Dynamic Control and Optimization of Wireless Virtual Networks

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Université Paris-Saclay, CentraleSupélec, CNRS, L2S and Nokia Bell Labs

Advisors
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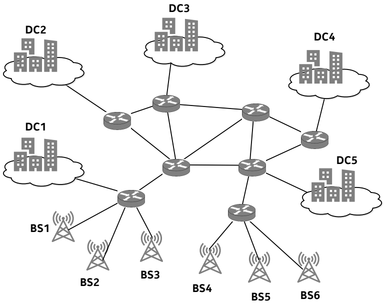
Sylvaine Kerboeuf (Nokia Bell Labs)

CentraleSupélec, Gif-sur-Yvette, June 7, 2021



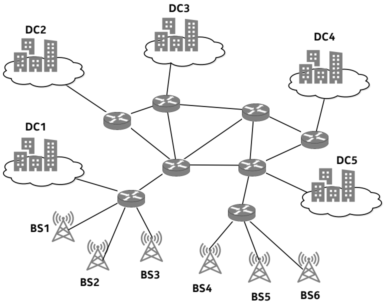
Past: physical dedicated devices: switches, routers, *etc*.

Network virtualization era:

- SDN (2008): decouples the control and data plane
- NFV (2012): virtualizes network functions → VNF

Network slicing (2015): leverages SDN and NFV [NGMN'15]

SDN: Software Defined Networking NFV: Network Function Virtualization VNF: Virtual Network Function



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Network slicing | Introduction

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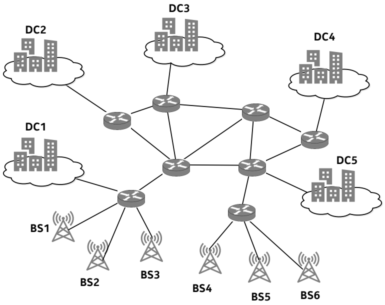

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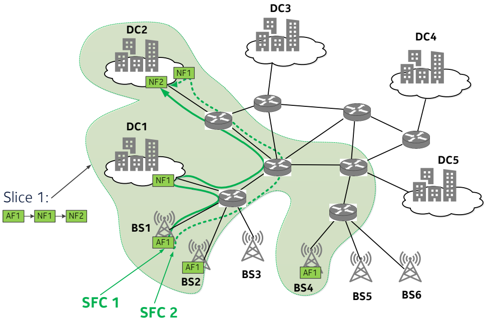

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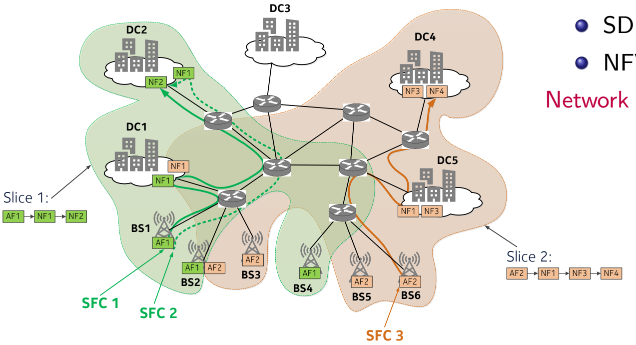

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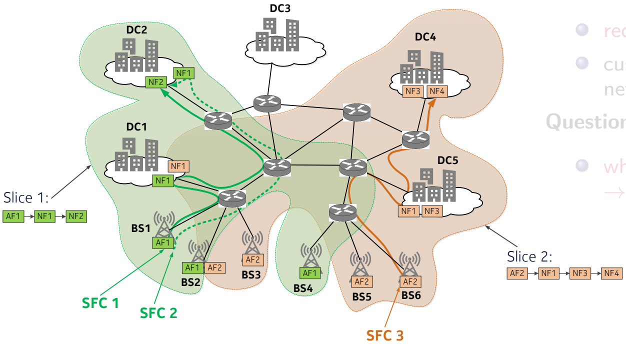

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- increase flexibility in network operations [Rost'17]
- reduce overall equipment and management costs [Liang'14]
- customers can manage their own apps by exploiting built-in network slices tailored to their needs [GSM'17]

Question:

- where to place VNFs to deploy SFCs (slice)
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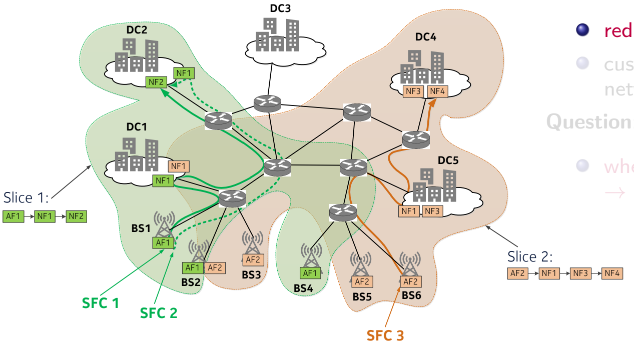

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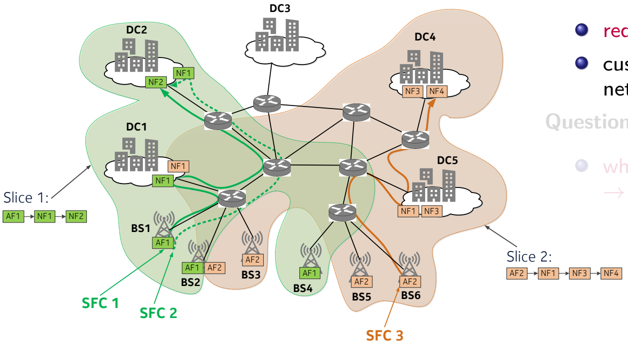

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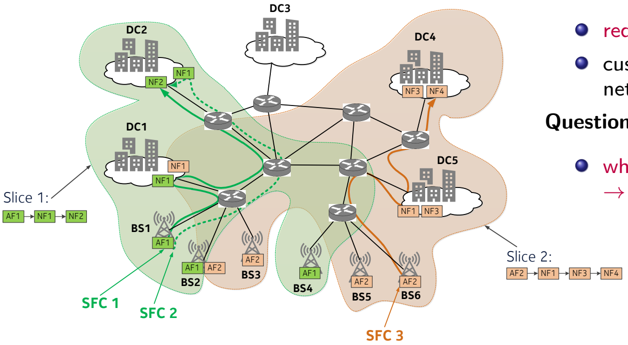

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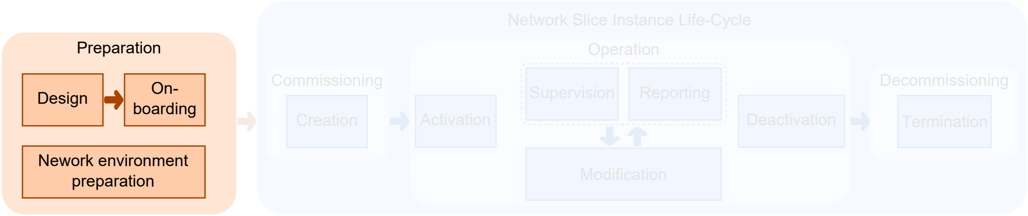
3GPP view on network slicing managements aspects



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Network slicing | Life-cycle

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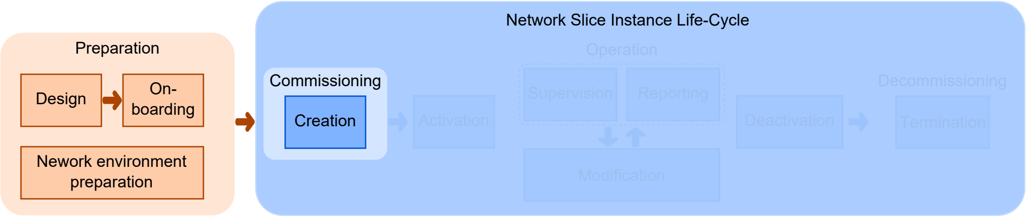

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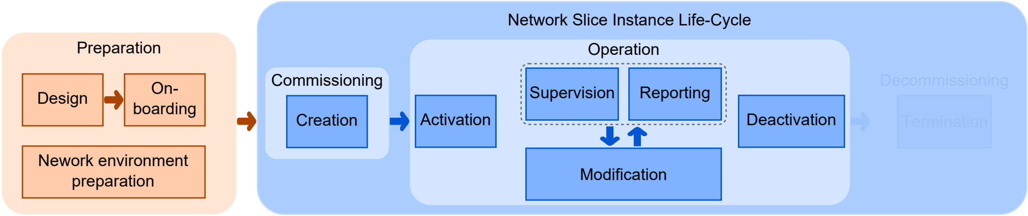

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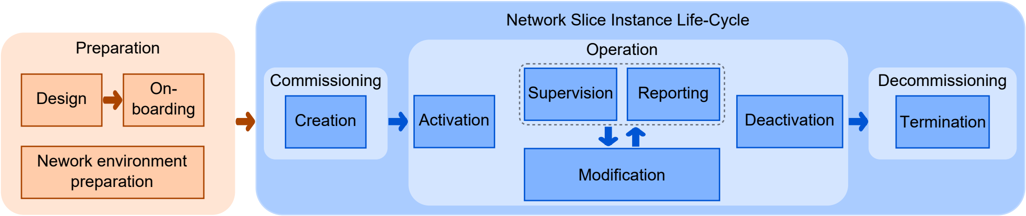

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Challenges addressed:

- Provision enough infrastructure resources to satisfy slice resource demands
- Account for coverage constraints
- Account for uncertainties
- Account for *in-advance* slice requests (anticipated provisioning)

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Contributions

Part I. Deterministic slice resource demands

Part II. Random slice resource demands

1

network provisioning

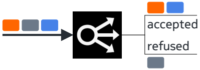
2

coverage-aware

3

uncertainty-aware

4



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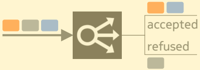

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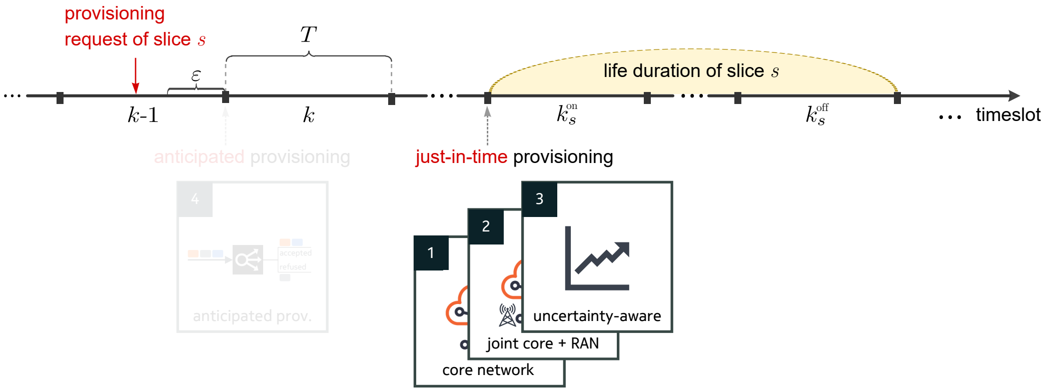
System Model | Slice provisioning requests



just-in-time: performed only for slices that need to be activated in the next time slot

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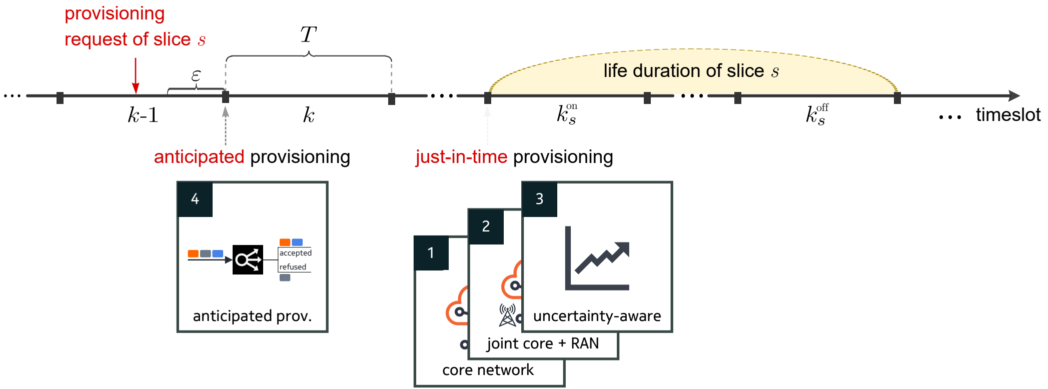

just-in-time: performed only for slices that need to be activated in the next time slot
anticipated: if not enough resources to satisfy all requests $\rightarrow$ useful to perform provisioning *in advance* to response to the request

Outline

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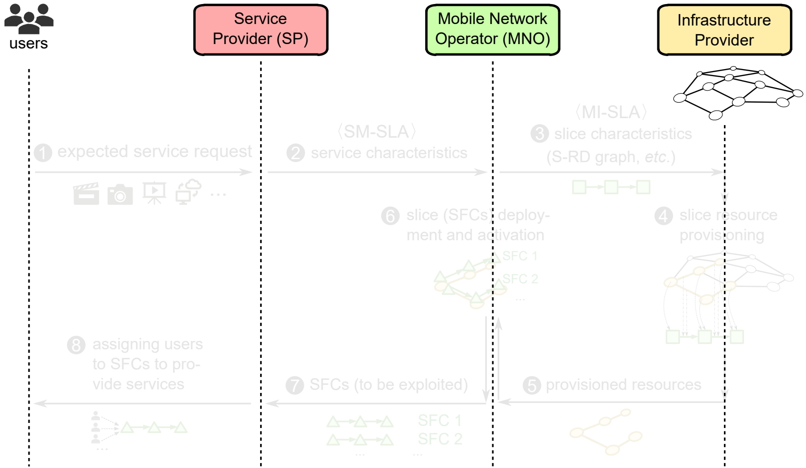
1. System model
2. Main contributions
   - Contribution 1: Network resource provisioning
   - Contribution 4: Anticipated provisioning
3. Conclusions and Perspective
   - Contribution 2: Coverage-aware resource provisioning
   - Contribution 3: Uncertainty-aware resource provisioning

System Model | Slice request processing



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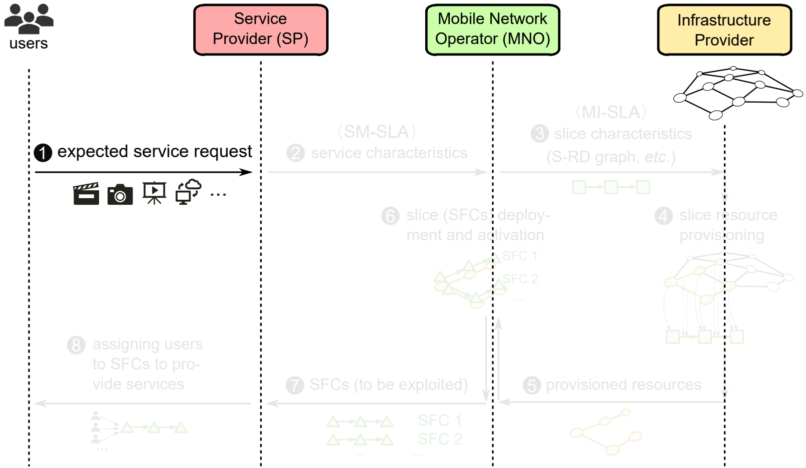

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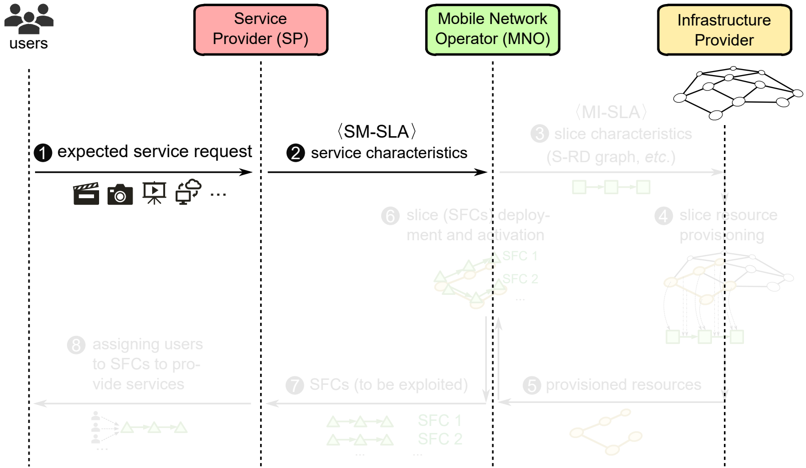

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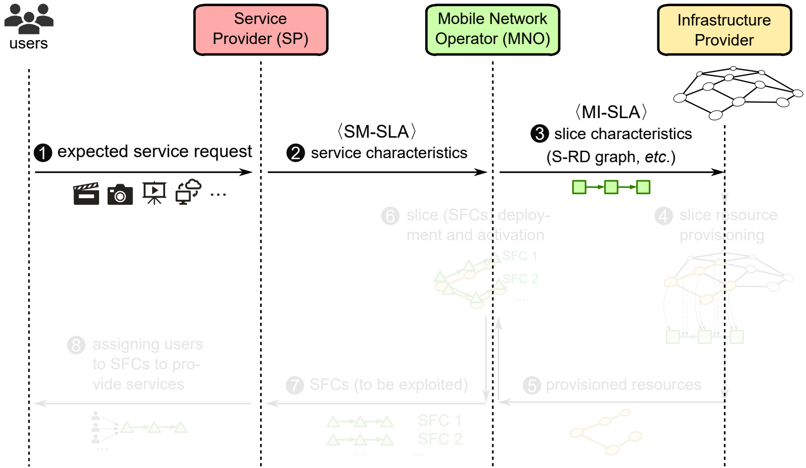

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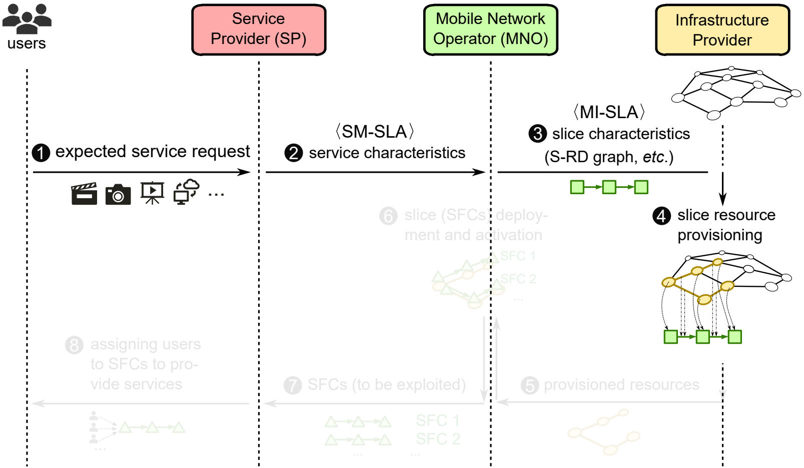

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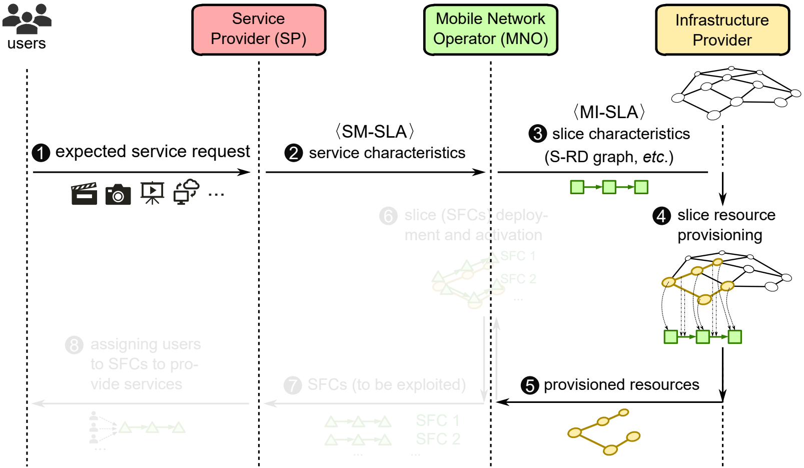

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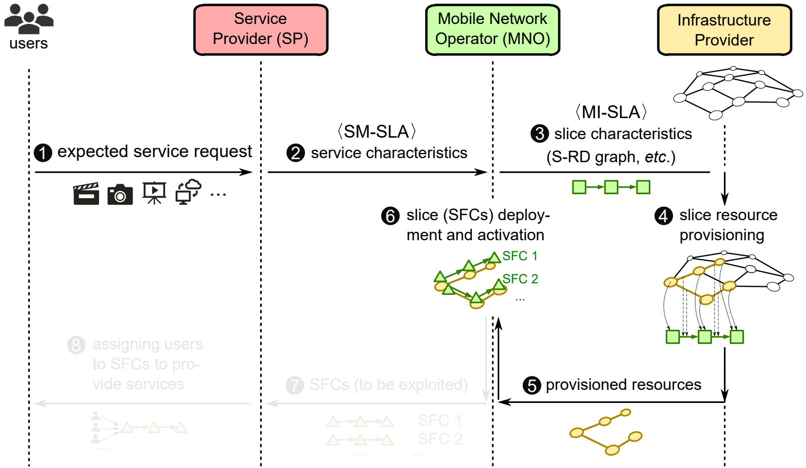

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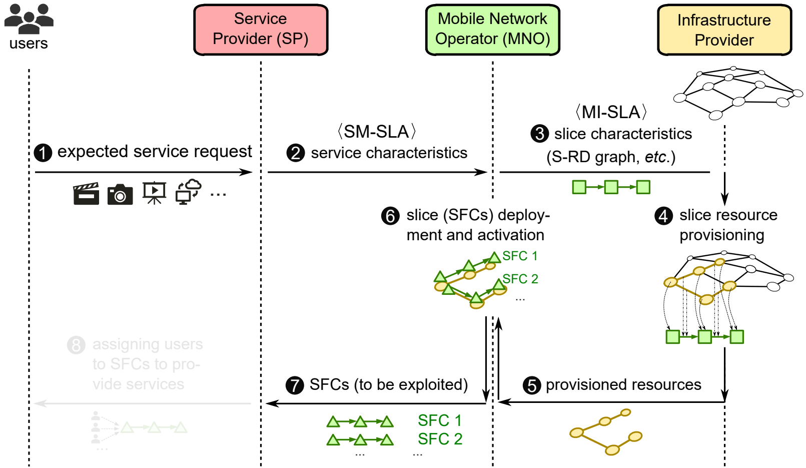

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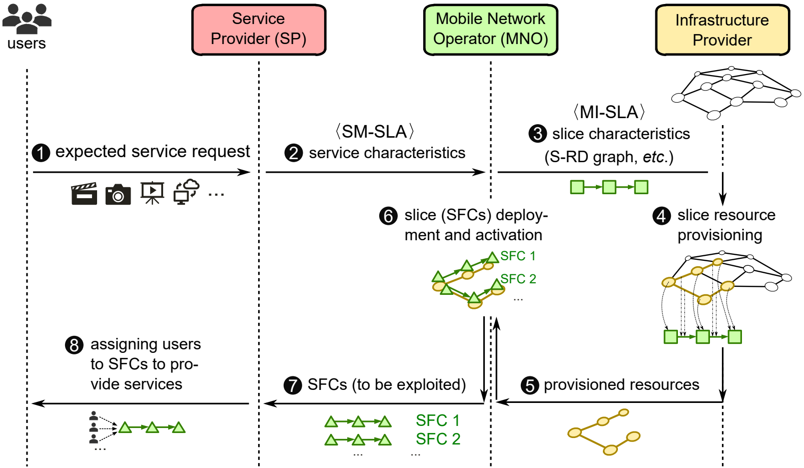

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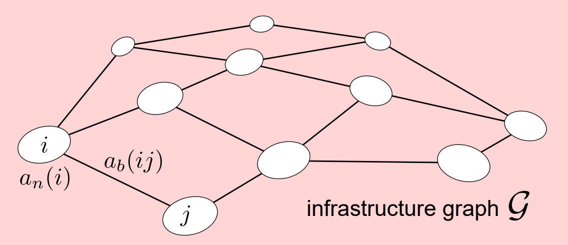
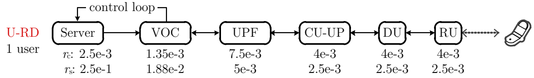


Infrastructure provides resources with associated costs

- node $i \in \mathcal{N}$: computing $a_c(i)$, memory $a_m(i)$, wireless $a_w(i)$
- link $ij \in \mathcal{E}$: bandwidth $a_b(ij)$
- costs: $c_c(i)$, $c_m(i)$, $c_w(i)$, $c_b(ij)$

Resource demand of a typical user (U-RD): $\mathbf{U}_s$



Resource demand of a slice (S-RD): $\mathbf{R}_s$

Resource demand of an SFC (SFC-RD): $\mathbf{r}_s$

System Model | Virtual graphs of resource demand

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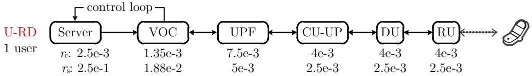

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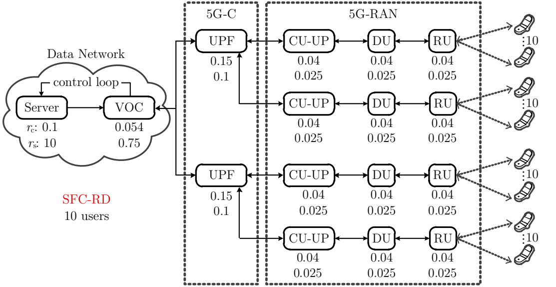

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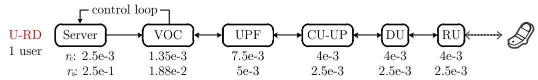

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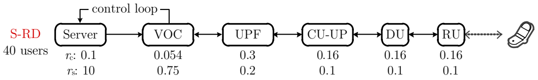

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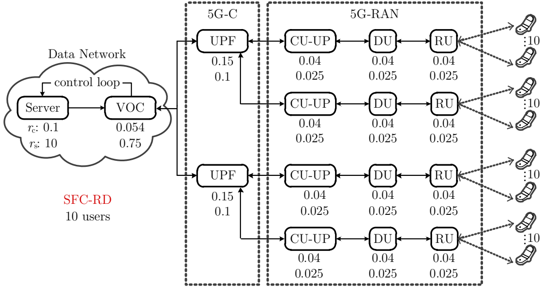

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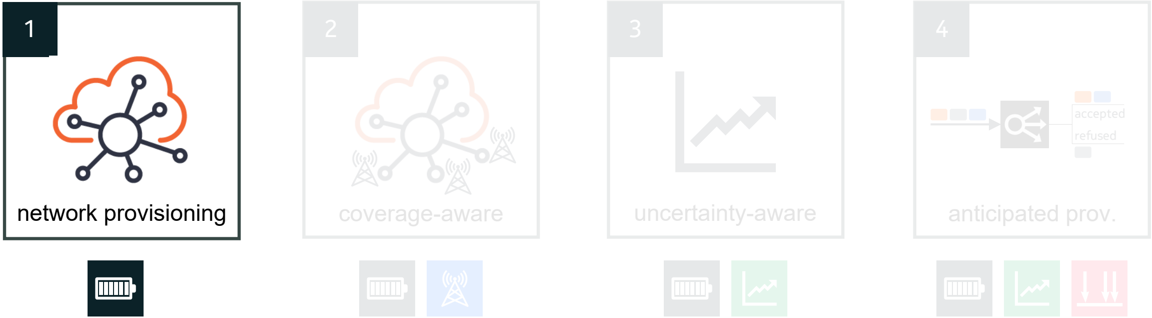

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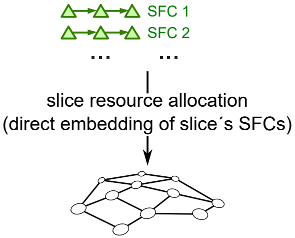
Direct embedding vs provisioned embedding

Prior works: Direct embedding (one-to-one mapping)



(1) Network provisioning | Problem statement

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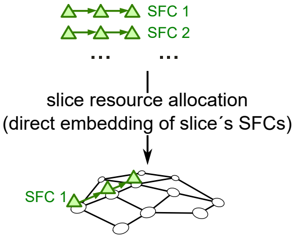

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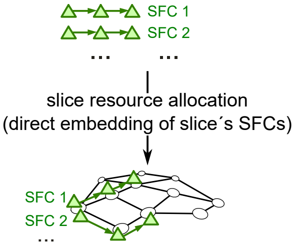

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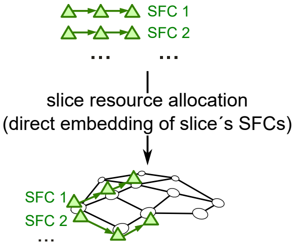

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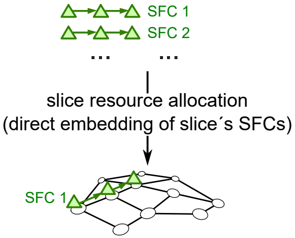

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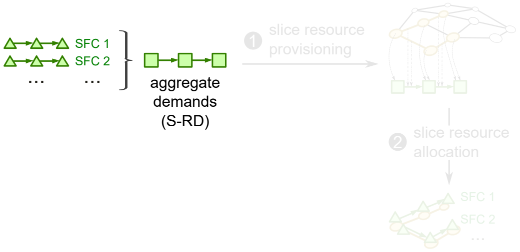

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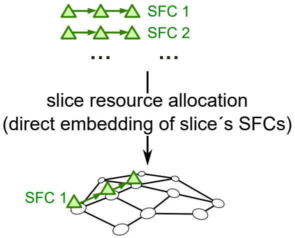

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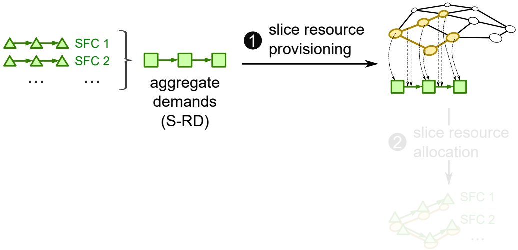

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Direct embedding vs provisioned embedding

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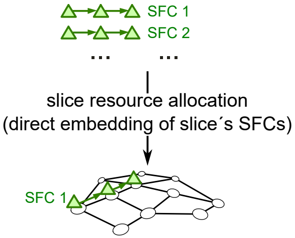
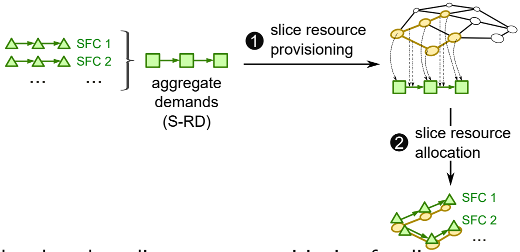


Offen formulated as (Mixed) Integer Linear Programming and solved either directly or using heuristics

ILP: [Cohen2015], [Riera2016], [Vizarreta2017]

heuristics: column generation [Liu2017] , eigendecomposition [Mechtri2016]

Slice resource provisioning: (many-to-one mapping)



Related work: radio resource provisioning for slices: [Sun2019], [Xiong2019]

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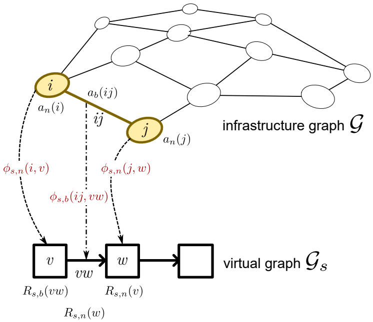
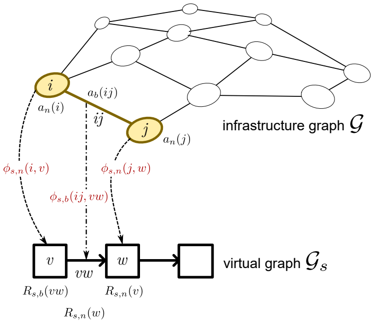


- $\phi_{s,n}(i,v) \in [0,1]$: Proportion of provisioned node resources
- $\phi_{s,b}(ij,vw) \in [0,1]$: Proportion of provisioned link resources
- $\widetilde{\phi}_{s,n}(i,v) \in \{0,1\}$: Node mapping indicator

Objective function

$$
\begin{aligned}
c_{\text{total}}(\boldsymbol{\Phi}) &= \sum_{s} c_{\text{total}}(\boldsymbol{\Phi}_s) \\
&= \sum_{s,i,v,n} a_n(i)\,\phi_{s,n}(i,v) c_n(i) && \text{(node resource leasing)} \\
&+ \sum_{s,ij,vw} a_b(ij)\,\phi_{s,b}(ij,vw) c_b(ij) && \text{(link resource leasing)} \\
&+ \sum_{s,i,v} \widetilde{\phi}_{s,n}(i,v)\, c_d(i) && \text{(VNF deployment)}
\end{aligned}
$$



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\end{aligned}
$$

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Constraint 1: Slice resource requirements

$$\sum_{i} \underbrace{a_n(i)\,\phi_{s,n}(i,v)}_{\text{prov. rsrc from } i \text{ to } v} \geq \underbrace{R_n(v)}_{\text{S-RD at } v}, \forall s \in \mathcal{S}, v \in \mathcal{N}_s, n \in \Upsilon$$

$$\sum_{ij} \underbrace{a_{\mathrm{b}}(ij)\,\phi_{s,\mathrm{b}}(ij,vw)}_{\text{prov. rsrc from } ij \text{ to } vw} \geq \underbrace{R_{\mathrm{b}}(vw)}_{\text{S-RD at } v}, \forall s \in \mathcal{S}, vw \in \mathcal{E}_s$$

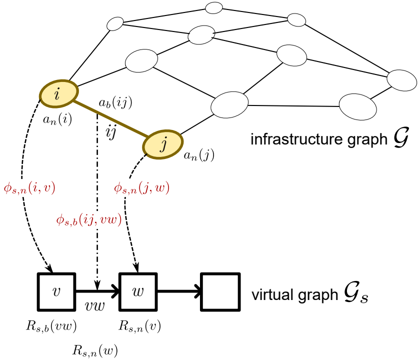
Constraint 2: Infrastructure resource limit

$$\sum_{s,v} \phi_{s,n}(i,v) \leq 1, \forall i \in \mathcal{N}, n \in \Upsilon,$$

$$\sum_{s,vw} \phi_{s,\mathrm{b}}(ij,vw) \leq 1, \forall ij \in \mathcal{E}$$

Other constraints:

- proportionality of provisioned node resources (computing-memory-wireless)
- flow conservation: ensures flow continuity



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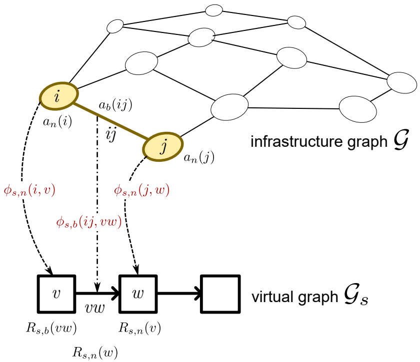

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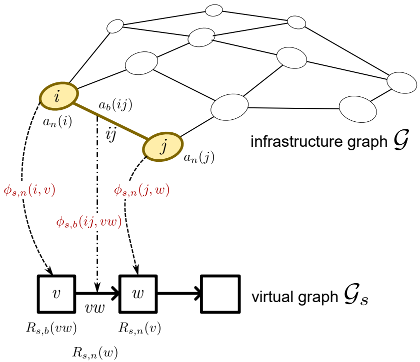

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MILP network resource provisioning

minimize $c_{\text{total}}(\mathbf{\Phi}) = \sum_{s \in \mathcal{S}} c_{\text{total}}(\mathbf{\Phi}_s)$,

subject to

(1) slice resource requirements

(2) infrastructure resource limits

(3) resource proportionality

(4) flow conservation

Provisioning approaches:

(1) Sequential approach (SP): Resources are provisioned slice-by-slice

(2) Joint approach (JP): Provisioning performed for all slices simultaneously

(1) Network provisioning | Main constraints

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(1) Sequential approach (SP): Resources are provisioned slice-by-slice

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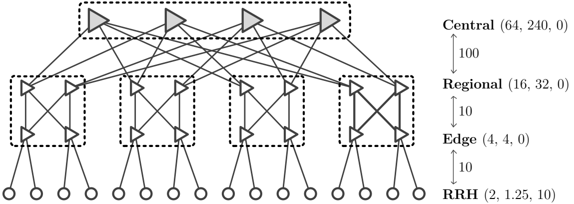
k-ary fat-tree topology

- Per-unit resource cost $= 1$ (whatever the type of resource)
- Deployment cost $c_{\mathrm{d}} = 50$



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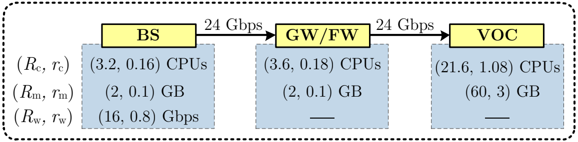
Slices: HD video streaming with *deterministic* S-RD

- Data rate at 4 Mbps for $N_s = 4000$ users.



Simulation schemes

Comparison of 2 resource provisioning approaches:

- Sequential approach (SP)
- Joint approach (JP)

Both schemes are evaluated using CPLEX MILP solver interfaced with MATLAB.

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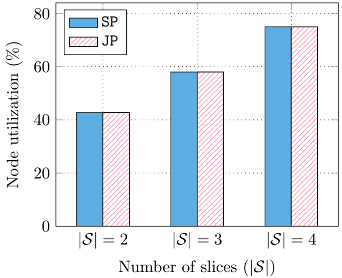
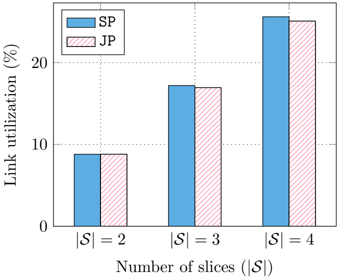
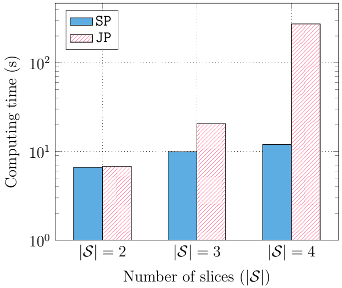
Sequential (SP) vs Joint (JP) approaches, with different $|\mathcal{S}|$



node utilization



link utilization



computing time

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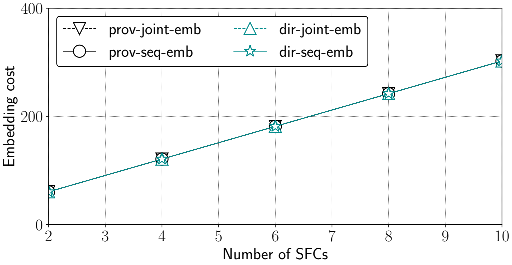
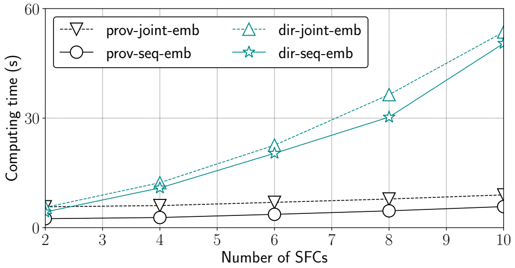
Provisioned embedding vs Direct embedding (single slice)



Embedding cost



Computing time

Provisioned embedding: embedding is performed with only a subset of the infrastructure graph

- S-RD graph: aggregation of resource demands
- Slice resource provisioning: mapping of infrastructure graph to S-RD graph
- Two slice resource provisioning approaches:
  - Sequential approach (`SP`): more efficient in terms of computing time
  - Nevertheless: degraded node and link utilization compared to Joint approach (`JP`)
- Once provisioning completed, SFC embedding is faster

Contributions

Part I. Deterministic slice resource demands

1

network provisioning

2

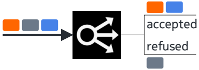
coverage-aware

Part II. Random slice resource demands

3

uncertainty-aware

4



anticipated prov.

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Related works

- dynamic slice/SFC deployment
  - [Liu'17]: deployment of newly arrived SFCs and readjustment of in-service SFCs
  - [Wang'19]: slice reconfiguration at two levels: SFCs within a slice at small time intervals, or multiple slices at larger time interval
- slice admission control:
  - [Bega'17], [Bega'20]: online SAC for radio resources at base stations
  - [Han'20]: SAC with dynamic requests, but not accounting for uncertainties

(4) Anticipated provisioning | Problem statement

Related works

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(4) Anticipated provisioning | Problem statement

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This contribution:

Multiple slice requests from tenants to MNO

Uncertainties

- slice resource demands
- available infrastructure resource

Dynamic nature of slice provisioning requests

- arrive at anytime
- various activation times
- various lifetime
- resource needs vary during slice operation

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NOKIA Bell Labs

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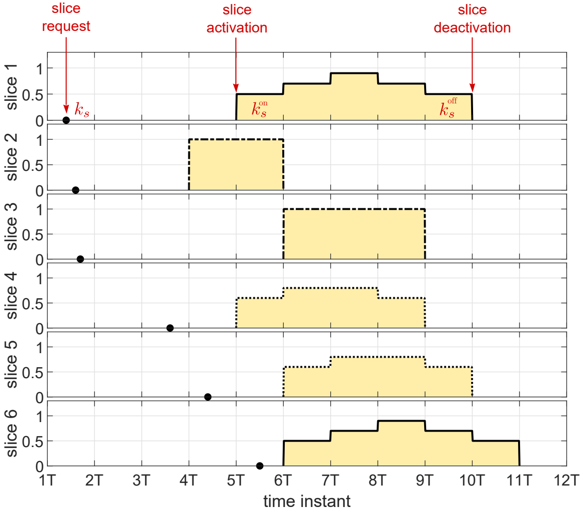
(4) Anticipated provisioning | System model

Slice provisioning requests



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Slice classes: Premium and Standard
Initial priority assignment

$$P_{s,k} = \begin{cases} P_{\max}, & \text{for Premium slices,} \\ 0 & \text{for Standard slice, if } k_s^{\text{on}} > k+1, \\ P_{\max} - 1 & \text{for Standard slice, if } k_s^{\text{on}} = k+1. \end{cases}$$

Only slices with $P_{s,k} \geqslant P_{\text{thres}}$ are processed

$$P_{\text{thres}} = \alpha \left(P_{\max} - 1 \right), \text{ with } \alpha \in [0, 1] \, .$$

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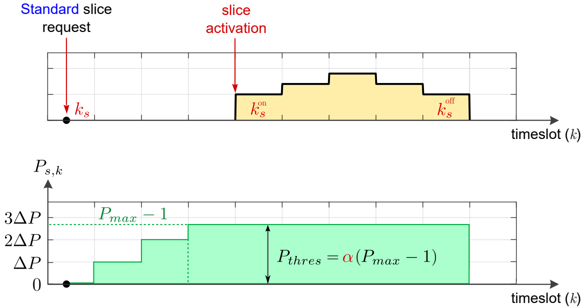
Only slices with $P_{s,k} \geqslant P_{\text{thres}}$ are processed

$$P_{\text{thres}} = \alpha \left(P_{\max} - 1 \right), \text{ with } \alpha \in [0,1],$$

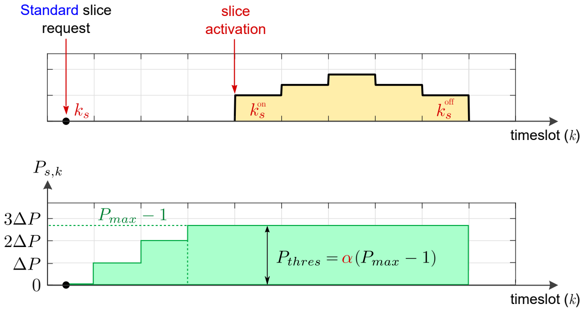
Priority update for unprocessed Standard slices in next time slots:

$$P_{s,k} = \begin{cases} \min\left\{ P_{s,k-1} + \Delta P, P_{\max} - 1 \right\} & \text{if } k_s^{\text{on}} > k+1, \\ P_{\max} - 1 & \text{if } k_s^{\text{on}} = k+1, \end{cases}$$

$\Delta P \geqslant 0$: priority increment.



(4) Anticipated provisioning | Priority assignment



Parameterized priority level with α and ΔP

- $\alpha = 0$: Premium = Standard, $\forall \Delta P \rightarrow$ min benefit for Premium slices
- $\alpha = 1$, $\Delta P = 0$, Standard slices are delayed until the time slot preceding their activation $\rightarrow$ max benefit for Premium slices

(4) Anticipated provisioning | S-RD

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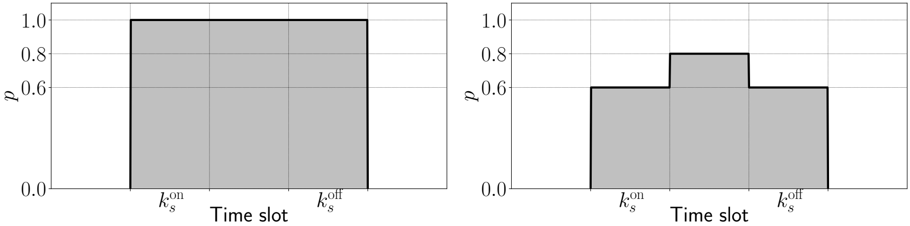
Slice resource demands:

- Number of users of slice s follows binomial distribution $\mathcal{B}\left(p_{s,k}\right)$
- Temporal evolution of $p_{s,k}$



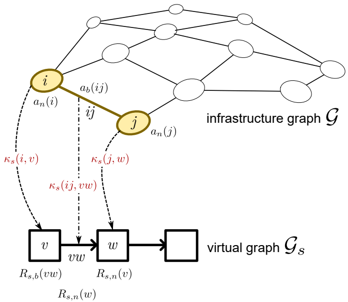
constant over a time interval | piece-wise constant

Service usage pattern

(4) Anticipated provisioning | Variables

Resource provisioning for slice s defined by mapping between $\mathcal{G}$ and $\mathcal{G}_s$, for time slot ℓ

- $d_s \in \{0, 1\}$ indicates whether slice s is accepted or not
- $\kappa_{s,\ell}(i, v) \in \mathbb{N}$ determines number of VNFs that node i can provide resources for virtual node v
- $\kappa_{s,\ell}(ij, vw) \in \mathbb{N}$ determines bandwidth provisioned by link ij to support the traffic between virtual nodes of type v and w



Note:
Contributions 1 and 2 use $\mathbf{\Phi}_s$ as main decision variables
Here: $\boldsymbol{\kappa}_s$

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Assignment $\boldsymbol{\kappa}_{s,\ell}$ for slice s over time slot ℓ must satisfy

- infrastructure node and link capacity limits, w.r.t
  - background traffic
- service satisfaction probability, w.r.t
  - usage uncertainties
  - resource availability
- flow conservation constraint

(4) Anticipated provisioning | SSP constraint

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Service Satisfaction Probability (SSP) of slice s at time slot k for a given assignment $\boldsymbol{\kappa}_{s,\ell}$

$$p_{s,\ell}\left(\boldsymbol{\kappa}_{s,\ell}, d_s\right) = \Pr\left\{\begin{array}{l} \underbrace{\sum_i \kappa_{s,\ell}(i,v)\, r_{s,n}(v)}_{\text{prov. rsrc for } v} \geqslant d_s \underbrace{R_{s,n,\ell}(v)}_{\text{S-RD of } v}, \forall v, n, \\ \underbrace{\sum_{ij} \kappa_{s,\ell}(ij,vw)\, r_{s,\mathrm{b}}(vw)}_{\text{prov. rsrc for } vw} \geqslant d_s \underbrace{R_{s,\mathrm{b},\ell}(vw)}_{\text{S-RD of } vw}, \forall vw \end{array}\right\} \geqslant \underbrace{\underline{p}_s^{\mathrm{sp}}}_{\text{required min SSP}}, \forall s \in \mathcal{R}_k, \ell \in \mathcal{K}_s$$

Relaxed constraints:

$$\sum_i \kappa_{s,\ell}(i,v)\, r_{s,n}(v) \geqslant d_s \underbrace{\left[\overline{R}_{s,n,\ell}(v) + \gamma_{s,\ell} \widetilde{R}_{s,n,\ell}(v)\right]}_{\text{S-RD of } v}, \forall \ell > k, v \in \mathcal{N}_s, \forall n \in \Upsilon,$$

$$\sum_{ij} \kappa_{s,\ell}(ij,vw)\, r_{s,\mathrm{b}}(vw) \geqslant d_s \underbrace{\left[\overline{R}_{s,\mathrm{b},\ell}(vw) + \gamma_{s,\ell} \widetilde{R}_{s,\mathrm{b},\ell}(vw)\right]}_{\text{S-RD of } vw}, \forall \ell > k, vw \in \mathcal{E}_s.$$

$\mathcal{R}_k$: set of slices processed at time slot k
$\overline{R}$, $\widetilde{R}$: mean and standard deviation of S-RD
$\gamma_{s,\ell}$: safety factor

(4) Anticipated provisioning | SSP constraint

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Service Satisfaction Probability (SSP) of slice s at time slot k for a given assignment $\boldsymbol{\kappa}_{s,\ell}$

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$\mathcal{R}_k$: set of slices processed at time slot k
$\overline{R}$, $\widetilde{R}$: mean and standard deviation of S-RD
$\gamma_{s,\ell}$: safety factor

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Impact Probability (ImP) constraints on background services at infrastructure node i and link ij:

$$p^{\mathrm{im}}_{n,\ell}\left(\boldsymbol{\kappa}_{\mathcal{R}_k}, i\right) = \Pr\left\{ \underbrace{\sum_s \sum_v \kappa_{s,\ell}\left(i,v\right) r_{s,n}\left(v\right)}_{\text{resources prov. by } i} \geqslant a_n\left(i\right) - \underbrace{B_{n,\ell}\left(i\right)}_{\text{bkgd serv. at } i} \right\} \leqslant \underbrace{\overline{p}^{\mathrm{im}}}_{\text{required max ImP}},$$

$$p^{\mathrm{im}}_{\mathrm{b},\ell}\left(\boldsymbol{\kappa}_{\mathcal{R}_k}, ij\right) = \Pr\left\{ \underbrace{\sum_s \sum_{vw} \kappa_{s,\ell}\left(ij,vw\right) r_{s,\mathrm{b}}\left(vw\right)}_{\text{resources prov. by } ij} \geqslant a_{\mathrm{b}}\left(ij\right) - \underbrace{B_{\mathrm{b},\ell}\left(ij\right)}_{\text{bkgd serv. at } ij} \right\} \leqslant \underbrace{\overline{p}^{\mathrm{im}}}_{\text{required max ImP}}.$$

Relaxed constraints:

$$\sum_s \sum_v \kappa_{s,\ell}\left(i,v\right) r_{s,n}\left(v\right) \leqslant a_n\left(i\right) - \left[\overline{B}_{n,\ell}\left(i\right) + \gamma_{\mathrm{B},\ell}\widetilde{B}_{n,\ell}\left(i\right)\right], \forall \ell > k, i \in \mathcal{N}, n \in \Upsilon,$$

$$\sum_s \sum_{vw} \kappa_{s,\ell}\left(ij,vw\right) r_{s,\mathrm{b}}\left(vw\right) \leqslant a_{\mathrm{b}}\left(ij\right) - \underbrace{\left[\overline{B}_{\mathrm{b},\ell}\left(ij\right) + \gamma_{\mathrm{B},\ell}\widetilde{B}_{\mathrm{b},\ell}\left(ij\right)\right]}_{\text{background services}}, \forall \ell > k, ij \in \mathcal{E}.$$

$\overline{B}$, $\widetilde{B}$: mean and standard deviation of resource consumption of background services

$\gamma_{\mathrm{B},\ell}$: safety factor

(4) Anticipated provisioning | ImP constraint

Impact Probability (ImP) constraints on background services at infrastructure node i and link ij:

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$$p^{\mathrm{im}}_{\mathrm{b},\ell}\left(\boldsymbol{\kappa}_{\mathcal{R}_k}, ij\right) = \Pr\left\{ \underbrace{\sum_s \sum_{vw} \kappa_{s,\ell}(ij,vw)\, r_{s,\mathrm{b}}(vw)}_{\text{resources prov. by } ij} \geqslant a_{\mathrm{b}}(ij) - \underbrace{B_{\mathrm{b},\ell}(ij)}_{\text{bkgd serv. at } ij} \right\} \leqslant \underbrace{\overline{p}^{\mathrm{im}}}_{\text{required max ImP}}.$$

Relaxed constraints:

$$\sum_s \sum_v \kappa_{s,\ell}(i,v)\, r_{s,n}(v) \leqslant a_n(i) - \left[\overline{B}_{n,\ell}(i) + \gamma_{\mathrm{B},\ell}\widetilde{B}_{n,\ell}(i)\right], \forall \ell > k, i \in \mathcal{N}, n \in \Upsilon,$$

$$\sum_s \sum_{vw} \kappa_{s,\ell}(ij,vw)\, r_{s,\mathrm{b}}(vw) \leqslant a_{\mathrm{b}}(ij) - \underbrace{\left[\overline{B}_{\mathrm{b},\ell}(ij) + \gamma_{\mathrm{B},\ell}\widetilde{B}_{\mathrm{b},\ell}(ij)\right]}_{\text{background services}}, \forall \ell > k, ij \in \mathcal{E}.$$

$\overline{B}$, $\widetilde{B}$: mean and standard deviation of resource consumption of background services
$\gamma_{\mathrm{B},\ell}$: safety factor

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Earnings of InP = costs charged to MNOs

Max-min problem: InP tries to

- maximize the nb of accepted slices
- minimize the cost for MNOs

Max-min anticipated provisioning problem

$$\max_{\mathrm{d}_{\mathcal{R}_k}} \min_{\boldsymbol{\kappa}_{\mathcal{R}_k}} \quad E_k^{\mathrm{InP}}\left(\mathrm{d}_{\mathcal{R}_k}, \boldsymbol{\kappa}_{\mathcal{R}_k}\right) = \sum_{s \in \mathcal{R}_k} \sum_{\ell \in \mathcal{K}_s} \left(\underbrace{C_{\mathrm{r}}\left(\boldsymbol{\kappa}_{s,\ell}\right)}_{\text{resource}} + \underbrace{C_{\mathrm{f}}\left(\boldsymbol{\kappa}_{s,\ell}\right)}_{\text{node disposal}} + \underbrace{C_{\mathrm{a}}\left(\boldsymbol{\kappa}_{s,\ell}, \boldsymbol{\kappa}_{s,\ell-1}\right)}_{\text{adaptation}} \right)$$

subject to service satisfaction probability constraints

impact on background services constraints

flow conservation constraint

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Approaches

Sequential: solve problem for each slice s with initial $d_s = 1$

- $\min_{\boldsymbol{\kappa}_{s_1}} E_k^{\mathrm{InP}}\left(\boldsymbol{\kappa}_{s_1}, 1\right), \min_{\boldsymbol{\kappa}_{s_2}} E_k^{\mathrm{InP}}\left(\boldsymbol{\kappa}_{s_2}, 1\right), \ldots$

Joint: start with $\mathrm{d}_{\mathcal{R}_k} = 1$ $(d_s = 1, \forall s)$, then refuse progressively low-prioritized slices if no solution found

- iteration 1: $\min_{\boldsymbol{\kappa}_{\mathcal{R}_k}} E_k^{\mathrm{InP}}\left(\boldsymbol{\kappa}_{\mathcal{R}_k}, \{1, 1, \cdots, 1, 1\}\right)$
- iteration 2: $\min_{\boldsymbol{\kappa}_{\mathcal{R}_k}} E_k^{\mathrm{InP}}\left(\boldsymbol{\kappa}_{\mathcal{R}_k}, \{1, 1, \cdots, 1, 0\}\right)$
- iteration 3: $\min_{\boldsymbol{\kappa}_{\mathcal{R}_k}} E_k^{\mathrm{InP}}\left(\boldsymbol{\kappa}_{\mathcal{R}_k}, \{1, 1, \cdots, 0, 0\}\right)$
- ... until a feasible solution found

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Approaches

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- ... until a feasible solution found

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Slice model:

- Three types of slice
  - HD videos streaming, SSP constraint: $\underline{p}_s^{\mathsf{sp}} = 0.99$
  - SD video streaming, SSP constraint: $\underline{p}_s^{\mathsf{sp}} = 0.95$
  - video surveillance and traffic monitoring, SSP constraint: $\underline{p}_s^{\mathsf{sp}} = 0.9$
- Slice type and demand pattern chosen uniformly at random.
- Number of provisioning request arrivals/time slot $\mathrm{Pois}(1)$
- Arrival time uniformly distributed within each time slot
- Activation delay $\mathcal{U}(1,6)$, lifetime $\mathcal{U}(1,3)$

Background services:

- consume on average 20% of available infrastructure resources (with 5% std. dev.)
- ImP constraint: $\bar{p}^{\mathsf{im}} = 0.1$

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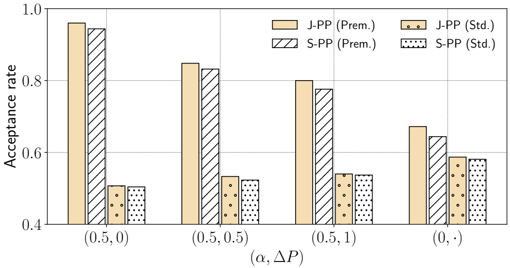
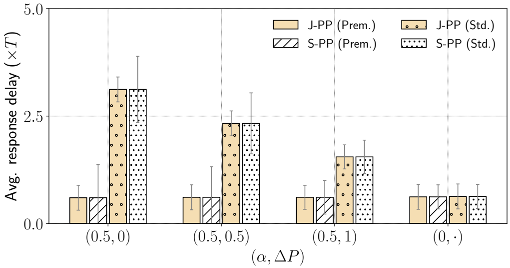
Multiple slice provisioning

J-PP vs. S-PP with different processing strategies $(\alpha, \Delta P)$



acceptance rate



average response delay

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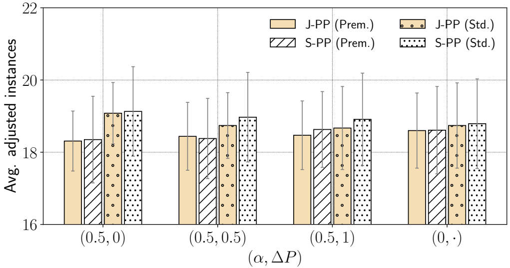
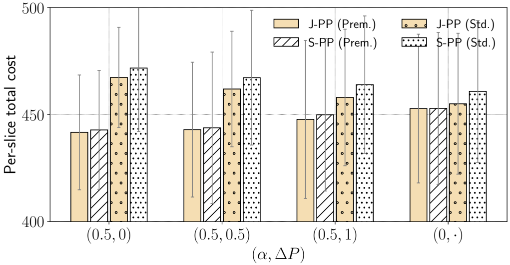
Multiple slice provisioning

J-PP vs. S-PP with different processing strategies $(\alpha, \Delta P)$



average adjusted instances

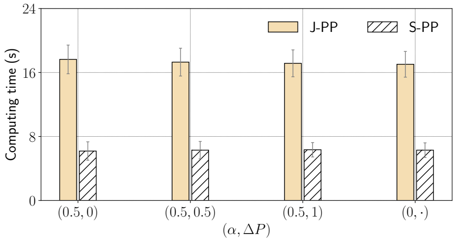


average cost per slice

Objective: to minimize cost and nb of adjusted instances

Multiple slice provisioning

J-PP vs. S-PP with different processing strategies $(\alpha, \Delta P)$



computing time

Two prioritized slice resource provisioning (PP) variants to

- maximize acceptance rate,
- maximize earnings of the InP + minimize costs charged to MNO

Advantages

- adapt to dynamic nature of slice provisioning requests;
- robustness to uncertainties.

Outline

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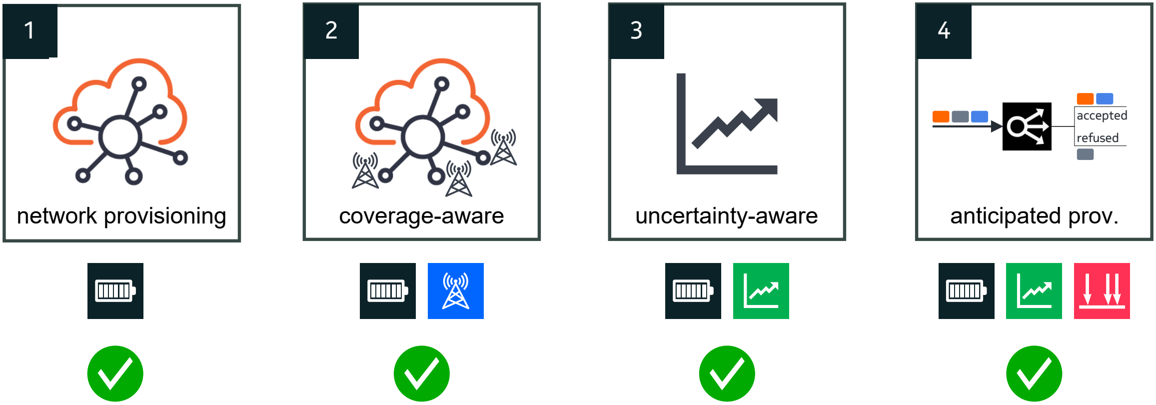
Conclusions and Perspective

Contributions

Part I. Deterministic slice resource demands

Part II. Random slice resource demands



Conclusions and Perspective

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Perspectives

- Additional constraints, *e.g.*, latency, end-to-end error rate probability
- Efficient heuristics to scale up to more realistic setups
  - *eigen-decompostion* [Mechtri'16]
  - *column generation* [Nemhauser'12]
- Multiple domains network slicing (*e.g.*, multi-InPs)
  - each InP finds its own resource provisioning solution
  - afterwards: coordination between InPs to obtain final provisioning solution
- Slot-by-slot provisioning: instead of considering all active time slots simultaneously, provision resources for the slice slot-by-slot $\rightarrow$ reduce time complexity

Conclusions and Perspective

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Conclusions and Perspective

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Publications

Journal papers

(J1) Admission Control and Resource Provisioning for Prioritized Slice Requests with Uncertainties (IEEE TNSM 2021, submitted)

(J2) Uncertainty-Aware Resource Provisioning for Network Slicing (IEEE TNSM 2021, published)

(J3) Coverage-Aware Resource Provisioning Method for Network Slicing (IEEE/ACM TNET 2020, published)

Conference/Workshop Papers

(C1) Foresighted Resource Provisioning for Network Slicing (IEEE HPSR 2021, to appear).

(C2) Radio Resource Provisioning for Network Slicing with Coverage Constraints (IEEE ICC 2020, published)

(C3) Aggregated Resource Provisioning for Network Slices (IEEE GLOBECOM 2018, published)

Project Deliverable

(D1) Virtual Network Orchestration Framework and Algorithms (ANR MAESTRO-5G Project Deliverable D3.1, 2020)

Patents

(P1) Method and Apparatus for Mapping Network Slices Onto Network Infrastructures With SLA Guarantee. WIPO Patent No. WO2020114608A1 (filed on Dec. 07, 2018 by Nokia Solutions and Networks)

BACK UP

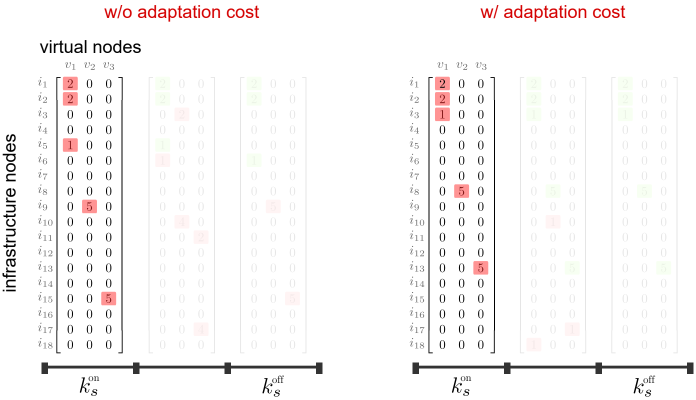
(4) Anticipated provisioning | Evaluation

Single slice provisioning

$$E_k^{\mathrm{InP}}\left(\boldsymbol{\kappa}_{\mathcal{R}_k}, \mathrm{d}_{\mathcal{R}_k}\right) = \sum_{s\in\mathcal{R}_k}\sum_{\ell\in\mathcal{K}_s}\Big(\underbrace{C_{\mathrm{r}}\left(\boldsymbol{\kappa}_{s,\ell}\right)}_{\text{resource}} + \underbrace{C_{\mathrm{f}}\left(\boldsymbol{\kappa}_{s,\ell}\right)}_{\text{node disposal}} + \underbrace{C_{\mathrm{a}}\left(\boldsymbol{\kappa}_{s,\ell}, \boldsymbol{\kappa}_{s,\ell-1}\right)}_{\text{adaptation}}\Big)$$

Changes of $\kappa_{s,\ell}(i,v)$ along with ℓ:

- red: increase of $\kappa_{s,\ell}(i,v)$
- green: $\kappa_{s,\ell}(i,v)$ remains the same



(4) Anticipated provisioning | Evaluation

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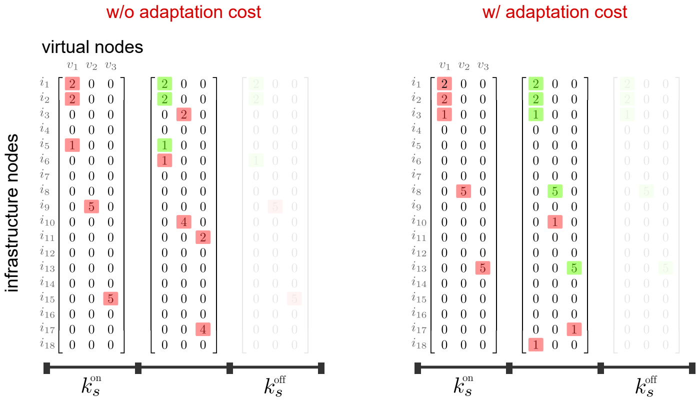

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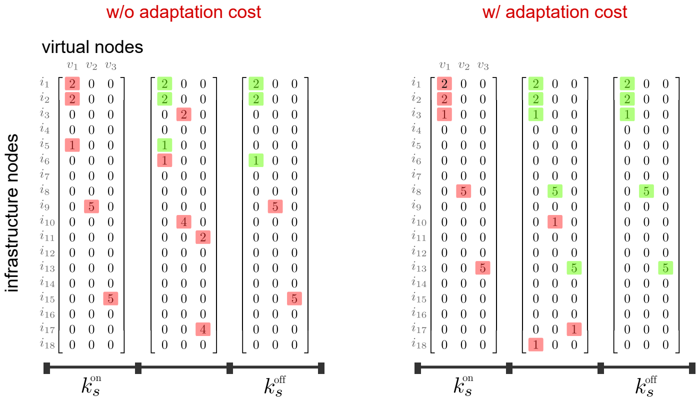
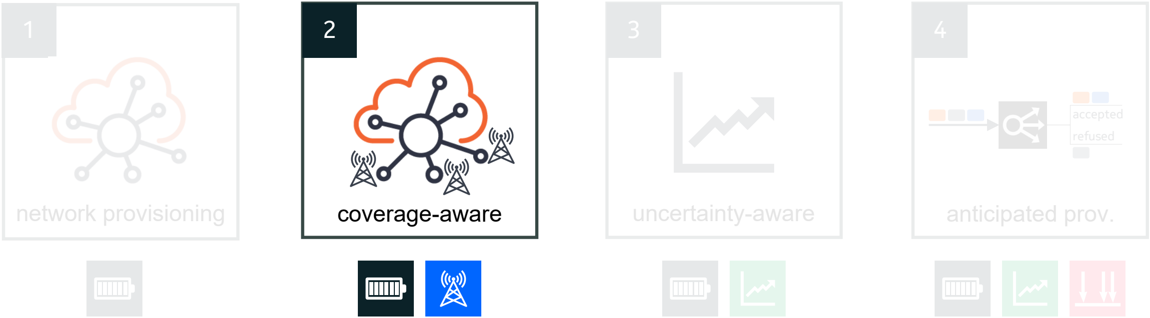


Contributions

Part I. Deterministic slice resource demands

Part II. Random slice resource demands



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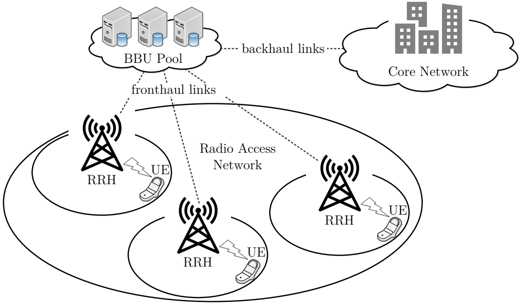
- **RP**: **R**adio resource **P**rovisioning: radio
- **NP**: (other) **N**etwork resource **P**rovisioning: computing, storage, and bandwidth



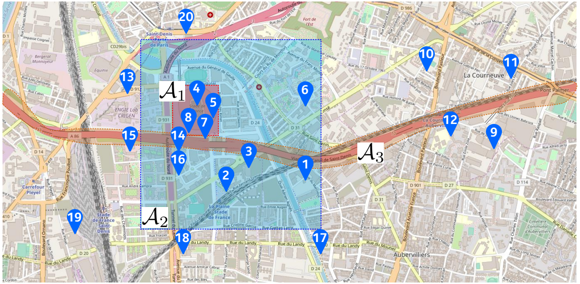
Cloud Radio Access Network (CRAN) general architecture

- RRH: Remote Radio Head
- BBU: Base Band Unit

(2) Coverage-aware | Radio provisioning (RP)

Problem statement

- SM-SLA involves:
  - coverage constraints: geographical distribution slice users. This distribution is described by the user density function $\rho_s(x)$, with $x \in \mathcal{A}$.
  - supported service type
  - targeted QoS such as a minimum average data rate $U_{s,\mathrm{u}}$ and $U_{s,\mathrm{d}}$ for the wireless uplink and downlink traffic for each user



$\mathcal{A}$: the geographical area under study,

$\mathcal{A}_s$: the subarea over which service s has to be made available

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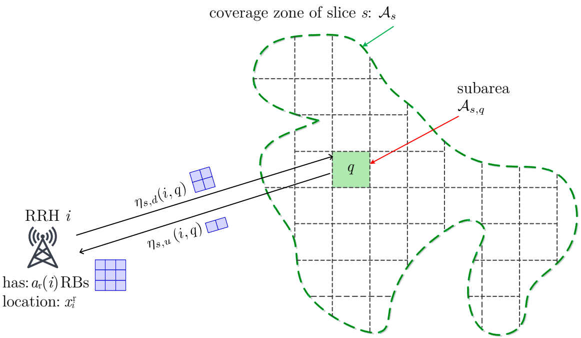
Proposed approach for RP

- For slice s, InP has to provide a minimum data rate $(U_{s,\mathrm{u}}, U_{s,\mathrm{d}})$ to each user spread over $\mathcal{A}_s$ with density $\rho_s(x)$
- Each RRH has a fixed amount $a_\mathrm{r}(i)$ of resource blocks (RB) per time unit



- $\mathcal{A}_s$ is partitioned into Q_s convex subareas $\mathcal{A}_{s,q}$, $q \in \mathcal{Q}_s = \{1, \ldots, Q_s\}$
- Instead of allocating RBs to users, RRH nodes allocate RBs to subareas

(2) Coverage-aware | Radio provisioning (RP)

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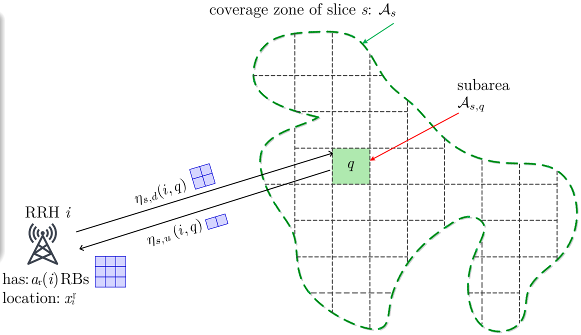
RP cost function

Cost function of RP problem

$$c_{\mathrm{rr}}(\boldsymbol{\eta}) = \sum_{\sigma \in \mathcal{S}} \sum_{i \in \mathcal{N}_{\mathrm{r}}} c_{\mathrm{f}}(i)\, \widetilde{\eta}_s(i)$$
$$+ \sum_{s \in \mathcal{S}} \sum_{i \in \mathcal{N}_{\mathrm{r}}} \sum_{q \in \mathcal{Q}_s} \left[c_{\mathrm{r}}(i) - \lambda b_{\mathrm{u}}\left(x_i^{\mathrm{r}}, \mathcal{A}_{s,q}\right)\right] a_{\mathrm{r}}(i)\, \eta_{s,\mathrm{u}}(i,q)$$
$$+ \sum_{s \in \mathcal{S}} \sum_{i \in \mathcal{N}_{\mathrm{r}}} \sum_{q \in \mathcal{Q}_s} \left[c_{\mathrm{r}}(i) - \lambda b_{\mathrm{d}}\left(x_i^{\mathrm{r}}, \mathcal{A}_{s,q}\right)\right] a_{\mathrm{r}}(i)\, \eta_{s,\mathrm{d}}(i,q)$$

- $\eta_s(i,q) \in [0,1]$: proportion of RBs that RRH i provisions to subarea q
- $\lambda b\left(x_i^{\mathrm{r}}, \mathcal{A}_{s,q}\right) a_{\mathrm{r}}(i) \eta_s(i,q)$: rate-related discount to penalty the use of far RRHs



(2) Coverage-aware | Radio provisioning (RP)

RP main constraints

(1) RRH capacity limit: $\forall i \in \mathcal{N}_\mathrm{r}$,

$$\sum_{s \in \mathcal{S}} \sum_{q \in \mathcal{Q}_s} \left(\eta_{s,\mathrm{u}}(i,q) + \eta_{s,\mathrm{d}}(i,q) \right) \leqslant 1,$$

(2) Rate requirement per user: $\forall s \in \mathcal{S}, q \in \mathcal{Q}_s$,

$$\sum_{i \in \mathcal{N}_\mathrm{r}} \eta_{s,\mathrm{u}}(i,q)\, a_\mathrm{r}(i)\, b_\mathrm{u}\left(x_i^\mathrm{r}, \mathcal{A}_{s,q}\right) \geqslant U_{s,\mathrm{u}} \int_{\mathcal{A}_{s,q}} \rho_s(x)\,\mathrm{d}x,$$

$$\sum_{i \in \mathcal{N}_\mathrm{r}} \eta_{s,\mathrm{d}}(i,q)\, a_\mathrm{r}(i)\, b_\mathrm{d}\left(x_i^\mathrm{r}, \mathcal{A}_{s,q}\right) \geqslant U_{s,\mathrm{d}} \int_{\mathcal{A}_{s,q}} \rho_s(x)\,\mathrm{d}x,$$

(3) Rate requirement per slice: $\forall s \in \mathcal{S}$,

$$\sum_{q \in \mathcal{Q}_s} \sum_{i \in \mathcal{N}_\mathrm{r}} \eta_{s,\mathrm{u}}(i,q)\, a_\mathrm{r}(i)\, b_\mathrm{u}\left(x_i^\mathrm{r}, \mathcal{A}_{s,q}\right) \geqslant R_{s,\mathrm{u}}(v_\mathrm{r}),$$

$$\sum_{q \in \mathcal{Q}_s} \sum_{i \in \mathcal{N}_\mathrm{r}} \eta_{s,\mathrm{d}}(i,q)\, a_\mathrm{r}(i)\, b_\mathrm{d}\left(x_i^\mathrm{r}, \mathcal{A}_{s,q}\right) \geqslant R_{s,\mathrm{d}}(v_\mathrm{r}),$$

(4) UL-DL proportionality: $\forall q \in \mathcal{Q}_s$,

$$\frac{\eta_{s,\mathrm{u}}(i,q)\, a_\mathrm{r}(i)\, b_\mathrm{u}\left(x_i^\mathrm{r}, \mathcal{A}_{s,q}\right)}{R_{s,\mathrm{u}}(v_\mathrm{r})} = \frac{\eta_{s,\mathrm{d}}(i,q)\, a_\mathrm{r}(i)\, b_\mathrm{d}\left(x_i^\mathrm{r}, \mathcal{A}_{s,q}\right)}{R_{s,\mathrm{d}}(v_\mathrm{r})}.$$

(2) Coverage-aware | Single-step vs two-step provisioning

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- Global provisioning problem (single-step):

$$\begin{aligned} \min \quad & c_{\text{tot}}(\boldsymbol{\eta}, \boldsymbol{\Phi}) = c_{\text{rr}}(\boldsymbol{\eta}) + c_{\text{wr}}(\boldsymbol{\Phi}) \qquad (1) \\ \text{s.t.} \quad & \text{NP and RP constraints} \end{aligned}$$

- When the size of $\boldsymbol{\Phi}$ and $\boldsymbol{\eta}$ increases, the problem may become intractable

→ Two-step provisioning algorithm: CARP (Coverage-Aware Resource Provisioning), which minimizes both terms of (1) separately.

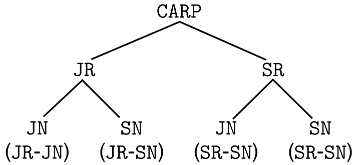

Figure: Four variants of CARP.

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Infrastructure model:

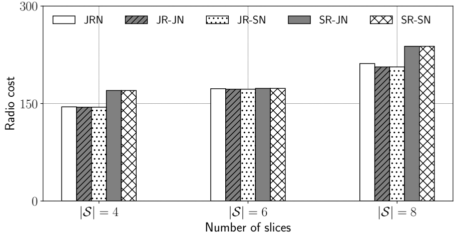
- k-ary fat tree topology
  - Leasing cost for each resource unit $= 1$
  - For coverage constraints, we consider a $1.43\,\mathrm{km} \times 4.95\,\mathrm{km}$ area around the Stade de France in Seine-Saint-Denis

Slices: three types:

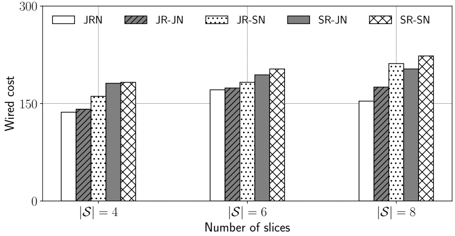
- HD video streaming
- SD video streaming
- Video surveillance and traffic monitoring

(2) Coverage-aware | Evaluation

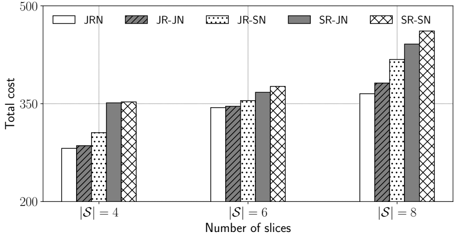
Performance of JRN vs 4 CARP variants.



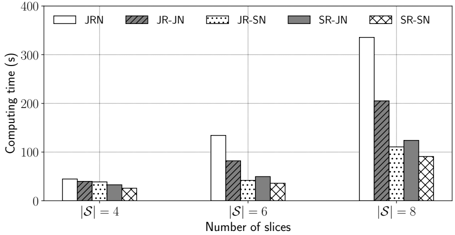
(a) Radio cost



(b) Wired cost



(c) Total cost



(d) Computing time

- Extension to Contribution 1: Slice resource provisioning accounting coverage constraints:
  - provide a minimum data rate for users in the geographical areas covered by slices
- Two-step approach to decompose the global optimization problem (`JRN`)
- `JRN` vs 4 variants of `CARP`:
  - least provisioning cost
  - but requires a much larger time complexity

Contributions

Part I. Deterministic slice resource demands

Part II. Random slice resource demands

1 network provisioning

2 coverage-aware

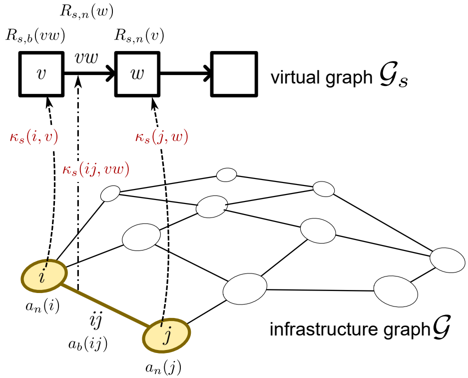
3 uncertainty-aware

4 anticipated prov.

- Uncertainties may lead to slice QoS $<$ expected level
  - S-RDs: traffic dynamics, *e.g.*, flow arrival/departure
  - available infrastructure resources
- This contribution:
  - provisions infrastructure resources for network slices, while being robust to a partly unknown number of users with a random usage of the slice resources.
  - guarantees a predefined service satisfaction probability (SSP)
  - moreover, provisioning is performed so as to limit its impact on background services

Resource provisioning for slice s

- $\kappa_s(i, v) \in \mathbb{N}$, $\kappa_s(ij, vw) \in \mathbb{N}$
- $\widetilde{\kappa}_s(i, v) \in \{0, 1\}$ node mapping indicator function.
- $\widetilde{\kappa}(i) \in \{0, 1\}$ indicator function for use of infrastructure node i.



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Slice resource demand constraints

Static constraints: S-RD $\mathrm{R}_s = \left(R_{s,n}(v), R_{s,\mathrm{b}}(vw)\right)^{\top}_{n\in\Upsilon,(v,vw)\in\mathcal{G}_s}$ is deterministic

$$\sum_{i\in\mathcal{N}} \kappa_s(i,v)\, r_{s,n}(v) \geqslant R_{s,n}(v), \forall s\in\mathcal{S}, v\in\mathcal{N}_s, n\in\Upsilon$$

$$\sum_{ij\in\mathcal{E}} \kappa_s(ij,vw)\, r_{s,\mathrm{b}}(vw) \geqslant R_{s,\mathrm{b}}(vw), \forall s\in\mathcal{S}, vw\in\mathcal{E}_s$$

Uncertainty-aware constraints: S-RD R_s is random $\rightarrow$ Service Satisfaction Probability (SSP) constraint:

$$p_s(\boldsymbol{\kappa}_s) = \Pr\left\{\begin{array}{l} \sum_{i\in\mathcal{N}} \kappa_s(i,v)\, r_{s,n}(v) \geqslant R_{s,n}(v), \forall v, n, \\ \sum_{ij\in\mathcal{E}} \kappa_s(ij,vw)\, r_{s,\mathrm{b}}(vw) \geqslant R_{s,\mathrm{b}}(vw), \forall vw \end{array}\right\} \geqslant \underline{p}_s, \forall s\in\mathcal{S}.$$

$\underline{p}_s$: minimum SSP for slice s.

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Slice resource demand constraints

Static constraints: S-RD $\mathrm{R}_s = \left(R_{s,n}(v), R_{s,\mathrm{b}}(vw)\right)^{\top}_{n \in \Upsilon, (v,vw) \in \mathcal{G}_s}$ is deterministic

$$\sum_{i \in \mathcal{N}} \kappa_s(i,v)\, r_{s,n}(v) \geqslant R_{s,n}(v), \forall s \in \mathcal{S}, v \in \mathcal{N}_s, n \in \Upsilon$$

$$\sum_{ij \in \mathcal{E}} \kappa_s(ij,vw)\, r_{s,\mathrm{b}}(vw) \geqslant R_{s,\mathrm{b}}(vw), \forall s \in \mathcal{S}, vw \in \mathcal{E}_s$$

Uncertainty-aware constraints: S-RD R_s is random $\rightarrow$ Service Satisfaction Probability (SSP) constraint:

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$\underline{p}_s$: minimum SSP for slice s.

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Slice resource demand constraints

Relaxed SSP constraints:

$$\sum_{i\in\mathcal{N}} \kappa_s(i,v)\, r_{s,n}(v) \geqslant \overline{R}_{s,n}(v) + \gamma_s \widetilde{R}_{s,n}(v), \forall s \in \mathcal{S}, v \in \mathcal{N}_s, n \in \Upsilon$$

$$\sum_{ij\in\mathcal{E}} \kappa_s(ij,vw)\, r_{s,\mathrm{b}}(vw) \geqslant \overline{R}_{s,\mathrm{b}}(vw) + \gamma_s \widetilde{R}_{s,\mathrm{b}}(vw), \forall s \in \mathcal{S}, vw \in \mathcal{E}_s$$

The SSP becomes

$$p_s(\gamma_s) = \Pr\left\{ \begin{array}{l} \widehat{R}_{s,n}(v,\gamma_s) \geqslant R_{s,n}(v), \forall s \in \mathcal{S}, v \in \mathcal{N}_s, n \in \Upsilon \\ \widehat{R}_{s,\mathrm{b}}(vw,\gamma_s) \geqslant R_{s,\mathrm{b}}(vw), \forall s \in \mathcal{S}, vw \in \mathcal{E}_s \end{array} \right\}$$

A sufficiently large γ_s would satisfy the SSP constraint.

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Slice resource demand constraints

Finding γ_s: The smallest smallest value of γ_s such that $p_s(\gamma_s) \geqslant \underline{p}_s$

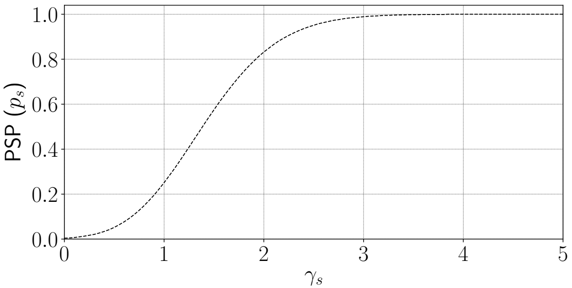

Figure: Evolution of p_s as function of γ_s.

γ_s can then be found by applying a bisection search[1].

[1] R. L. Burden and J. Douglas Faires, *Numerical Analysis*, 9th ed. Brooks/Cole, Cengage Learning, 2011.

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Impact on background service (ImP) constraints

Static constraints: Infrastructure resources $(a_n(i), a_\mathrm{b}(ij))$ are deterministic

$$\sum_{s\in S}\sum_{v\in\mathcal{N}_s}\kappa_s(i,v)\,r_{s,n}(v)\leqslant a_n(i),\forall i\in\mathcal{N},n\in\Upsilon,$$

$$\sum_{s\in S}\sum_{vw\in\mathcal{E}_s}\kappa_s(ij,vw)\,r_{s,\mathrm{b}}(vw)\leqslant a_\mathrm{b}(ij),\forall ij\in\mathcal{E},$$

Uncertainty-aware constraints: $(a_n(i), a_\mathrm{b}(ij))$ are random $\rightarrow$ Impact Probabilities (ImPs) constraints:

$$p_n^{\mathrm{im}}(i)\leqslant\overline{p}^{\mathrm{im}},\forall i\in\mathcal{N},n\in\Upsilon,$$

$$p_\mathrm{b}^{\mathrm{im}}(ij)\leqslant\overline{p}^{\mathrm{im}},\forall ij\in\mathcal{E},$$

$\overline{p}^{\mathrm{im}}$: minimum ImP on background services.

Relaxed ImP constraints:

$$\sum_{s,v}\kappa_s(i,v)\,r_{s,n}(v)\leqslant a_n(i)-\left[\overline{B}_n(i)+\gamma_\mathrm{B}\widetilde{B}_n(i)\right],\forall n\in\Upsilon,i\in\mathcal{N},$$

$$\sum_{s,vw}\kappa_s(ij,vw)\,r_{s,\mathrm{b}}(vw)\leqslant a_\mathrm{b}(ij)-\left[\overline{B}_\mathrm{b}(ij)+\gamma_\mathrm{B}\widetilde{B}_\mathrm{b}(ij)\right],\forall ij\in\mathcal{E},$$

$\rightarrow$ Optimality: $\gamma_\mathrm{B}=\Phi^{-1}\left(1-\overline{p}^{\mathrm{im}}\right)$ guarantees $p_n^{\mathrm{im}}(i)\leqslant\overline{p}^{\mathrm{im}}$, $\forall i\in\mathcal{N},n\in\Upsilon$, and $p_\mathrm{b}^{\mathrm{im}}(ij)\leqslant\overline{p}^{\mathrm{im}}$, $\forall ij\in\mathcal{E}$.

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Uncertainty-aware provisioning for multiple slices

$$\underset{\{\boldsymbol{d},\boldsymbol{\kappa}\}=\{d_s,\boldsymbol{\kappa}_s\}_{s\in\mathcal{S}}}{\text{maximize}} \quad \sum_{s\in\mathcal{S}} \left(l_s d_s - C_s\left(\boldsymbol{\kappa}_s\right)\right),$$

$$\text{subject to} \sum_{i\in\mathcal{N}} \kappa_s\left(i,v\right) r_{s,n}\left(v\right) \geqslant \widehat{R}_{s,n}\left(v,\gamma_s\right) d_s, \forall s\in\mathcal{S}, v\in\mathcal{N}_s, n\in\Upsilon$$

$$\sum_{ij\in\mathcal{E}} \kappa_s\left(ij,vw\right) r_{s,\mathrm{b}}\left(vw\right) \geqslant \widehat{R}_{s,\mathrm{b}}\left(vw,\gamma_s\right) d_s, \forall s\in\mathcal{S}, vw\in\mathcal{E}_s,$$

$$\sum_{s\in\mathcal{S}}\sum_{v\in\mathcal{N}_s} \kappa_s\left(i,v\right) r_{s,n}\left(v\right) \leqslant a_n\left(i\right) - \widehat{B}_n\left(i,\gamma_{\mathrm{B}}\right), \forall i\in\mathcal{N}, n\in\Upsilon,$$

$$\sum_{s\in\mathcal{S}}\sum_{vw\in\mathcal{E}_s} \kappa_s\left(ij,vw\right) r_{s,\mathrm{b}}\left(vw\right) \leqslant a_{\mathrm{b}}\left(ij\right) - \widehat{B}_{\mathrm{b}}\left(ij,\gamma_{\mathrm{B}}\right), \forall ij\in\mathcal{E}.$$

flow conservation constraint

Table: Provisioning approaches.

	Jointly	Sequentially
background services not taken into account	JP	SP
background services accounted	JP-B	SP-B

- Background services: consume on average 20% of available infrastructure resources (5% std. dev.)
- Types of slices:
  (1) HD video streaming at 4 Mbps. $N_s \sim \mathcal{B}(300, 0.9)$, $l_s = 900$, $\underline{p}_s = 0.99$
  (2) SD video streaming at 2 Mbps. $N_s \sim \mathcal{B}(1000, 0.8)$, $l_s = 1000$, $\underline{p}_s = 0.95$
  (3) Video surveillance and traffic monitoring at 1 Mbps. $N_s = 50$, $l_s = 800$, $\underline{p}_s = 0.9$

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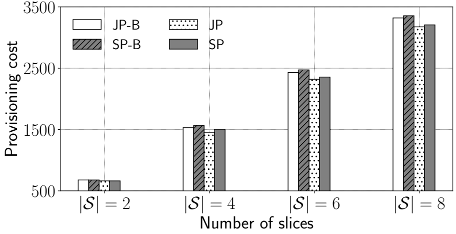
- Provisioning of a single slice of Type 1, with $\underline{p}_s = 0.99$ and $\overline{p}^{\text{im}} = 0.1$
- SP-B vs and SP (w/ and w/o background traffic):
  - SP has a lower provisioning cost, and yields a higher earning, but has a higher impact on background services

Table: SP-B vs and SP (w/ and w/o background traffic).

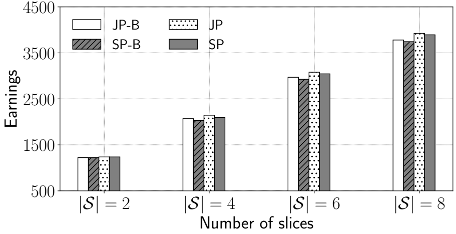
Criteria	SP-B	SP
Maximal p^{im}	1.26e-4	0.58
Provisioning cost	332	326
Total earnings	568	574
#impacted nodes	0	1
#impacted links	0	0

(3) Uncertainty-aware | Evaluation

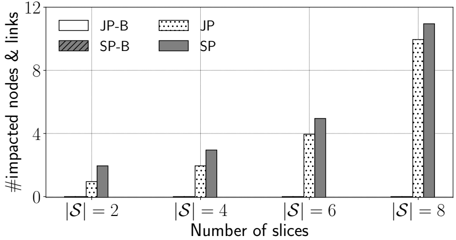
Provisioning of several slices of different types



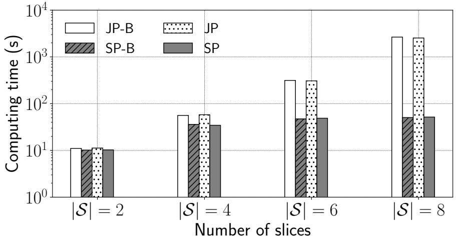
(a) Provisioning cost



(b) Earnings



(c) #impacted nodes & links



(d) Computing time

(3) Uncertainty-aware | Evaluation

Benefits of the uncertainty-aware slice resource provisioning

- UPE: uncertainty-aware provisioning and embedding solution
- DPE: deterministic provisioning and embedding solution
- S-RD: nb of users associated to the slice follows a binomial distribution $\mathcal{B}(m, p)$
  - m is fixed to 300
  - p varies from 0.4 to 0.9

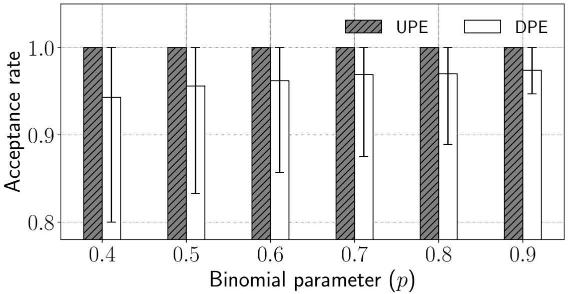


Figure: UPE vs DPE in terms of SFC acceptance rate.

- Resource provisioning method for network slicing that maximizes
  - acceptance rate,
  - earnings of the InP
- Advantages
  - robustness to uncertainties
  - keep the impact on the background services under a threshold imposed by the InP.

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