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Tutorial: Data-analytics based orchestration

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Acknowledgement: The material of this tutorial and keynote speech has been based on the work that the presenter is doing in the H2020 5G-TOURS European project (Grant Agreement No. 856950).

Tutorial outline

- Network slicing
- Network Softwarization
- Network orchestration
- Data analytics and AI

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Requirements for 5G

	4G IMT-A		5G IMT-2020
Practical user transfer speed	10Mbps	High-res video streaming (HD, 4K, 8K...)	100Mbps~1Gbps
Peak transfer speed	1Gbps	High-capacity file download (DVD → BD class)	20Gbps
Max. device movement speed	350km/h	High-speed transportation (e.g. maglev/linear-motor vehicles)	500km/h
Permissible latency (wireless areas)	10ms	Even lower latency (AR, fighting games, remote-controlled medical treatment)	1ms
Device connection density	10^5/km^2	Popularization of IoT (17% annual growth rate)	10^6/km^2
Area traffic capacity	0.1Mbps/m^2	Increase in traffic (40%+ annual growth rate)	10Mbps/m^2

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Requirements heterogeneity

>10 Gbit/s peak data rates

100 Mbit/s whenever needed

10 – 100 x more devices

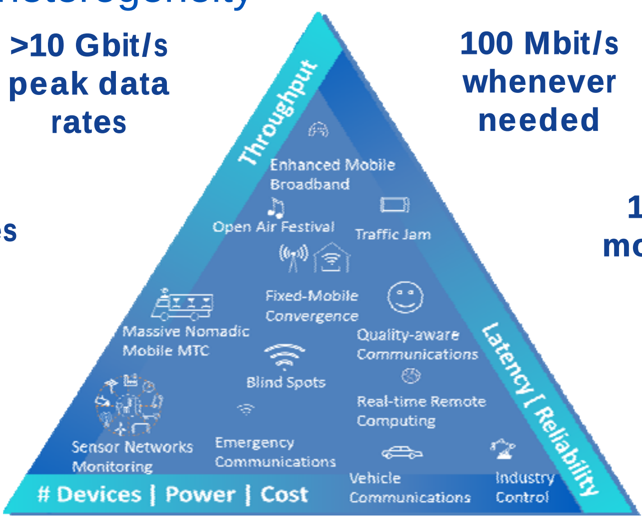
10 000 x more traffic

M2M ultra low cost

ultra reliability

10 years battery lifetime

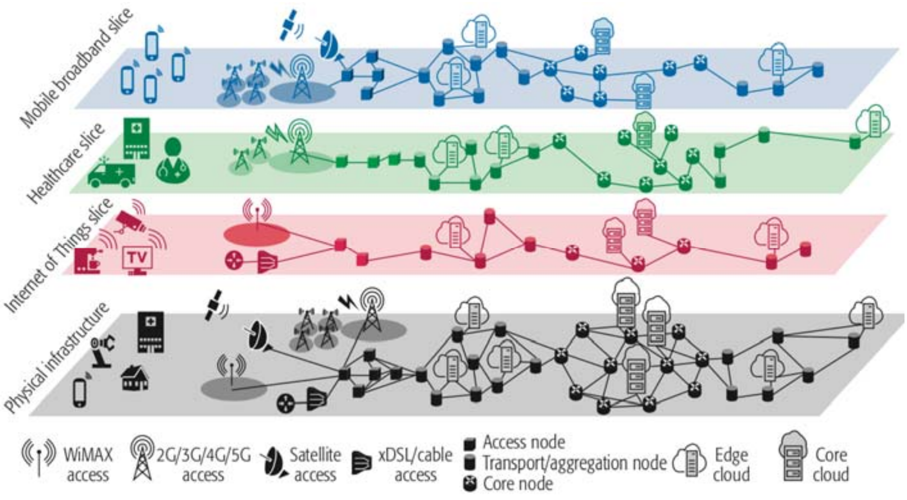
<1 ms radio latency



What is network slicing?

- **Network Slice:** A set of infrastructure resources and service functions that has attributes specifically designed to meet the needs of an industry vertical or a service
- **Network Slicing:** A management mechanism that Network Slice Provider can use to allocate dedicated infrastructure resources and service functions to the user of the Network Slice
- **3GPP definition:**
  - “A logical network that provides specific network capabilities and network characteristics”
  - “A network created by the operator customized to provide an optimized solution for a specific market scenario which demands specific requirements with end to end scope”
  - Implemented by “slice instances”
  - Created from a “network slice template”

What is network slicing?



From: J. Ordonez-Lucena, P. Ameigeiras, D. Lopez, J. J. Ramos-Munoz, J. Lorca and J. Folgueira, "Network Slicing for 5G with SDN/NFV: Concepts, Architectures, and Challenges," in *IEEE Communications Magazine*, vol. 55, no. 5, pp. 80-87, May 2017.

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Network slice types

- **Enhanced Mobile Broadband** (eMBB) to deal with hugely increased data volumes, overall data capacity and user density
- **Massive Machine-type Communications** (mMTC) for the IoT, requiring low power consumption and low data rates for very large numbers of connected devices
- **Ultra-reliable and Low Latency Communications** (URLLC) to cater for safety-critical and mission critical applications

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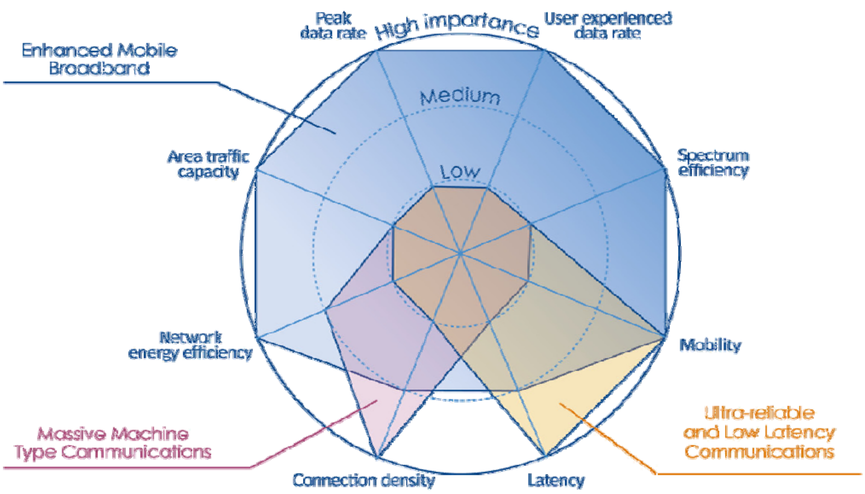
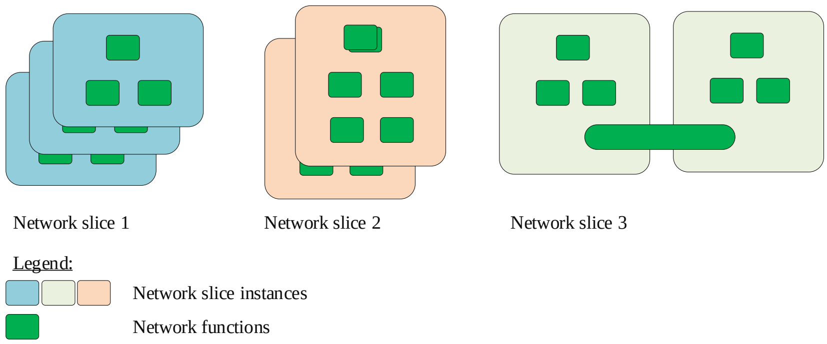
Slice types' requirements



Network Slices vs. Network Slice Instances



- Network Slice: A logical network that provides specific network capabilities and network characteristics.
- Network Slice instance: A set of Network Function instances and the required resources (e.g. compute, storage and networking resources) which form a deployed Network Slice.

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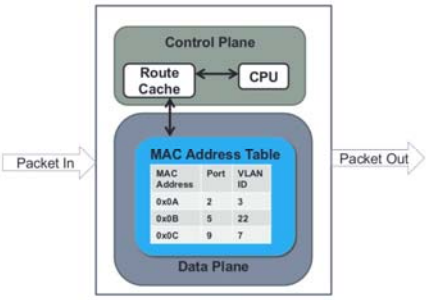
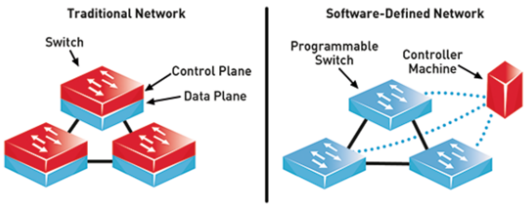
Software Defined Networking (SDN)

- Separate user plan from control plane, bringing controller to a centralized location
- Allow to modify the behavior of the control plane by means of “user policies”





From: McKeown et. al “OpenFlow: Enabling Innovation in Campus Networks,” ACM CCR 2008

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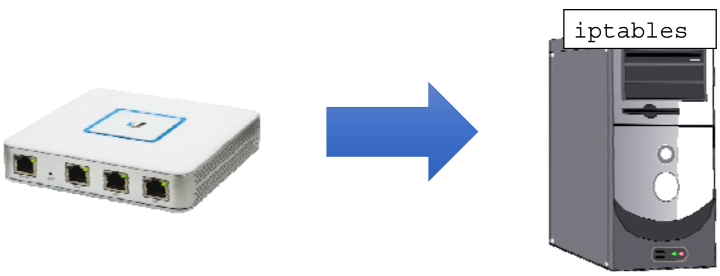
Network Function Virtualization (NFV)

- Complementary technology to SDN, which depends on SDN to deliver its benefits
- Network Function: Building block of a communication service
- E.g., gateway, load balancer, firewall



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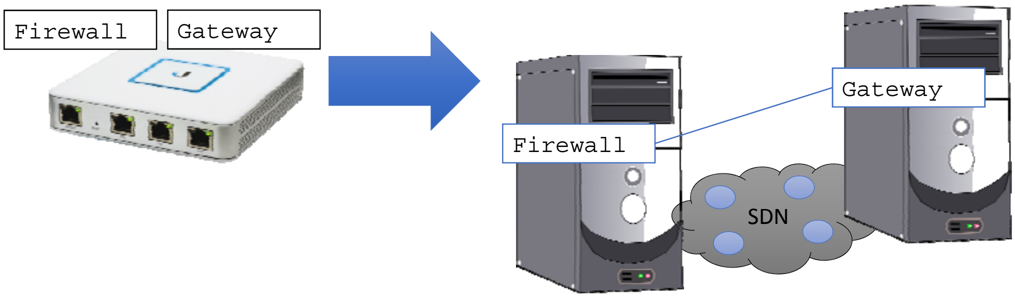
NFV definition

- Use technologies of IT virtualization to virtualize and connect network node functions



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Benefits of NFV

- Reduced equipment costs and reduced power consumption through consolidating equipment and exploiting the economies of scale of the IT industry
- Increased velocity of Time to Market by minimizing the typical network operator cycle of innovation
- Much more efficient test and integration
  - Production, test and reference facilities can be run on the same infrastructure
- Targeted service introduction based on geography or customer sets is possible
  - Services can be rapidly scaled up/down as required
  - Service velocity is improved by provisioning remotely

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Virtualizing Network Functions

NF1 NF2 NF3 NF4 NF5

"decoding" "scheduling" "authentication" ...

Network Fucntions (NFs)

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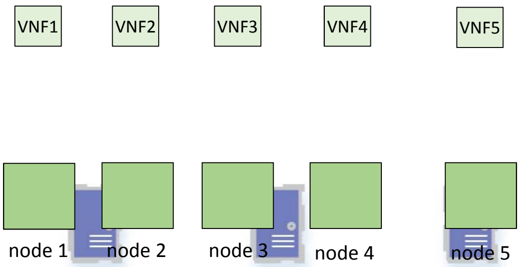
Virtualizing Network Functions

NF1 NF2 NF3 NF4 NF5

node 1 node 2 node 3 node 4 node 5

Traditional network:
network functions (NFs)
attached to node

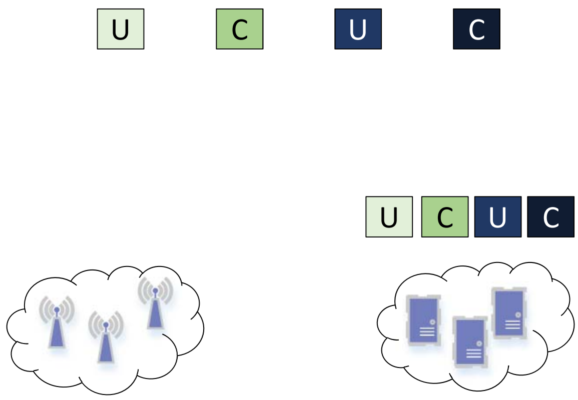
Virtualizing Network Functions



Virtualized network functions (VNFs)

Nodes: general purpose processors

Orchestration of VNFs



Virtual Network Functions (VNFs)

- U U-plane CN
- C C-plane CN
- U U-plane RAN
- C C-plane RAN

Nodes: general purpose processors

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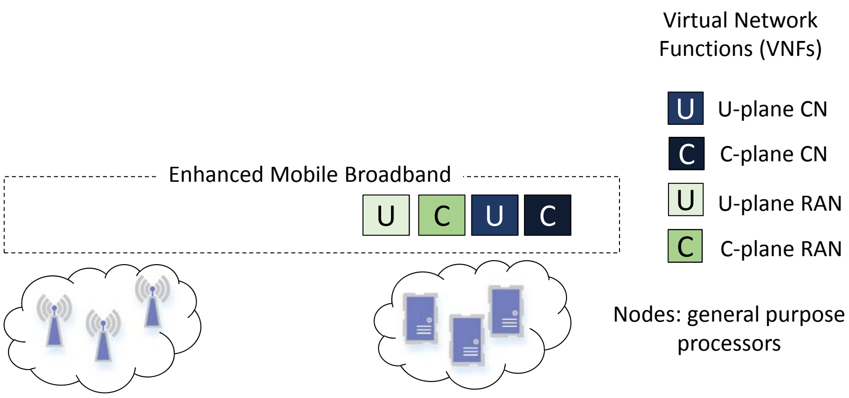
Orchestration of VNFs



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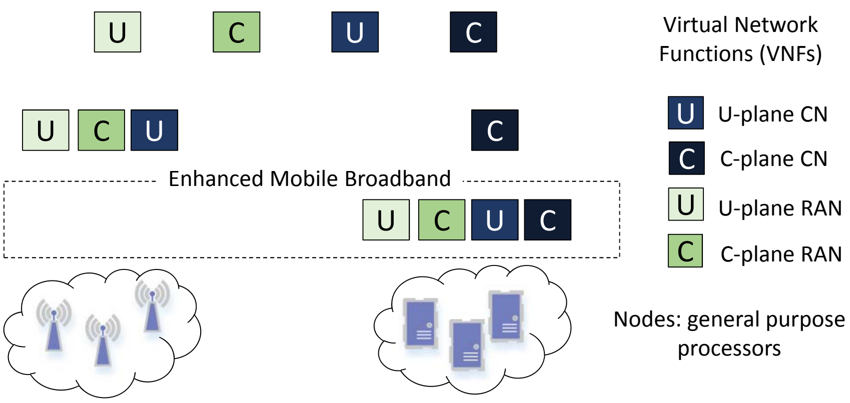
Orchestration of VNFs



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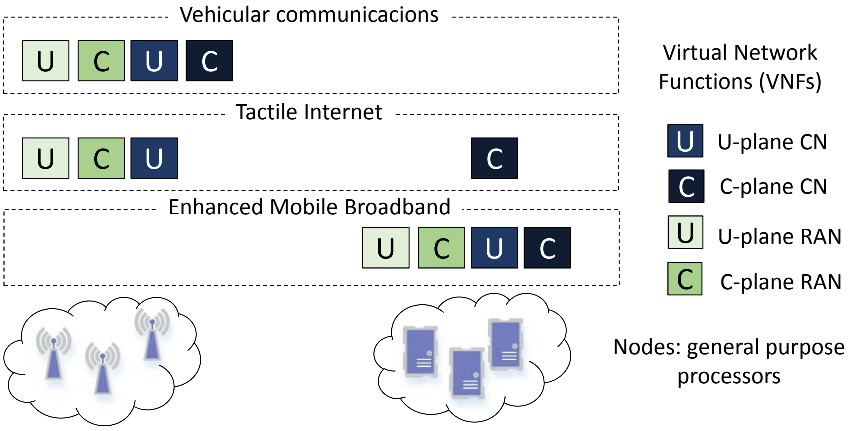
Orchestration of VNFs



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- Network orchestration
- Data analytics and AI

Motivation

- SDN and NFV have brought a revolutionary paradigm on network management
- This allows for enhanced network features but increases the complexity for the management of the network
- Moreover, new management functionality has to be provided
  - Network function placement
  - Resource orchestration
- Therefore, the management system in 5G needs to be heavily revisited

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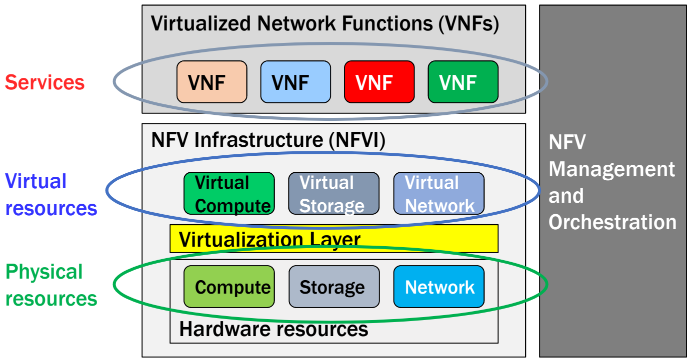
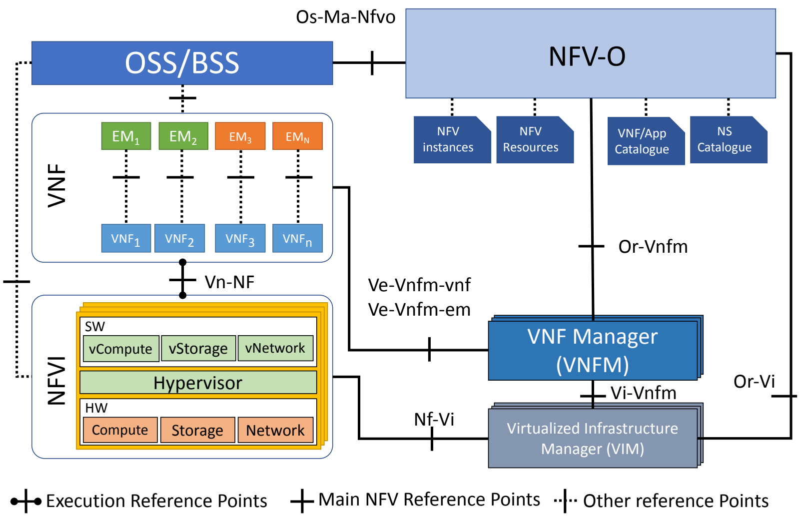
Management and Orchestration

- Also known as MANO or M&O
- Management
  - Network Function Selection
  - Network Function Configuration
  - Network Function Chaining
- Orchestration
  - Network Function Placement
  - Resource Allocation
  - Including both cloud and RAN resources

High-level NFV framework



ETSI NFV MANO Architecture



Service and Resource Orchestration

- 5G Networks relies on two different kind of orchestration
- Resource orchestration
  - Assignment to each slice of the needed resources
  - Proper configuration of the associated resources (i.e., spectrum)
  - No understanding of the "semantic" of the deployed VNFs
  - The underlying topology is also out of the scope of resource orchestration
- Service orchestration
  - Understanding the service needed by the slice and translate it into VNFs
  - Also their chaining and relation shall be provided

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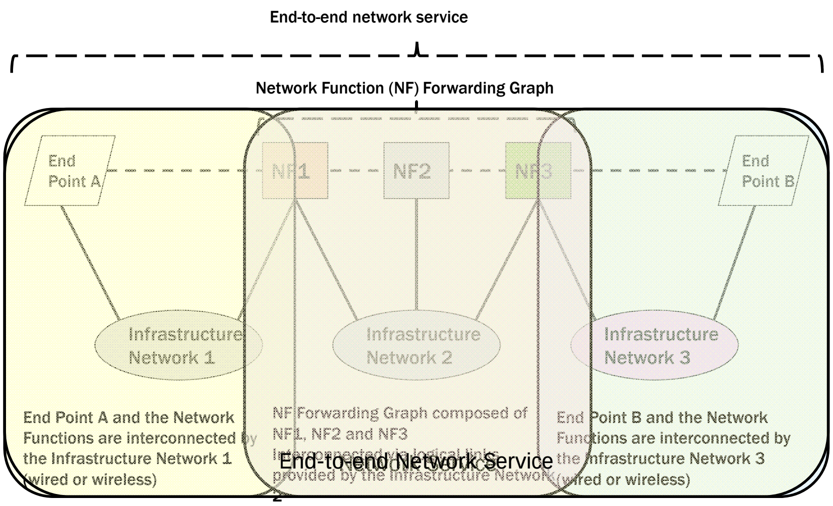
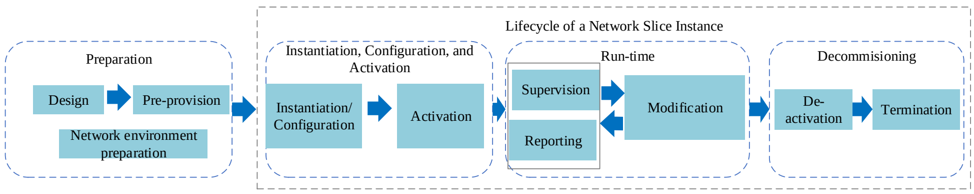
End-to-end service Orchestration

- To orchestrate an end-to-end service, the NFV Orchestrator (NFVO) instantiates the network slice as follows:
  - It issues the corresponding requests to the Software-Defined Networking (SDN) controller to instantiate connections between the different network nodes
  - It requests the Virtualized Infrastructure Manager (VIM) to reserve the virtual resources at the different network nodes
  - It commands the Virtual Network Function Manager (VNFM) to instantiate the VNFs
  - It configures the VNFs and PNFs (Physical Network Functions)



Network Slice Lifecycle management

- Preparation
  - Translation of slice requirements to network function chain
- Activation
  - Slice kick-off on the shared infrastructure
- Runtime
  - Scaling of the NF, according to the conditions
- Decommissioning
  - When the service is not available anymore



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Shared and non-shared NFs

- A NSI may contain functions that are shared among network slice instances (NSIs), while other are dedicated
  - For example, a shared AMF (Access Management Function)
- When creating a new NSI, we check if there are existing shared network functions that can be used for creation of a new NSI
  - In this case they become shared NFs
  - In the case some shared network functions are available, only additional (non-shared) network functions may need to be created
  - The existing shared network functions may need to be reconfigured, and the resources supporting them may need to be added to ensure that all NSI(s) can be served
- In the case where no existing network functions are available for the new NSI, both the shared and the non shared shall be created
  - The new shared are just ”shareable”
  - They only belong to the new single NSI at this point until being shared by other NSIs (where they become "shared")

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Artificial intelligence & data analytics

- AI is a computation paradigm that endows machines with intelligence
  - Aiming to teach them how to work, react, and learn like humans
  - Many techniques fall under this broad umbrella
- Machine learning enables the artificial processes to absorb knowledge from data and make decisions without being explicitly programmed
  - Data needs to be collected and made availably to AI algorithms
  - Machine learning is closely related to data analytics
- Machine learning has become very popular driven by:
  - Modern challenges are “high-dimensional” in nature
  - We have rich data sources and processing power that can be use to solve problems
  - Machine learning can be integrated into working software to support products demanded by industry
- In line with the rising popularity of machine learning, this tool is being widely used for many networking problems including 5G

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Data analytics and Artificial Intelligence for Orchestration

- Artificial Intelligence is a natural choice for driving orchestration decision
  - We need to make predictions, classifications and decisions based on data
- 3GPP has identified this and started efforts towards defining an AI-based Data Analytics
  - Autonomous and efficient control, management and orchestration
- Modules defined by 3GPP to this end
  - Network Data Analytics Function (NWDAF)
  - Management Data Analytics Function (MDAF)
- Standardization efforts are still ongoing
  - There is no current full-blown data analytics-assisted architecture ready

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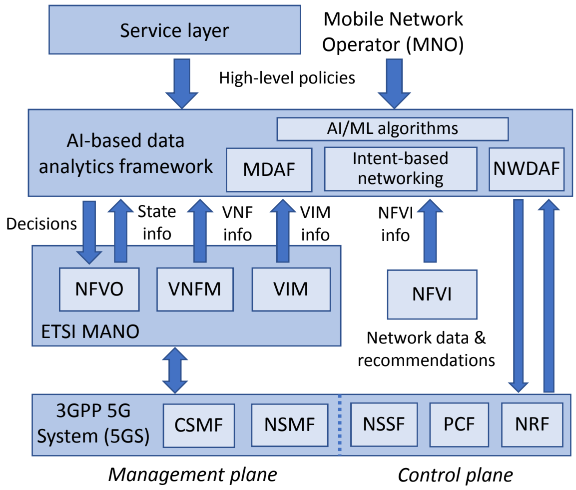
AI-based data Analytics framework



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Data analytics for the control plane

- In the control plane, analytics allow NFs to optimize their behavior at run-time, typically at a much faster speed than what network management and orchestration systems allow
- NWDAF analytics can be leveraged to improve
  - Slice-level load balancing
  - Service experience and Quality of Experience (QoE)
- Examples of data analytics usage
  - NSSF: Selecting the set of Network Slice instances serving a UE
  - PCF: Unified policy framework to govern network behavior, including the QoS parameters
  - NRF: Selection of a NF instance when a certain NF type is needed

Examples of data analytics for the control plane

- NSSF: Slice selection
  - NWDAF: monitors both load status and service experience statistics and predictions
  - Slice selection and load control functionality to decide which slice optimally serves each of the new UEs arriving in the network
- PCF: QoS control
  - Informed by NWDAF analytics on UE and application service experience
  - Adapt service QoS parameters across all UEs on a slice in such a way that the slice SLA is satisfied.
- NRF: Selection of NF instance
  - Keep NF profile of all NFs belonging to a slice, including their instantaneous load
  - Pre-selection step so that not only instantaneous NF load is taken into account, but also statistics and predictions
  - Load balancing is embedded in the selection process of the new NF instance among the candidate set

Data analytics for the management plane

- Data used as input by the AI-based analytics framework
  - NFV Infrastructure (NFVI): knowledge on the computational resources' capabilities (such as the type of CPU and memory, accelerators, etc.) along with their availability (i.e., the status and utilization level)
  - MANO system: requirements of the network slices
- Decision taken
  - NFVO: NF placement and resource allocation decisions while ensuring that the resulting resource allocation satisfies the respective slice SLA
  - VNFM: Run-time up and down scaling of resources
  - CSMF (Communication Service Management Function) and NSMF (Network Slice Management Function (NSMF): Admission control of new slices

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Keynote: Resource Allocation for network slicing

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Keynote outline

- Research challenges with network slicing & orchestration
- Analysis of the benefits of dynamic orchestration
- Realizing dynamic orchestration with machine learning

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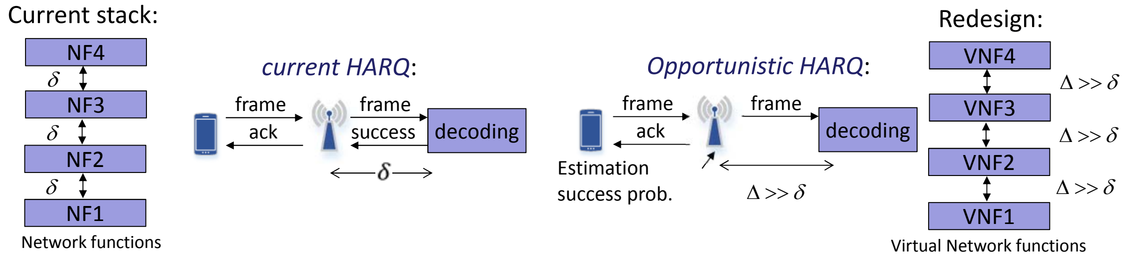
Protocol Stack redesign

- Current protocol stack
  - Designed considering that certain functions are co-located and can exchange data with no latency
  - This has introduced temporal dependencies that limit the flexibility in the placement
- Research challenge: remove tight constraints



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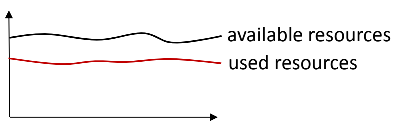
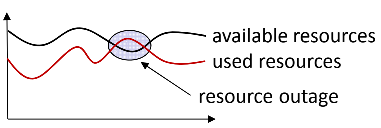
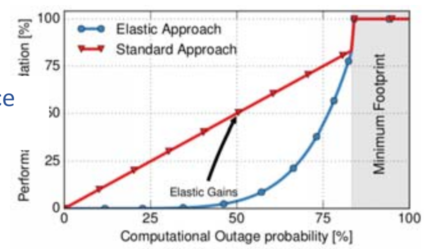
Bringing resource awareness: design of elastic VNFs

- Traditional environment for wireless functions
  - Capacity and computational load are known: Resources are always available
- Environment with virtualized wireless functions
  - Fluctuations on the capacity and load: resource outages may occur





Graceful performance degradation



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Designing the algorithms

- 3GPP provides the definition of the modules and the interfaces
  - However, the algorithms run by the different modules are not specified
  - The internals of the different modules are not in the scope of the standards
  - Furthermore the standards are still at a very early stage
  - Research work is required instead to fill this gap
- These are new paradigms that require completely new algorithms
  - Algorithms to determine the required resource allocation for the different VNFs to ensure that the respective SLAs with the tenants are met
  - Algorithms to determine the best location for the different VNFs
  - We need to account both for communications and for computing resources
  - Artificial Intelligence is a natural candidate for many of these problems

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Some research results

- Resource sharing for network slicing
  - "Network slicing games: Enabling customization in multi-tenant networks", IEEE INFOCOM 2017
  - "Multi-tenant radio access network slicing: Statistical multiplexing of spatial loads", IEEE/ACM ToN 2017
  - "Network Slicing Games: Enabling Customization in Multi-Tenant Mobile Networks", IEEE/ACM ToN 2019
- Resource allocation for network slicing
  - "Mobile traffic forecasting for maximizing 5G network slicing resource utilization", IEEE INFOCOM 2017
  - "RL-NSB: Reinforcement Learning-Based 5G Network Slice Broker", IEEE/ACM ToN 2019
- Admission control for network slicing
  - "Optimising 5G infrastructure markets: The business of network slicing", IEEE INFOCOM 2017
  - "Network slicing for guaranteed rate services: Admission control and resource allocation games", IEEE TWC 2018
  - "A machine learning approach to 5G infrastructure market optimization", IEEE TMC 2019
- Orchestration efficiency
  - "How should i slice my network?: A multi-service empirical evaluation of resource sharing efficiency", ACM MOBICOM 2018
  - "Resource sharing efficiency in network slicing", IEEE TNSM 2019
- Orchestration algorithms
  - "DeepCog: Cognitive Network Management in Sliced 5G Networks with Deep Learning," IEEE INFOCOM 2019
  - "Optimizing Resource Provisioning in Network Slicing with AI-based Capacity Forecasting", IEEE JSAC 2019
- Elastic VNFs
  - "CARES: Computation-Aware Scheduling in Virtualized Radio Access Networks" IEEE TWC 2018
  - "vrAIn: A Deep Learning Approach Tailoring Computing and Radio Resources in Virtualized RANs", ACM MOBICOM 2019
- Orchestration architecture/implementation
  - "POSENS: a practical open source solution for end-to-end network slicing", IEEE Wireless Communications 2018
  - "A 5G Mobile Network Architecture to Support Vertical Industries", IEEE Communications Magazine 2019

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Focus of the keynote

- Analyzing the advantages of dynamic orchestration
  - Gains resulting from dynamically adjusting the resources allocated to different slices
  - Shows the need for devising intelligent orchestration algorithms
  - Publication at ACM MOBICOM 2018
- Design of an intelligent orchestration algorithm
  - Example of how machine learning can be used to address a mobile network problem
  - Realizing the gains resulting form the above analysis
  - In line with the MDAF module considered by 3GPP
  - Publication at IEEE INFOCOM 2019

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Empirical evaluation of network slicing efficiency

- Following a data driven approach we want to
  - Quantify the price paid in efficiency when suitable algorithms for dynamic resource allocation are not available, and the operator has to resort to physical network duplication
  - Evaluate the impact of sharing resources at different levels of the network, including the cloudified core, the virtualized radio access, or the individual antennas
  - Outline the benefit of dynamic resource allocation at different timescales under various slice specifications
- Methodology
  - Our approach can be used for generic kinds of resource allocation
  - Still, it is not an optimization, but rather an indication of how well slices will behave

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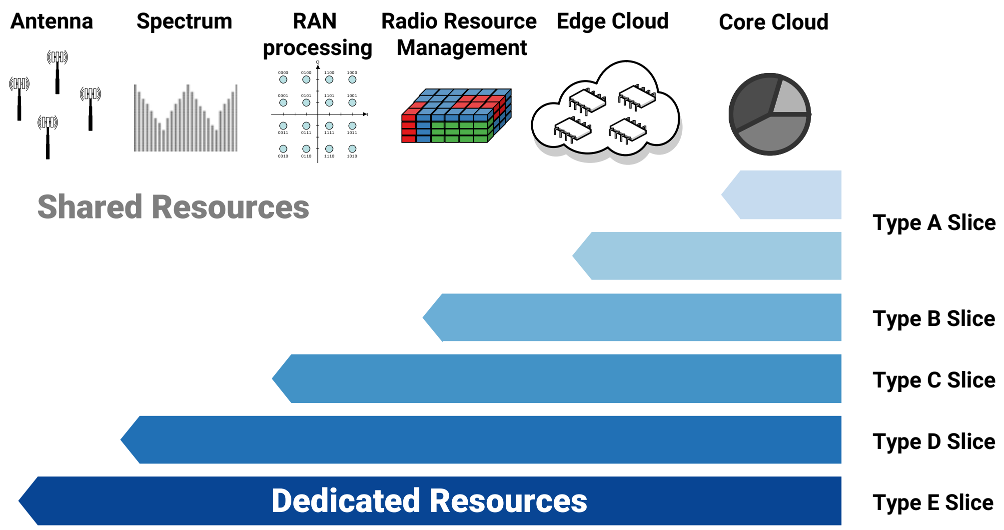
Slicing types



Network slicing model

Discrete set of levels
- Antenna $\ell = 1$
- Complete cloud $\ell = L$
- Set of network nodes C_ℓ

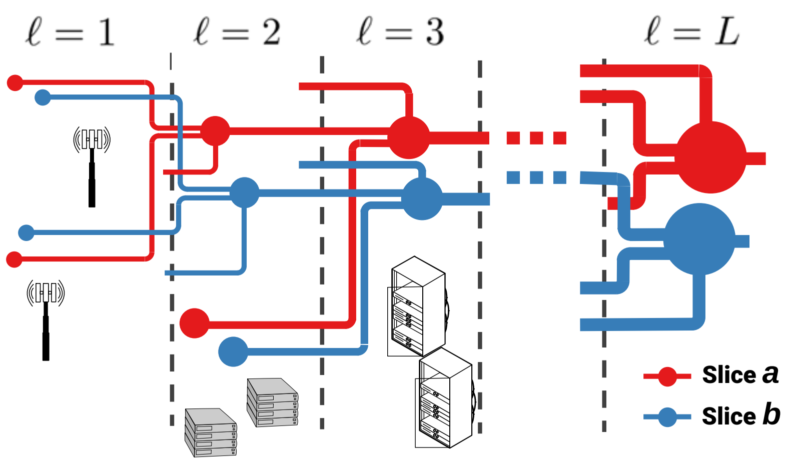
Network slice specifications $\mathbb{Z}$

$$\mathbb{Z} = (f, w)$$

- Guaranteed time fraction f
  - The percentage of time the operator is engaged to fully serve a slice
- Averaging window length w
  - The above is meant over a set of discrete time intervals

Reconfiguration intervals
- Each slice can be re-orchestrated every interval $\tau \gg w$

Network level & Aggregation



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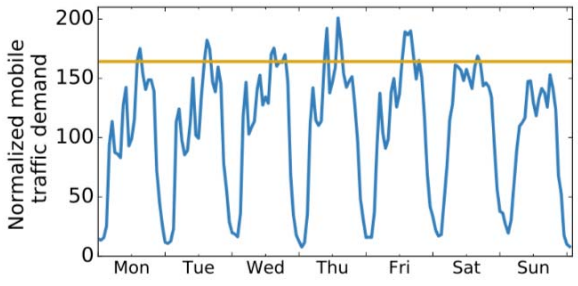
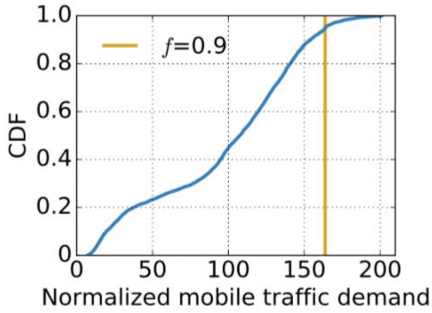
Meeting slice requirements

f 90% w 1 hour





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Efficiency evaluation

We evaluate the efficiency of a multi-slice scenarios by comparing

- A sliced scenario in which we need to statically provision each slice with the necessary resources to meet the slice requirements

$$\mathbb{R}^{\mathbb{Z}}_{\ell,\tau} = \sum_{s\in\mathcal{S}} \sum_{c\in C_\ell} \sum_{n\in\mathcal{T}} \tau \cdot \hat{r}^{\mathbb{Z}}_{c,s}(n).$$

- A perfect slicing scenario, in which the exact amount of resources are shared instantaneously among all slides

$$\mathbb{P}^{\mathbb{Z}}_{\ell,\tau} = \sum_{c\in C_\ell} \sum_{n\in\mathcal{T}} \tau \cdot \hat{r}^{\mathbb{Z}}_{c}(n),$$

- Ideal algorithm
- Very difficult to implement in practice
- Used in this analysis as benchmark

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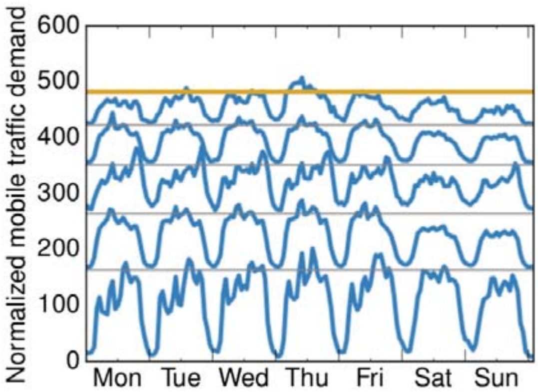
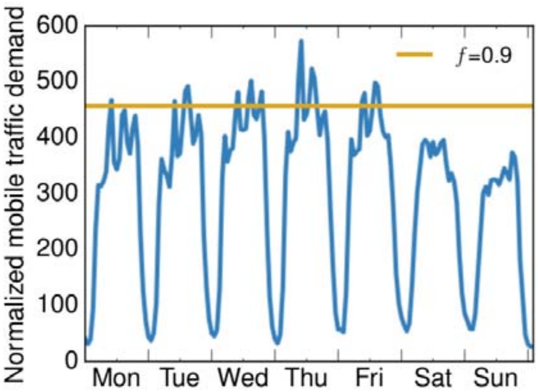
Efficiency example

f 90% w 1 hour





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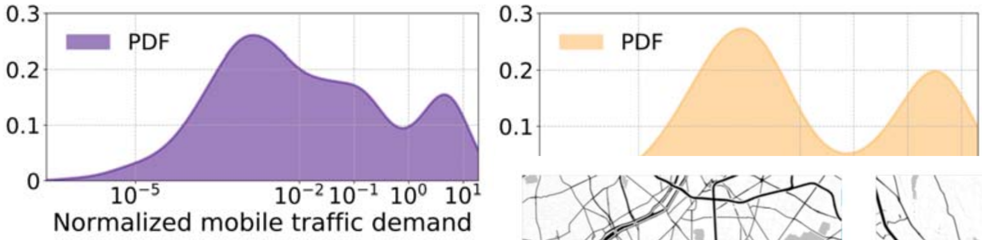
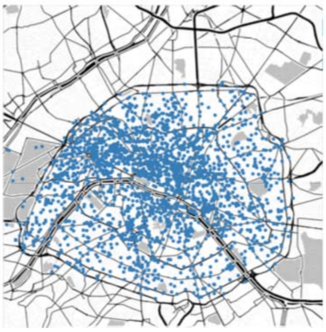
Empirical evaluation



Two large cities
Three months of data
Granularity in space: sector
Granularity in time: 5 minutes
38 services in total



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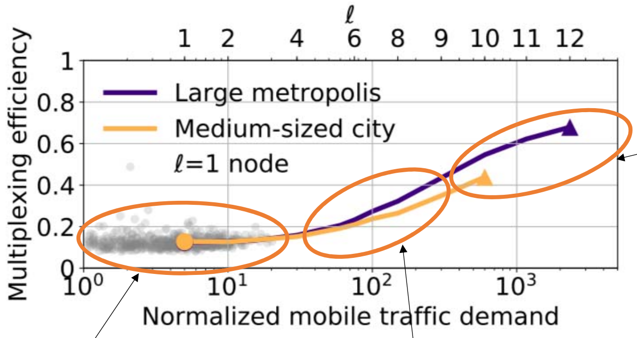
Global efficiency view

f 100% w 5 minutes



Still, we need to double the resources

Extremely low efficiency at antenna

Multiplexing gains start to be there

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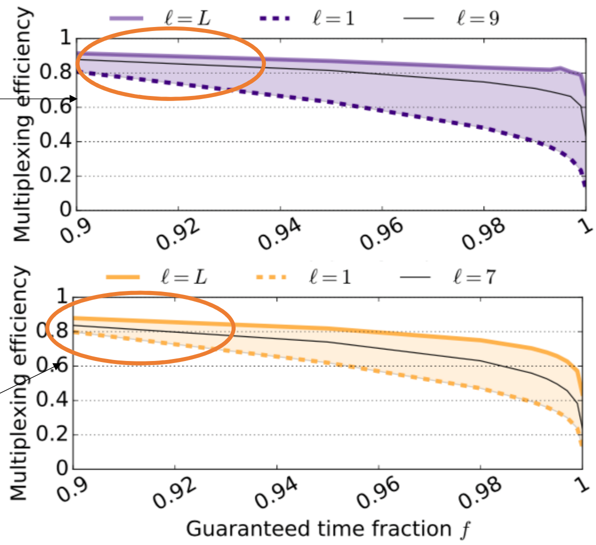
Relaxing the constraints

Good efficiency is achieved by relaxing the constraints a lot



Still, this is a +20% in the resources

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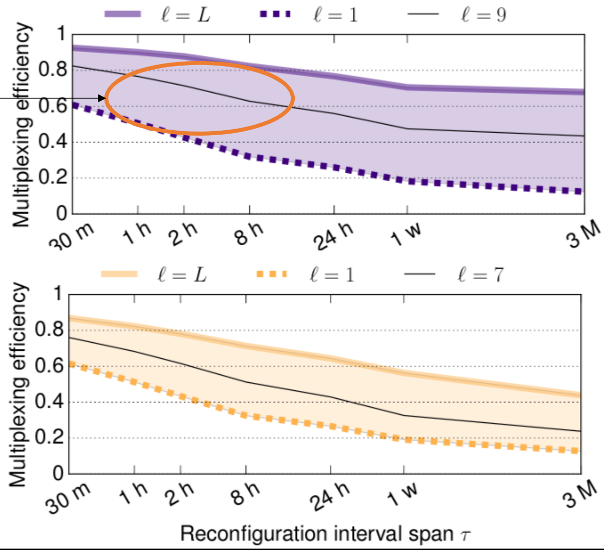
Reconfiguration interval impact

Reconfiguration sweetspot is here



Either we allow such timescale, otherwise we don't have much gain over static

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A model for resource deployment

The previous efficiency model is good to evaluate continuous time efficiency

- OPEX scenario (i.e., maintenance, dynamic resource assignment)

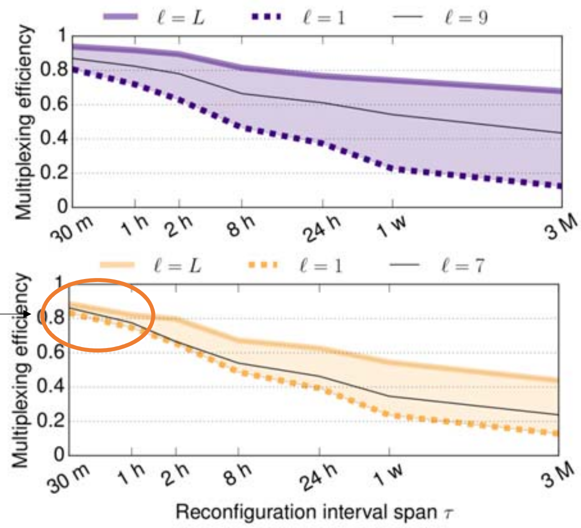
Extension of the model to consider an operator point of view

- CAPEX scenario (i.e., size of the deployed infrastructure)

$$\mathbb{R}^{\star\mathbb{Z}}_{\ell,\tau} = \sum_{s\in\mathcal{S}} \sum_{c\in\mathcal{C}_\ell} \max_{n\in\mathcal{T}} \left(\hat{r}^{\mathbb{Z}}_{c,s}(n)\right) \qquad \mathbb{P}^{\star\mathbb{Z}}_{\ell,\tau} = \sum_{c\in\mathcal{C}_\ell} \max_{n\in\mathcal{T}} \left(\hat{r}^{\mathbb{Z}}_{c}(n)\right)$$

Deployment scenario

Similar efficiency is achieved across aggregation levels



Takeaway messages

- Multi-service requires more resources
  - At least 20% more in the less challenging scenario
- Geography has limited impact
  - The two cities considered show similar trends
- Direction is a factor
  - Uplink is more challenging
- Moderating the requirements may not help
  - Good efficiency values are only achieved with non realistic service requirements
- Reconfiguration plays a key role
  - We need of orchestration algorithms that allow to dynamically re-allocate resources
  - Deployment cost may be mitigated: crucial for the 5G deployment

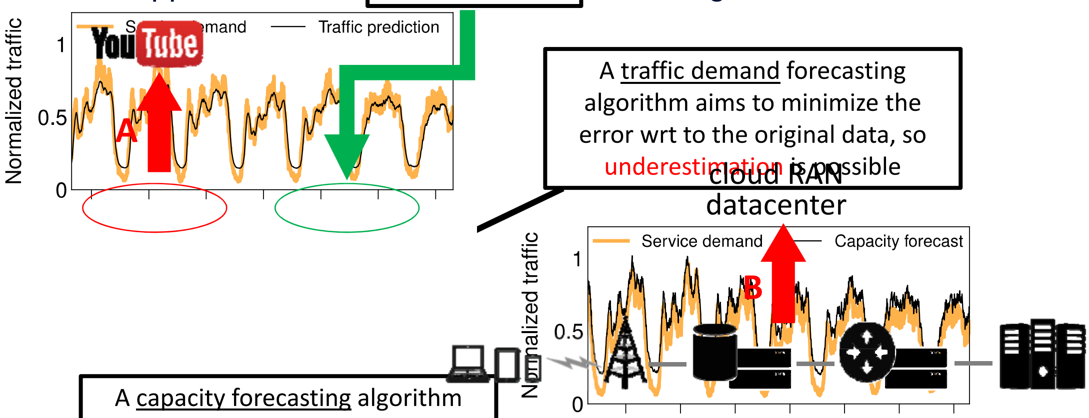
Keynote outline

- Research challenges with network slicing & orchestration
- Analysis of the benefits of dynamic orchestration
- Realizing dynamic orchestration with machine learning

Capacity vs Demand forecasting

- Traditional approaches deal [...] forecasting

DeepCog

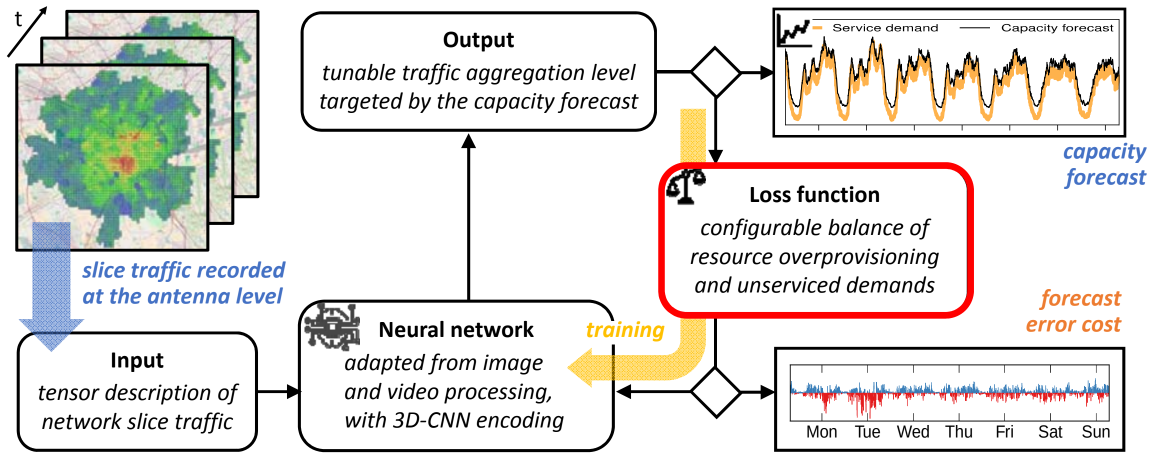


A traffic demand forecasting algorithm aims to minimize the error wrt to the original data, so underestimation is possible

A capacity forecasting algorithm minimizes the amount of resources needed to serve a given demand

DeepCog

- DeepCog's design follows a deep learning approach



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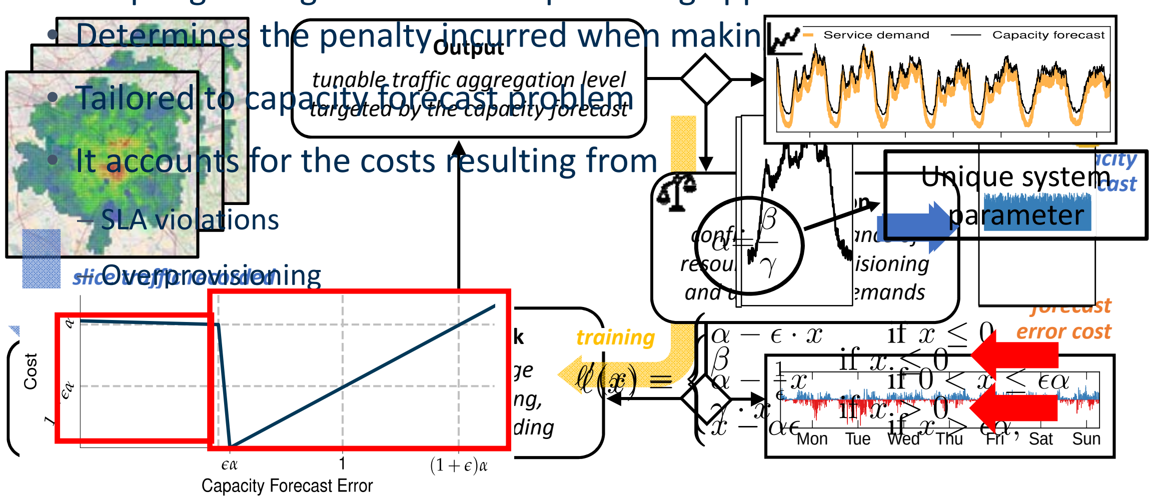
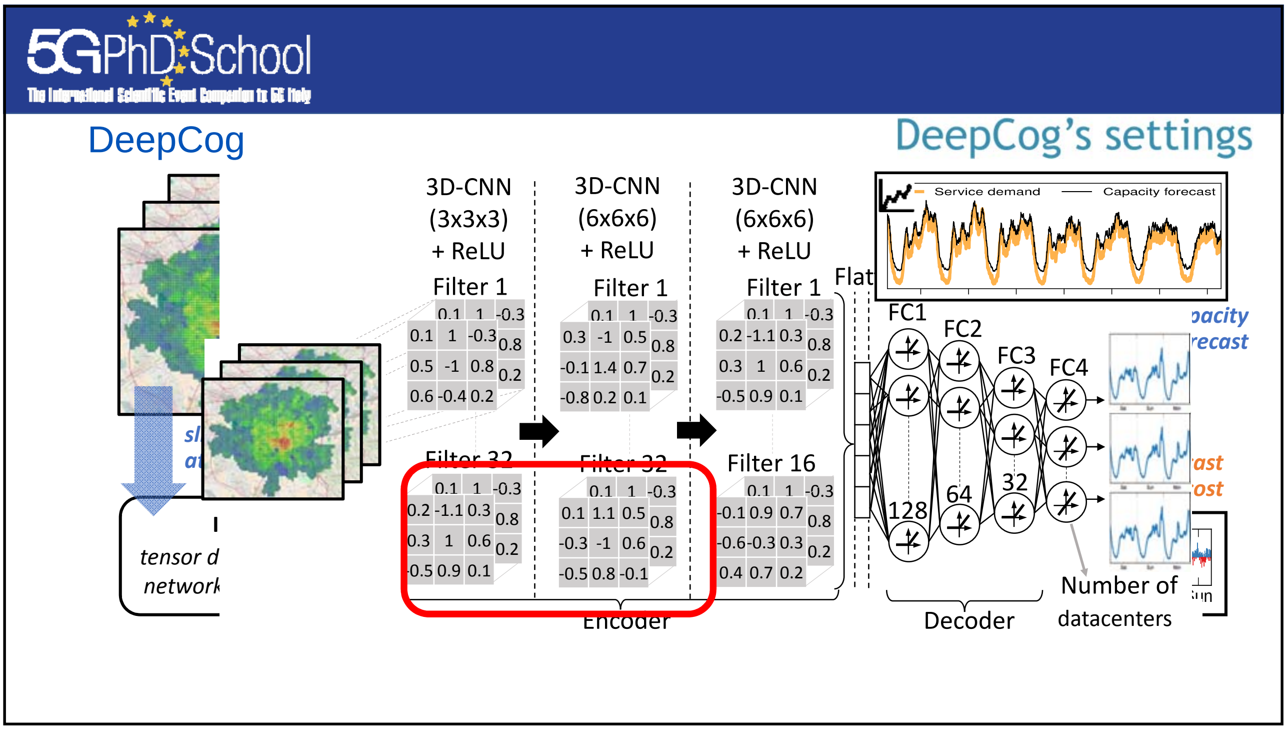
DeepCog — Loss function

- DeepCog's design follows a deep learning approach
- Determines the penalty incurred when makin
- Tailored to capacity forecast problem
- It accounts for the costs resulting from
  - SLA violations
  - Overprovisioning



$$\ell(x) = \begin{cases} \alpha - \epsilon \cdot x & \text{if } x \le 0 \\ \alpha - \frac{1}{\epsilon} x & \text{if } 0 < x \le \epsilon\alpha \\ x - \alpha\epsilon & \text{if } x > \epsilon\alpha \end{cases}$$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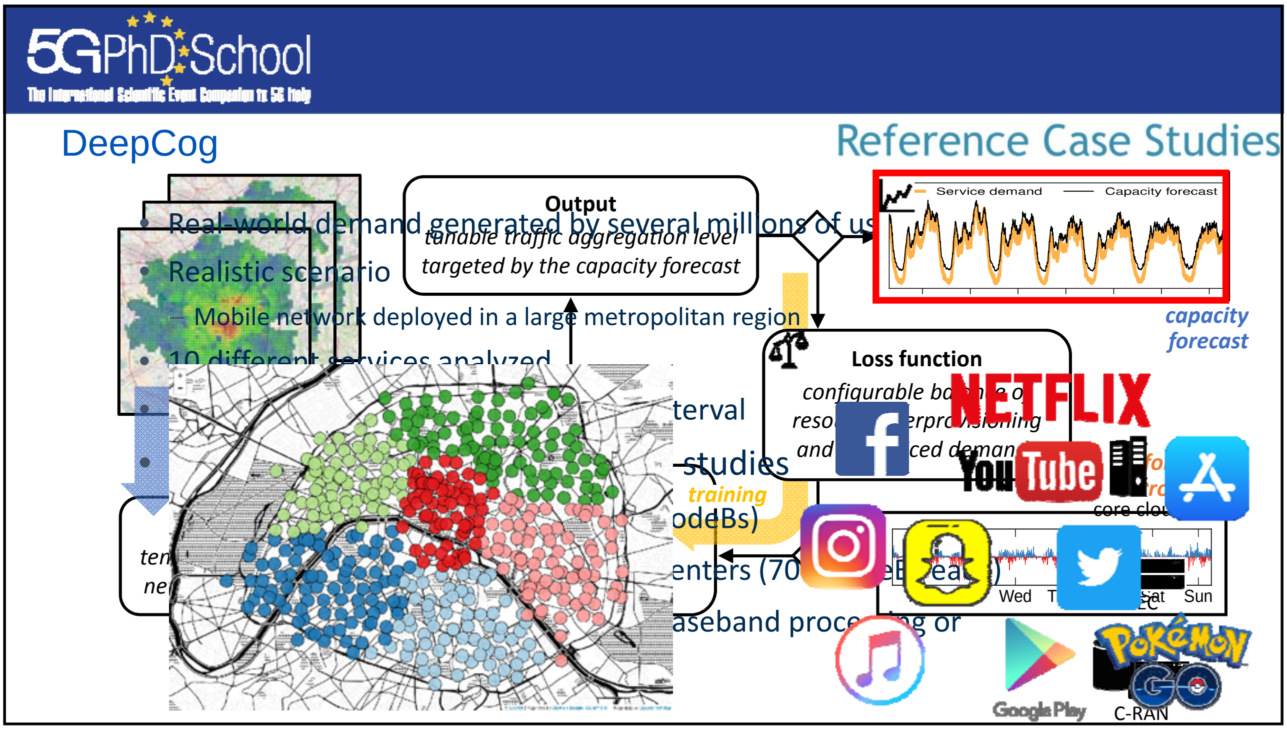
DeepCog
DeepCog's settings
3D-CNN (3x3x3) + ReLU
3D-CNN (6x6x6) + ReLU
3D-CNN (6x6x6) + ReLU
Filter 1
Filter 32
Filter 16
Encoder
Service demand
Capacity forecast
FC1
FC2
FC3
FC4
128
64
32
Decoder
Number of datacenters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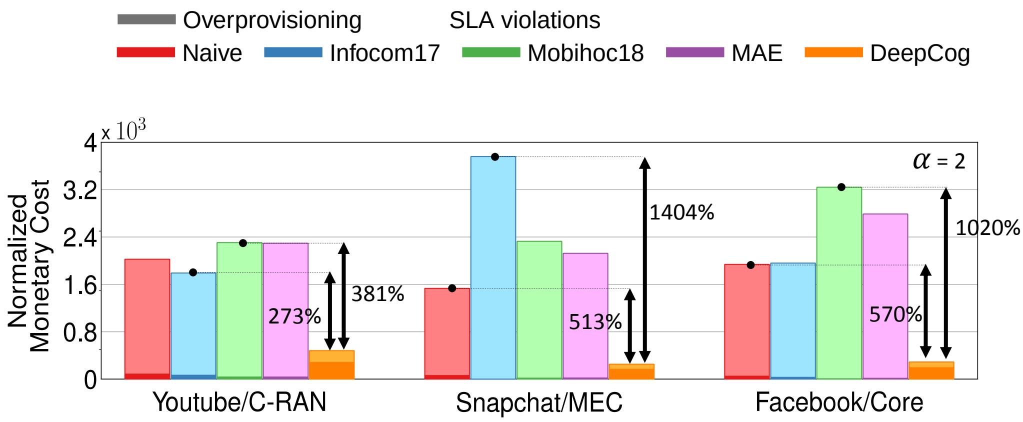
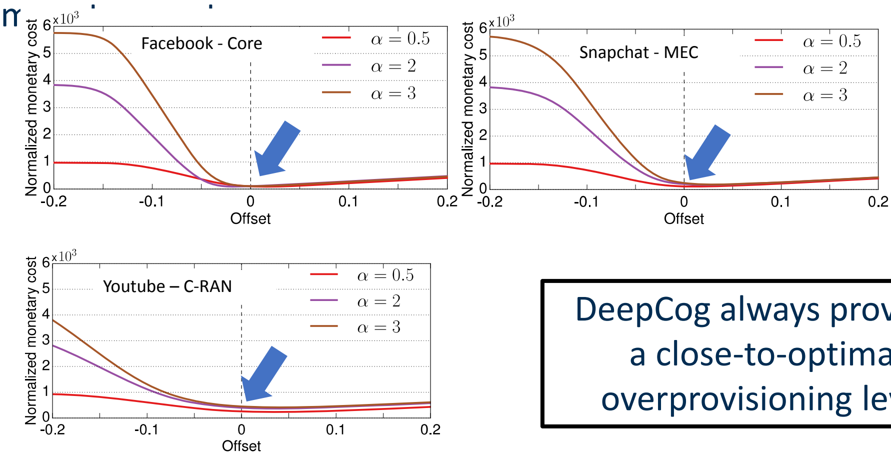
DeepCog
Reference Case Studies
Output
targeted by the capacity forecast
Realistic scenario
Mobile network deployed in a large metropolitan region
Loss function
Service demand
Capacity forecast
capacity forecast
training
NETFLIX
YouTube
Google Play
C-RAN

Results



Monetary cost minimization

- DeepCog provides an overprovisioning level (x-axis origin) that entails a given m



DeepCog always provides a close-to-optimal overprovisioning level

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Conclusions

- DeepCog represents a novel data analytics tool for cognitive resources management in sliced 5G networks
- Leverages on Deep Neural Network structure
- Customized loss function employed aiming at capacity forecasting
- First work to date where DL architecture is explicitly tailored for mobile networks problem
- Extensive evaluations with real-world data show the substantial advantages provided by DeepCog

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Questions?

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Deputy Director, IMDEA Networks institute

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