Optical Networks – A "Key" to the Society's Digitisation: Research Challenges

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Introduction

- **Optical networks are powering the hyper-digitalization of our society**

Broadband Internet in Home

Transport Networks for 5G/6G

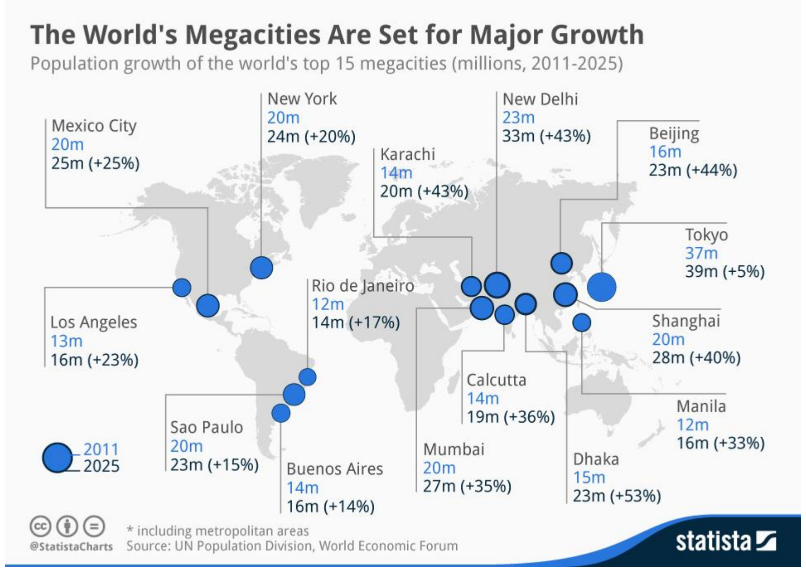
Edge, Cloud, Datacenters

Introduction

- **Greece becomes a key player in ICT infrastructures**
- FTTH & FTTC installations will increase the following years
- Submarine fibre-optic cables in the Aegean and Ionian Seas
- Hub of international subsea cables, through respective cable landing stations (e.g. 2Africa, Ionian)
- Datacenters by major providers (e.g., Google, Microsoft, Amazon, Lamda Hellix, Lancom)

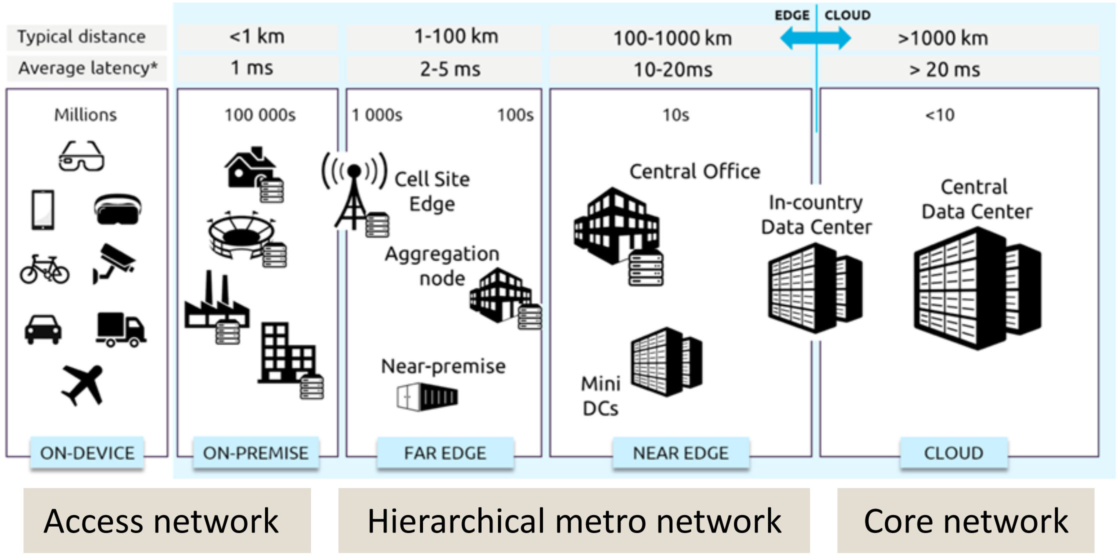
Motivation

- Beyond the business developments, several research challenges also arise
- These involve among others the design and optimization of the ICT infrastructures that operate in the cities
- Popular on-line services, the Internet of Things (IoT) and smart-city applications have increased requirements in computing, storage and network resources
- Service providers tend to push more and more content, data and services as close as possible to the end-users/devices (**<u>to the edge</u>**)
- **Smart cities are becoming the main data source**



The edge computing paradigm

- *"Edge computing is a computing paradigm that brings computation and data storage closer to the sources of data. This is expected to improve response times and save bandwidth. It is an architecture rather than a specific technology. It is a topology- and location-sensitive form of distributed computing".*

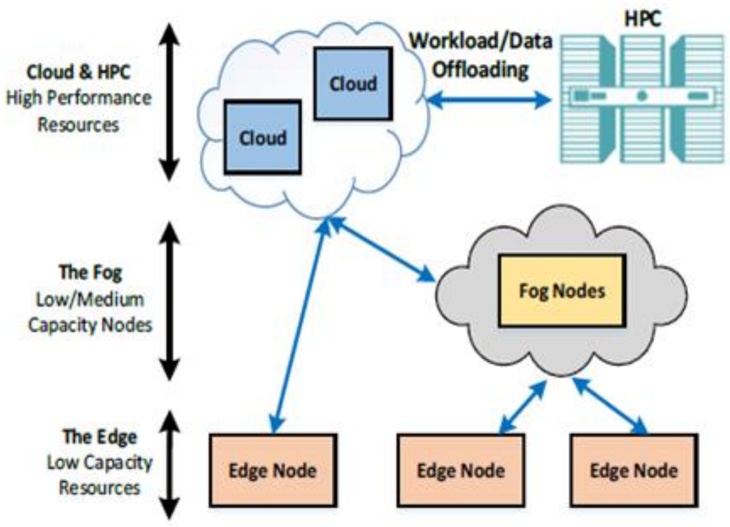


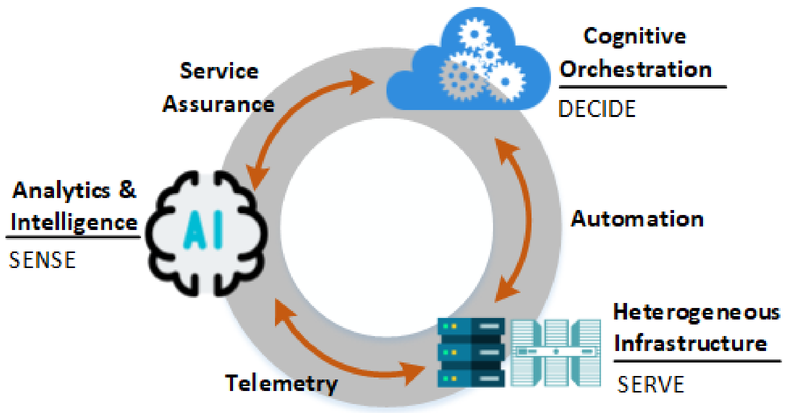
- Advantages for applications:
  - Decreased latency
  - Decrease in bandwidth use and associated cost
  - Decrease in server resources and associated cost
  - Enabling data processing with zero perceived latency

The movement of data and workload from the devices, to the edge and the core cloud and vice versa. This horizontal (edge-to-cloud) and vertical (edge-to-edge) movement requires efficient allocation of optical networking resources in the core, the metro and the access segments.

Challenges

- Multiple resources at with heterogeneous characteristics:
  - CPUs, GPUs, Mini DC, RAM, Storage nodes, HPC
  - Device that enable **acceleration** (FPGAs, ASICS) and **approximation**
- Application requirements and resource characteristics change rapidly:
  - **Couple orchestration with a continuous closed-loop control**
- Resource orchestration mechanisms that enable the efficient data movement and resource allocation.
- Efficient telemetry mechanisms are required to support the operation.





Cloud native applications resource allocation

- **Challenge:** Enable cloud native applications' resource allocation based on the characteristics of the heterogeneous cloud, edge, HPC infrastructure,
- Cloud-native applications consist of **container-based microservices** with computing requirements and networking constraints (**DAG**) among them.
- A microservice architecture breaks down VNFs into independent components, from each other, with own computing and latency requirements.
- Containers allow apps to be packaged and isolated with their entire runtime environment, making it easy to move them between environments while retaining full functionality.

Microservices characteristics

- **Execute in partial isolation within the host OS**
- **Do not include a full copy of the OS.**
- **Higher container-to-host deployment ratios**
- **Greater elasticity for IoT scenarios**

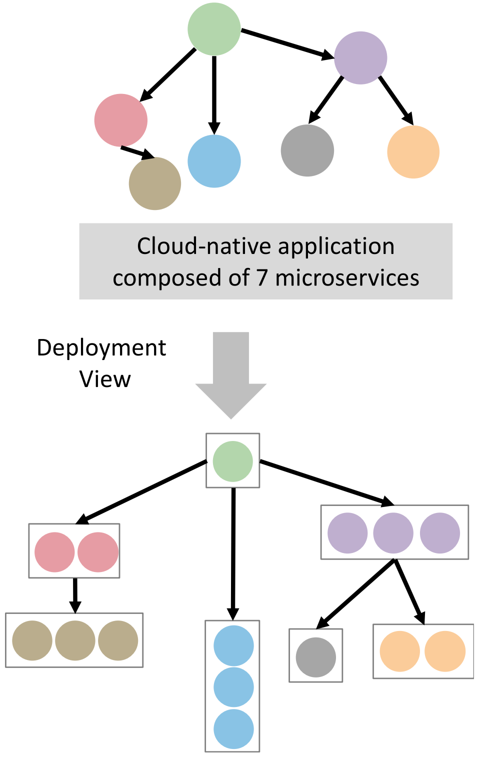
↓

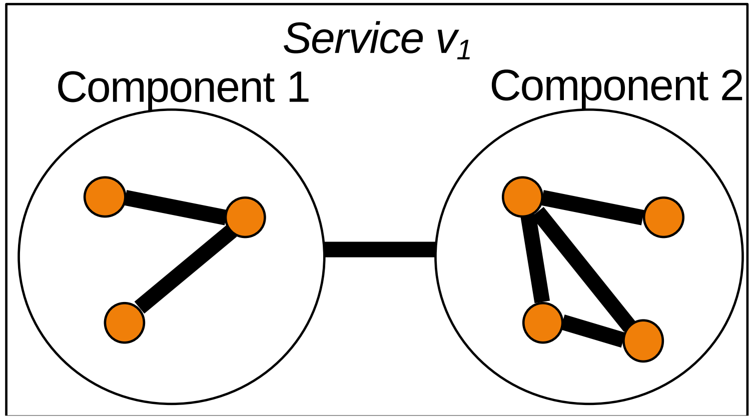
- ✓ **Performance, footprint, and utilization benefits**
- ✓ **Typically better than full VMs**

- Need of **appropriate resource allocation** mechanisms to address varying with time application demands.
- Enable flexibility with more granularity.
- But Microservices have more complex dependencies (expressed as a DAG) that need to be accounted for.

The problem of weighted delay-cost optimization

- Graph *G*=(*V*,*E*) represents the edge-fog-cloud infrastructure.
- c_v processing units , r_v RAM units and s_v storage units are available in nodes $V^p \subseteq V$.
- Depending on the type of the resources a respective monetary cost $t_{c,v}, t_{r,v}, t_{s,v}$ respectively is assumed for allocating these resources of node $v \in V^p$.
- Each edge that connects two nodes (v, v') introduces a latency $l_{v,v'}$ and has a bandwidth capacity $b_{v,v'}$





- A cloud native application a described by:
  - Set of microservices D_a. Each microservice $d \in D_a$ has a computing demand $p_{d,a}$, a RAM demand $m_{d,a}$ and a storage demand $\sigma_{d,a}$
  - Application's latency limit Θ_a
  - A DAG of dependencies
  - Latency limit between a pair of microservices $(d, d'), \theta_{a,d,d'}$

MILP Formulation

Objective function: the weighted total latency-cost introduced by the assignment.

$$minimize \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{K_j}[w \cdot (t_{c,v} \cdot p_{d,a} \cdot x_{d,a,v} + t_{r,v} \cdot r_{d,a} \cdot x_{d,a,v} + t_{s,v} \cdot \sigma_{d,a} \cdot x_{d,a,v}) + (1-w) \cdot \theta_a]$$

the weighted total latency-cost introduced by the assignment

s.t. the following constraints

$$\forall\, a \in A, \forall d \in D_a, \sum_{v \in V} x_{d,a,v} = 1$$

Se… di…

Total available processing, RAM and storage capacity per node constraints

$$\forall\, v \in V \sum_{a \in A}\sum_{d \in D_a} x_{d,a,v} \cdot p_{d,a} \leq P_v, \sum_{a \in A}\sum_{d \in D_a} x_{d,a,v} \cdot m_{d,a} \leq M_v, \sum_{a \in A}\sum_{d \in D_a} x_{d,a,v} \cdot \sigma_{d,a} \leq \Sigma_v$$

$$\forall\, a \in A, \forall d \in D_a, x_{d,a,v} \cdot \theta_{s_a,d} \leq \Theta_a, \theta_a \geq \theta_{s_a,d}$$

Application latency constraint

$$\forall\, a \in A, \forall d, d' \in D_a, \forall v, v' \in V, \theta_{b,v_d,v_{d'}} \leq \theta_{d,d'} + (2 - x_{d,a,v} - x_{d'a,v'}) \cdot U$$

Latency between microservices of an application

$$\forall\, v \in V \sum_{a \in A}\sum_{d,d' \in D_a | e_{d,d'}=1} \theta_{b,v_d,v_{d'}} \cdot b_{d,d'} \leq B_v, \sum_{a \in A}\sum_{d \in D_a} \ldots$$

Bandwidth constraint per node

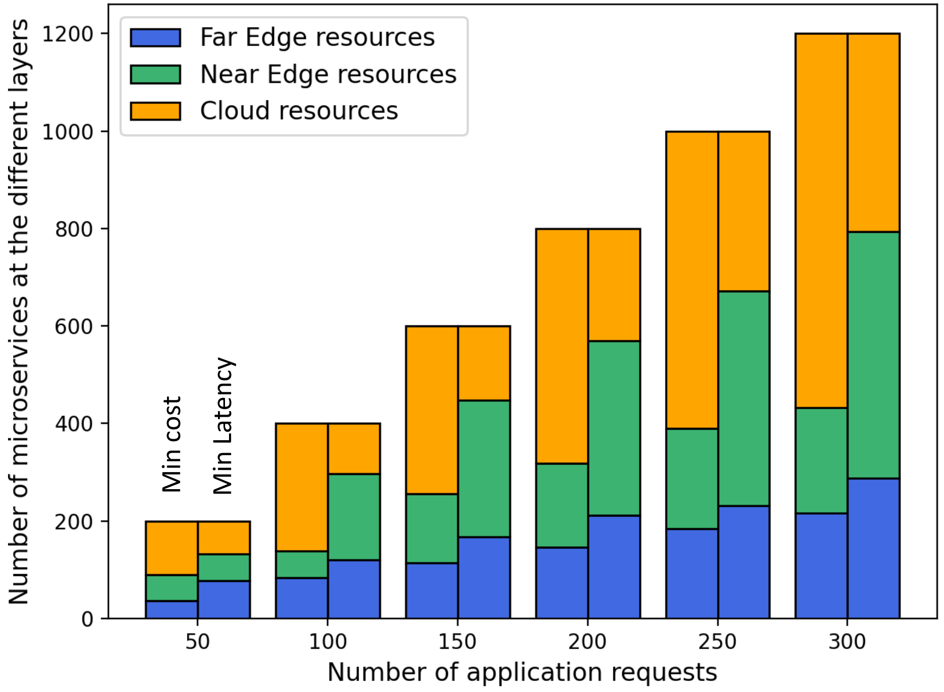
Variables

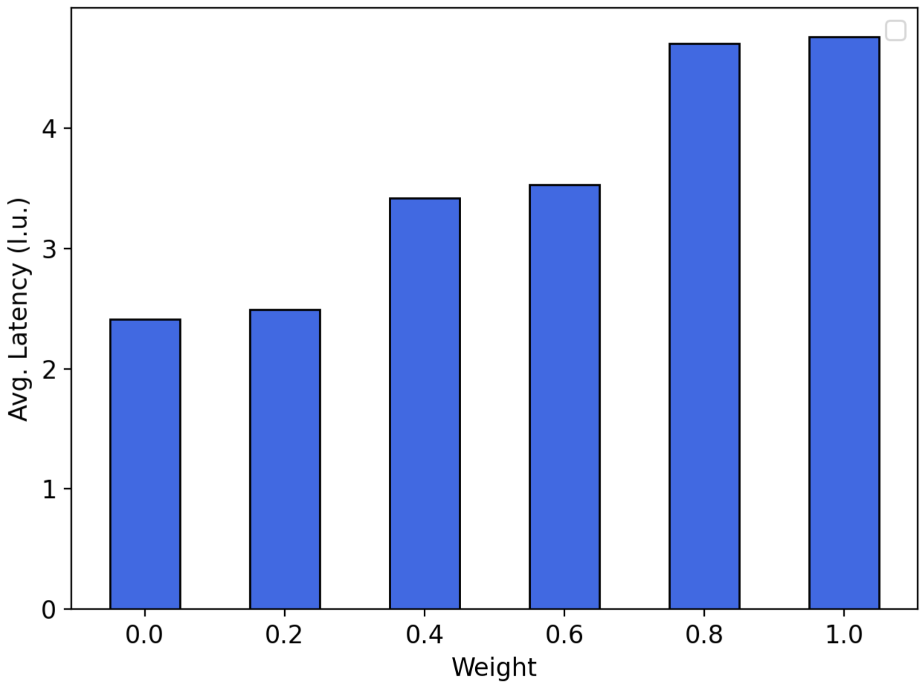
$x_{d,a,v}$: Binary variable equal to 1 if microservice *d* of application a is placed at node *v*.

$\theta_{b,v_d,v_{d'}}$: Integer variable that denotes the latency between nodes *v,v'*, where communicating microservices *d,d'* of an application a are placed and communicate with rate *b*.

θ_a : Integer variable that denotes the latency of application *a*.

Simulation Experiments





Objective Weights

Min latency w=0

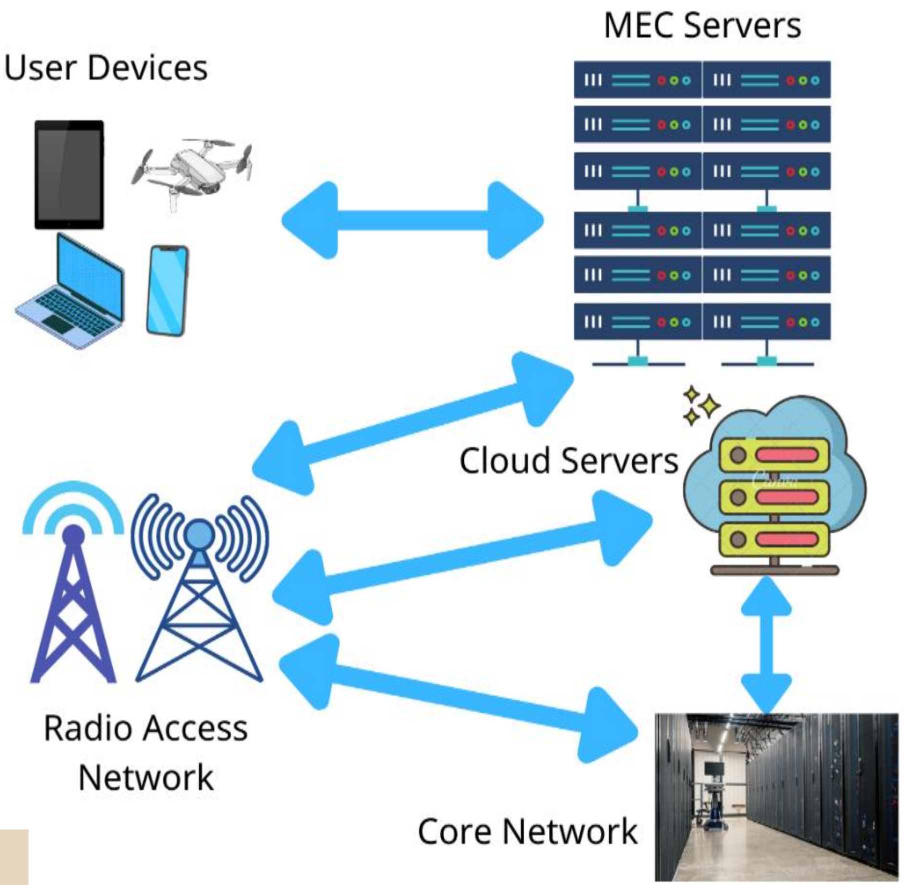
Min mon. cost w=1

The left chart shows the load of microservices per layer of our infrastructure. Increased (far & near) edge resource utilization.

Trade offs cost for latency with horizontal and vertical scaling

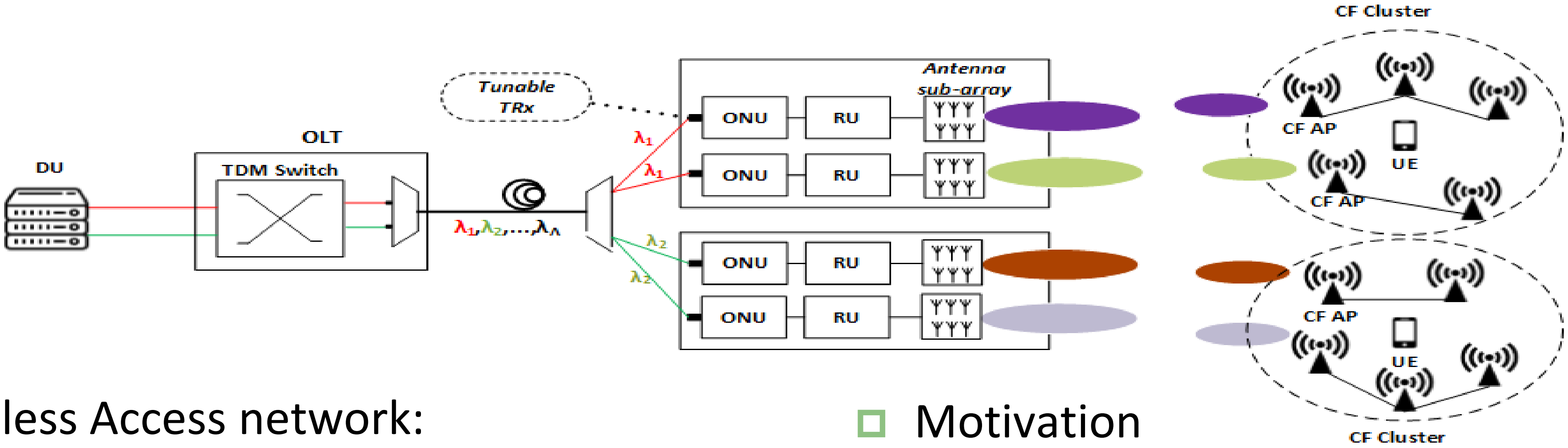
Mobile Edge Computing for B5G mobile networks

- Mobile network deployments at the edge have benefits including:
  - Lower latency, optimized network efficiency, reduced network congestion.
- These benefits open up or improve use cases including autonomous vehicles, mobile gaming, and support for the IoT.
- 5G and beyond RAN incorporates virtualization and edge computing into its infrastructure:
  - VRAN
  - ORAN



Cell Free networks have been proposed as a candidate solution for 6G networks. Their operation is based on joint signal processing from many distributed access points

Joint Fiber Wireless resource allocation



- Wireless Access network:
  - APs that operate in cell free (CF) manner
  - mMIMO BS that transmit beams towards the APs
- Wired transport network
  - TDM PON to transport the traffic to the appropriate computing nodes
- Edge computing nodes

- Motivation
  - Users are served by CF Clusters of APs
  - Clusters change dynamically in a user centric manner
  - Fronthaul traffic is served by a converged fiber wireless infrastructure
  - Develop resource allocation algorithms for the carried traffic and the required computations

MILP formulation

$$\text{Min } w \cdot \left(\sum_{b=1}^{B} \sum_{l=1}^{L} \sum_{m=1}^{M} \sum_{t=1}^{T} \gamma_{b,l,m,t} \cdot s_m + \lambda \right) - (1-w) \cdot \sum_{k=1}^{K} \sum_{c=1}^{C} \sum_{t=1}^{T} y_{k,c,t} \cdot r_c$$

objective function that considers fronthaul and UE rates

BS related constraints

CF AP cluster configuration selection constraints

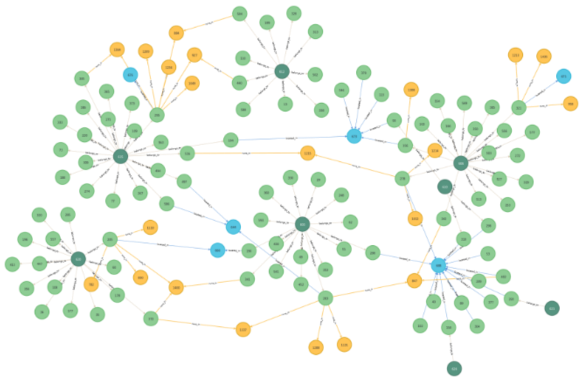
Optical capacity constraint

mMIMO Spectrum continuity constraints both for APs and BSs

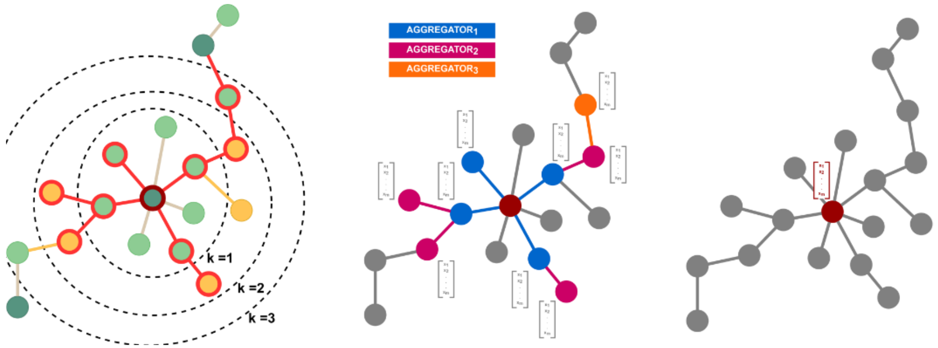
ML based computing resources event detection

- Computing resources:
  - Subject to failures
  - Resource allocation algorithms may fail to address efficiently the application results
- Proactive and reactive re-optimization adjustments can be achieved through real-time telemetry and AI/ML:
  - Provide load predictions
  - Detect performance degradation
  - Provide recommendation actions, etc.

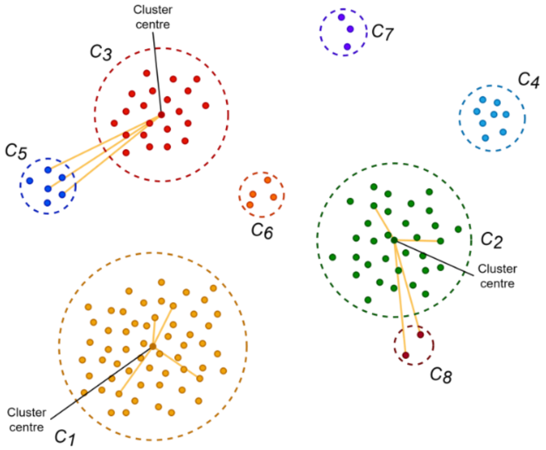
- The steps of our approach:
  - Step 1. Knowledge graph organize data of multiple sources, capture information about entities and forge connections between them
  - Step 2. Application of a graph embedding method to transform the graph entities (nodes, edges) into vectors, while preserving the graph’s topology
  - Step 3. ML based Anomaly detection techniques are applied to the created embeddings
    - Density-based and distance based algorithms



1. KG representation



2. Graph embeddings



3. Anomaly detection

Advantages of this approach

- For service Providers:
  - Modelling the dynamic aspects in a measurable way
  - Maximization of the overall resource efficiency and facilitating the implementation of complex billing models by forecasting the capacity needed to accommodate future demands
- From the end-user perspective:
  - Maximization of profit while ensuring QoS requirements
  - Additional layer of protection against adversarial attacks

Questions ?

Thank You !