$ 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.

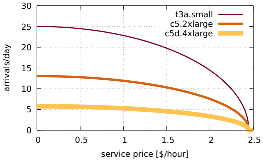

Figure 37: Impact of prices on arriving users.

Increase of P leads to:

- less user arrivals
- larger reward

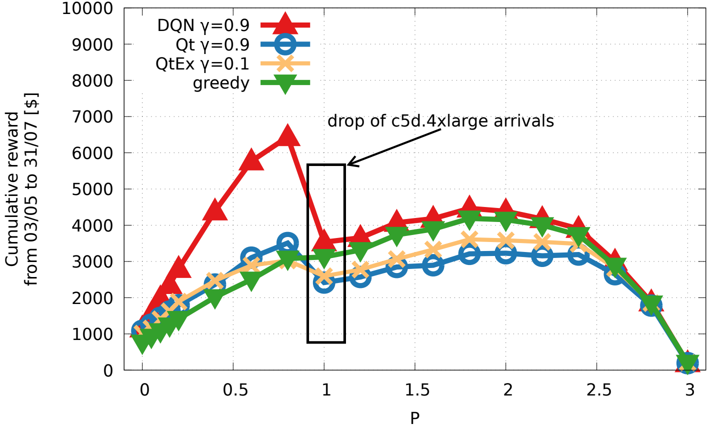

Figure 38: Impact of the marginal benefit P in the commutative reward achieved by each solution.

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**

uc3m

OKpi only connects $\tilde{n}_1^{d_1,r_1}$ with $\tilde{n}_2^{d_2,r_2}$ if:

1. $d_1 + \gamma \cdot d(\tilde{n}_1, \tilde{n}_2) \leq d_2$
2. $r_1 + \gamma \cdot r(\tilde{n}_1, \tilde{n}_2) \leq r_2$

uc3m

Property

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

$$O\left((\gamma + 1)^4 \cdot |\widetilde{N}|^2 \cdot K\right) \tag{17}$$

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