Alma Mater Studiorum – University of Bologna
CdS Laurea Magistrale (MSc) in
Computer Science Engineering

Mobile Systems M course (8 ECTS)
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05 – 5G and Mobile Edge Computing

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5G converged world

Voice (VoIP)

Audio/Video Conference

Chat and messagging

Video on Demand (VoD)

And many more…

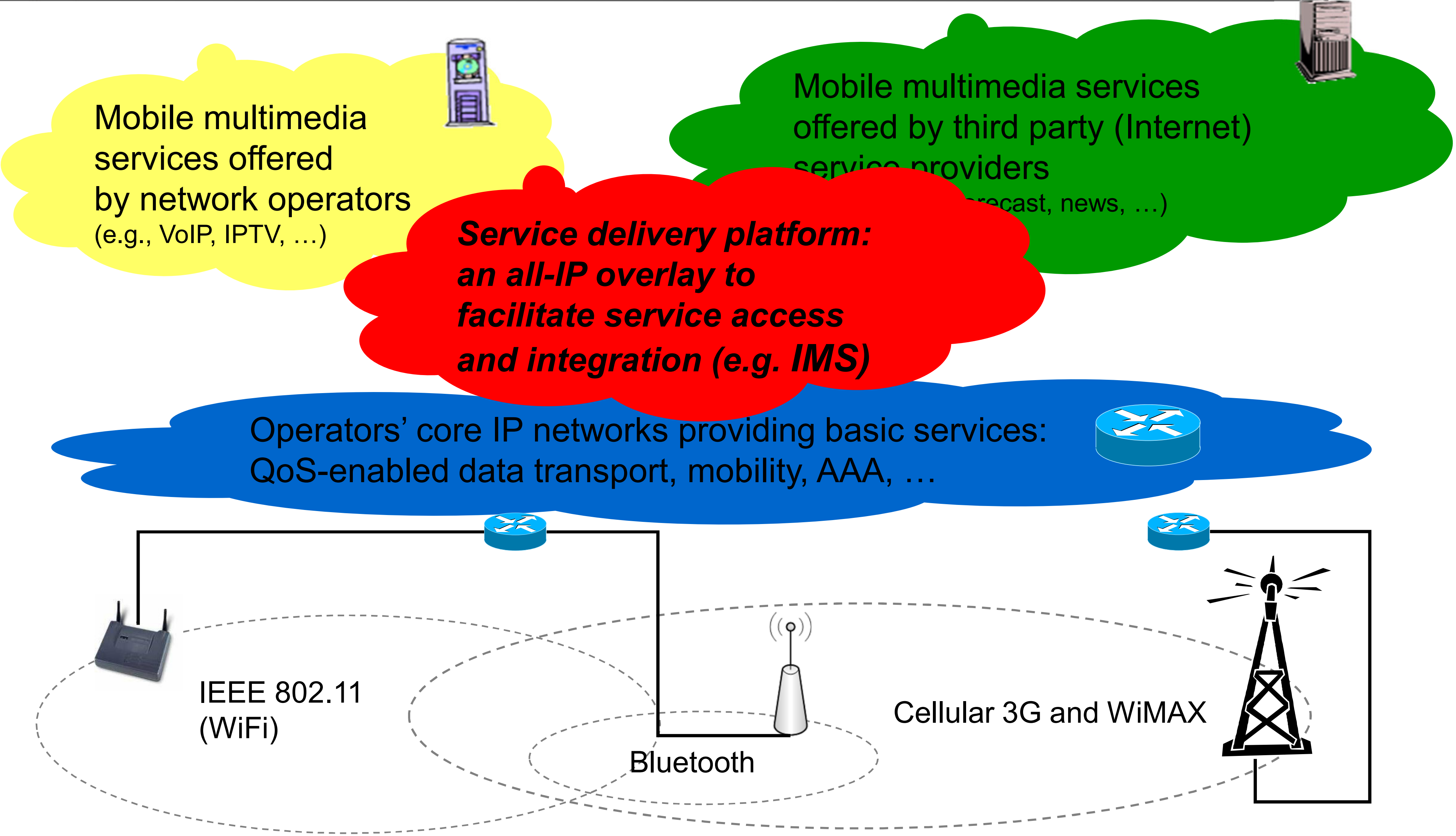
?…

- Push To Talk (PTT)
- PTT over Cellular (PoC)
- IPTV
- Video sharing
- …

Ever-increasing demand and diffusion of mobile multimedia services during the last two decades, driven by:

- New powerful ***devices*** and ***wireless technologies/infrastructures***
- New (mobile) ***services***

5G converged service delivery scenario

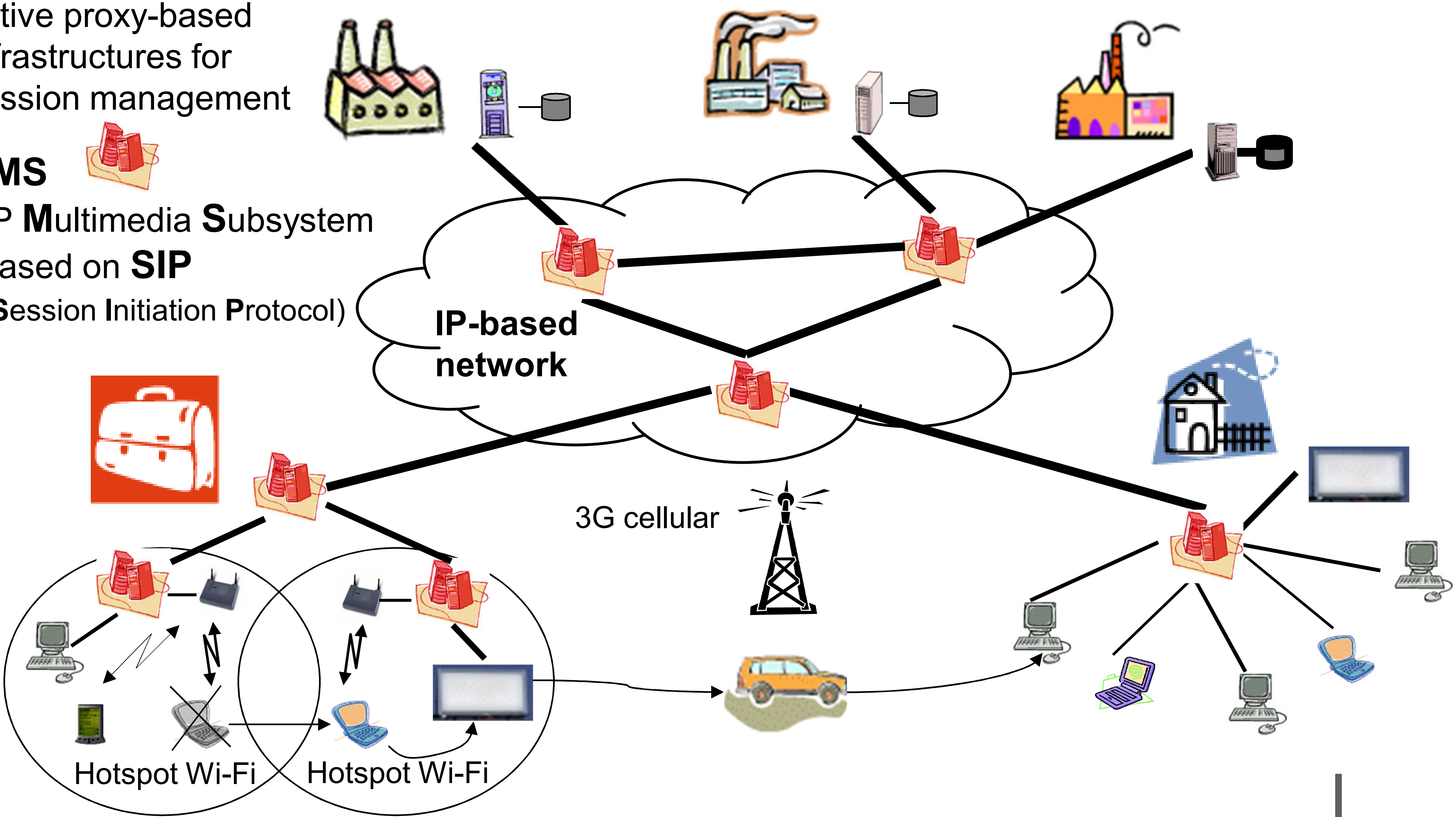


Highly differentiated ***(wireless) access networks***

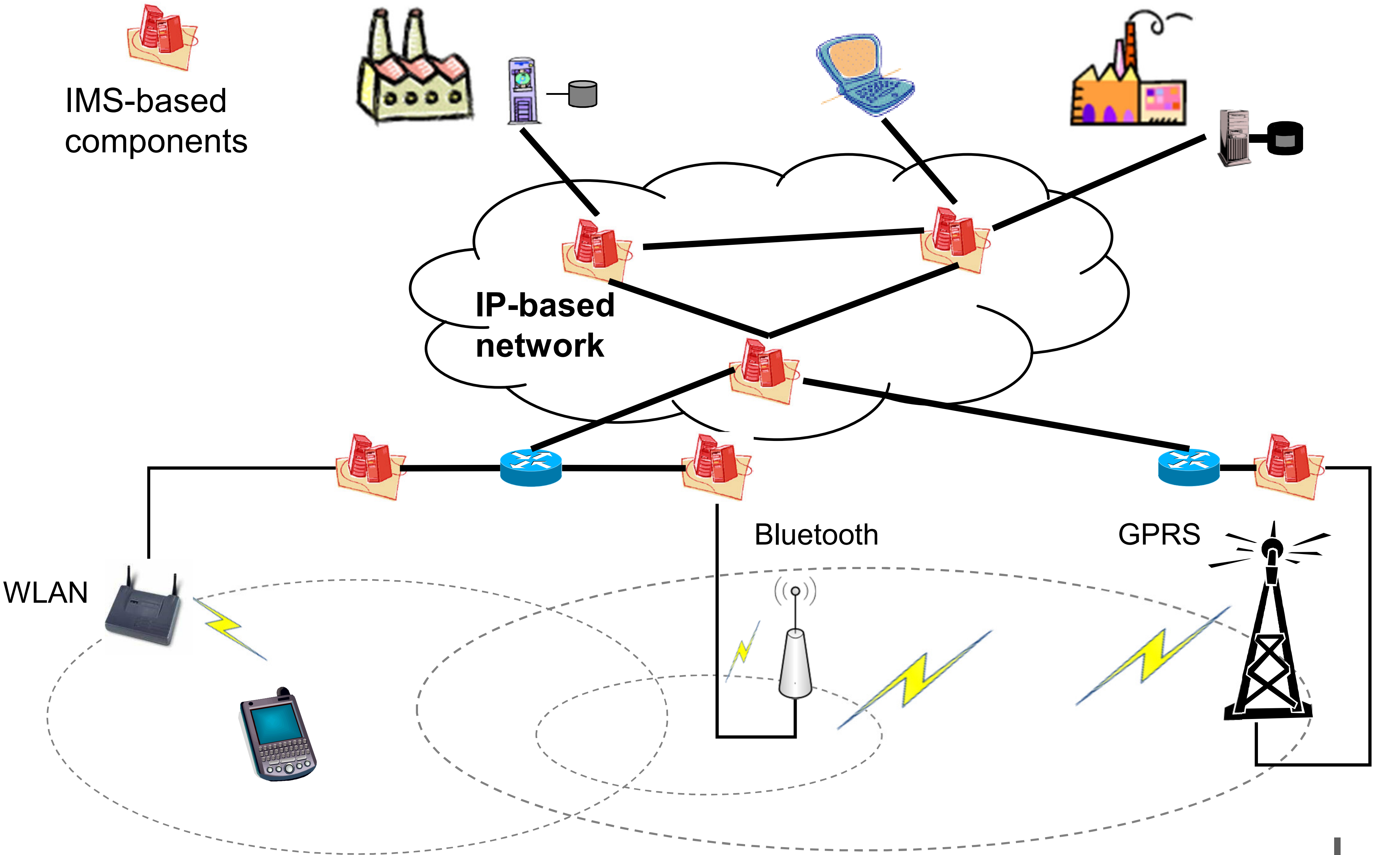
5G service & network management: a proxy-based approach

New protocols and active proxy-based infrastructures for session management

IMS
IP **M**ultimedia **S**ubsystem
based on **SIP**
(**S**ession **I**nitiation **P**rotocol)

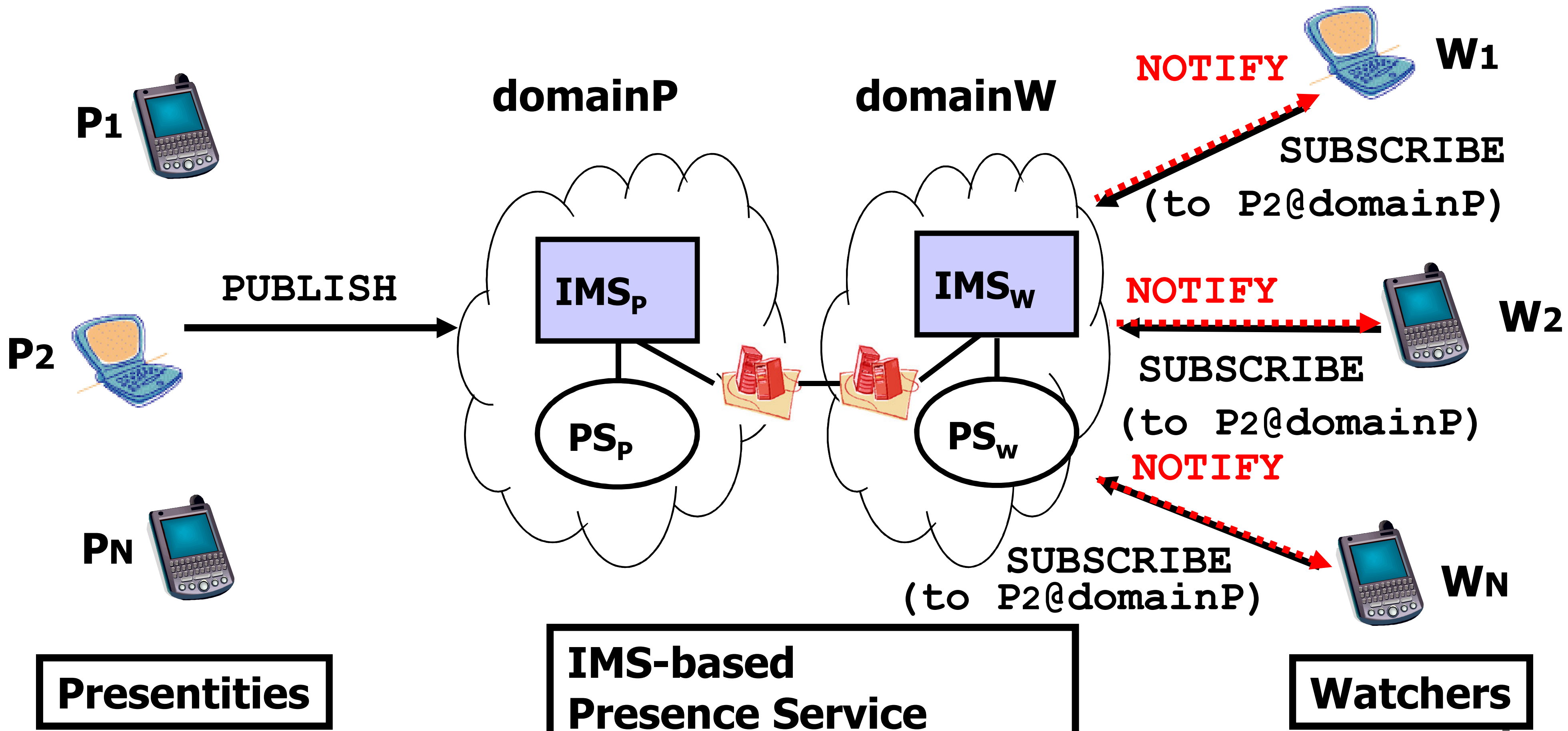


New 5G service scenarios: mobile multimedia handoff mngm



New support services in 5G: presence service

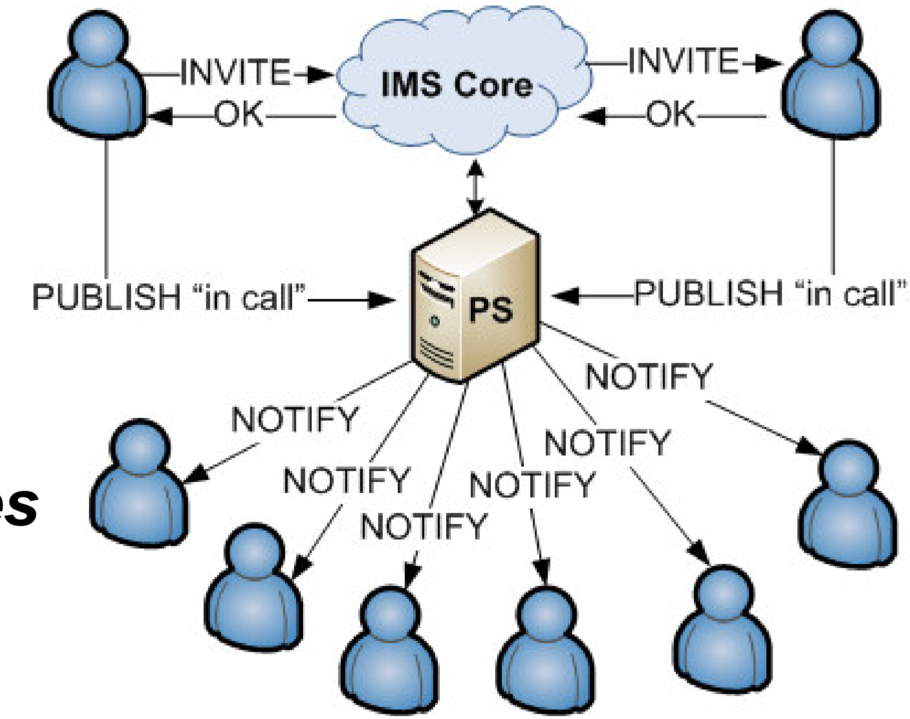
Presence service (PS) permits users and hw/sw components, called ***presentities (*P_i*)***, to convey their ability and willingness to communicate with subscribed ***watchers (*W_j*)***



Scalability issues at a glance

High mobility & context changes

New services VoIP+PS (call-status notification)



- Higher signaling traffic *(**message dimension + frequency**)*
- Richer services, such as VoIP+PS (message ***multiplying effect***)
- ***Many traversed signaling entities*** (proxies-based architecture…)
- Plus, specific SIP protocol issues (***message verbosity*** and ***ACKs***)

→ Need for a better understanding of IMS ***scalability shortcomings*** and ***load-balancing support*** both at ***infrastructure*** and ***service*** levels

Some background: SIP – Session Initiation Protocol

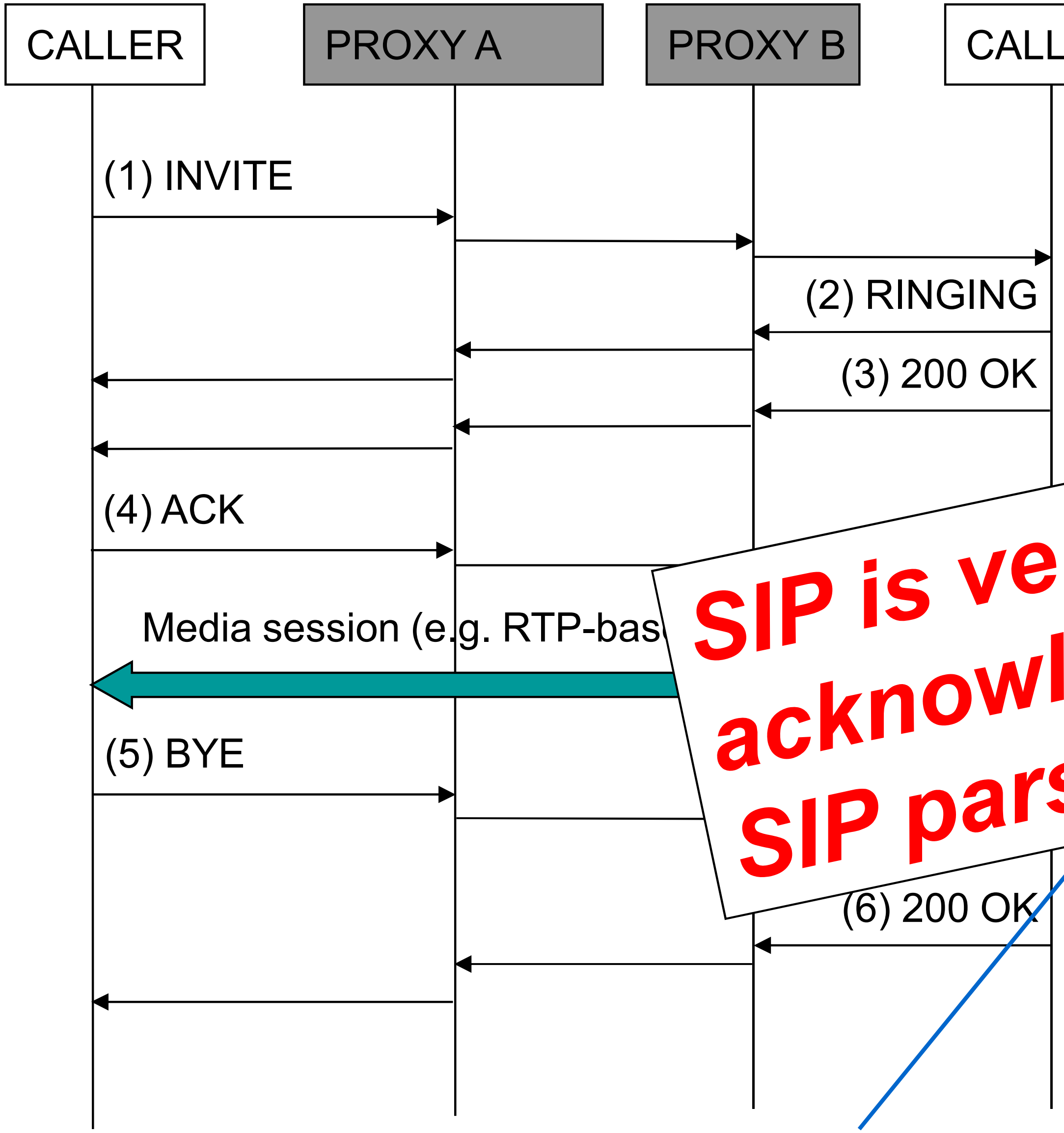
- SIP defines a ***signaling framework*** and related ***protocols and messages*** to setup ***any kind of session*** (work at the Open Systems Interconnection – OSI – ***session layer***)
  - SIP is very ***open*** and ***general purpose*** ☺
  - SIP includes several core facilities for ***mobility management***, ***session initiation***, ***termination***, and ***transfer***, …
  - SIP ***does not*** include some basic services ☹ (e.g., AAA, resource booking, …)
- SIP ***is not*** a ***data/media transmission protocol***

  Other specific protocols for that: Real-time Transport Protocol (RTP), RTP Control Protocol (RTCP), Real Time Streaming (RTSP),…
- SIP usage ***examples***
  - Setting up and tearing down VoIP voice calls
  - Instance messaging and presence service: SIP for Instant Messaging and Presence Leveraging Extensions – ***SIMPLE***
  - Session transfer and call re-direction

SIP in a nutshell

- SIP core signaling
  - HTTP-like text-based protocol and email-like SIP identifiers (**addresses**)
  - Client/server protocol (request/response protocol)
  - Standardized session control messages
    - INVITE, REGISTER, OK, ACK, BYE, …
- SIP proxy-based framework and ***main entities***
  - **User agents:** end points, can act as both user agent client and as user agent server
    - **User Agent Client:** create new SIP requests
    - **User Agent Server:** generate responses to SIP requests
  - **Dialog:** peer to peer relationship between two user agents, **established by specific methods**
  - **Proxy servers:** application level routers
  - **Redirect servers:** redirect clients to alternate servers
  - **Registrars:** keep tracks of users

SIP VoIP call initiation example: INVITE dialog



Start line:
- ***request line*** (in requests)
- ***status line*** (in responses)

```
INVITE sip:bob@biloxi.com SIP/2.0
```

```
Via: SIP/2.0/UDP pc33.atlanta.com;
branch=z9hG4bK776asdhds
Max-Forwards: 70
To: B
<sip:alice@pc33.atlanta.com>
Content-Type: application/sdp
Content-Length: 142
```

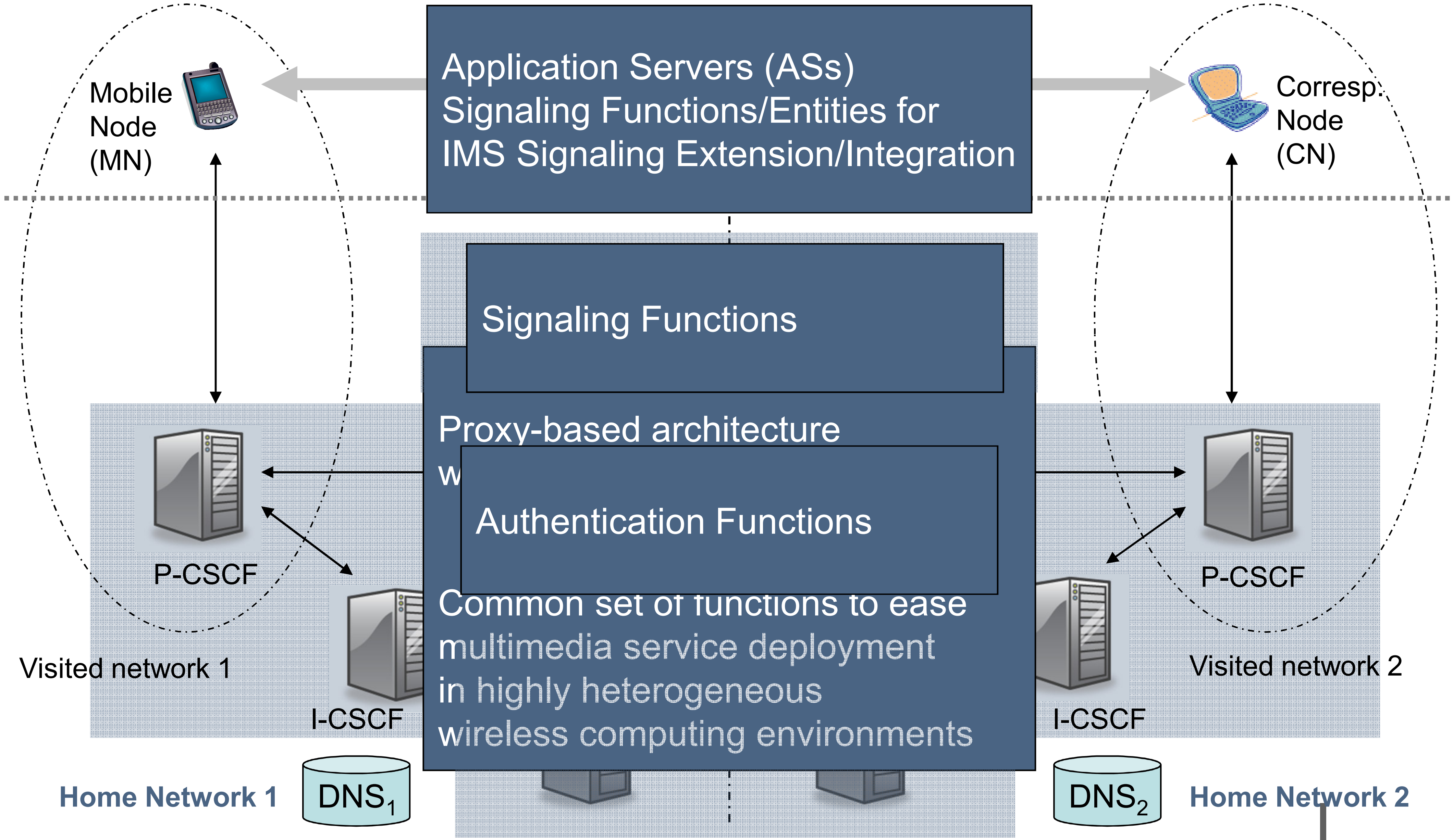
```
… SDP description …
```

Message body (optional): for example, an SDP description to negotiate audio/video codecs/formats

SIP is very verbose and acknowledged; in addition, SIP parsing is CPU-intensive

Header: with a number of ***header fields***

Some background: IMS – IP Multimedia Subsystem



IMS functional entities: DNS and HSS

Domain Name System (***DNS***):

- Standard Internet naming service
- Employed by IMS to ***resolve the IP addresses of CSCFs*** and ***ASs***

→ can be used for ***load balancing*** ☺
(but… only with limited DNS-query frequency)

Home Subscriber Server (***HSS***):

- ***SIP requests forwarding*** in the appropriate direction (terminals or IMS network)
- Storage of all user-related subscription data, such as authentication data and profiles for clients (by using standard Data Base Management System – DBMS)
- A network may contain one or several
  - Subscriber Location Function (SLF) to map users to specific HSS

IMS functional entities: Proxy-CSCF

Proxy-Call Session Control Function (***P-CSCF***):

- First contact point in the IMS network in ***either visited domain*** or ***home domain***
- Outbound / In-bound SIP proxy
  (all requests from/to IMS terminals go through it)

Main P-CSCF functions

- ***SIP requests forwarding*** in the appropriate direction
  (terminals or IMS network)
- Several ***other functions***:
  - Security
  - Generation of charging information
  - Compression and decompression of messages

IMS functional entities: Interrogating-CSCF

Interrogating-Call Session Control Function (***I-CSCF***):

- SIP proxy at the edge of the administrative ***home domain***
  - There may be several in the same network for scalability reasons
  - Listed in the domain name server (DNS-based scalability)
- SIP redirect stateless server

Main I-CSCF functions

- ***Interaction with HSS*** to determine the S-CSCF associated with the client (***Diameter*** protocol)
- ***Redirection*** and ***routing of incoming SIP requests*** to S-CSCF

  → can be used to ***dynamically select less-loaded S-CSCFs (e.g. through DNS)*** ☺

IMS functional entities: Serving-CSCF

Serving-Call Session Control Function (***S-CSCF***):

- Always located ***in home domain***
- SIP proxy + SIP registrar with possibility of performing session control

Main S-CSCF functions

- ***Binding*** between ***IP address*** (terminal location) and ***user SIP address***
- Interaction with application servers for ***value added service purpose***
- Translation services (Telephone number / Sip URIs)
- Message routing (by using so-called ***IMS filtering criteria***)

→ can be used to ***statically divide incoming load according to user identity/profile*** ☺

IMS functional entities: AS

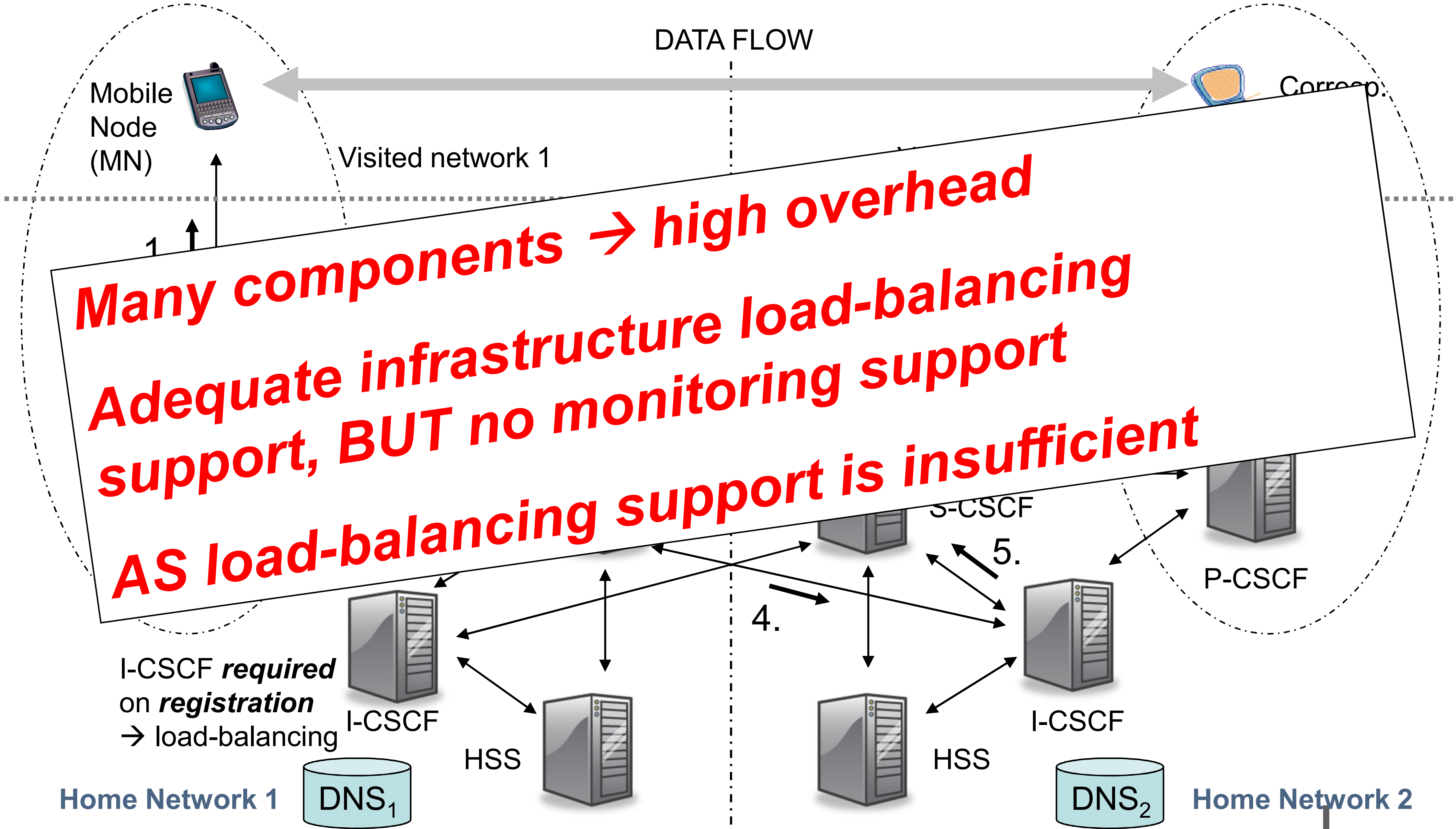
Application Server (***AS***):

- ***Host services*** and ***execute services***
- Communicates using SIP: ***very costly!!*** ☹
  - Each ***interposed AS*** generates 2 msgs (processed+ACK)
  - Complex coordination for ***stateful*** and ***distributed ASs***

Several AS types with different functions

- ***SIP AS***: ***signaling specific*** architecture (services can work only in SIP environment)
- Other types: Open Service Architecture – Service Capability Server (OSA/SCS), IP Multimedia Service Switching Function (IM-SSF), …

IMS Revisited



Many components → high overhead

Adequate infrastructure load-balancing support, BUT no monitoring support

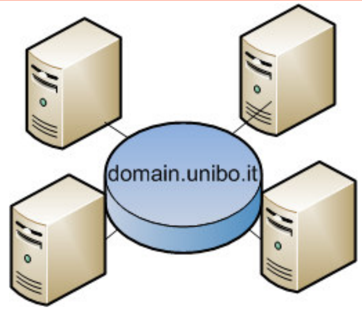
AS load-balancing support is insufficient

IMS scalability: (partial) solutions

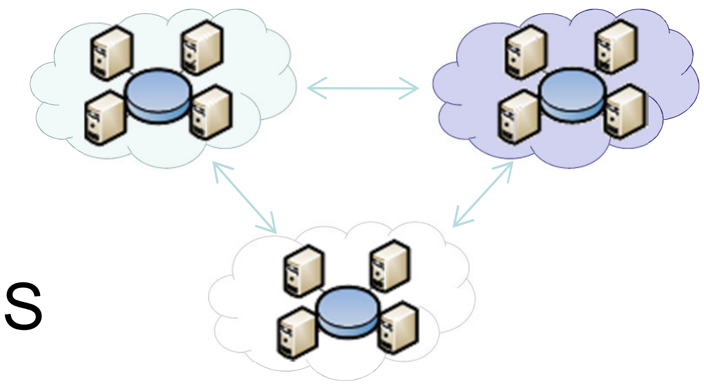
- **Single host** (local) optimizations w/out (or with minimal) coordination:
  - Selective ***message dropping***
  - SIP message ***compression*** and ***incremental parsing*** techniques
  - Stateful vs Stateless SIP proxies

Widely diffused and standardized

- **Intra-domain** (distributed) load-balancing:
  - ***Infrastructure-level*** ***monitoring*** and ***dynamic load-balancing*** operations
  - ***Service-level*** AS coordination protocols ***(also ad-hoc and NON-IMS-compliant optimized protocols!!)***



- **Inter-domain** protocol optimizations:
  - Limit traffic among different domains
  - ***Service-level*** message processing at IMS domain borders ***(BUT, IMS compliant)***



IMS scalability: open issues

- One ***unique framework*** able to provide an effective solution to all the different IMS load-balancing issues ***is still lacking***
- One ***solution*** that integrates ***local***, ***intra-domain***, and ***inter-domain*** load balancing is still missing
- One ***significantly tested solution***: ***most papers*** in the IMS literature are ***insufficiently validated*** and do not include extensive experimental results collected in ***real-world distributed testbeds***

IHMAS: emerging design guidelines for IMS scalability

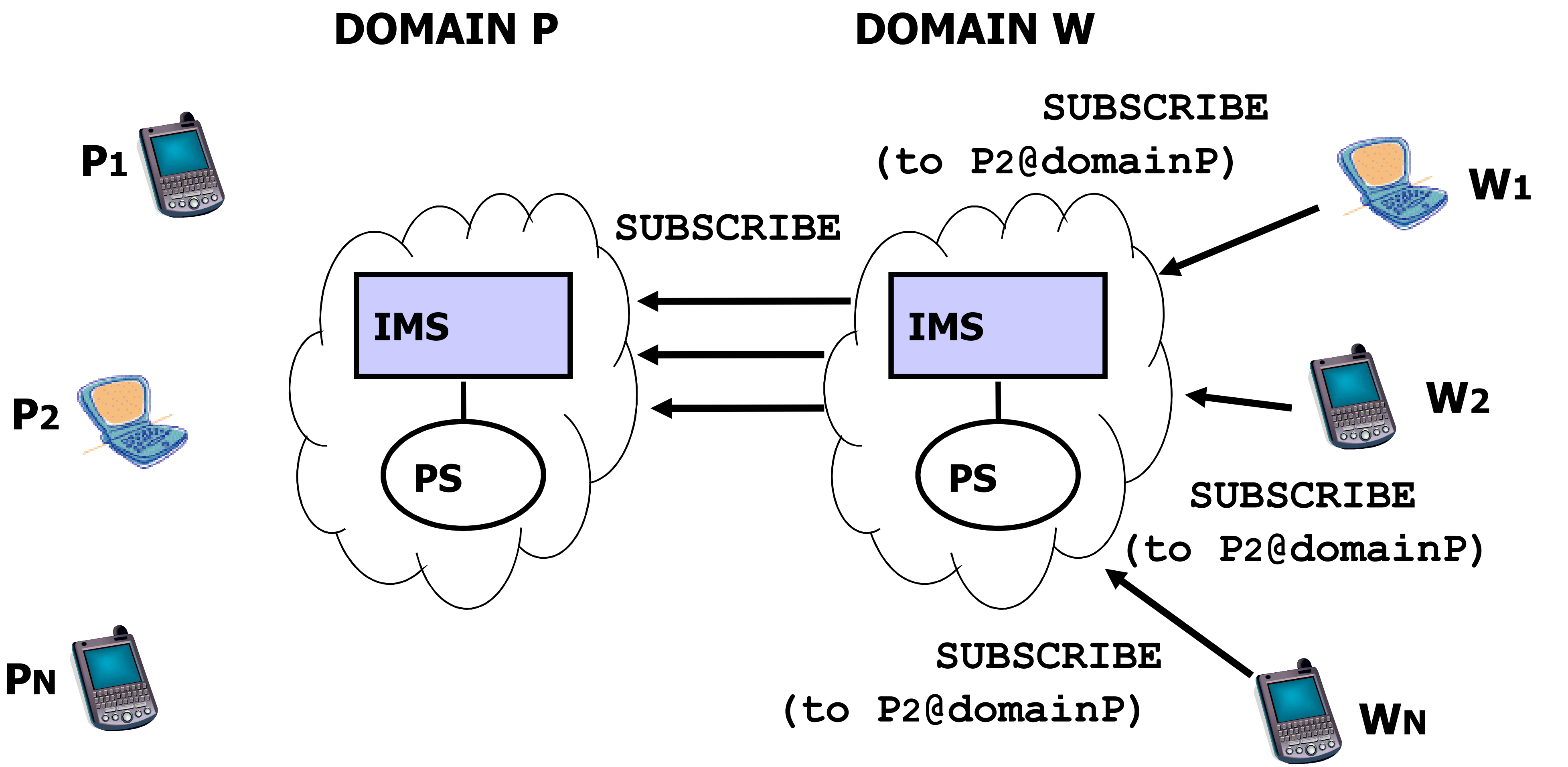
IMS-compliant **H**andoff **M**anagement **A**pplication **S**erver

- Active session signaling ***(proxy-based approach)***
- ***Intra-domain (IMS) infrastructure load balancing***
  - ***Collects*** service-aware distributed monitor alarms
  - ***Decides*** and ***executes*** needed load-balancing actions ***(dynamic addition/removal of CSCF components)***
- ***Intra-domain service load balancing***
  - ***Adopts a data-centric*** session management approach to share service state into AS pools
  - ***Exploits*** specific service knowledge ***(service awarereness)*** to divide intra-domain load into partitions
- ***Inter-domain*** transmission optimizations
  - ***Controls*** and ***reduces*** inter-domain traffic
  - ***Realizes service-aware message aggregation*** and ***batching*** techniques based on distributed AS federation models

IHMAS PS scalability use case

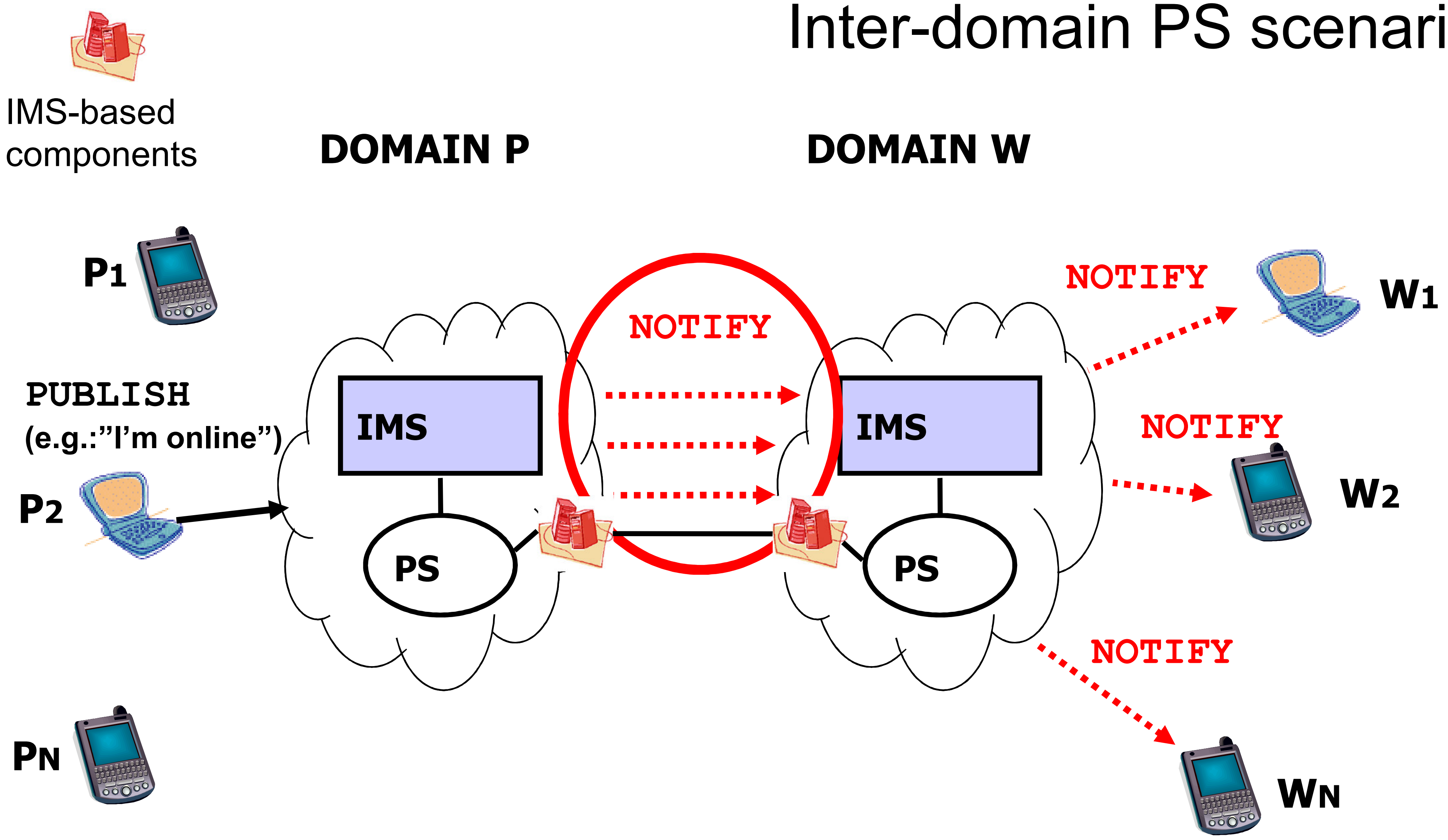
P: Presentity **PS**: Presence Server
W: Watcher

Inter-domain PS scenario



IHMAS PS scalability use case

Inter-domain PS scenario



PS is very prone to load-balancing issues!!

IHMAS inter-domain PS scalability: transmission optimizations

IHMAS inter-domain ***service*** optimizations

- **extends IMS PS** to support message aggregation/batching
  (diminishes the number of inter-domain NOTIFY transmissions)

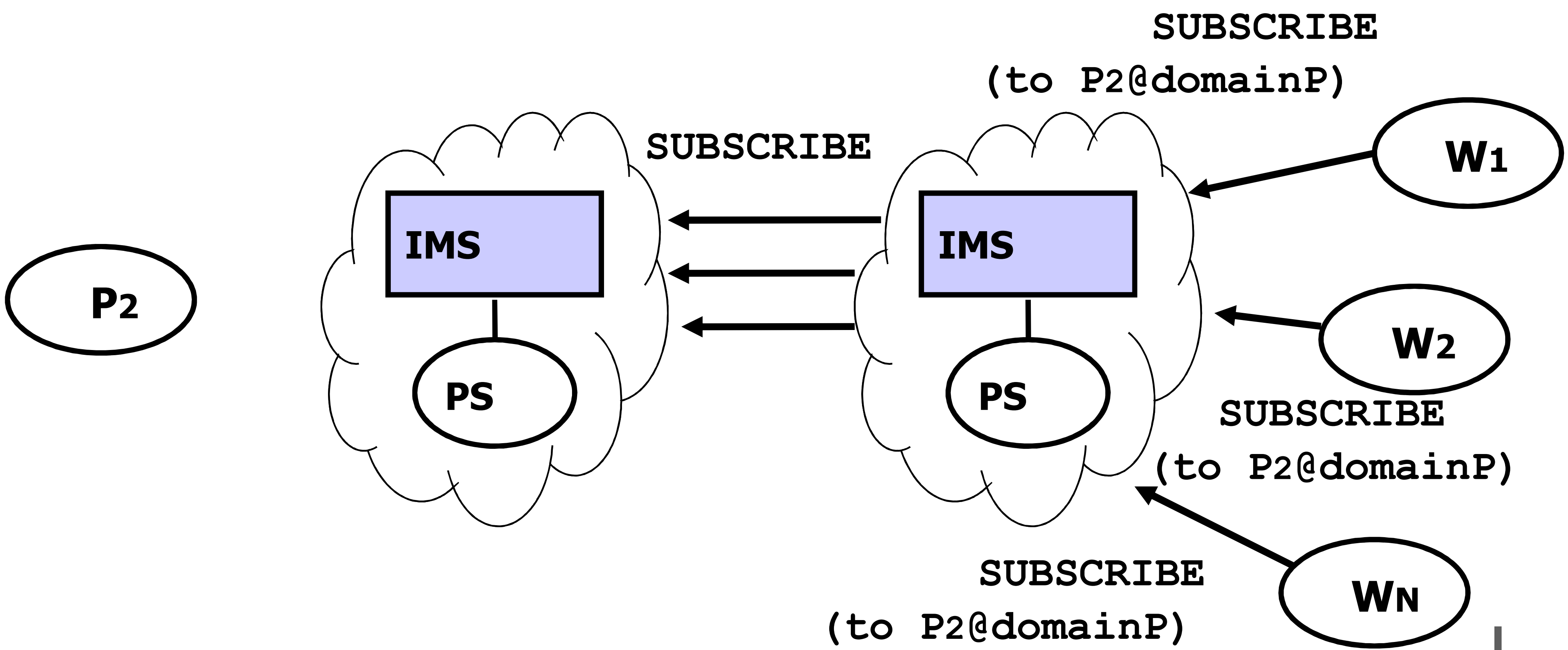
  → ***novel PS inter-domain optimization module for NOTIFY message parsing and inter-domain routing***
- **supports** mobile clients and **service differentiation** (gold, silver, copper, …)
  - **Gold:** ***instant*** presence info delivery → ***high cost***
  - **Silver:** ***slightly delayed*** presence info delivery → ***medium cost***
  - **Copper:** ***very delayed*** presence info delivery → ***low cost***
- **integrates** seamlessly with existing infrastructures

  → ***full compliance with IMS standard***

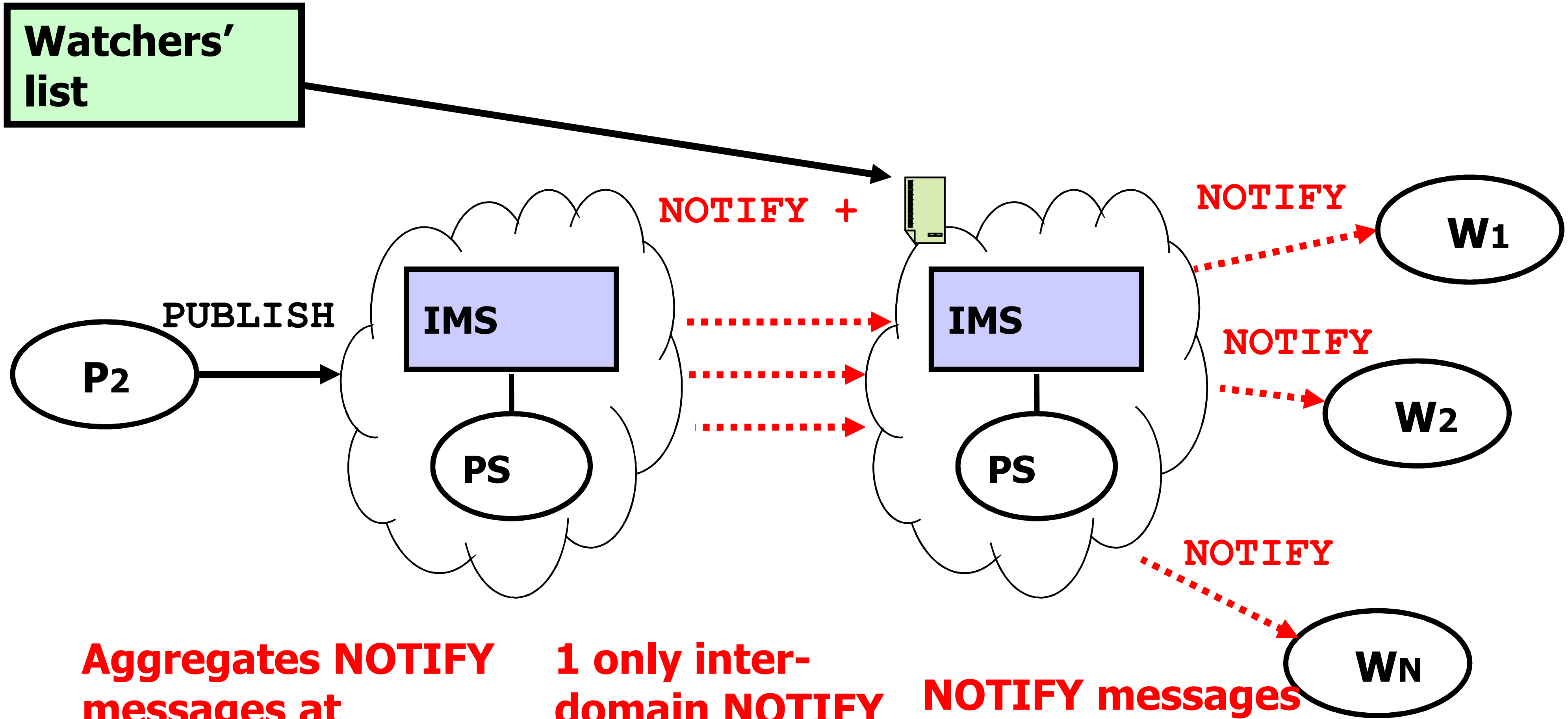
P. Bellavista, A. Corradi, L. Foschini, "**IMS-based Presence Service with Enhanced Scalability and Guaranteed QoS for Inter-Domain Enterprise Mobility**", IEEE Wireless Communications Magazine, vol. 16, no.3, Jun. 2009

Common NOTIFY

"***Several watchers*** subscribed to ***one presentity***"



Common NOTIFY



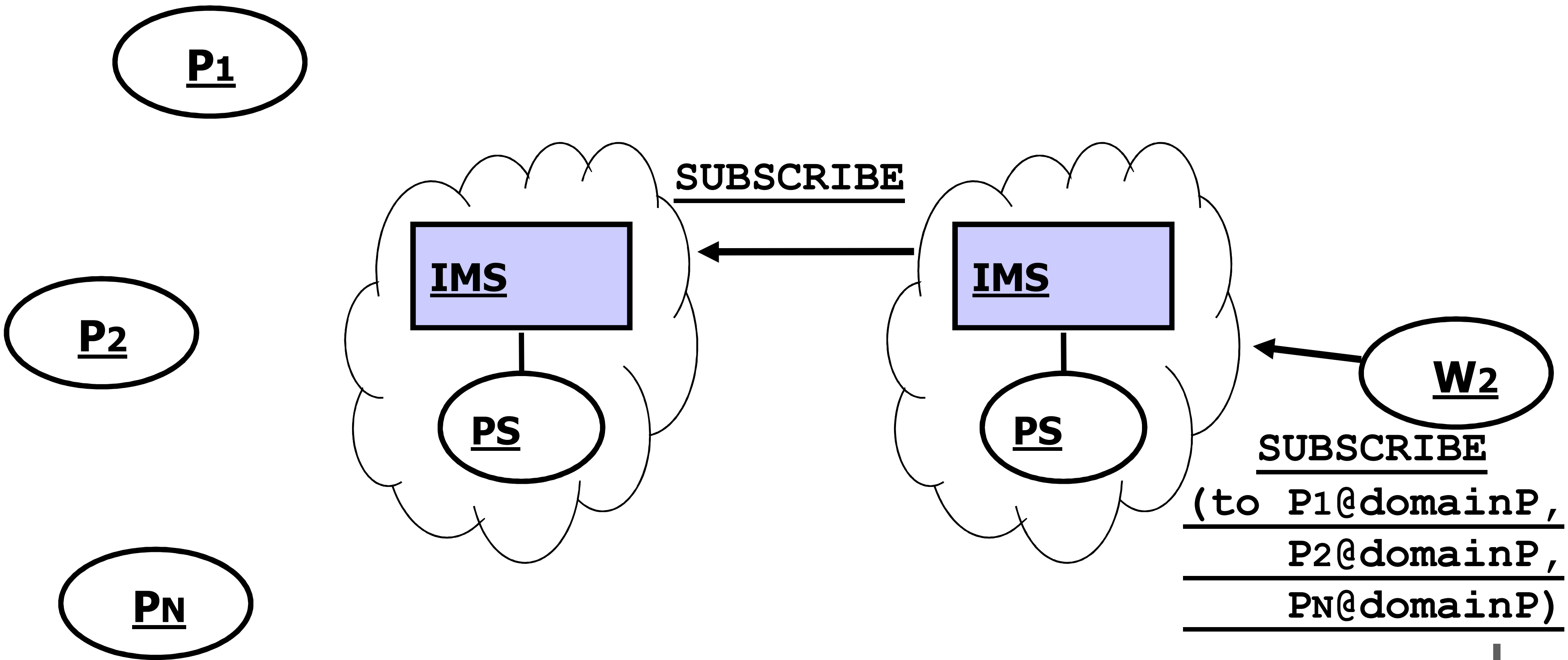
Aggregates NOTIFY messages at *Presentity's* domain

1 only inter-domain NOTIFY message

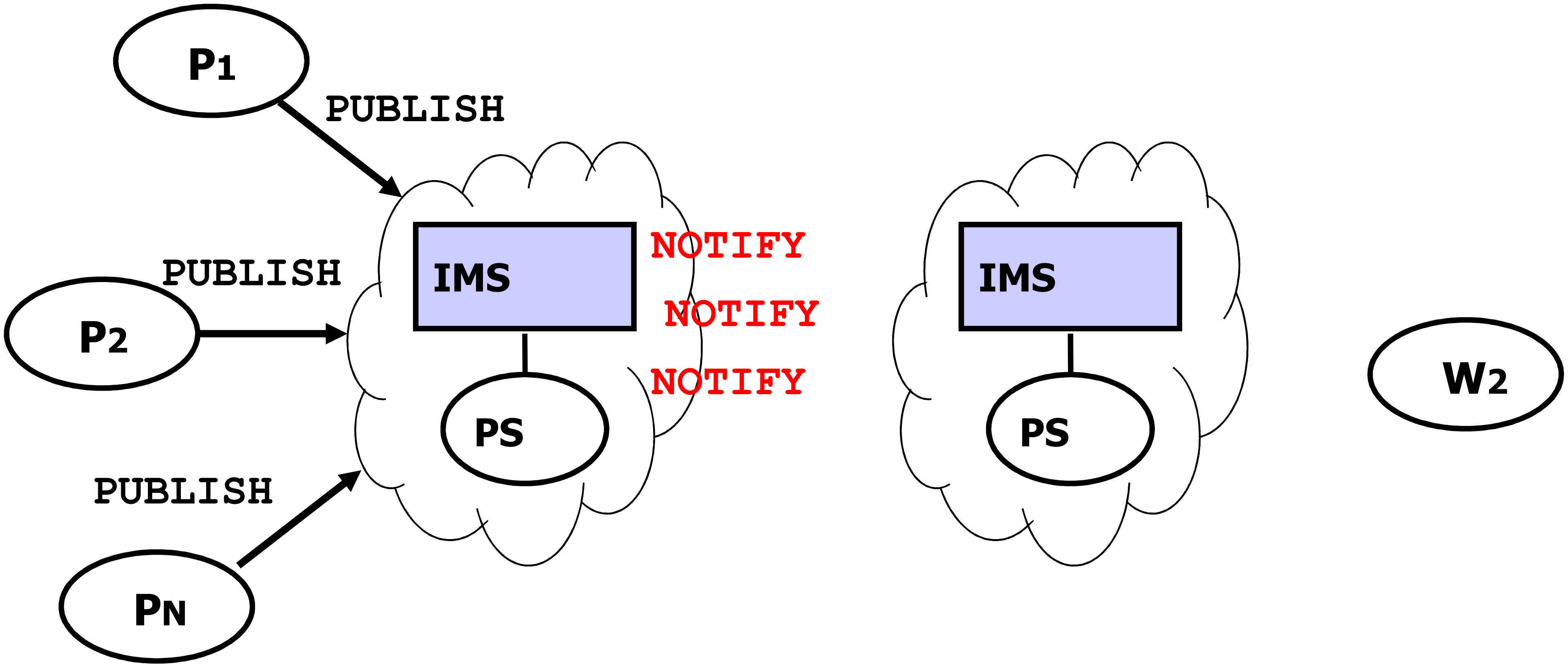
NOTIFY messages creation at Watchers's domain

Batched NOTIFY

"One ***single watcher*** subscribed for ***multiple presentities***"

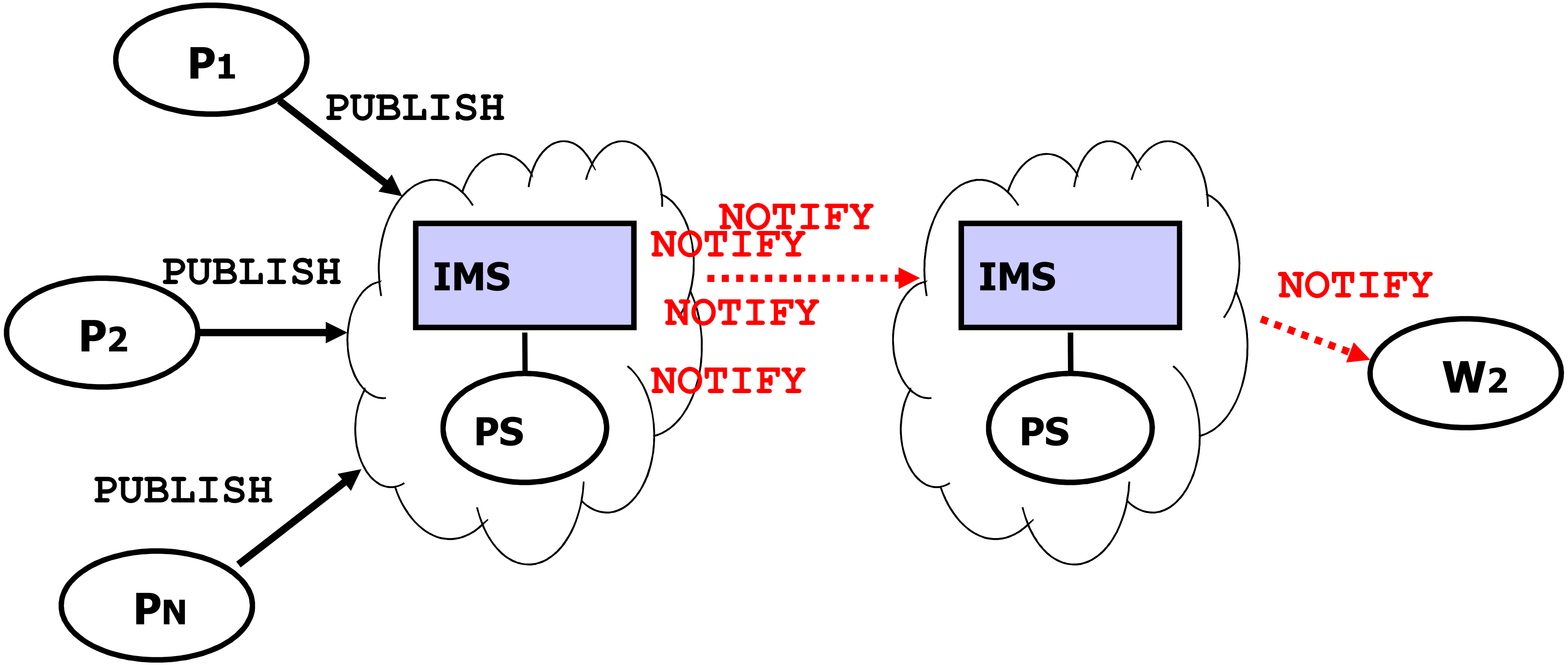


Batched NOTIFY



Time-based (periodic) NOTIFY message batching

Batched NOTIFY



only 1 inter-domain NOTIFY message

IHMAS intra-domain PS scalability: infrastructure load-balancing

IHMAS intra-domain ***infrastructure*** load-balancing

- **monitors** distributed infrastructure and service components (I-/P-/S-CSCFs, HSS, PS, any AS, …)

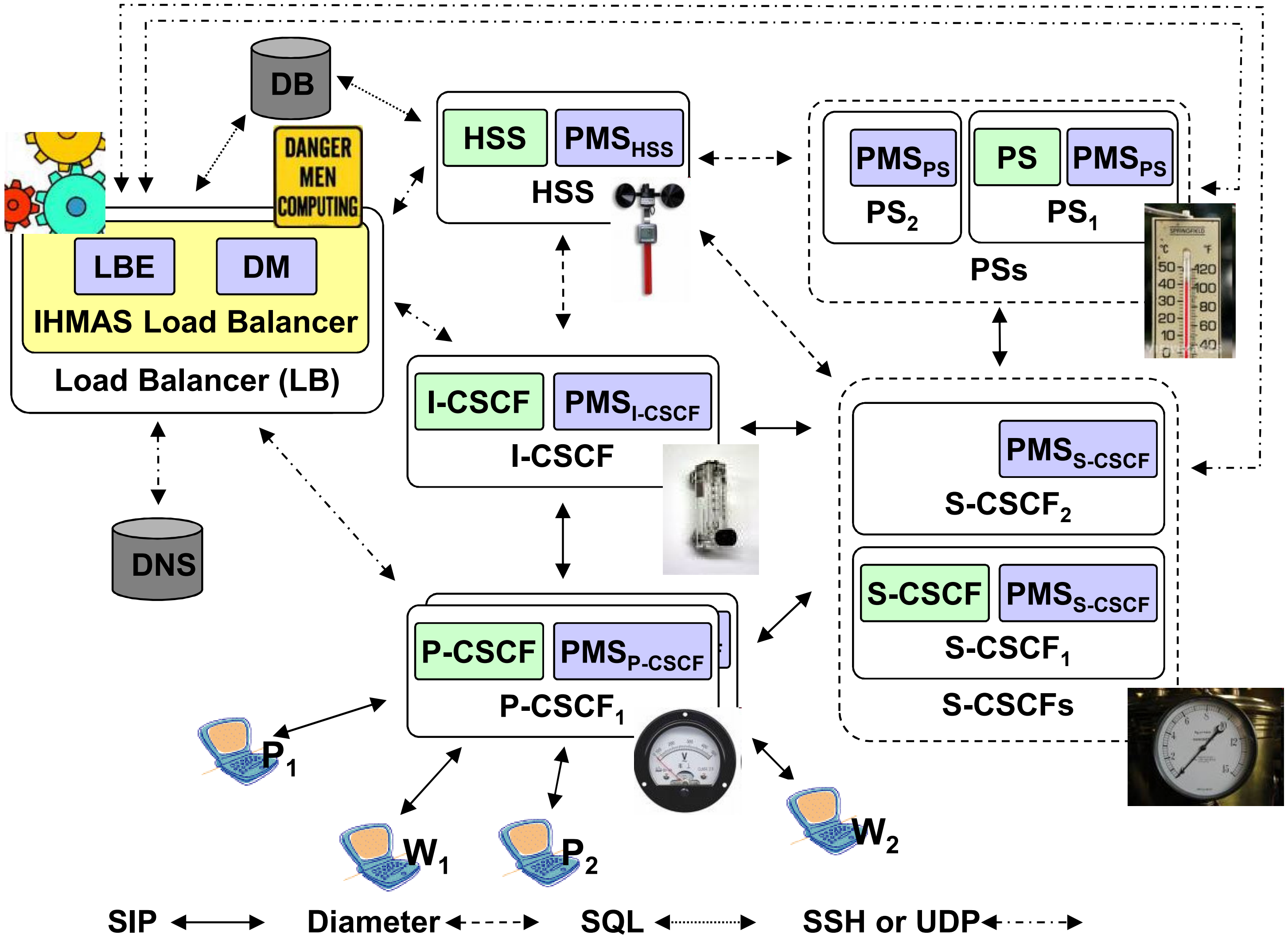
  → ***load monitoring actions tailored for the specific service (service-aware approach)***
- **executes** application-level specific **component load-balancing actions**

  → ***dynamic de-/activation of distributed components and DNS (de-)registration actions***
- **integrates** seamlessly with existing infrastructures

  → ***full compliancy with IMS standard***

P. Bellavista, A. Corradi, L. Foschini, "**Enhancing the Scalability of IMS-based Presence Service for LBS Applications**", IEEE COMPSAC, 2009

IHMAS intra-domain PS scalability: infrastructure load-balancing



PMS: Proactive Monitoring Stub **DM:** Decision Maker **LBE:** Load-Balancing Executor

- Decision Maker – ***DM***: takes load balancing and partitioning decisions
- Load-Balancing Executor – ***LBE***: enforces them
- Proactive Monitoring Stub – ***PMS$_x$***: monitor system/ component behavior and generate overload alerts towards DM
- ***IMS components***: I-/P-/S-CSCF, HSS, PS, DNS

IHMAS intra-domain PS scalability: service load balancing

IHMAS intra-domain ***service*** load-balancing

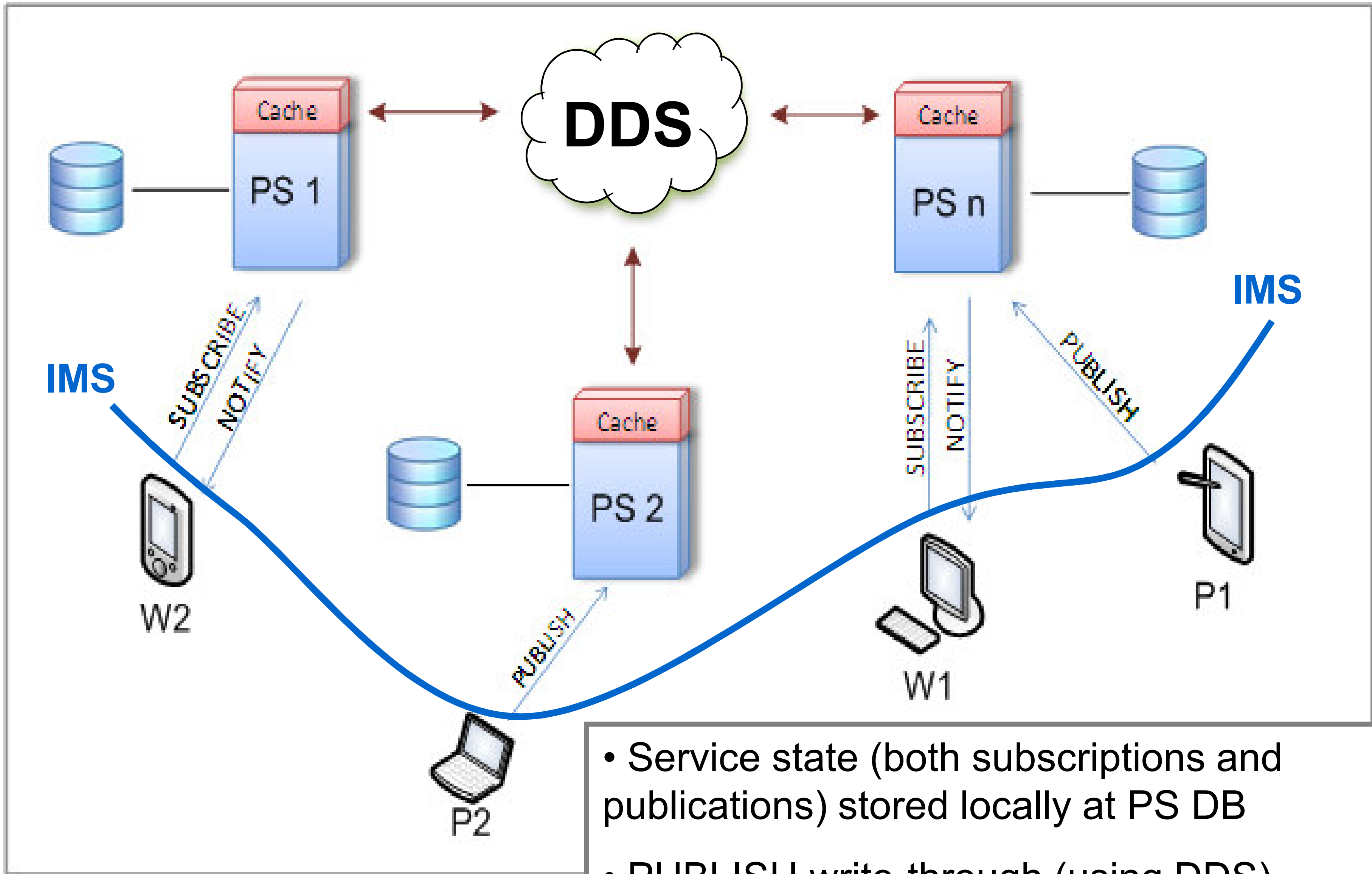
- **extends IMS PS** to support multiple AS service state storages and fast exchange of (and access to) shared session state among ASs

  → ***novel PS intra-domain module to enable data distribution overlays and caching techniques within AS partition***
- **exploits** existing standards for data distribution

  → ***data distribution is fully compliant with Data Distribution Service (DDS), an Object Management Group (OMG) standard***
- ***divides intra-domain service workload*** by applying a divide-and-conquer principle (for big domains)

  → ***IMS routing based on HSS and IMS filter criteria***

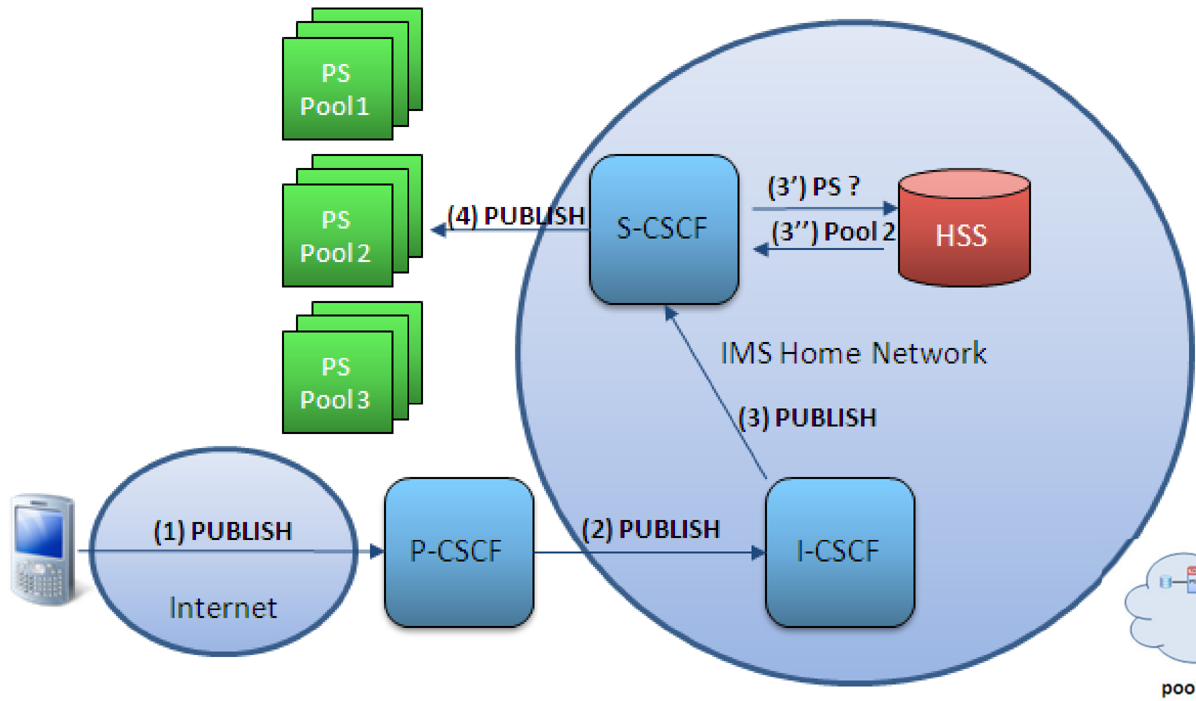
IHMAS intra-domain PS scalability: session data-centric management

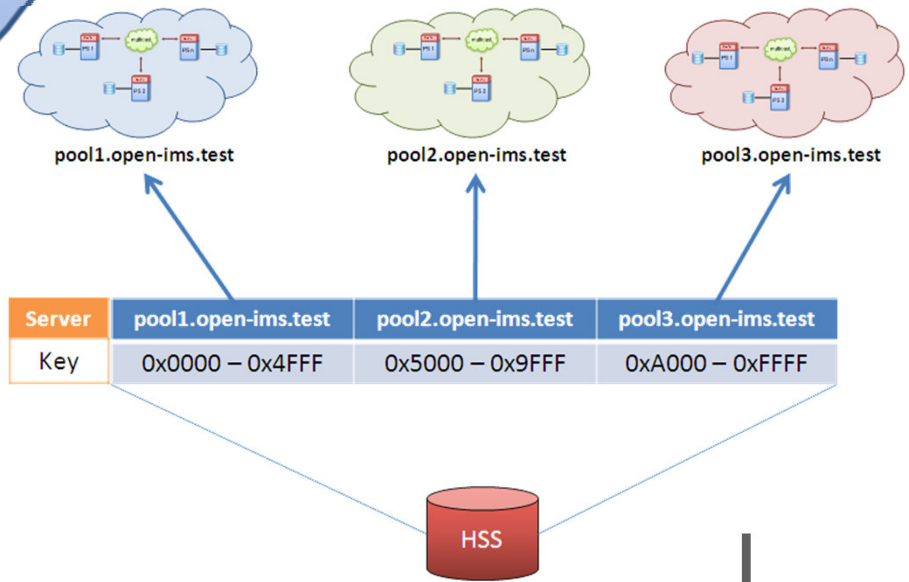


- Service state (both subscriptions and publications) stored locally at PS DB
- PUBLISH write-through (using DDS)

IHMAS intra-domain PS scalability: static balancing among PS pools

Message routing





Statistical load partition based on a hash function evaluated on presentity identifiers → ***exploits HSS + IMS filtering criteria***

Session Control and IMS Wrap-up

- Strong need for IMS scalable solutions
  - Both at the ***infrastructure*** and ***service*** level
  - Context- and service-aware approaches seem to be promising and should not be neglected
- Interoperability and standard compliancy
  - ***Full IMS standard compliance*** for inter-domain optimization techniques
  - ***Ad-hoc solutions*** and ***integration with other emerging standards*** at intra-domain level
- ***Real-world testbeds*** should be employed whenever possible

Mobile Edge Computing (and IoT…): Motivations

Number of connected devices worldwide continues to grow (triple by the end of 2019, ***from 15 to 50 billions***)

Deep transformation of how we organize, manage, and access ***virtualized distributed resources***

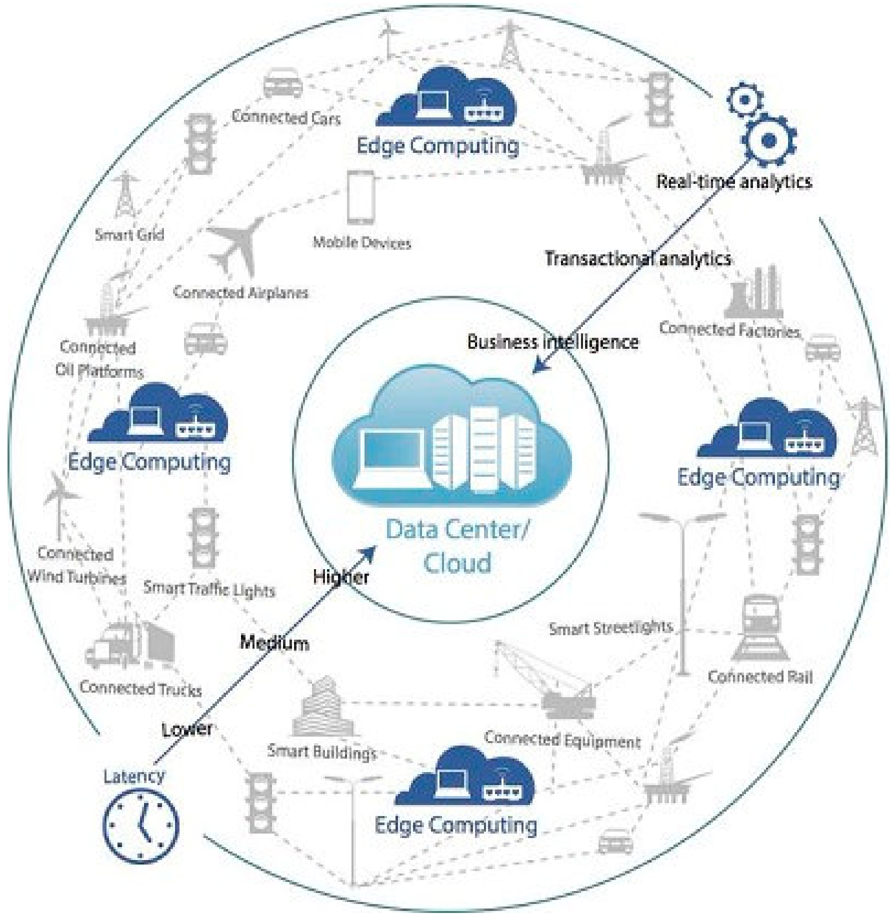
Is it reasonable that we continue to identify them with the ***global location-transparent cloud***?

In particular, in many ***industrial IoT application scenarios***:

- strict ***latency*** requirements
- strict ***reliability*** requirements
  - For instance, ***prompt actuation of control loops***
  - Also associated with ***overall stability and overall emerging behavior***

Edge Computing: Definition (to be discussed…)

Edge computing = ***optimization of "cloud computing systems"*** by performing data processing (only?) at ***the edge of the network***, near data sources. ***Possibility of intermittent connectivity***



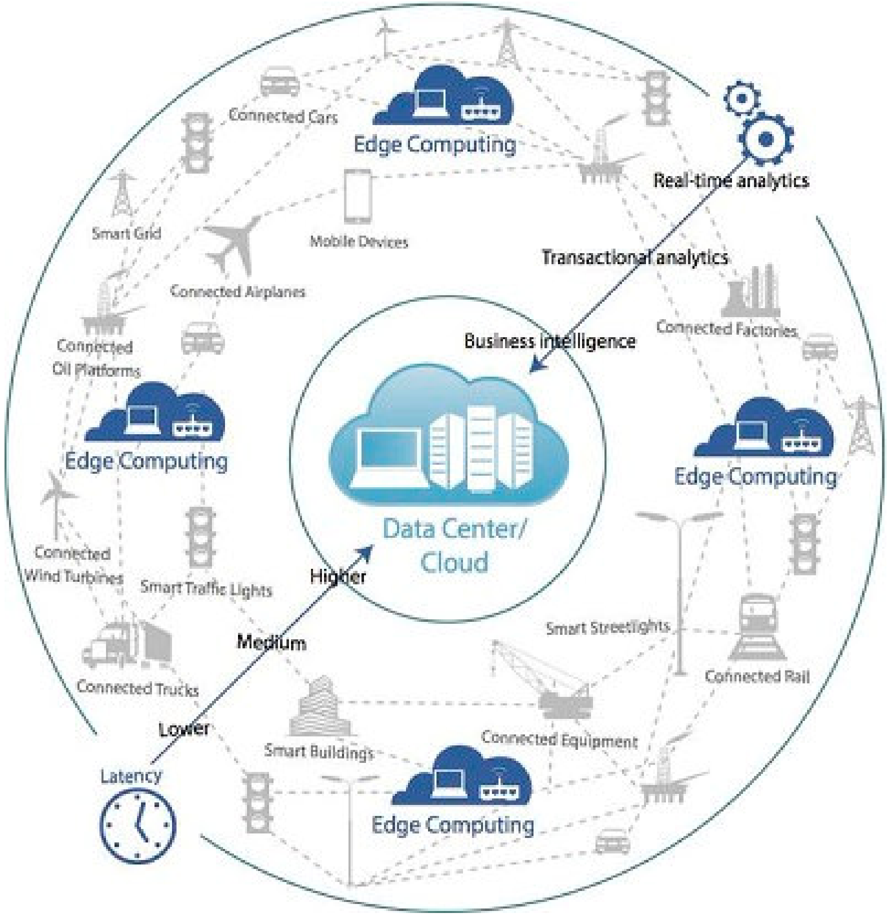
Edge computing can include technologies such as ***wireless sensor networks, mobile data acquisition,*** mobile signature analysis, ***cooperative distributed peer-to-peer ad hoc networking and processing***, distributed data storage and retrieval, ***autonomic self-healing networks***, remote cloud services, …

Edge Computing: Definition

Edge computing = ***optimization of "cloud computing systems"*** by performing data processing (only?) at ***the edge of the network***, near datasources. ***Possibility of intermittent connectivity***

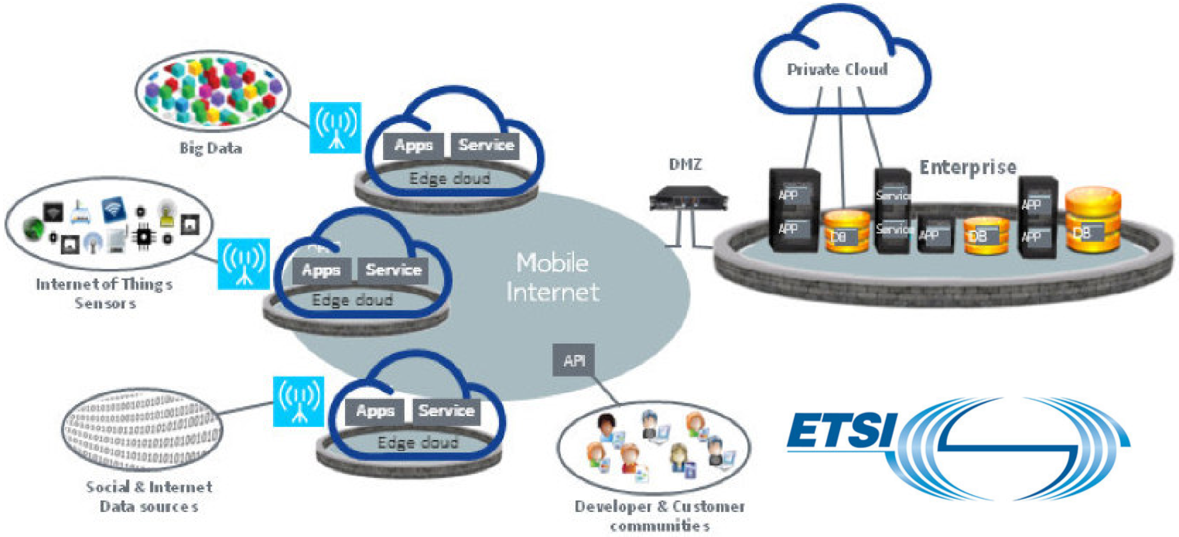
IMHO, crucial to have ***virtualization techniques at edge nodes***

Synonyms (???) = mobile edge computing, fog computing, cloudlets, …



Multi-access Edge Computing

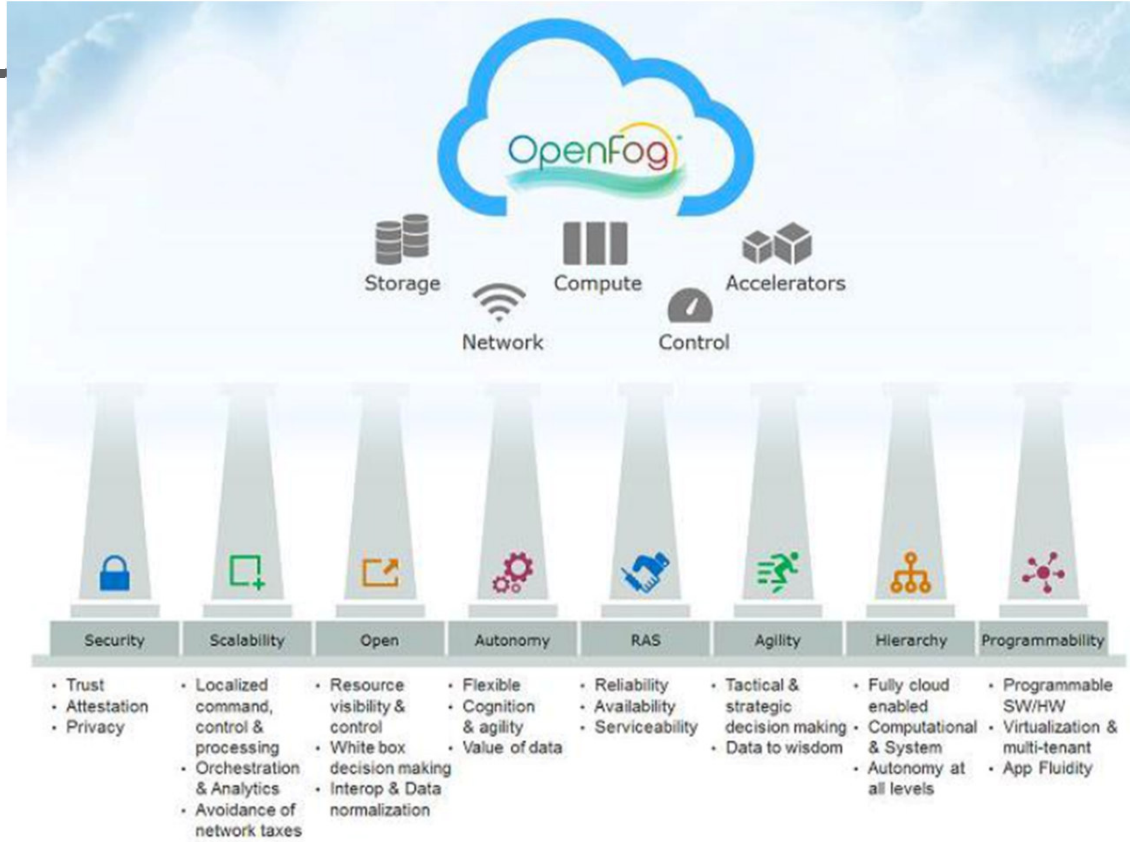
- The **MEC** architecture is proposed to overcome the challenges of limited-resources mobile devices
- MEC offers high bandwidth, low latency and support to the mobility of nodes



- **Cons**: limited number of edges and low re-configuration rate, due to high costs of configuration and maintenance

Fog Computing

- **Fog Computing** paradigm is proposed to overcome the limitations of Cloud Computing
- Fog supports the **IoT** concept

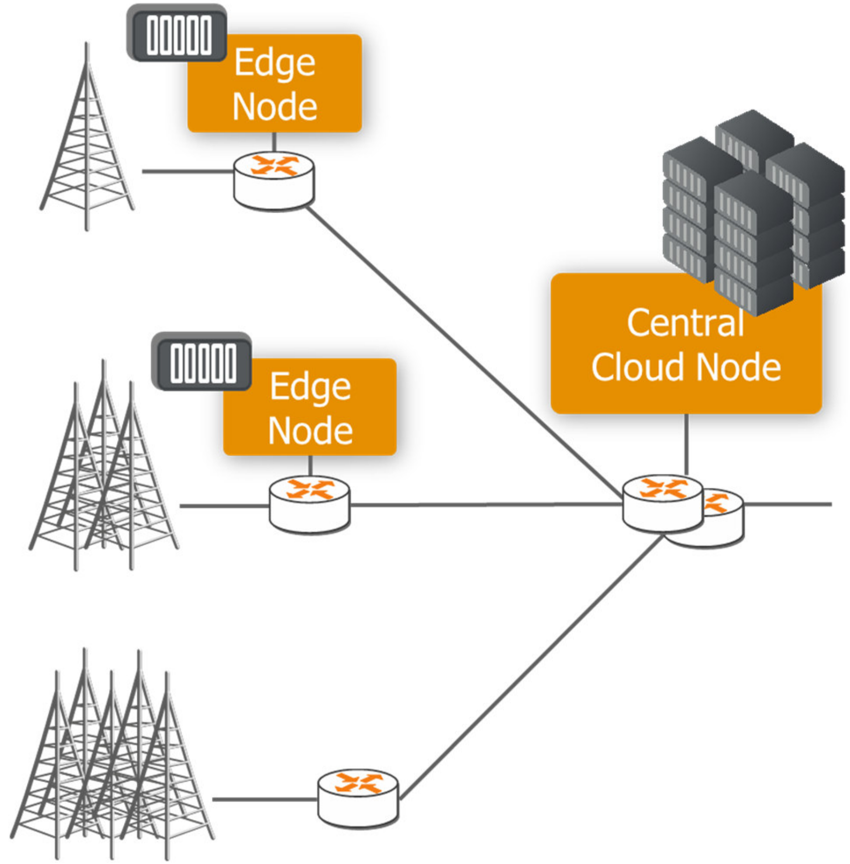


- **Cons**: typically fog is used for resource-poor devices and sensing scenario and **Smart Gateways (SGs)** are unable to host heavy computations

Notable example: ETSI Multi-access Edge Computing (MEC)

MEC is bringing computing close to the devices (in the base stations or aggregation points)

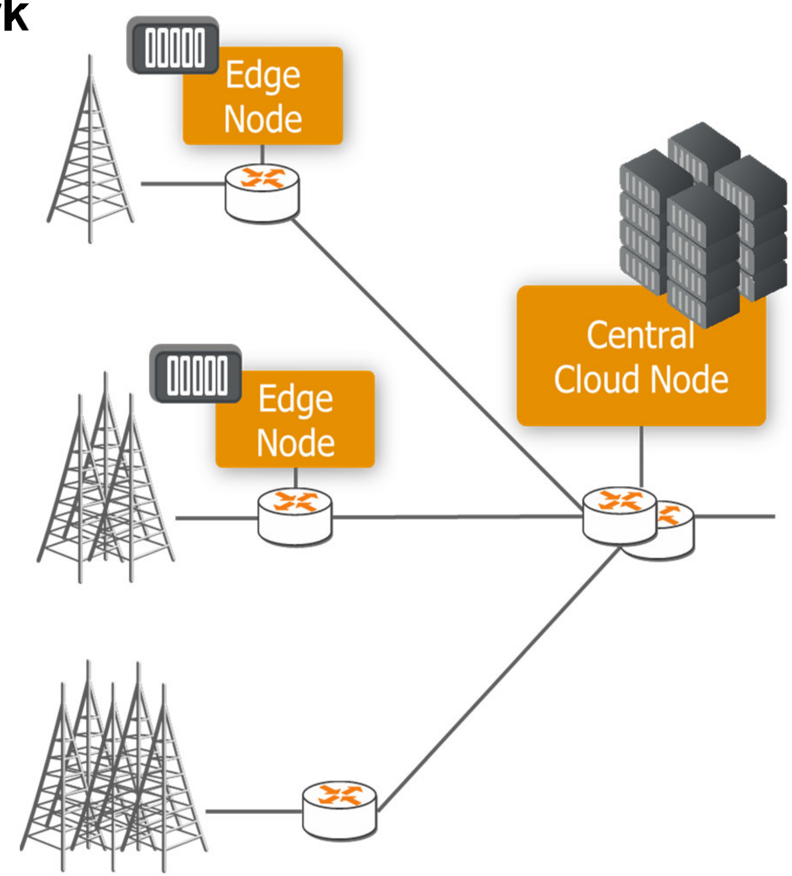
- **On-Premises:** the edge can be completely isolated from the rest of the network
- **Proximity:** capturing key information for analytics and big data
- **Lower Latency:** considerable latency reduction is possible
- **Location awareness:** for location-based services and for local targeted services
- **Network Information Context:** real time network data can be used by applications to differentiate experience



Local vs Global: the MEC Use Cases

Depending on the integration with the core network three types of use cases are defined

- **Private Network Communication (factory and enterprise communication)**
  - ❑ Providing support for on-premises low-delay private communication
  - ❑ Providing secure interconnection with external entities
- **Localized Communication (traffic information and advertisements)**
  - ❑ Providing support for localized services (executed for a specific area)
  - ❑ Specific ultra-flat service architectures
- **Distributed Functionality (content caching, data aggregation)**
  - ❑ Providing extra-functionality in specific network areas

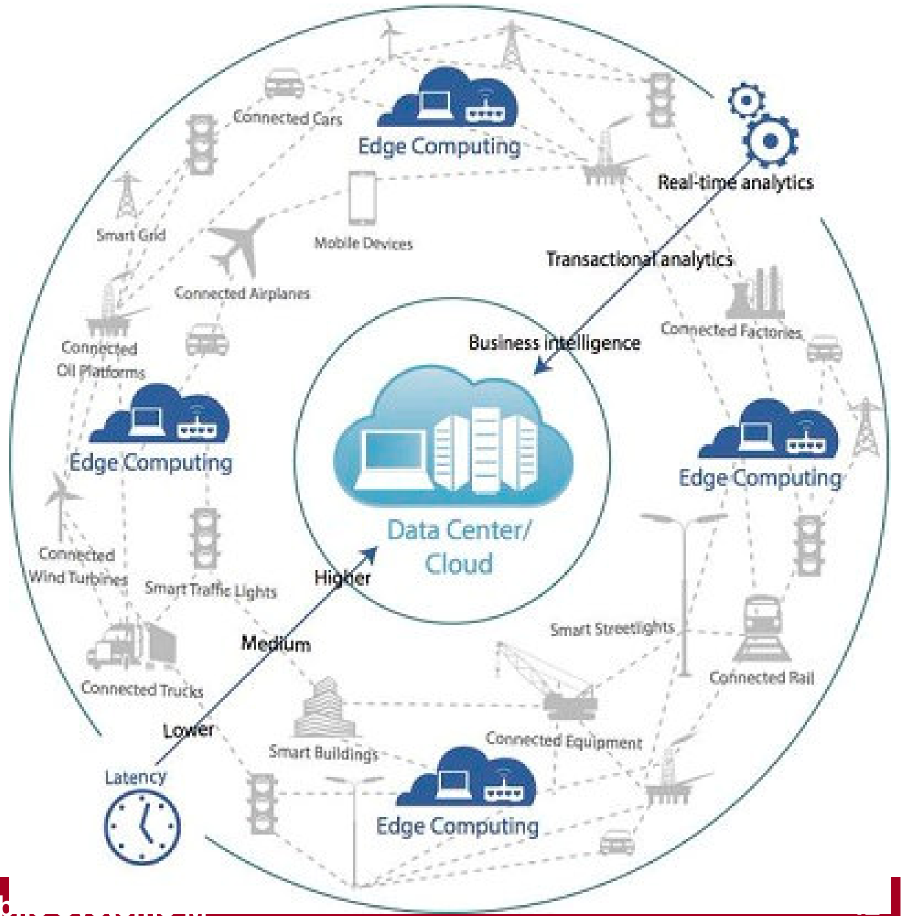


Edge Computing: Definition (again…)

Ongoing research towards merging:

- ***Multi-access Edge Computing (MEC)*** e.g., ETSI standardization
- ***and fog computing approaches*** e.g., Foud for V2G or MEFC, and IEEE Future Networks initiative (see reference section)

"Only" stronger accent on standard protocols (MEC), content caching (MEC), data aggregation (fog), distributed control (fog), orchestration of virtualized resources (both), mobile offloading (?)

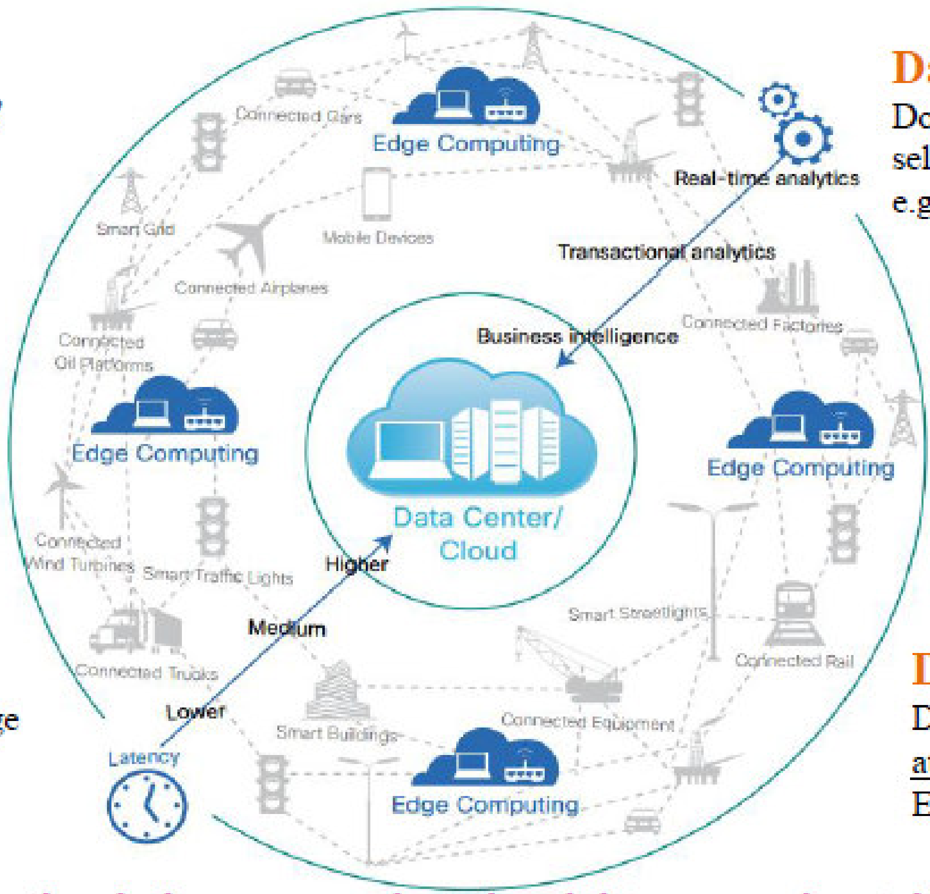


Edge Computing Applications

Application suitable at the Edge

Performance :
Is there a low latency requirement?
E.g. gaming, safety

Data preprocessing opportunities:
Does it make sense to compress or transmit selected data before transferring?
e.g. Video Surveillance, traffic monitoring



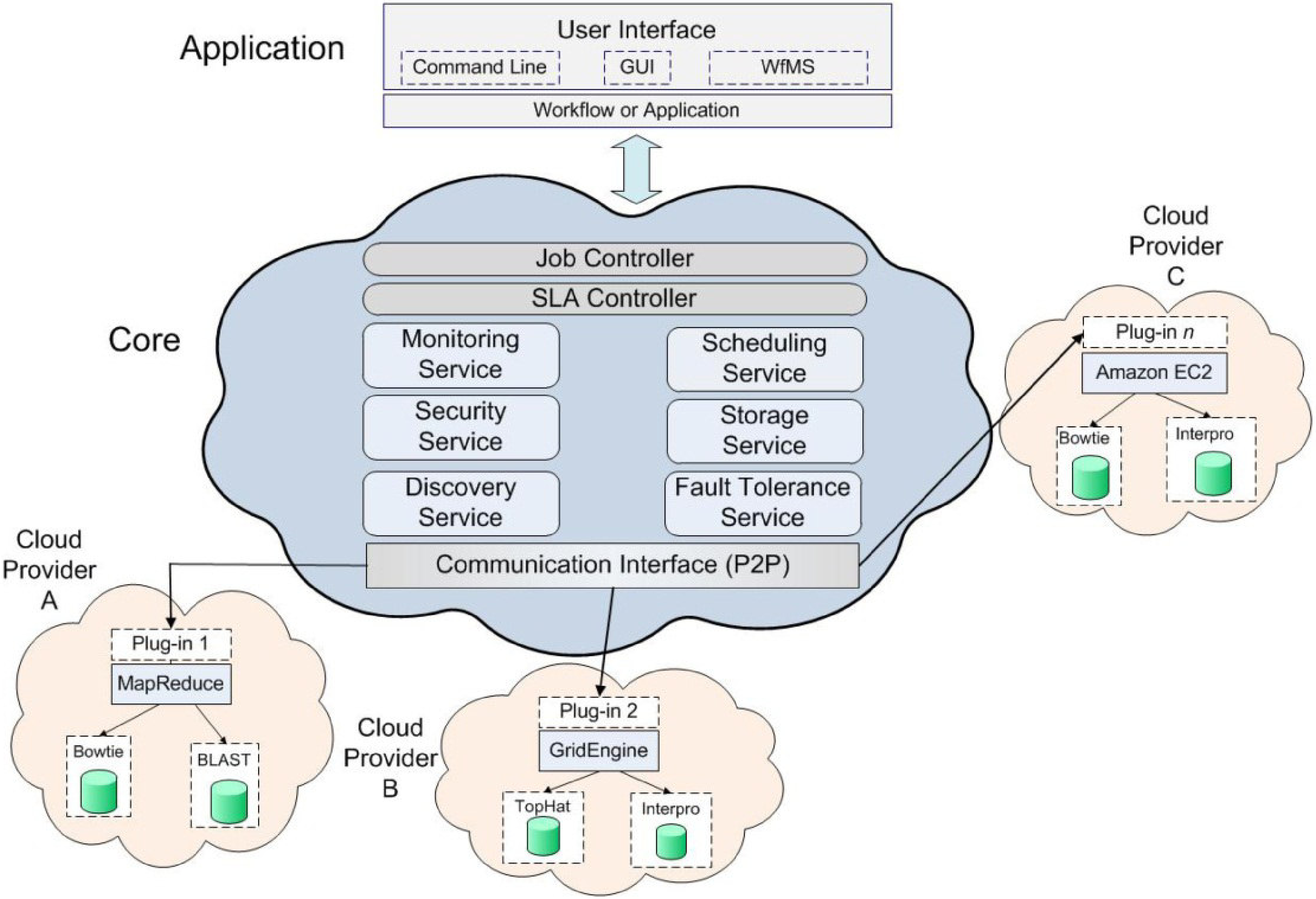
Process locally:
Is it better to process data at the edge vs. sending huge data to DC?
e.g. Big Data, data cleansing

Distributed application:
Does processing at the edge is more attractive?
E.g. smart city, monitoring, IoT?

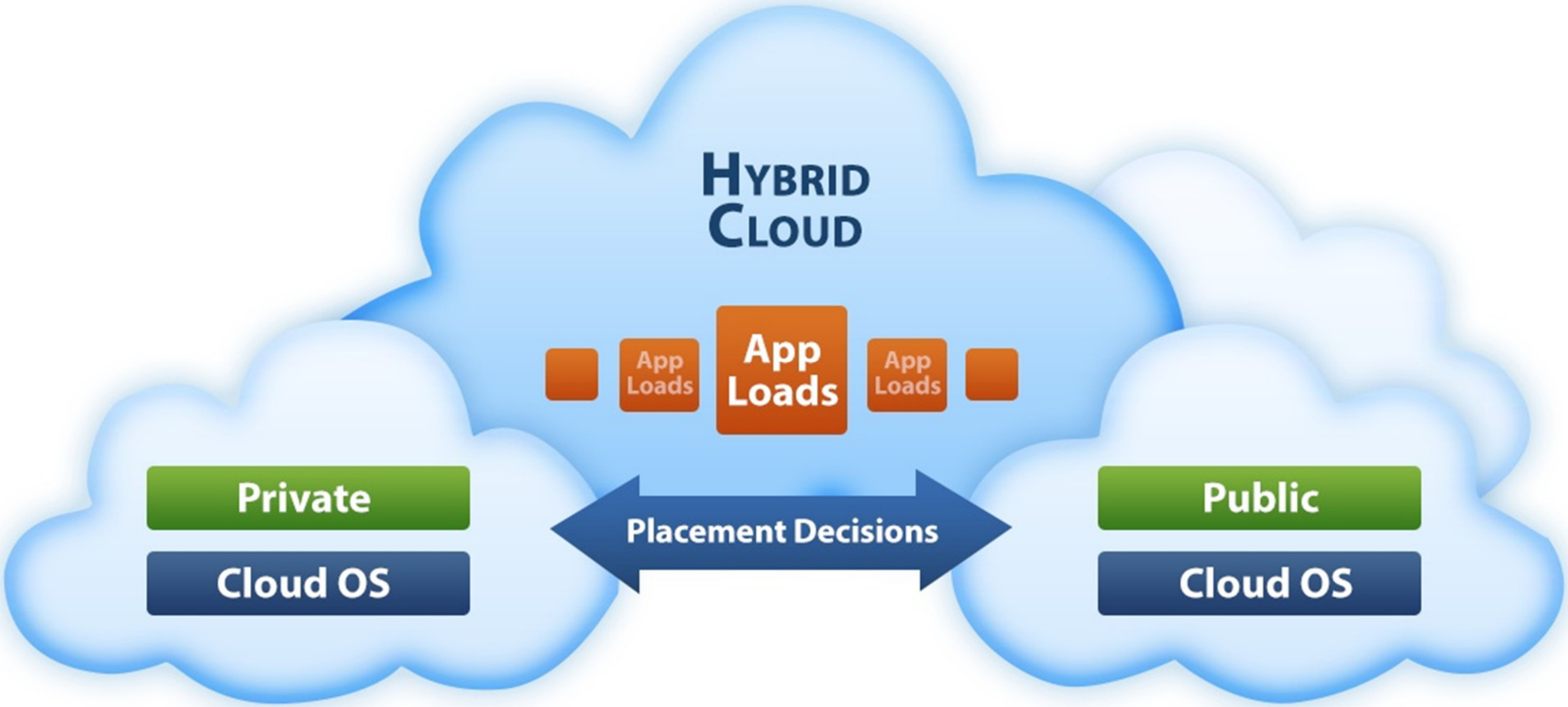
"Edge computing helps ensure that the right processing takes place at the right time and location" – CISCO

Attaining IoT Value: How To Move from Connecting Things to Capturing Insights *Gain an Edge by Taking Analytics to the Edge*. Andy Noronha Robert Moriarty Kathy O'Connell Nicola Villa. Cisco 2015

From traditional cloud to federated cloud…



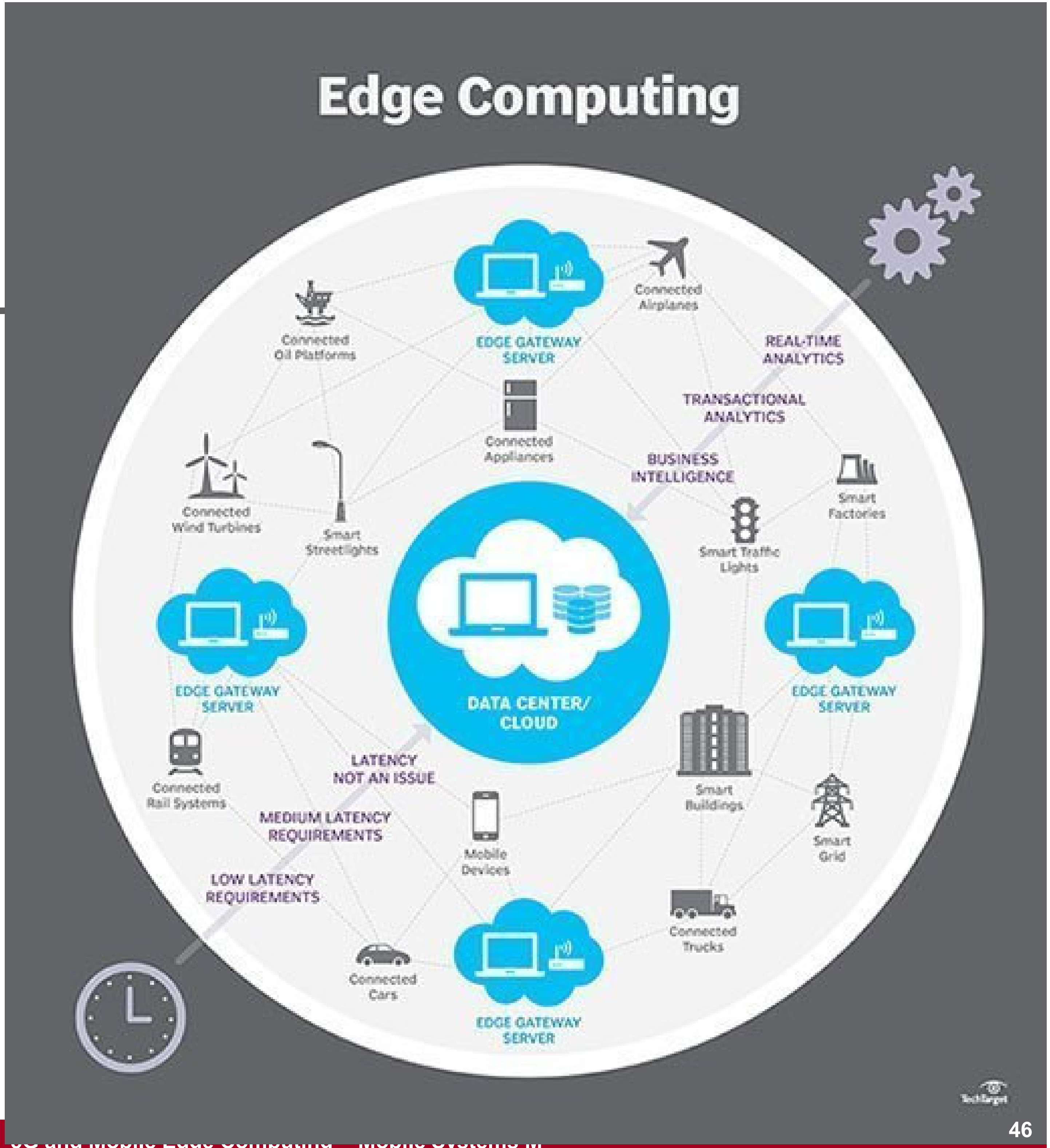
...to hybrid cloud



and of course towards the combination of federated and hybrid clouds

Growing relevance for:

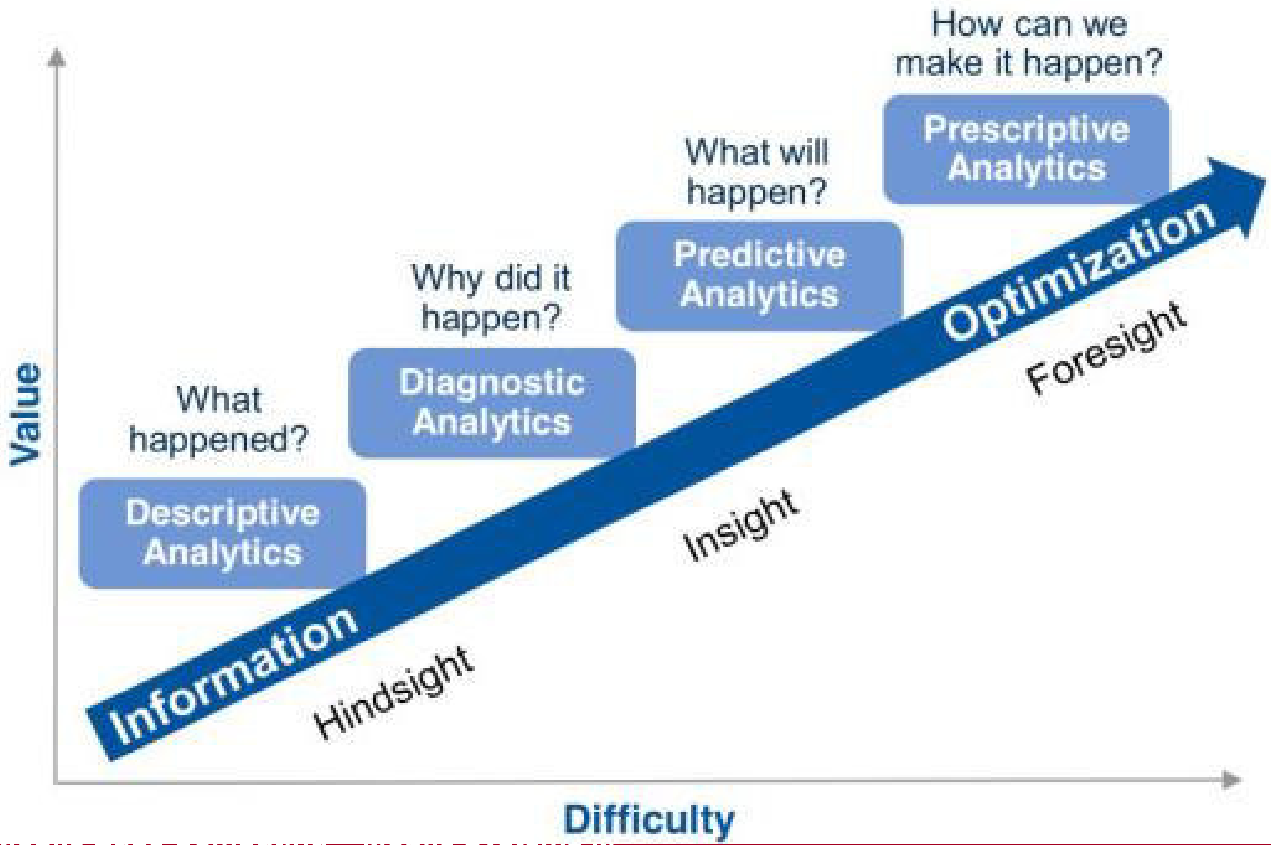
- Latency reduction
- Reliability increase
- Bandwidth reqs reduction
- On-premise processing
- Local interaction
- Privacy in machine learning
- ….



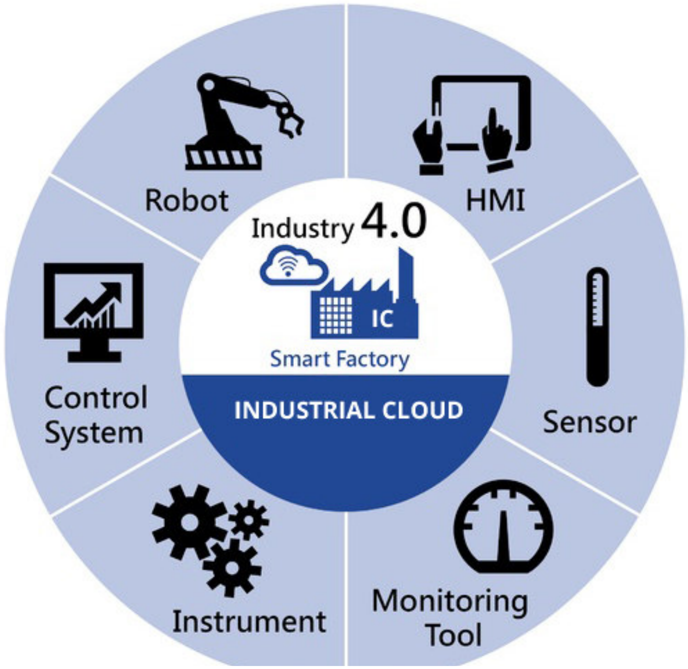
Use Case #1: Predictive Diagnostics and Optimization of Production Processes

Fault prevention/prediction and planning of efficient maintenance operations via Machine Learning techniques

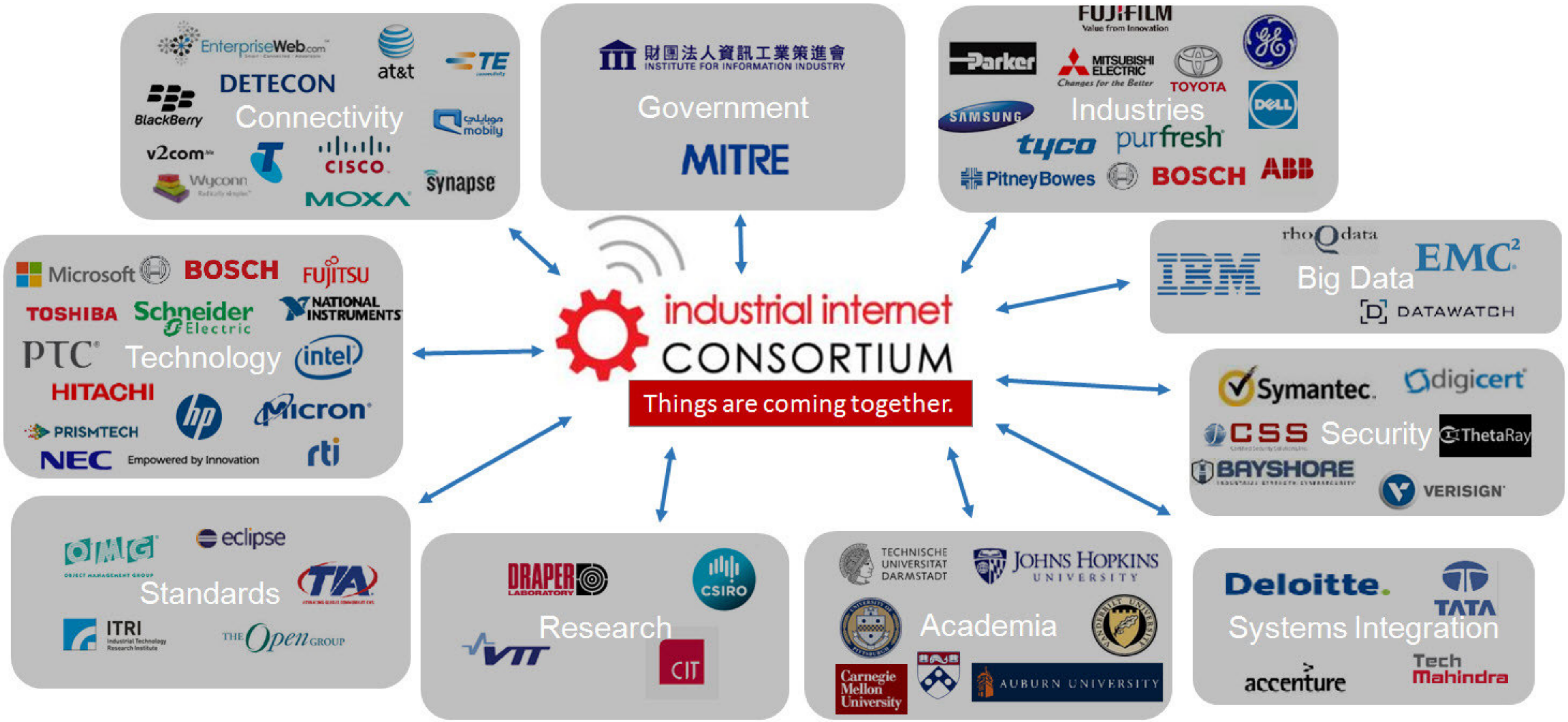
- Not only AI ☺…
- Efficiently interconnect IoT
- Industrial cloud and compliance with standard specifications and best practices
- Edge cloud computing and fog computing
- …



Use Case #1: Predictive Diagnostics

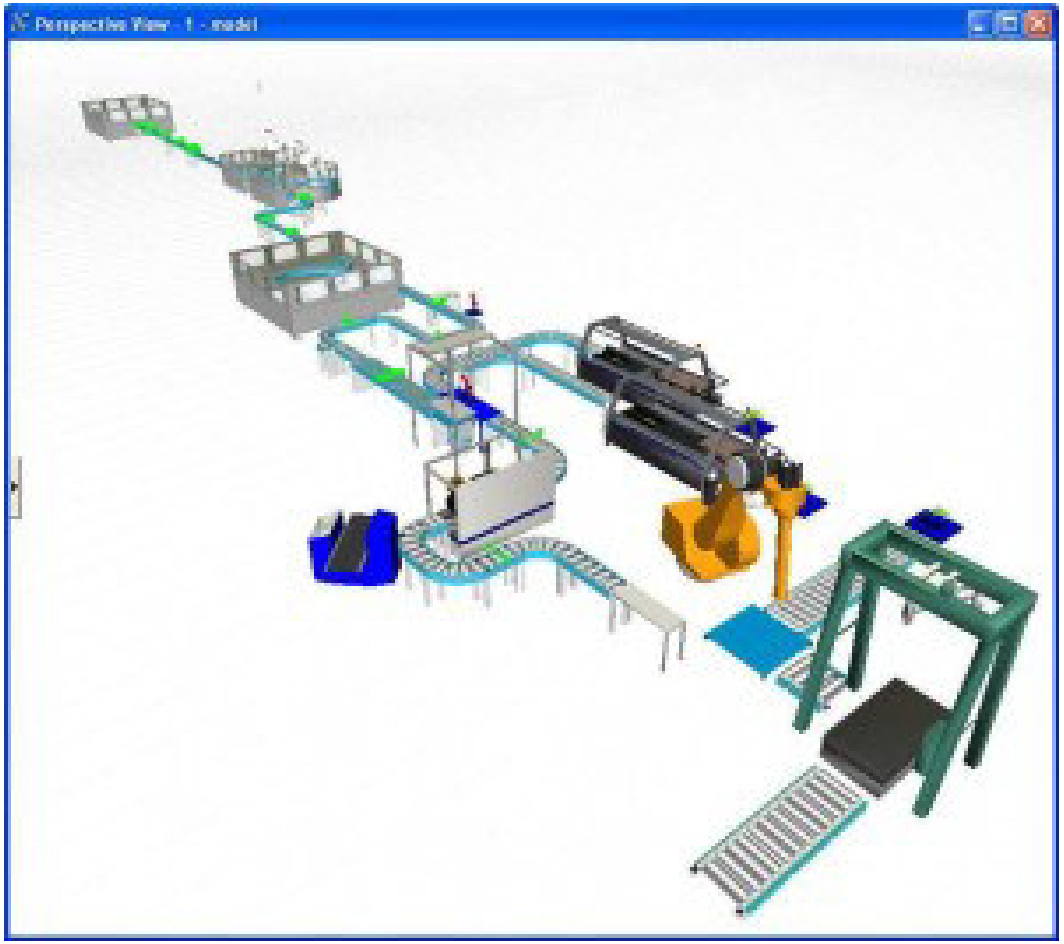


- Industrial cloud
- Compliance with standards and best practices



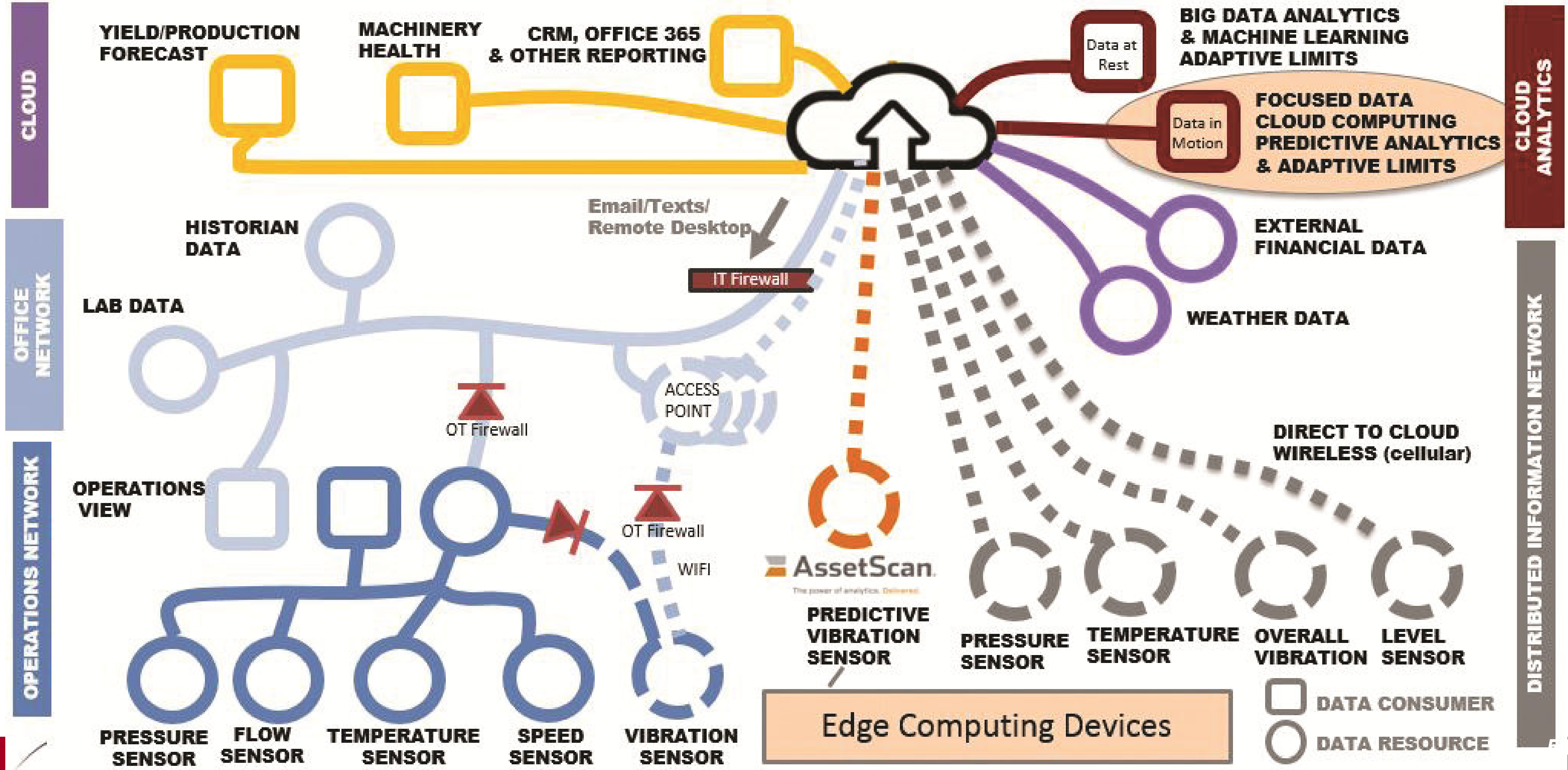
Use Case #1: Prescriptive Analytics and Optimization of Manufacturing Processes

- ***Digital Twins*** of production plants
- ***Automated configuration of production lines*** (system of systems)
- ***Dynamic reconfiguration*** of manufacturing production lines

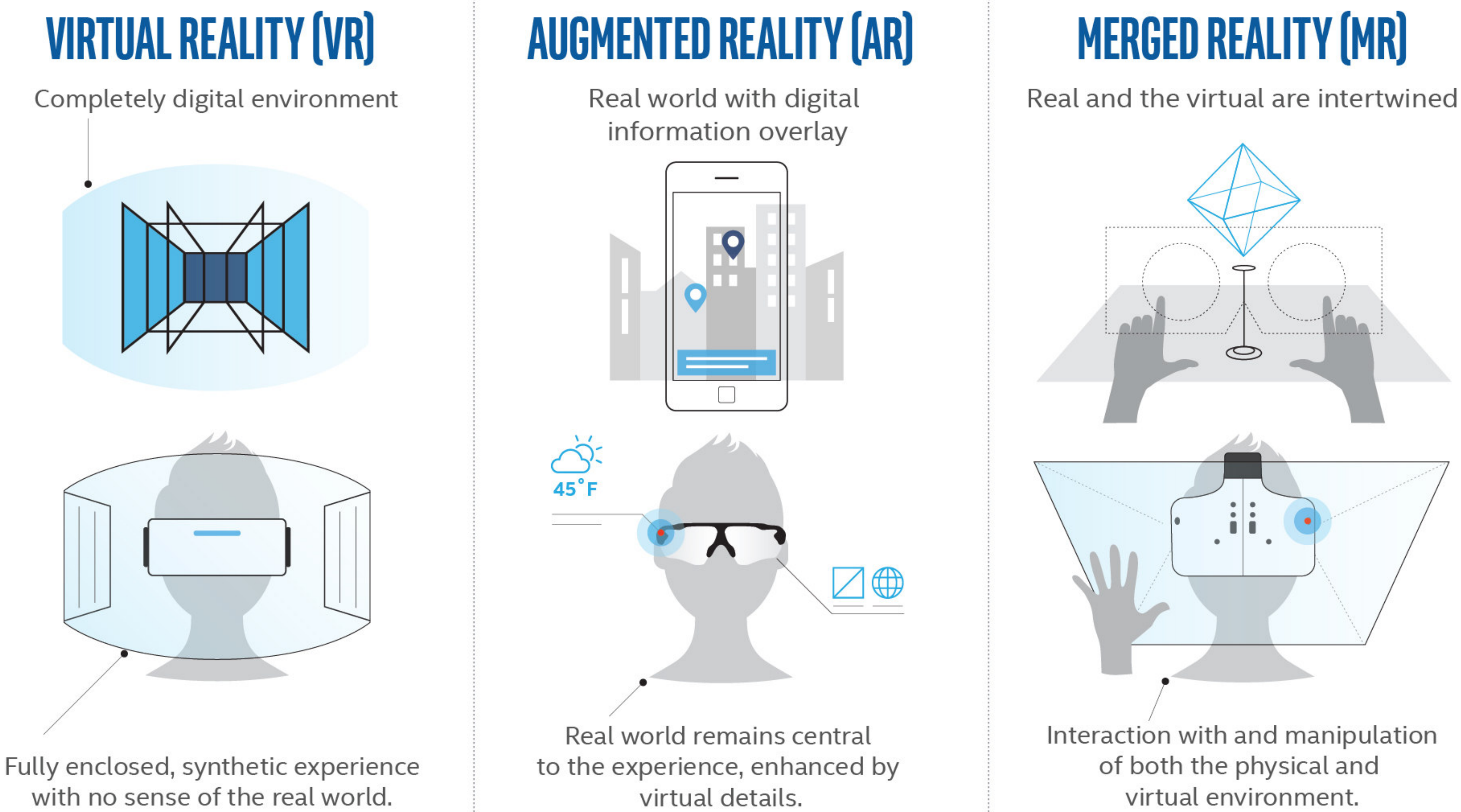


Use Case #1: Prescriptive Analytics and Optimization of Manufacturing Processes

Optimization of product quality and of process efficiency based on IoT monitoring in hard/soft-realtime and machine learning



Use Case #2:
Virtual and Augmented Reality

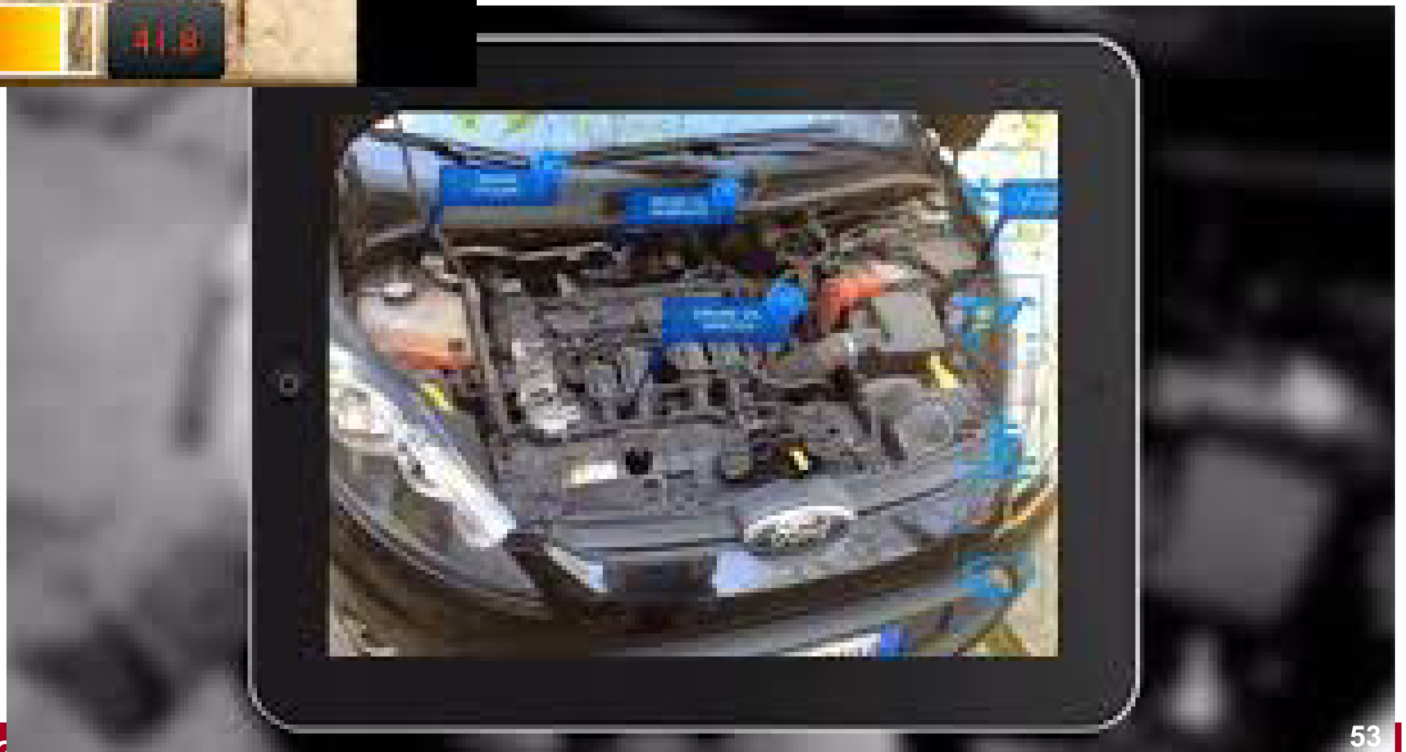


Virtual and Augmented Reality for Logistics

Virtual and Augmented Reality for Maintenance

Visualized models that integrate the info/knowledge on the «real world» in real-time

Also storage and tracking of previous maintenance interventions



Edge/Fog Computing in this context PLUS 5G

5G plus edge/foc cloud computing (***cloud continuum***) can contribute to improve:

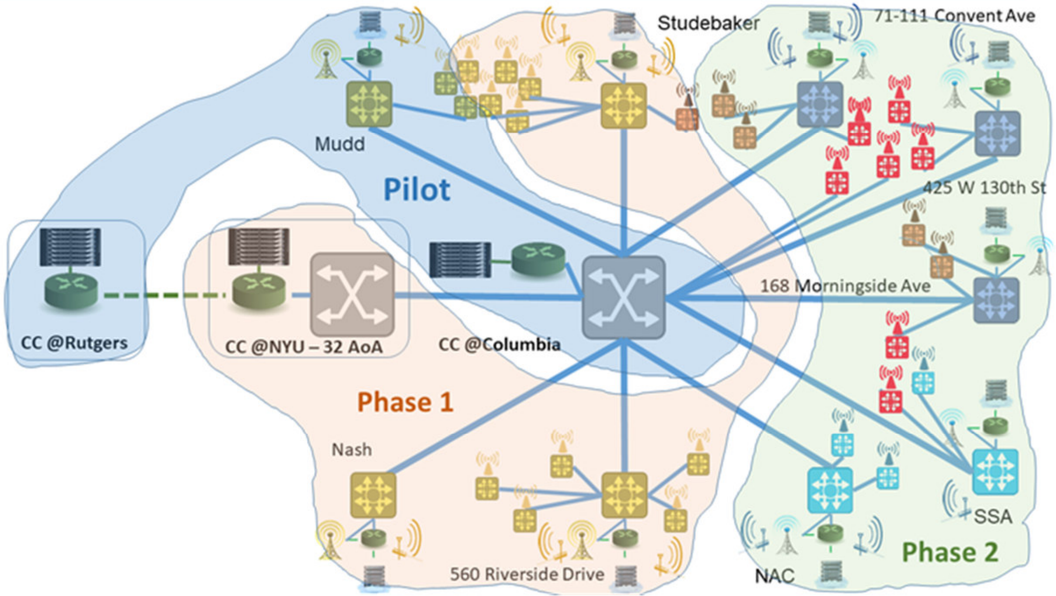
- ***Efficiency***
- ***Latency minimization***
- ***Cost reduction***
- ***QoE in terms of interaction and collaboration***
- ***With customized/personalized properties about security, privacy, data protection/ownership, …***

And not only for the above use cases!!!

Edge Computing

COSMOS Deployment: NYC Coverage Areas

- Pilot – planned for end of 2018
- Phase 1 in 2019, Phase 2 by 2020



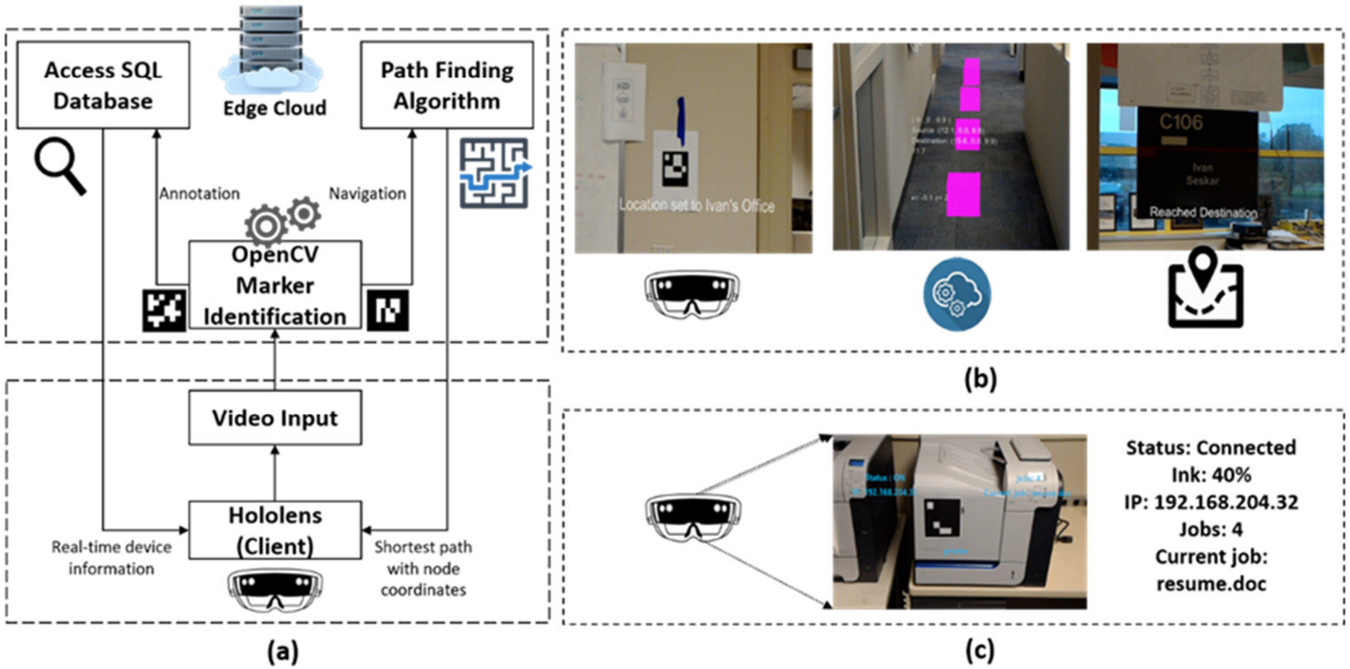
Mudd

Broadway

Amsterdam

- Phase 1 Columbia/CCNY – ~15-20 nodes
- Phase 2 – ~40 nodes

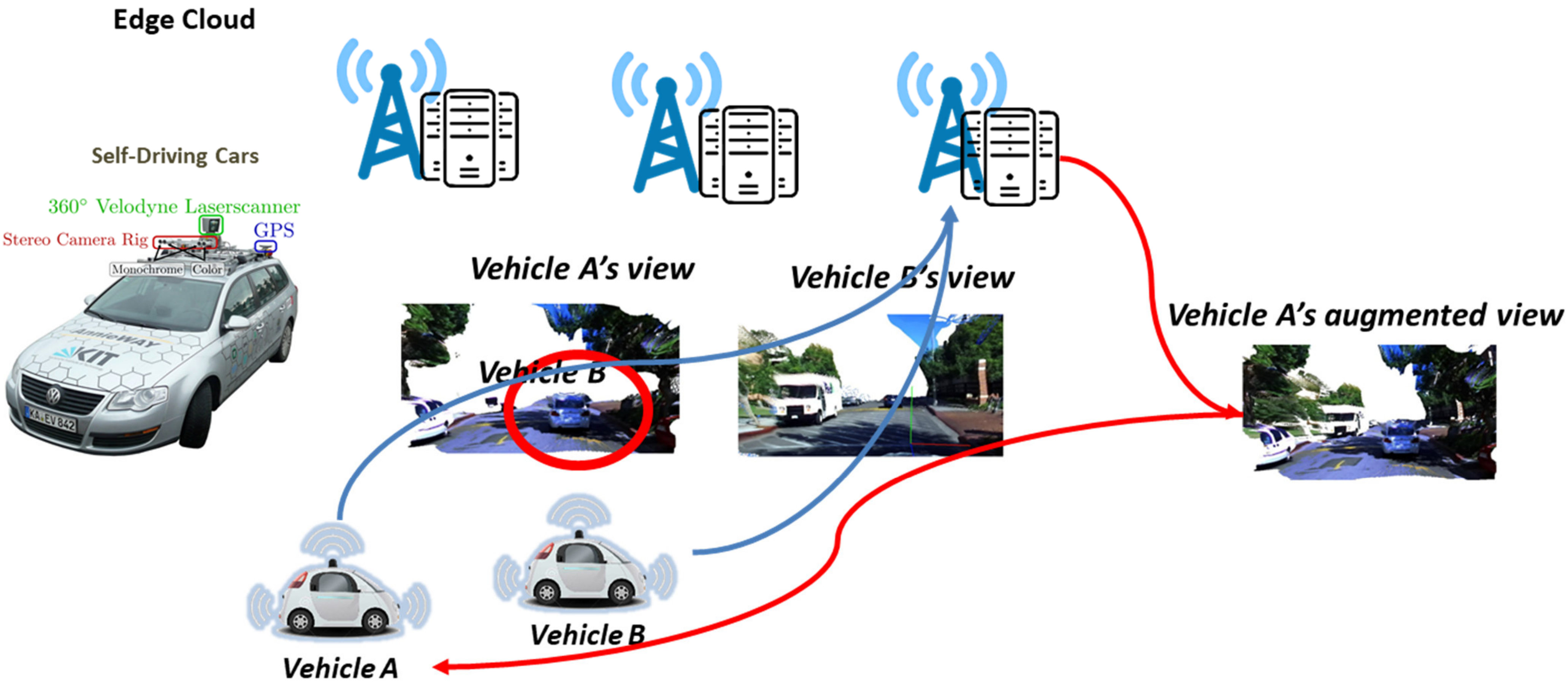
COSMOS Experiments: AR Applications



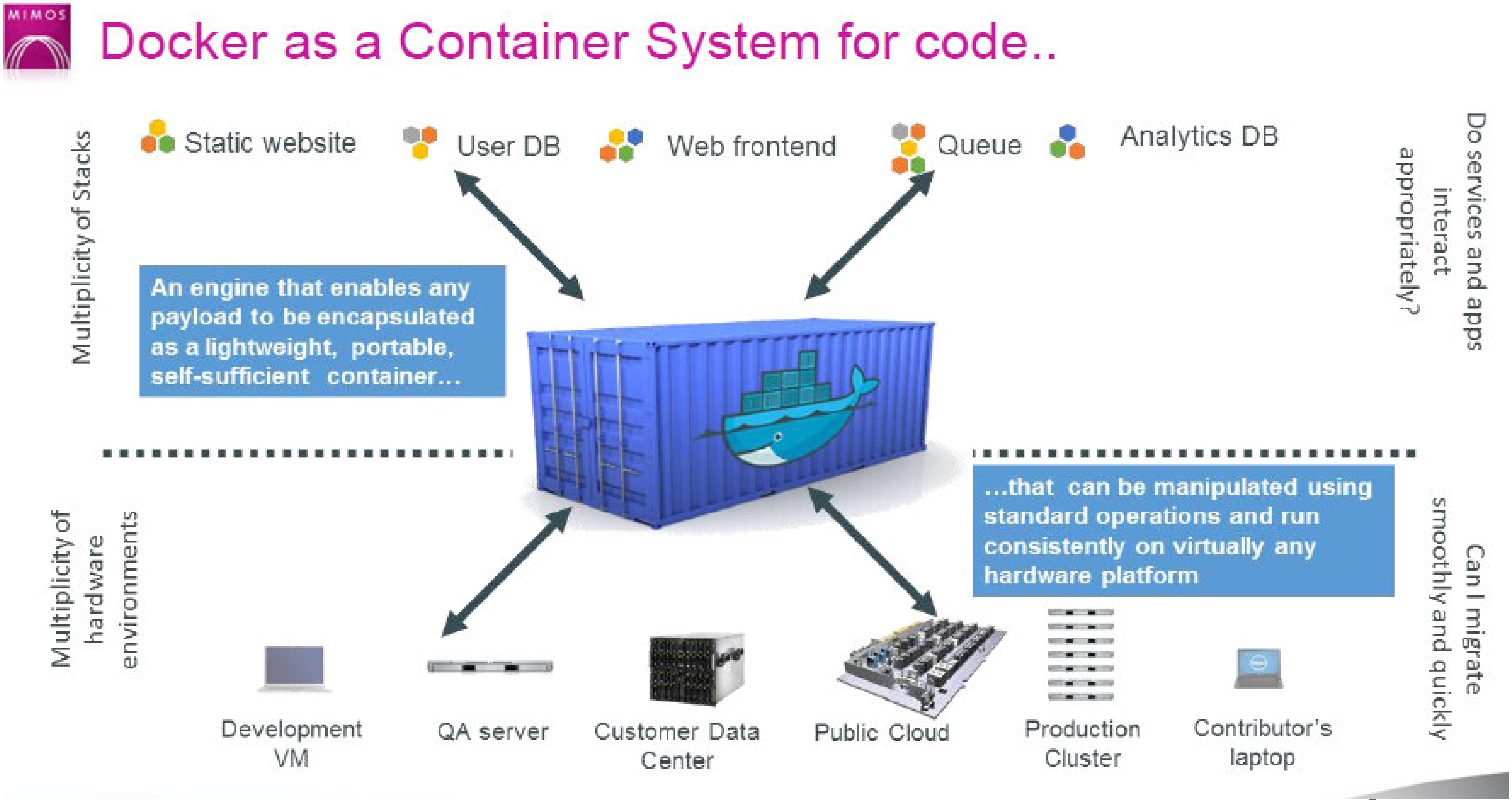
(a) AR application flow; (b) Smart meeting application using indoor navigation; (c) Annotation based assistance

Edge Computing

COSMOS Experiments: Cloud Assisted Autonomous Vehicle



Edge Computing & Docker

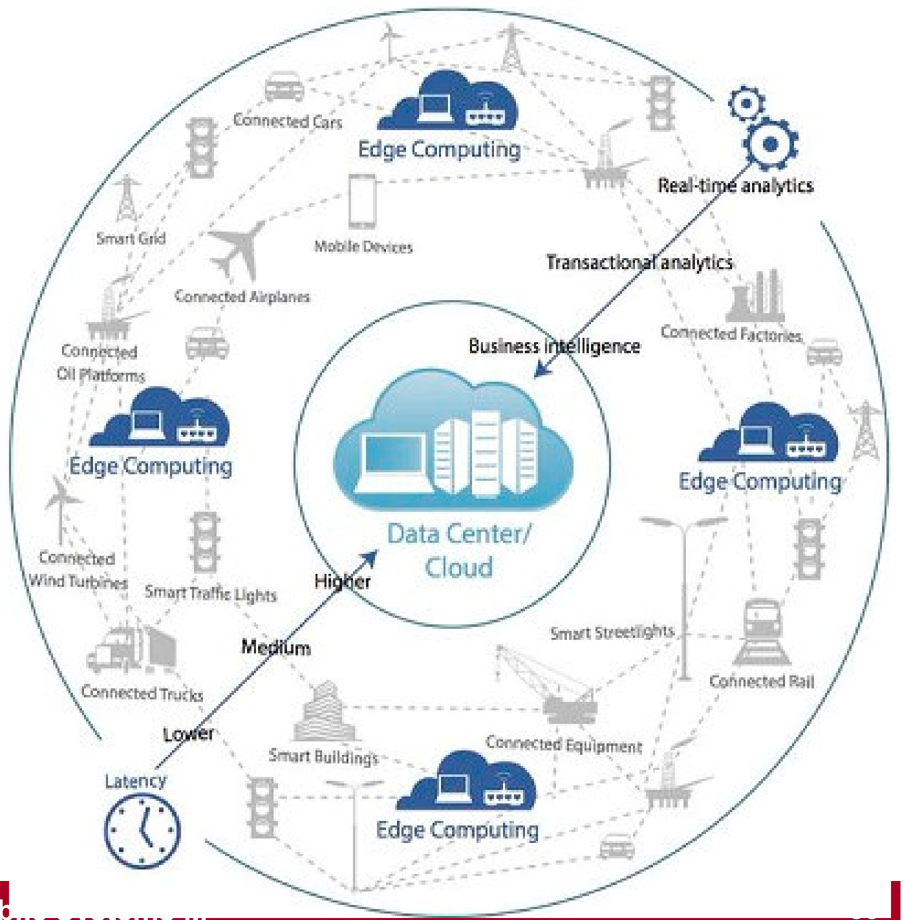


Edge Computing: Definition (again…)

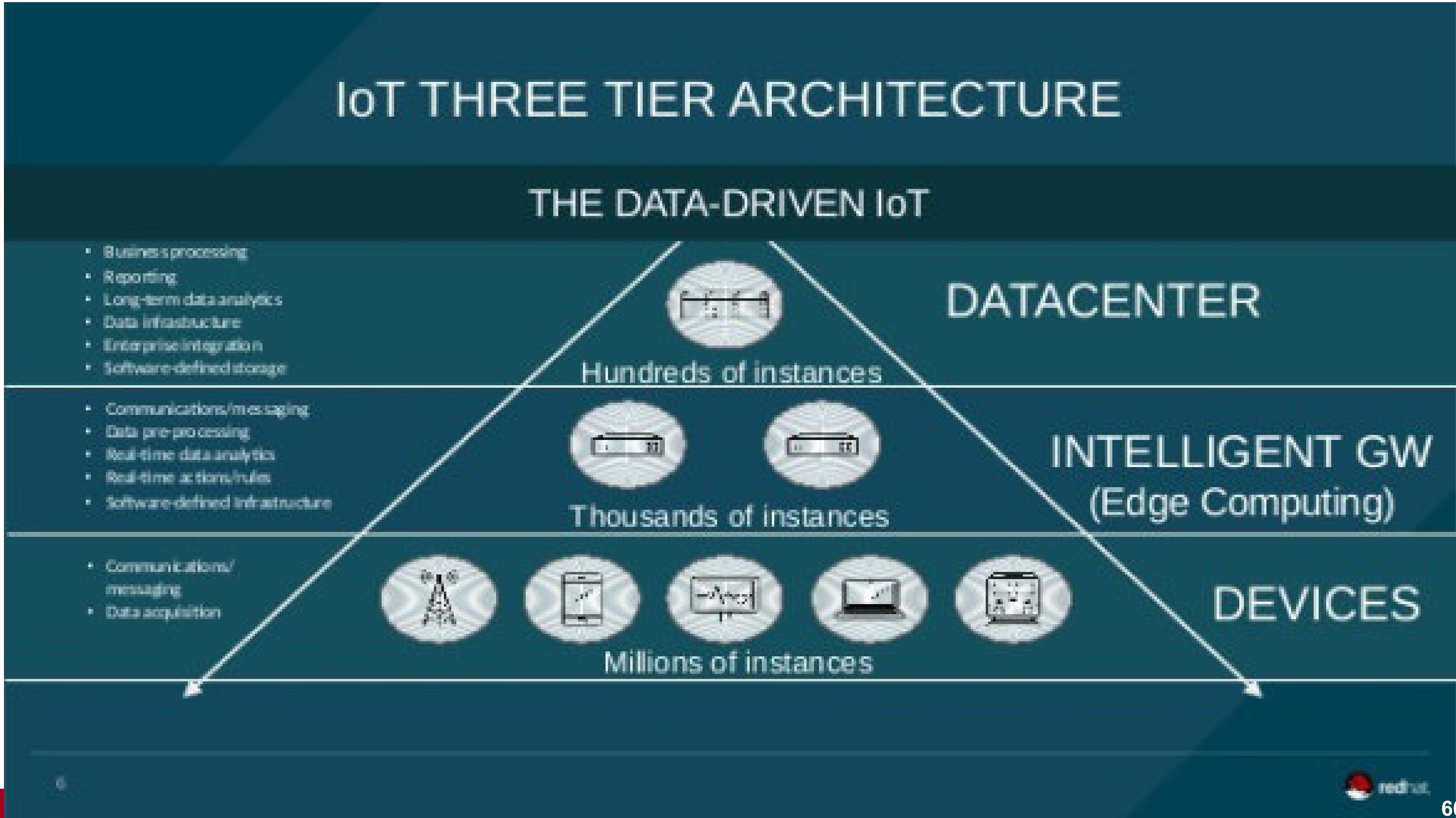
Ongoing research towards merging:

- ***Multi-access Edge Computing (MEC)*** e.g., ETSI standardization
- ***and fog computing approaches*** e.g., Foud for V2G or MEFC, and IEEE Future Networks initiative (see reference section)

“Only” stronger accent on standard protocols (MEC), content caching (MEC), data aggregation (fog), distributed control (fog), orchestration of virtualized resources (both), mobile offloading (?)



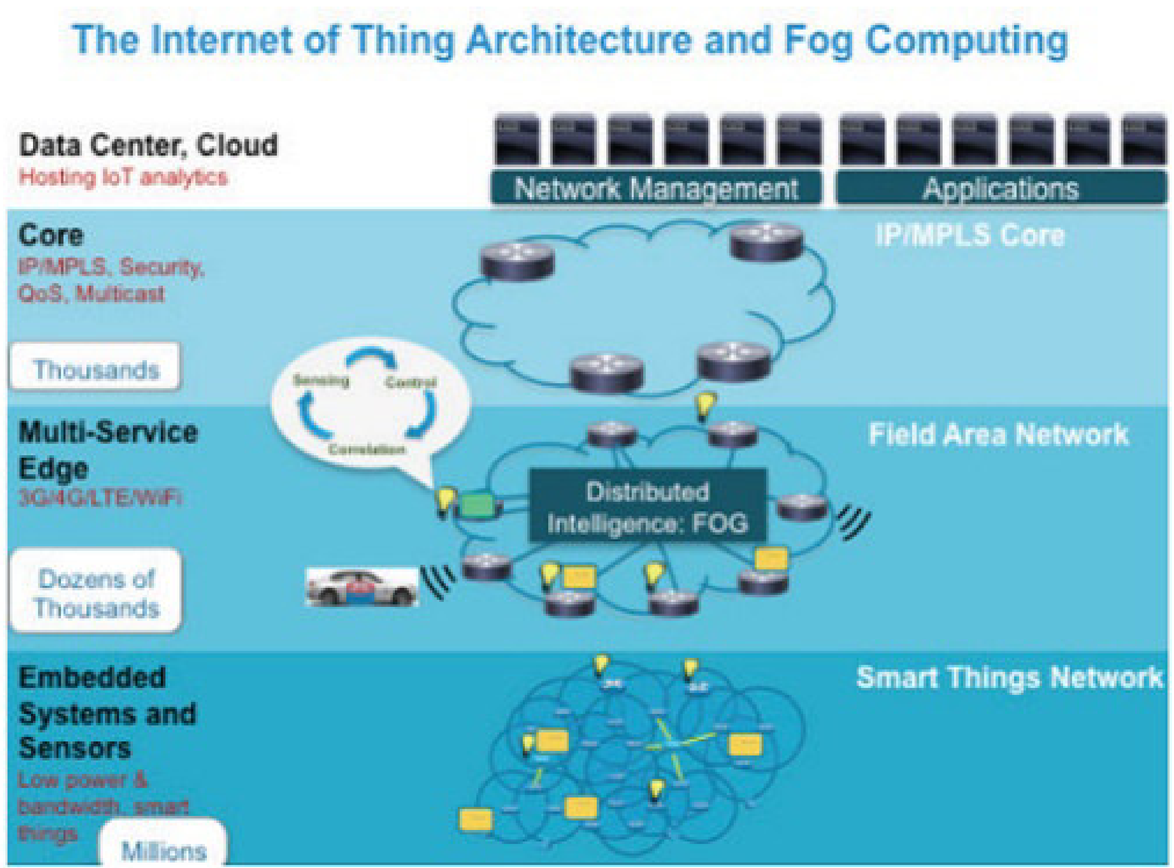
Edge Computing for Industrial IoT: Quality Requirements



Edge Computing for Industrial IoT: Quality Requirements

Towards the vision of ***efficient edge computing support*** for ***“industrial-grade” IoT applications***

- ***Latency constraints***
- ***Reliability***
- ***Privacy of industrial data***
- ***Decentralized control***
- ***Safe operational areas***
- ***Scalability***



For example, Edge and 5G for Constrained Latency

Industry 4.0

- Increase the **flexibility, versatility, productivity, resource efficiency & usability** of industrial production
- **Connectivity as a key enabler** for cyber-physical production systems

Future Industrial Connectivity Infrastructures

5G

- Strong focus on **machine-type communication** and the IoT[1]
- **URLLC[2] + mMTC[3]** enable completely new applications, also in industry
- 5G is **more than wireless**

Enabler for new applications & use cases and for lifting I4.0 to the next level

Images: BOSCH

For example, Edge and 5G for Constrained Latency

Selected Performance Requirements

Credits to Bosch

Industry 4.0




	Motion Control	Safety Traffic	Condition Monitoring	Augmented Reality
Latency / Cycle Time	250 µs – 1 ms	~10 ms	100 ms	10 ms
Reliability (PER[1])	1e-8	1e-8	1e-5	1e-5
Data Rate	kbit/s – Mbit/s	< 1 Mbit/s	kbit/s	Mbit/s - Gbit/s
Typical Data Block Size	20-50 byte	64 byte	1-50 byte	> 200 byte
Battery Lifetime	n/a	1 day	10 years	1 day

uRLLC[2] → most challenging (Motion Control, Safety Traffic)

Massive MTC[3] (Condition Monitoring)

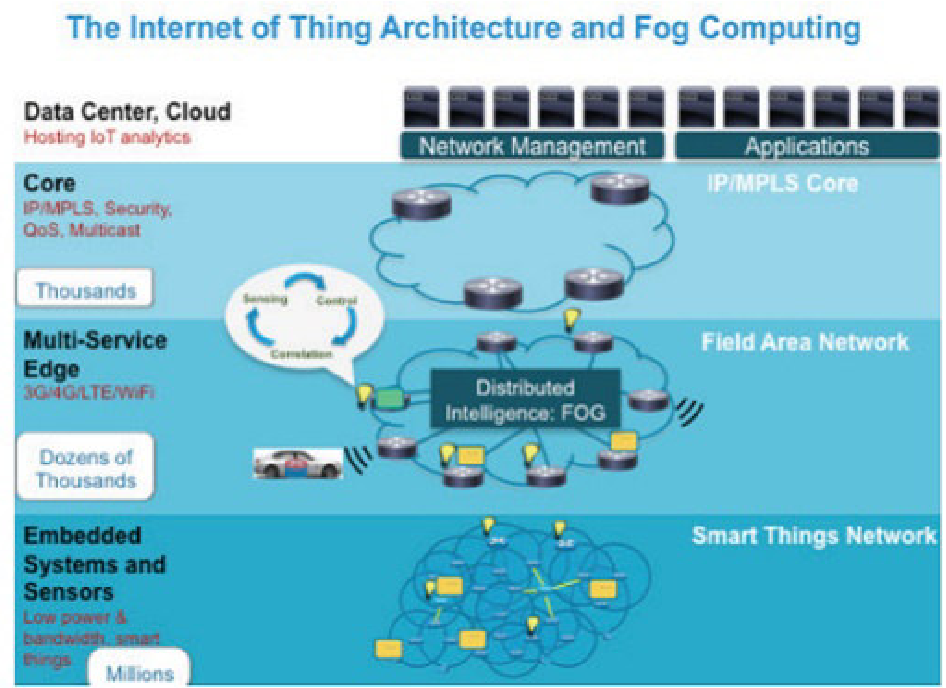
Extreme Broadband + Low Latency (Augmented Reality)

Edge Computing for IoT Apps: Research Directions

1. Architecture modeling
2. ***Quality support even in virtualized envs***
3. ***Scalability via hierarchical locality management***
4. ***Advanced Management Operations at the Edge***

But also:

- Data aggregation
- Control triggering and operations
- Mgmt policies and their enforcem
- …

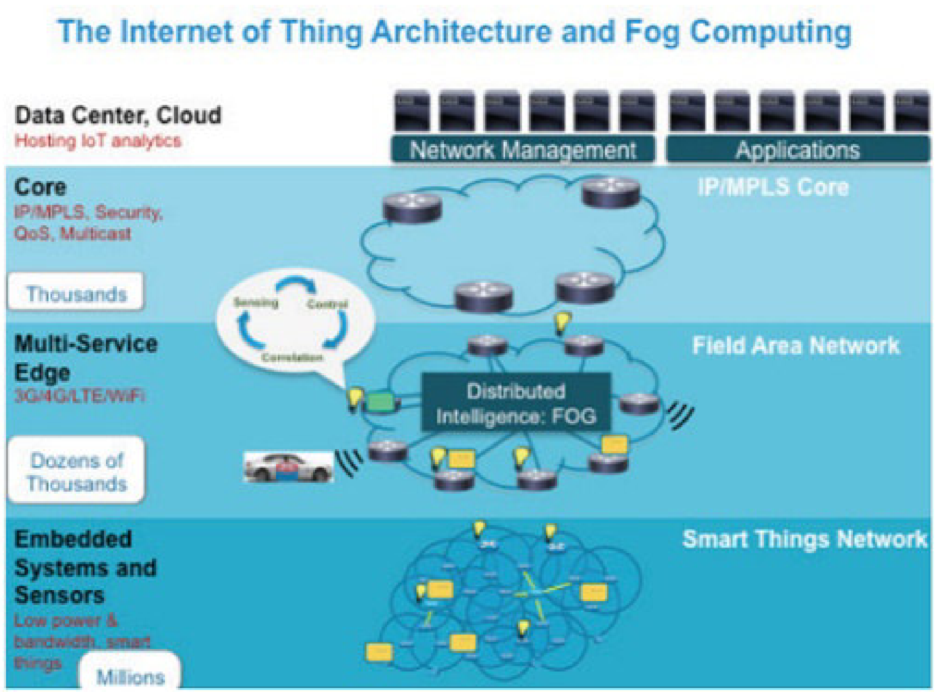


1) Architecture Modeling

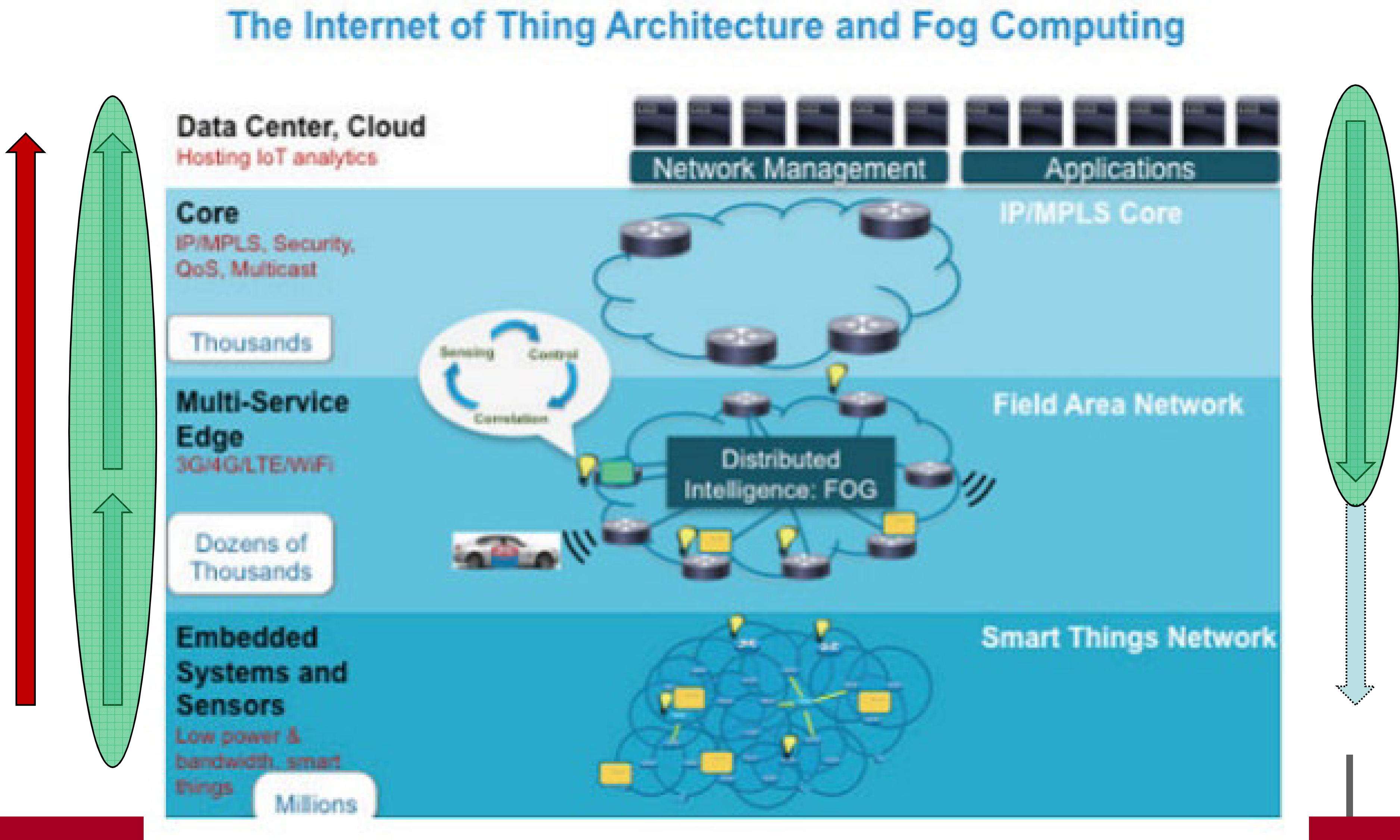
Dynamic distribution of storage/processing (network resource allocation?) functions in all the three layers of a node-edge-cloud IoT deployment environment

Different and richer concept of ***mobile offloading***

- mobile app avatars/clones in living in edge/core cloud
- not only offloading…



1) Architecture Modeling
Need for new models
Offloading and Onloading



1) Architecture Modeling
Need for new models

Need for new models for richer mobile offloading:

- From sensors/actuators to the cloud (traditional)
- **From sensors/actuators to the edge**
- **From the edge to the cloud**

But also:

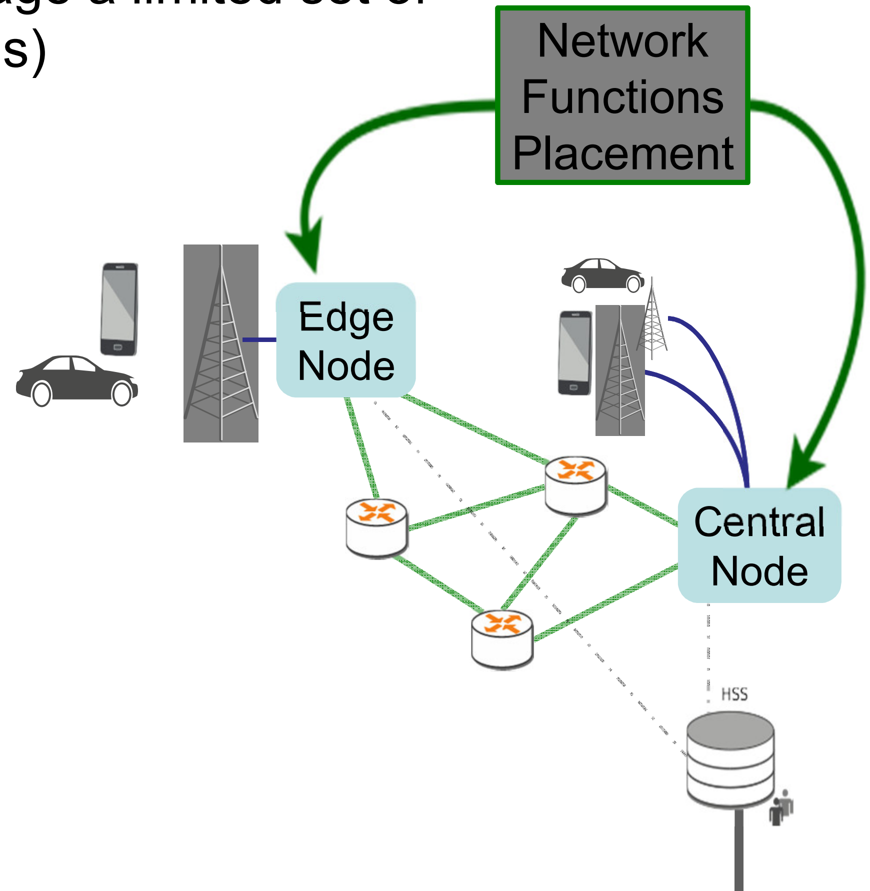
- **From the cloud to the edge**
- From the edge to sensors/actuators

Growing overall status visibility vs.
growing decentralization and autonomy

For example, Network Function Placement

Through ***edge cloud computing***:

- Network functions can be deployed in both ***edge nodes and central node***
- Edge controller has to be very simple to manage a limited set of devices (energy efficiency, compute limitations)

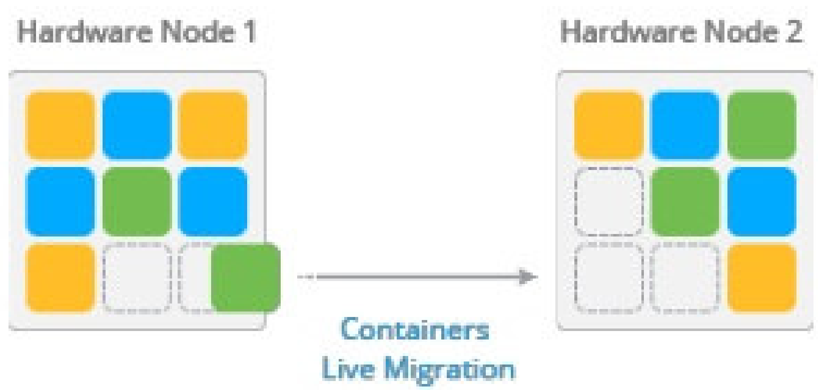


- ***Dynamic decisions*** about where to execute functionalities, depending on
  - ❑ state of subscribers
  - ❑ network congestion
  - ❑ single device/group) mobility pattern
- ***Autonomic functioning of edge nodes*** when no backhaul is available / backhaul communication is interrupted
- Policy-based functioning of edge networking for making decisions when edge routing is used

Edge computing empowered by ***containerization***

Container live migration and state maintenance:
which tradeoff between state consistency and overhead?

Live Migration for Containers

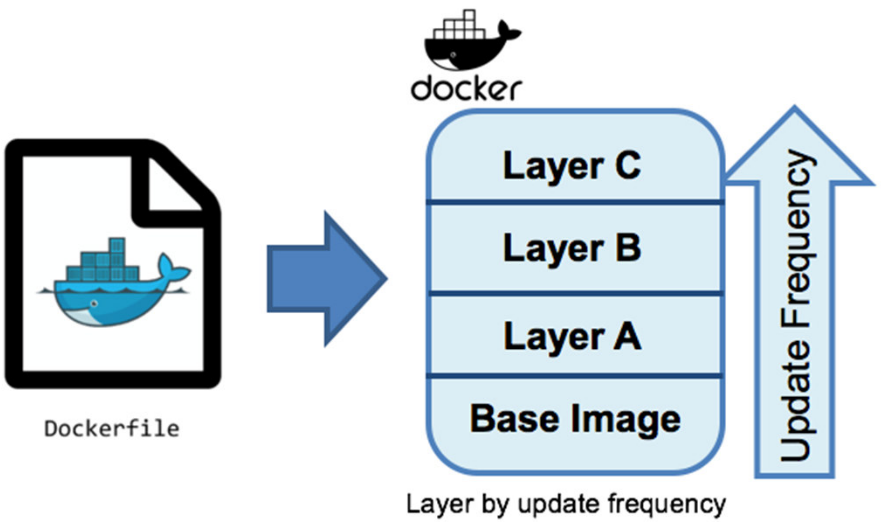


CRIU – Checkpoint/Restore In Userspace

OpenVZ
Virtuozzo Containers

Edge computing empowered by containerization

- ***Layering of session/application state***
- Big data analytics on ***probability of state modification*** in the different layers
- Dynamic tradeoff selected for each state layer separately
  - Migration, local/distributed checkpointing



- Service components?
- Data/state?

Plus ever-increasing frequencies in CI/CD DevOps processes…

I'll go back to this… and for additional details, please see our papers (refs section)

2) Quality Support even in Virtualized Envs

But definitely, here we are not starting from scratch…

Notable experience of mobile cloud networking for telco services with quality requirements

- ***Carrier-grade industrial usage of elastic*** distributed cloud resources for telco support infrastructures
- ***Quality constraints of typical telco providers***
  - ***Latency***
  - ***Scalability***
  - ***Reliability***

First lesson learnt: sufficient quality levels?

In the last years, growing industrial interest in Mobile Cloud Networking (MCN) as the opportunity to exploit the ***cloud computing paradigm through Network Function Virtualization (NFV)***

- primarily with the goal to reduce CAPEX/OPEX for future mobile networks deployment and operation

Risk/skepticism:

a virtualized infrastructure could not reach ***the levels of service reliability, availability, and quality usual for mobile telcos***

EU MCN project – http://www.mobile-cloud-networking.eu

First lesson learnt: sufficient quality levels?

EU MCN project – http://www.mobile-cloud-networking.eu

Large experimental campaigns and results from ***wide-scale industrial testbeds*** have demonstrated that it is possible via the adoption of advanced techniques for:

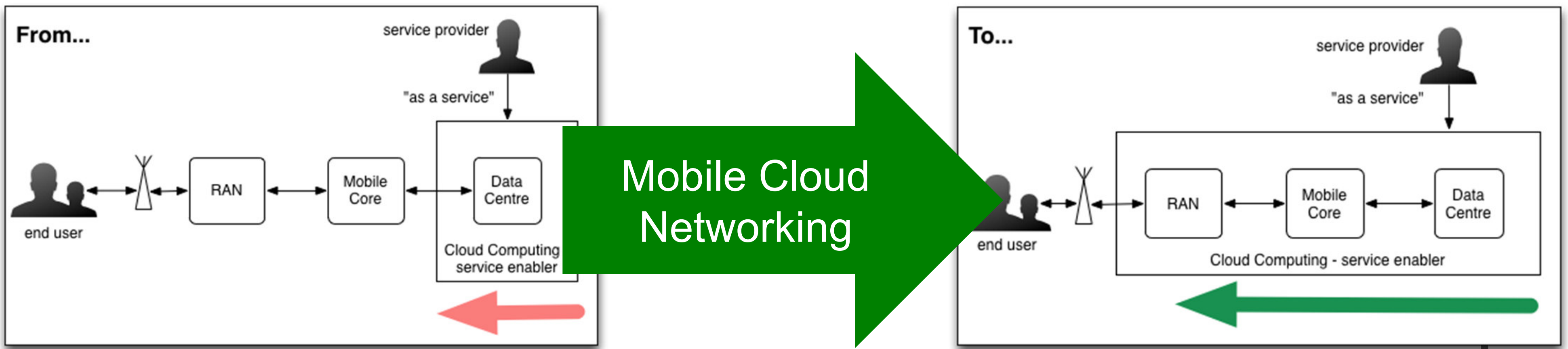
- ***lazy coordination*** of distributed cloud resources
- ***standardized*** virtualization of network functions
- ***proactive mobility-aware resource management***, including load balancing, handovers, …
- ***interoperable orchestration*** of ***infrastructure+service*** components

EU Mobile Cloud Networking Project: Network Functions as a Service

FP7 Integrated Project (2013-2016) targeted to bringing cloud computing features to mobile operator core networks (e.g., EPCaaS):

- Virtualization of components
- Software defined networking
- Elasticity
- Infrastructure sharing
- Redefining roaming

SAP inov CloudSigma intel soft telecom BT Fraunhofer FOKUS ONESOURCE NEXTWORKS UNIVERSITÄT BERN orange TELECOM ITALIA zhaw ITALTEL PT INOVAÇÃO NEC Technische Universität Berlin UNIVERSITY OF TWENTE.



Motivations: Why NFV is needed?

Source: www.cse.wustl.edu

① **Virtualization**: use network resource without worrying about where it is physically located, how much it is, how it is organized, etc

② **Orchestration & Automation**: configuration through complied global policies versus the current manual translation and per device download

③ **Programmability** & **Openness**: modular design allows evolvability and customization to own choices

④ **Dynamic Scaling**

⑤ **Visibility**: Monitor resources, connectivity

⑥ **Performance**: Optimize network device utilization

⑦ **Multi-tenancy**: Should be able to serve new business models

⑧ **Service Integration**: seamlessly integrating interdependent services

ETSI Network Functions Virtualization (NFV)

The objective of NFV is to translate the classic network appliances to software modules

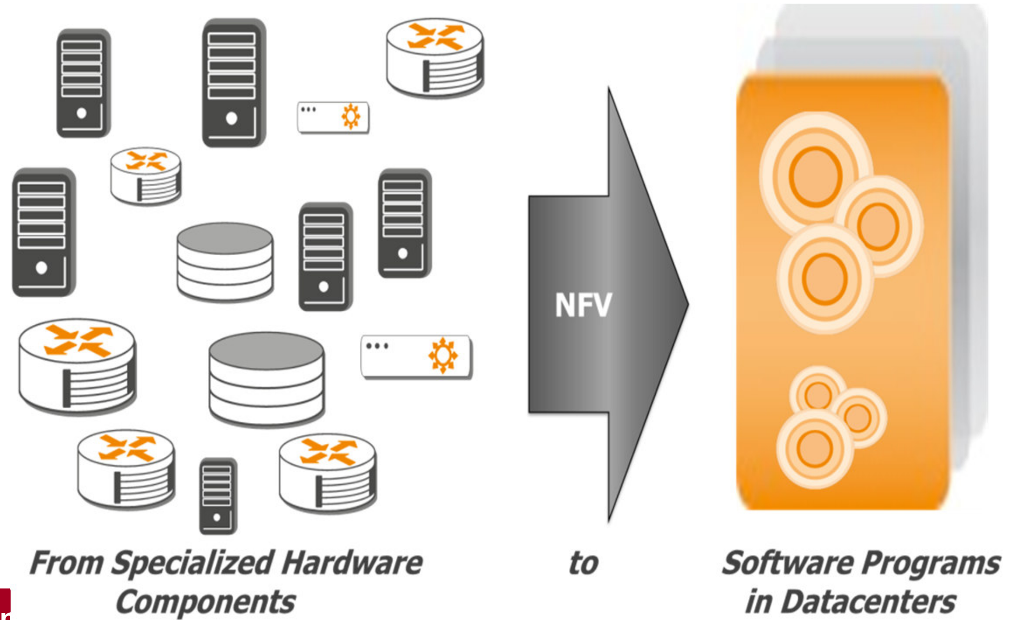
- Running on high volume servers with high volume storage
- Interconnected by generic high volume switches
- Automatically orchestrated and remotely installed

NFV is a novel paradigm that presumes that the network functions

- Are implemented only as software (programs)
- Can run on top of common servers

NFV has to fix the following main issues:

- ***Performance***
- ***Co-existence, portability, and interoperability***
- ***Automation***
- ***Scalability***



NFV and SDN as the support technologies for 5G

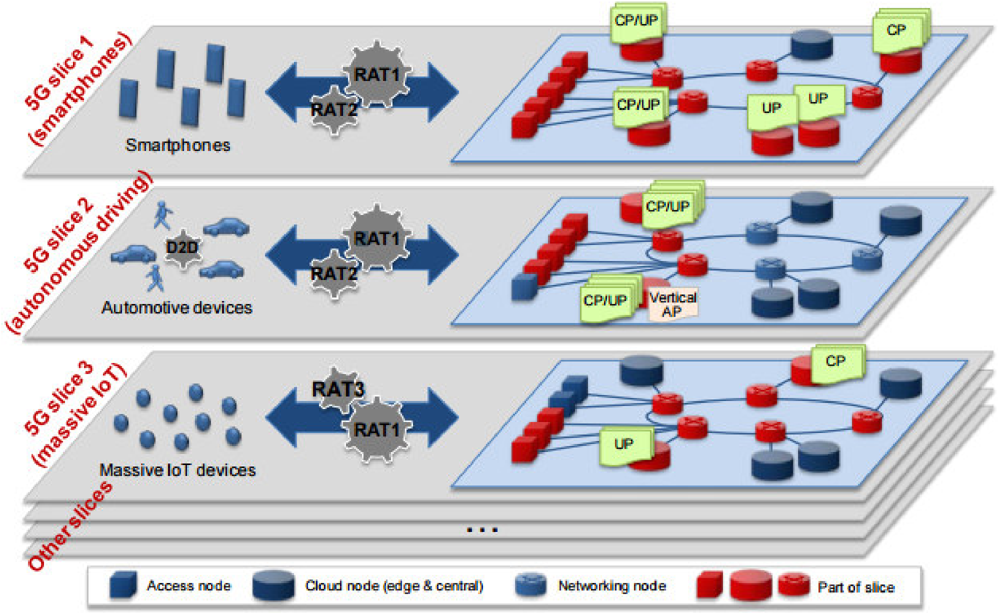
5G will be based on slices on top of same infrastructure

NFV and SDN as the main enablers for:

- ***business agility*** – with its capabilities for on-demand, fast deployments
- ***network adaptability and flexibility*** – requires redesign of network functions (to cloud native), support for functions variance, flexible function allocation, etc.
- ***composition*** – putting multiple services together in a slice – end-to-end management
- ***slicing*** – separation at network level
- ***programmability*** – software-only network functions and their interaction with physical systems

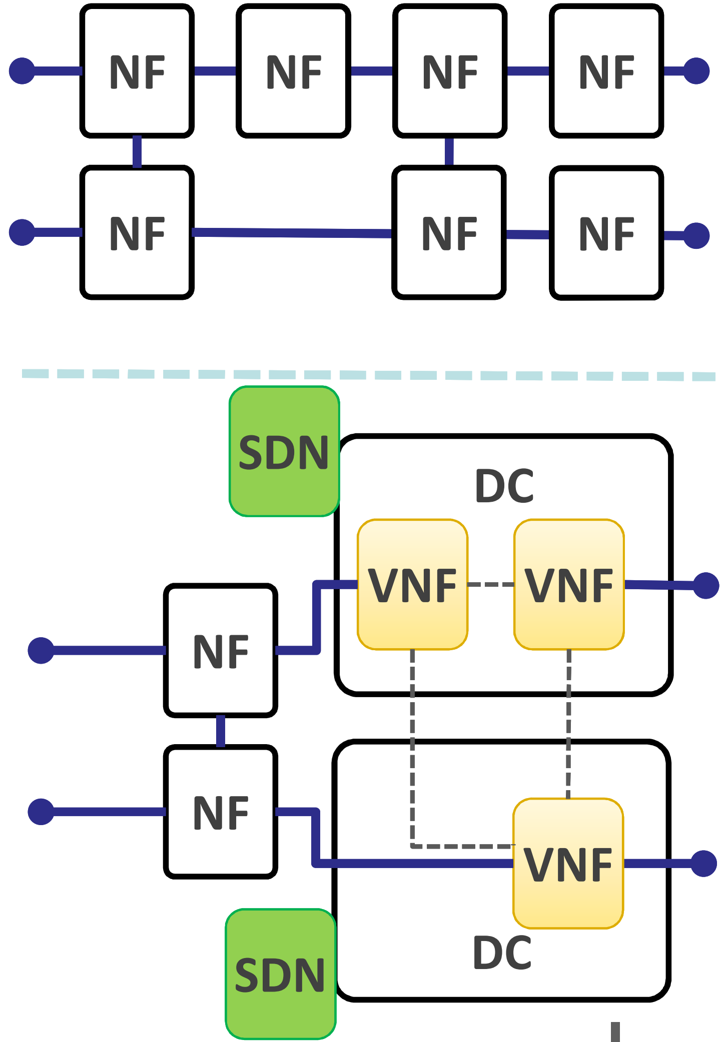
➔ ***Orchestration*** is the cornerstone for all of these features

Source: NGMN Alliance - 5G whitepaper



NFV and SDN

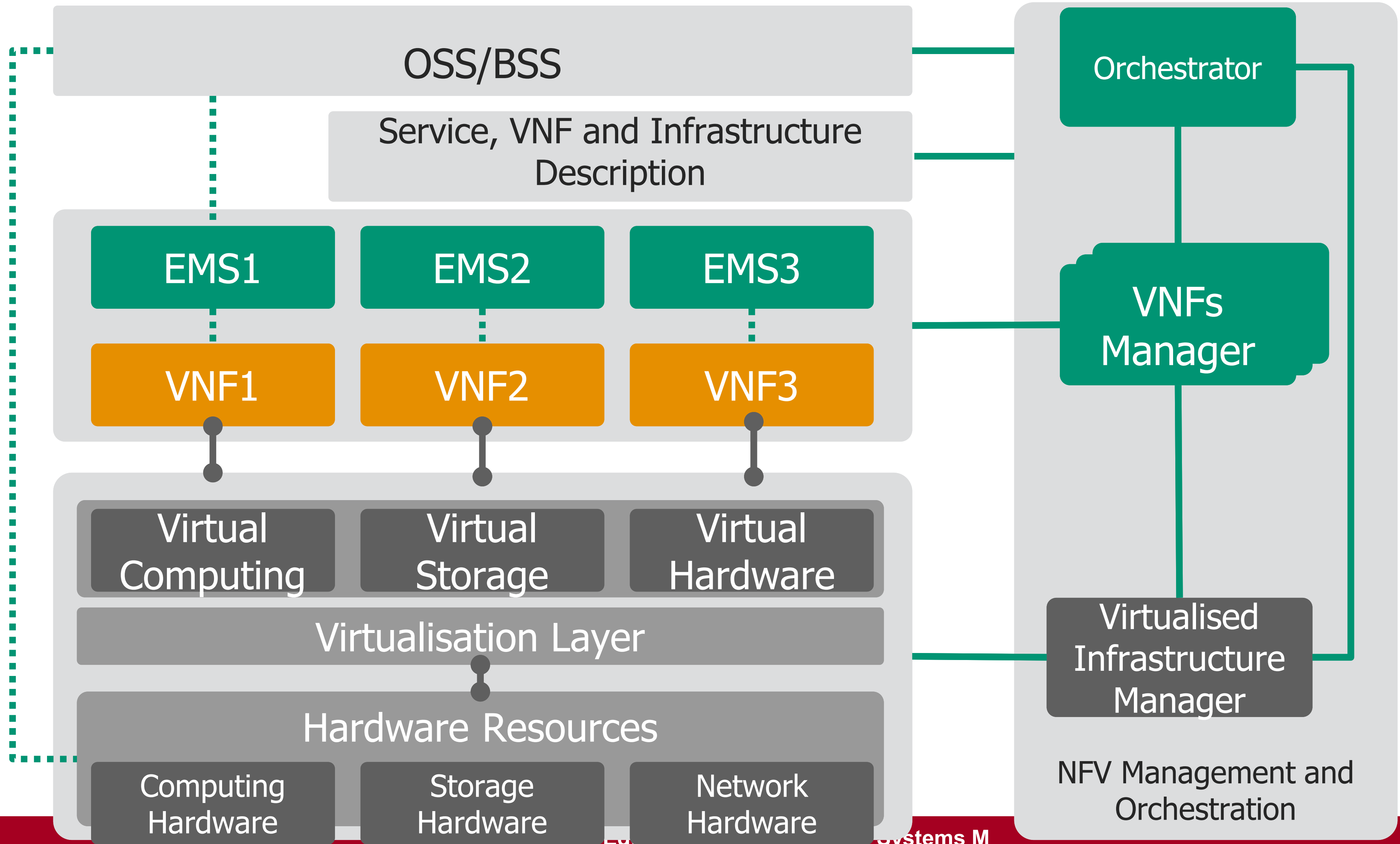
- NFV requires network functions to be implemented *as* ***software on top of common hardware***
- SDN brings ***remote programmability*** of the network
- NFV/SDN platform acts as an end-to-end middleware between:
  - ❑ A distributed heterogeneous infrastructure for compute and storage
  - ❑ Interconnected through a controlled network
  - ❑ Generic network functions implemented in software running in isolated containers/virtual machines
    - VPNs, NATs, DNSs, IMSs, EPCs, Application Servers, etc.



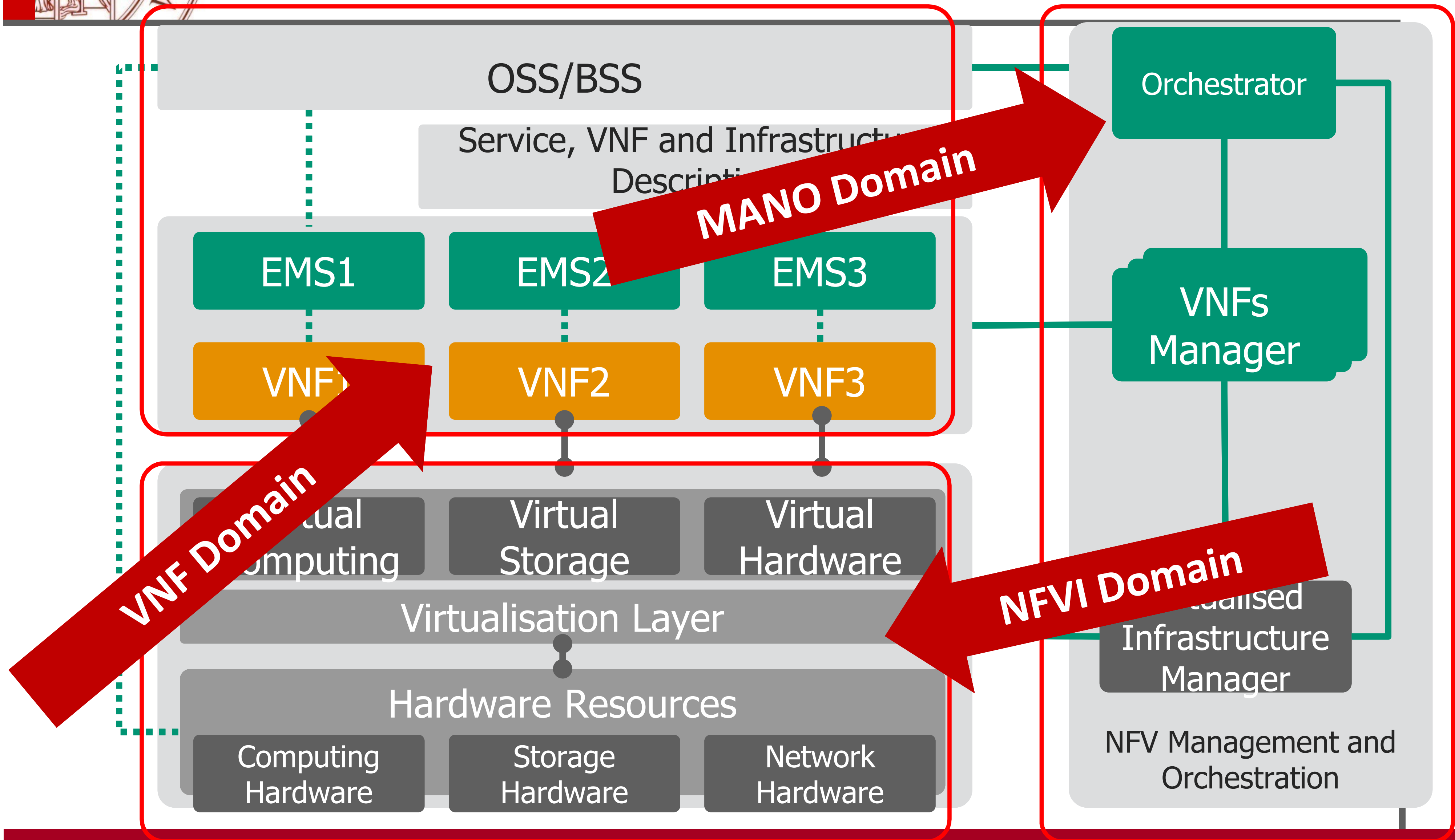
The main value added differentiator between different solutions is the *quality of the software*

- how well it can solve the specific service needs

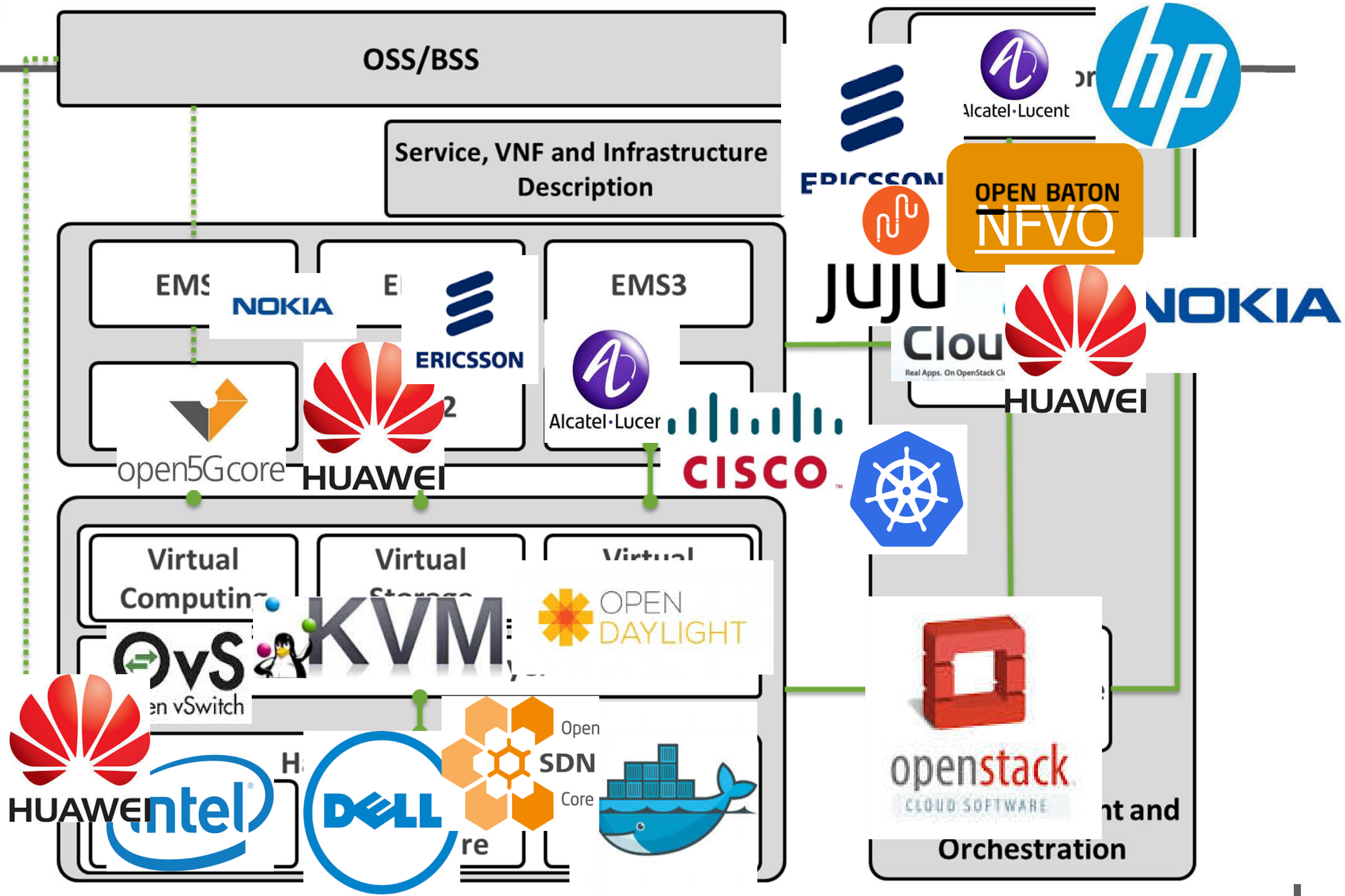
NFV Architecture Blue print is ready since Nov. 2012…



NFV Architecture Blue print is ready since Nov. 2012…

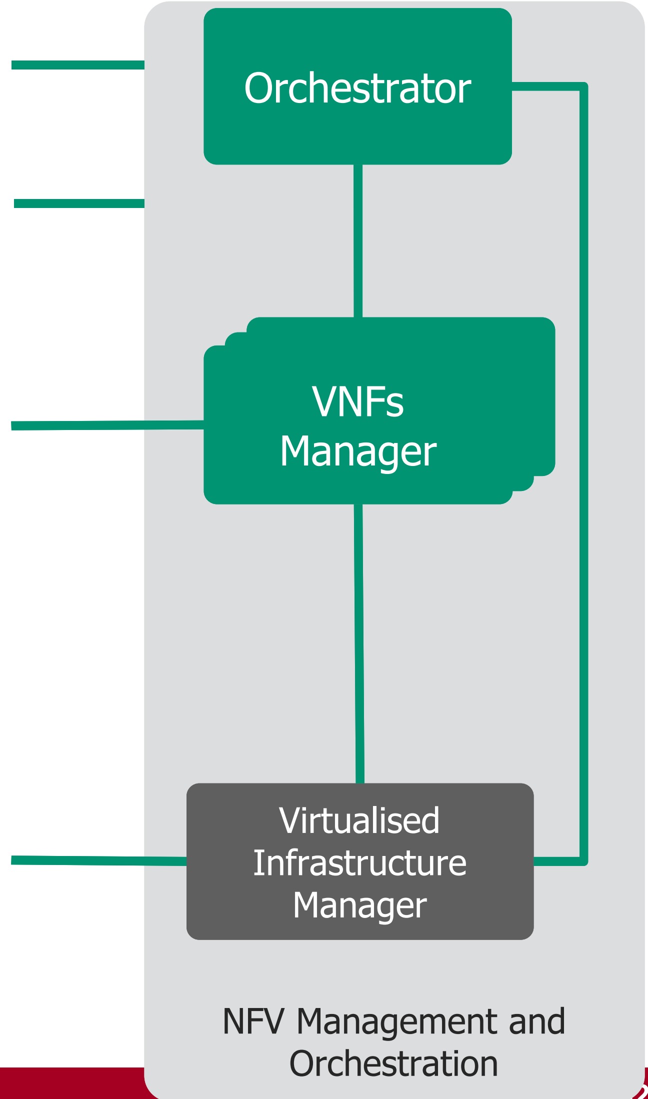


The NFV Ecosystem



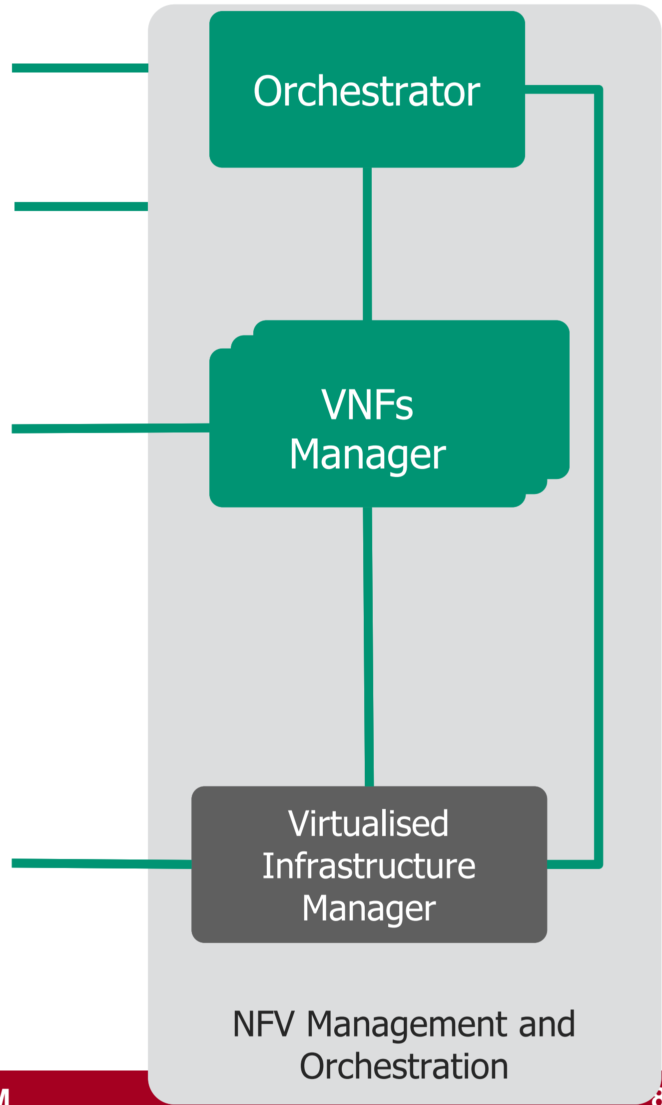
Virtualized Infrastructure Manager (VIM)

- Responsible for the ***lifecycle management*** of compute, storage and network resources provided by the NFVI
- It is basically a ***Cloud Management System*** which exposes an API for standard CRUD operations on those resources
- ***OpenStack*** is the ***de facto standard implementation*** of this functional block



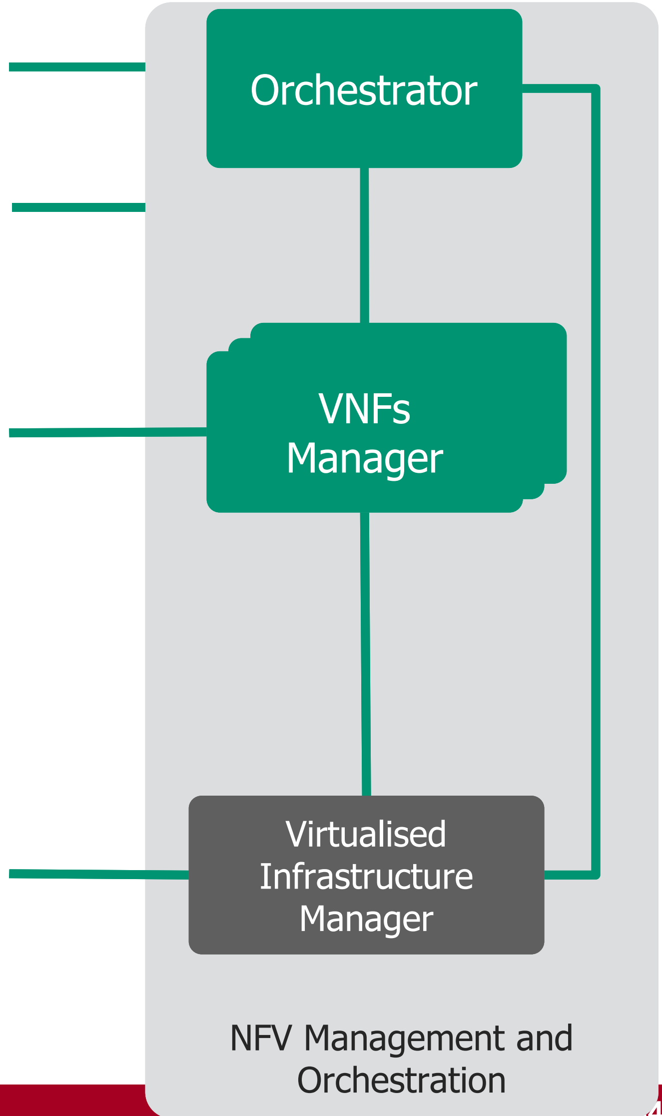
VNF Manager (VNFM)

- Responsible for the lifecycle management of Virtual Network Function instances
  - ❑One per NF
  - ❑One per multiple VNF instances even of different type
- It has to support the:
  - ❑VNF instantiation
  - ❑VNF configuration
  - ❑VNF update
  - ❑VNF scaling in / out
  - ❑VNF instance termination



Network Function Virtualization Orchestration (NFVO)

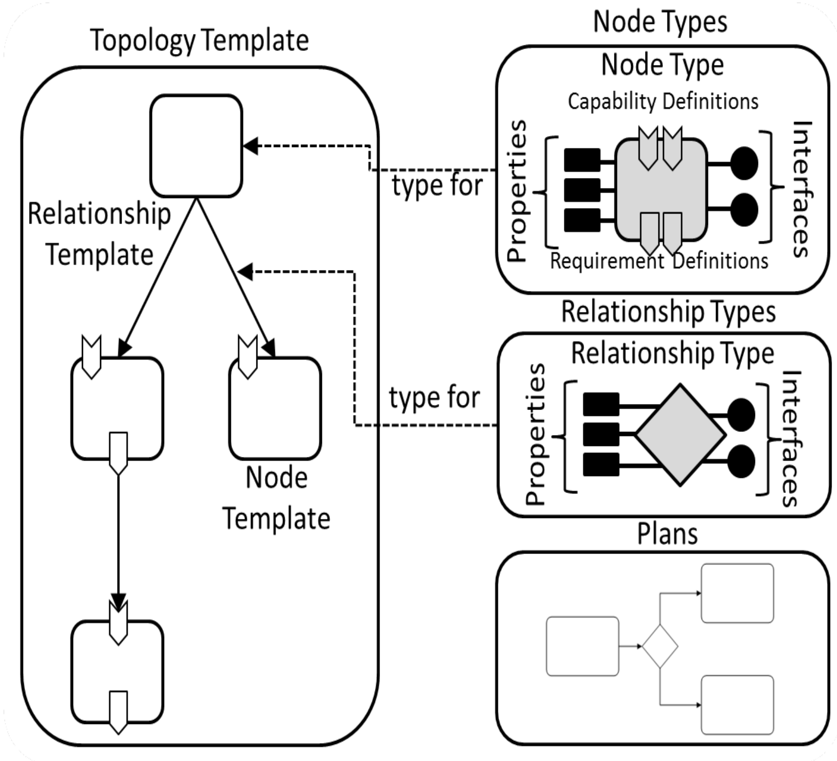
- Responsible for the ***lifecycle management of Network Services***:
  - ❑In a single domain
  - ❑Over multiple datacenters
- Applies policies for resource utilization
- Requests the instantiation of VNFs via the VNF Managers



OASIS TOSCA

Topology and Orchestration Specification for Cloud Applications (TOSCA)

- The ***OASIS TOSCA Technical Committee*** works to enhance the portability of cloud applications and services
- TOSCA will enable the ***interoperable description of application and infrastructure cloud services***, the relationships between parts of the service, and the operational behavior of these services (e.g., deploy, patch, shutdown) - independent of the supplier creating the service, and any particular cloud provider or hosting technology
- TOSCA will also make it possible for higher-level operational behavior to be associated with cloud infrastructure management



A comprehensive MANO orchestrator was (still) missing…

Two approaches in regard to orchestration were taken:

1) Orchestrating from the infrastructure perspective

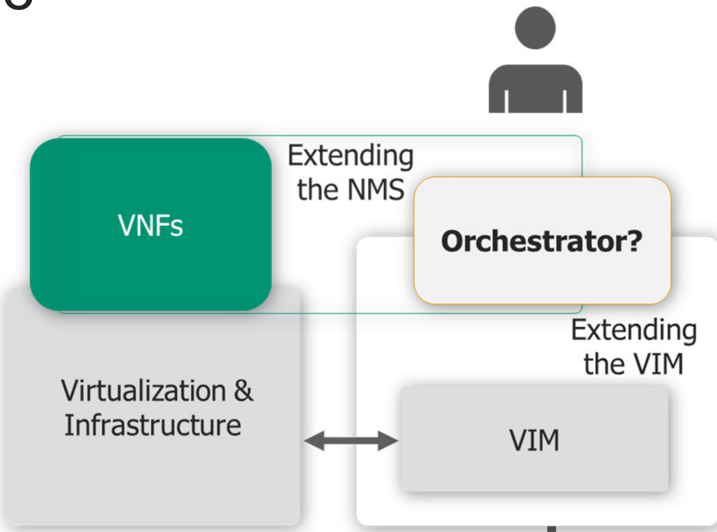
Extending VIM towards service orchestration. Missing:

- Adaptation to complex network services requirements, e.g. fault management, scaling, network function placement, virtual network configuration, information flow paths, security, reliability

2) Orchestrating from the network service perspective

Extending the Network Management System to handle orchestration. Missing:

- Capitalize through native components on cloud opportunities: scaling, dynamic resource allocation
- Define the appropriate network service KPIs, end-to-end fault management, end-to-end reliability insurance, etc.



What is OpenBaton?

OpenBaton is Open Source implementation of the ETSI MANO specification

OpenBaton aims to foster, within the NFV framework, the integration between:

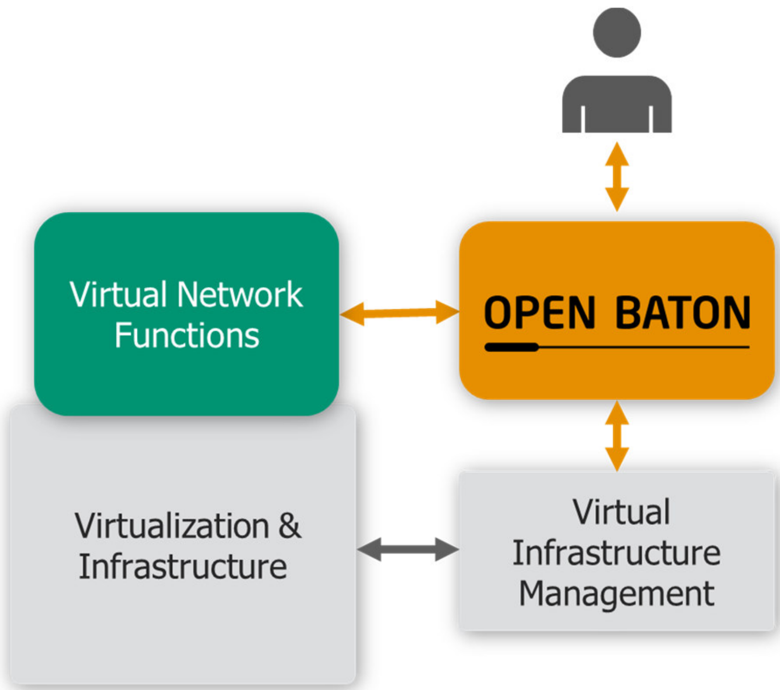
- ***Virtual Network Function providers***
- ***Cloud Infrastructure providers***

Functionality:

- Installation, deployment, and config. network services
- Runs on top of multi-site OpenStack
- Provides independent infrastructure slices
- Support for generic or specific VNF management

Designed for answering R&D requirements

- Easy to configure and to deploy
- Providing a centralized view of the testbed



github: https://github.com/openbaton

What OpenBaton stands for

- ***No vendor lock-in***: OpenBaton does not contain any vendor specific features. It follows open specifications and it is open to the community

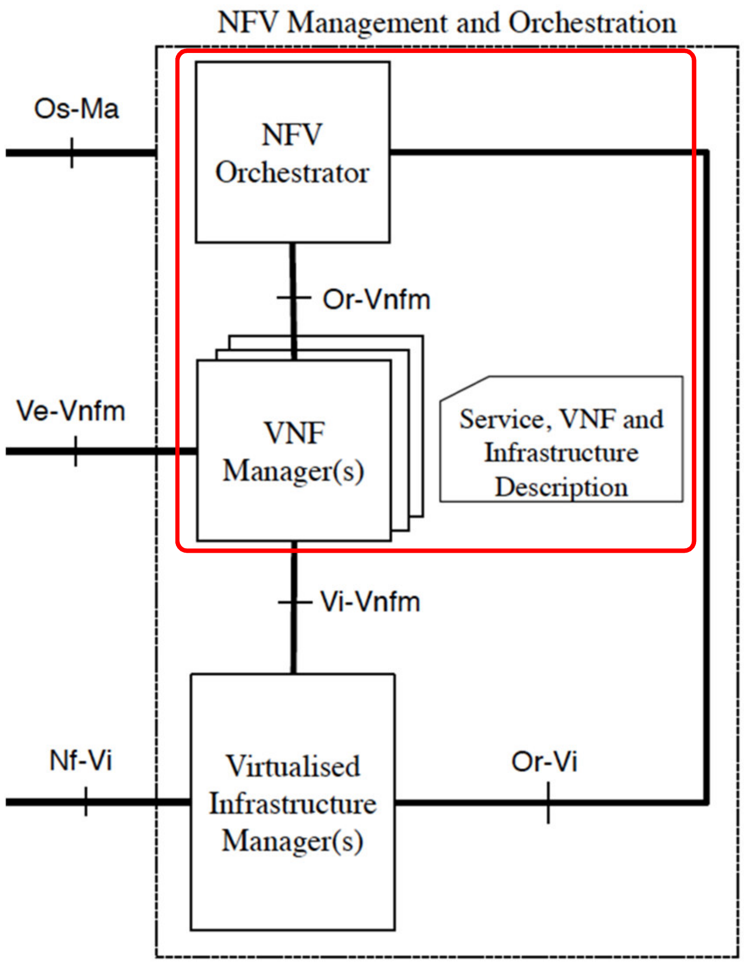
- Built from scratch following the ***ETSI MANO specification***
  - ❑The NFVO uses the ETSI NFV data model internally for the definition of the Network Service and Virtual Network Descriptors

- ***Allows interoperability***
  - ❑Being interoperable is one of the challenges brought by the fragmented ecosystem in the management and orchestration area. It requires a lot of work to make two different vendors solution working together → need of a single vendor-independent platform

OpenBaton

OpenBaton is based on the ETSI NFV MANO v1.1.1 (2014-12) specification. It provides:

- A ***NFV Orchestrator*** managing the lifecycle of Network Service Descriptors (NSD) and interfacing with one or more VNF Manager(s) (VNFM)
- A ***generic VNF Manager***, which can be easily extended for supporting different type of VNFs
- A ***set of libraries*** which could be used for building your own VNFMs (vnfm-sdk)
- A ***dashboard*** for easily managing all the VNFs

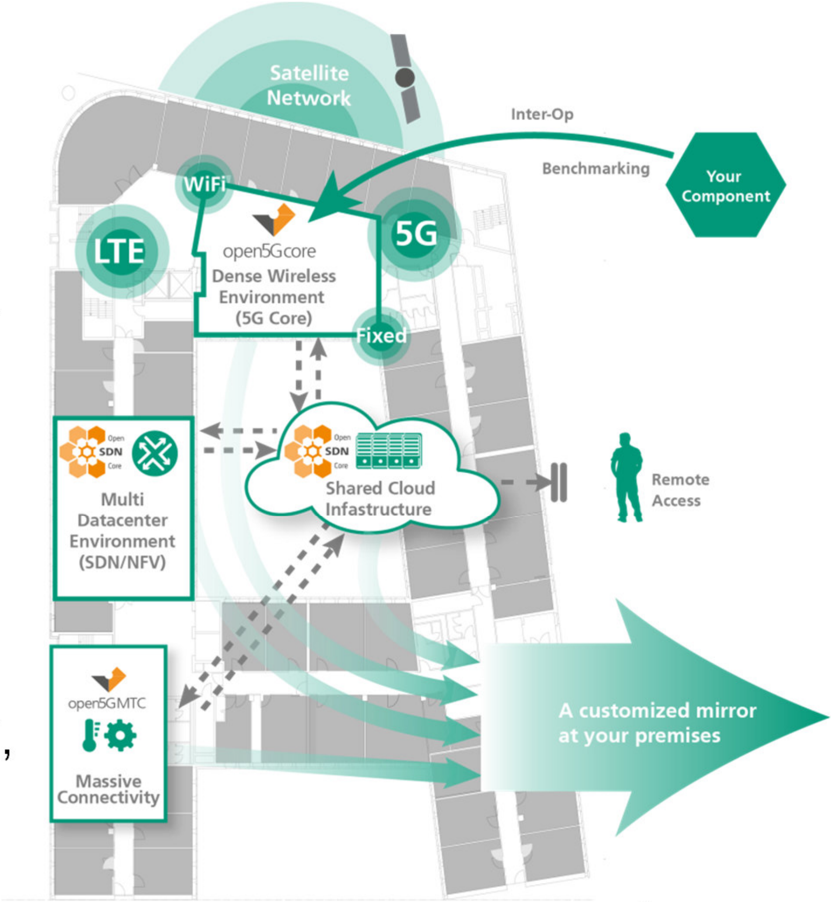


It currently integrates with OpenStack as main VIM implementation

The Fraunhofer FOKUS 5G Playground

5G Playground: A comprehensive testbed environment for prototyping 5G-ready VNFs using OpenBaton orchestration

- Open5GCore providing the next wireless system beyond LTE/EPC with more efficient communication for the subscribers and improved automation/reliability (applying SDN and NFV principles)
- Open5GMTC enabling connectivity management and end-to-end service establishment for a huge number of connected devices
- OpenSDNCore enabling SDN experimentation for data path, backhaul networks or customized network environments
- All those are software components and can be customized, deployed and configured on demand via OpenBaton enabling automatic just-in-time test environment creation, experimentation and demonstration



3) Scalability via Hierarchical Locality Management

For industrial IoT applications in particular, to achieve scalability but not only (smart city deployments, …)

Need for additional scalability based on:

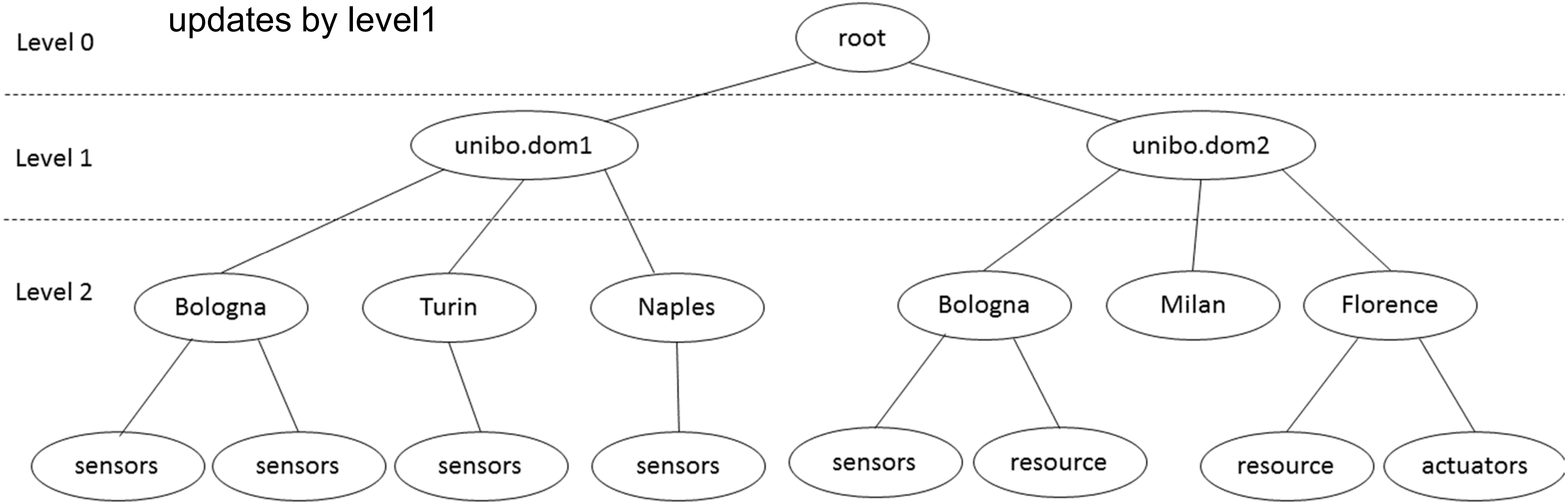
- ***Locality identification***
- ***Locality autonomy*** (partial)
- ***Locality coordination***
  - ***Hierarchical organization as simple tradeoff of practical usage***

Still quite uncovered research area, in particular with no industry-grade implementations, also in "more traditional" IoT gateways

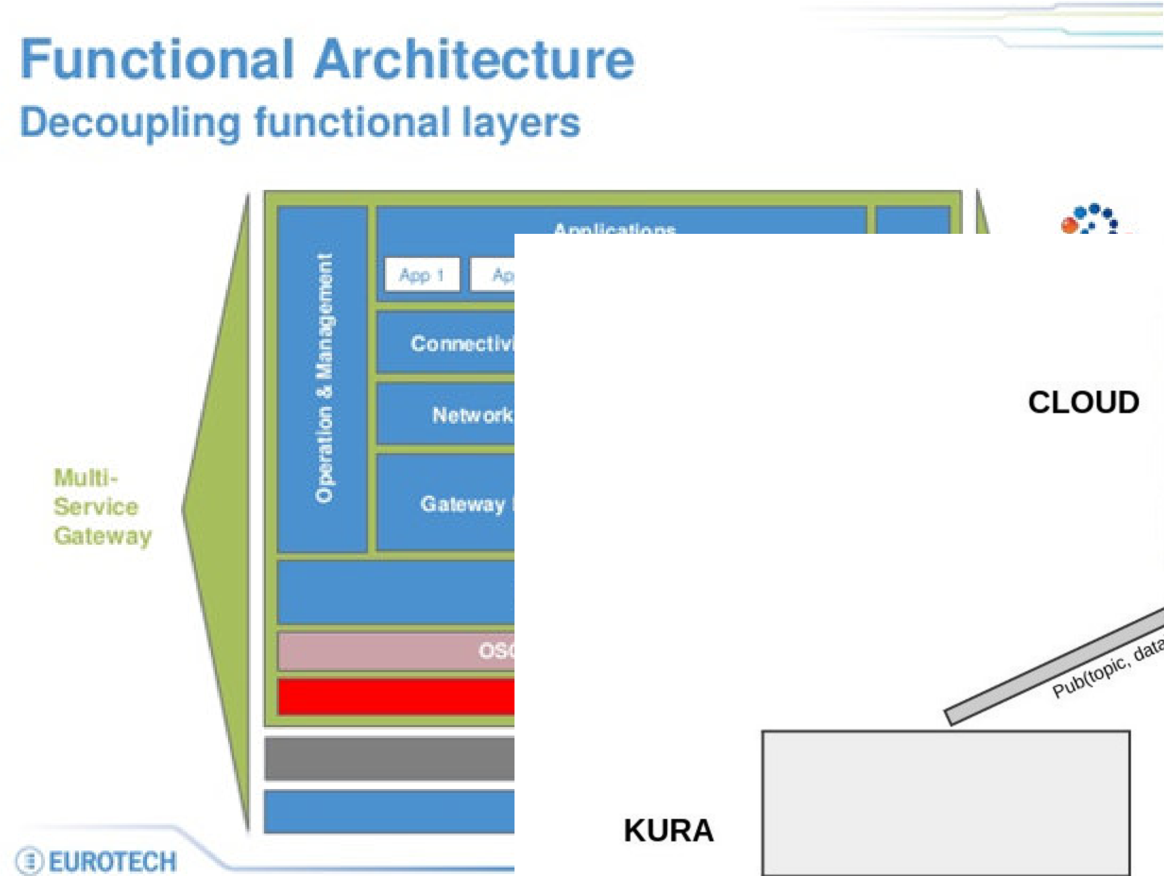
3) Scalability via Hierarchical Locality Management

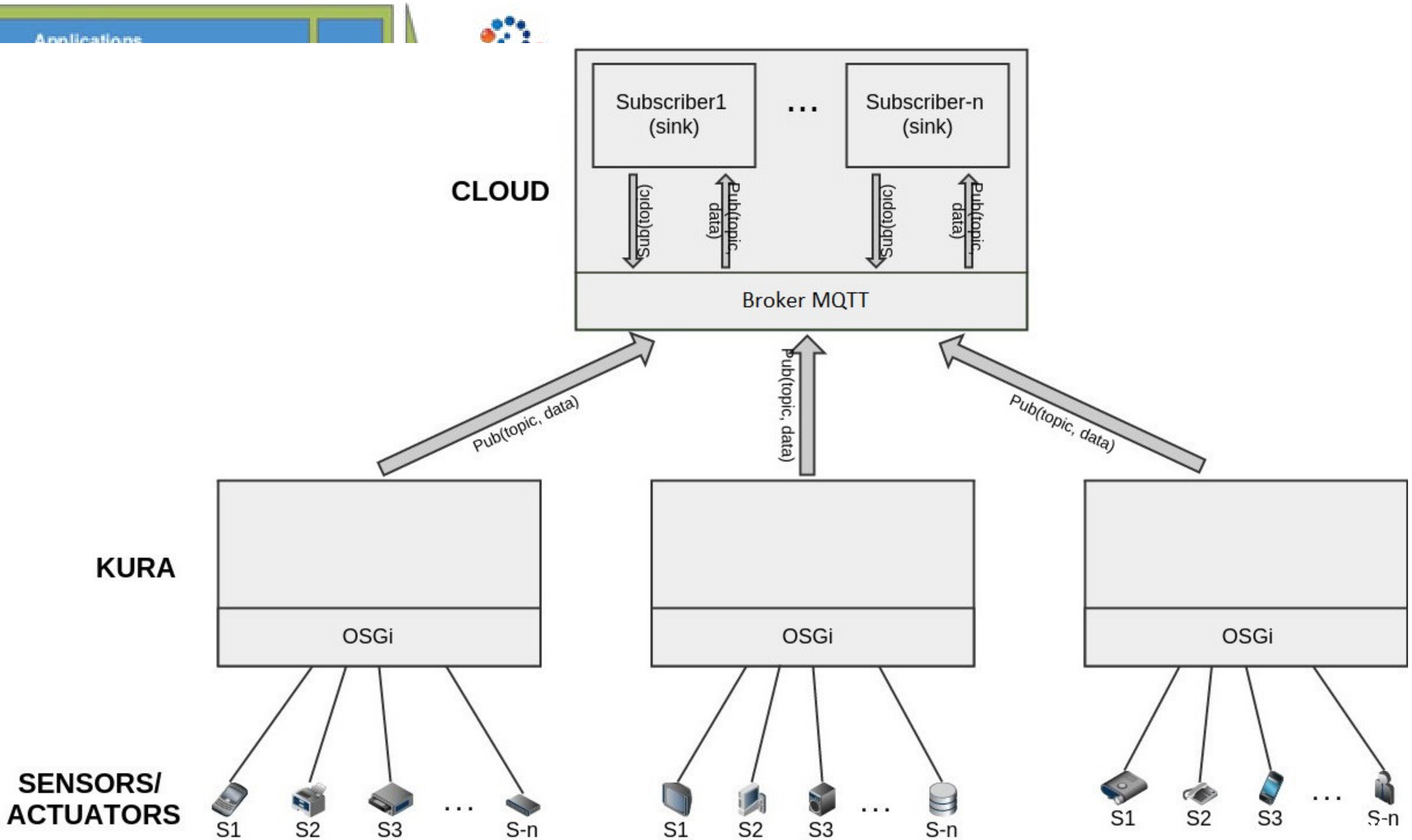
Multi-layers hierarchy (each node specifies domain/group to limit the interest towards external resources):

- **Level0** includes the root node, enables inter-localities communications
- **Level1** includes all the nodes belonging to a specific domain, updates level2 about hierarchy modification (quicker update)
- **Level2** includes all the nodes of a given domain and (sub)group, receives periodically updates by level1



Industry-grade Integration with IoT Gateways: Eurotech Kura





MQTT-CoAP Interworking in our Extended Kura Gateway

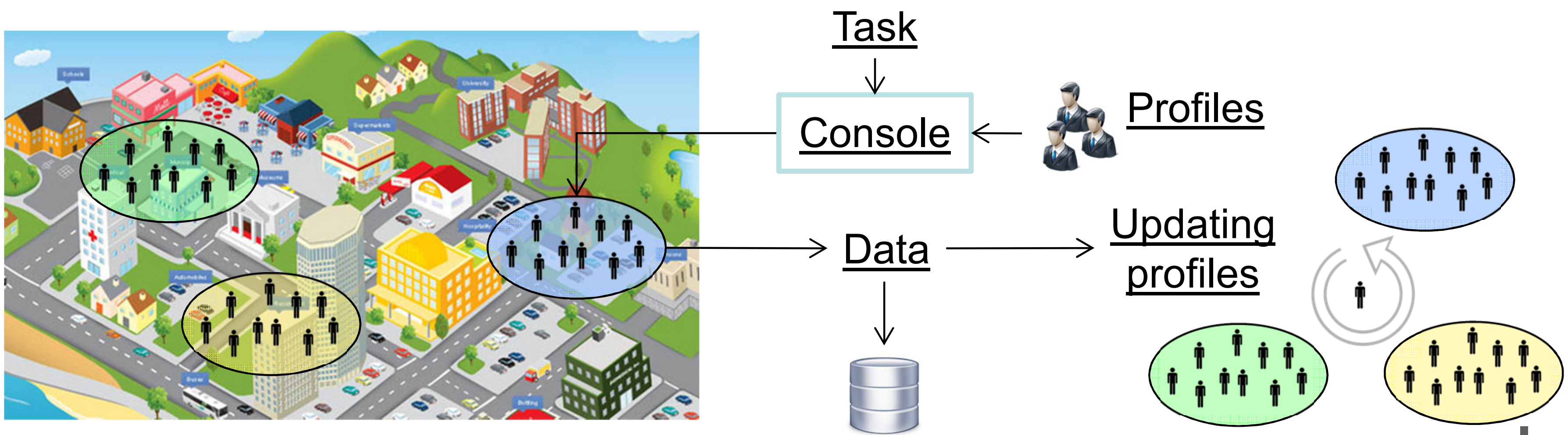
- Design and implementation of a **scalable distributed architecture** for the dynamic management of IoT resources **via hierarchical localities**
- Gateway coordination via integration of emerging standard protocols, i.e., **MQTT** and **CoAP**:
  - MQTT natively integrated into Kura
  - MQTT non-negligible limitations in terms of scalability
  - Introduction of more lightweight CoAP-based functionality, thus achieving scalable interactions
  - Improvement for system dynamic management (e.g., resource/device discoverability, resilience to disconnections, dynamic reconfiguration)

- ***What about virtualization support in Eurotech Kura/Kapua?***

Scalability and Adaptive MEC through Mobile Crowd Sensing

- **Citizens** are **active (participactive) actors** contributing to the collection of data along their usual routes/habits
- **Smartphones** as **sensors** used to opportunistically monitor phenomena in the Smart City

Mobile Crowd Sensing (MCS): find a **specific group of citizens** and send requests (tasks) for data collection



Smart City Crowdsensing:

the Bologna use case

ParticipAct – http://participact.unibo.it

Bologna heat-map:

- Eng School
- Via Zamboni
- Unibo colleges

Student movements interpolating points to save battery energy

Human-driven Edge Computing (HEC)

- HEC as a new model to ease the provisioning and to extend the coverage of more traditional MEC solutions
- How to exploit MCS
  - to support ***effective deployment of Fixed MEC*** (FMEC) nodes
  - to further extend their coverage through dynamic introduction of ***impromptu and human-enabled Mobile MEC (M^2EC) nodes*** for serving local MCS computing/storage needs

- Ongoing implementation in the ***MCS ParticipAct*** framework through the integration of the ***MEC Elijah (OpenStack++)*** platform

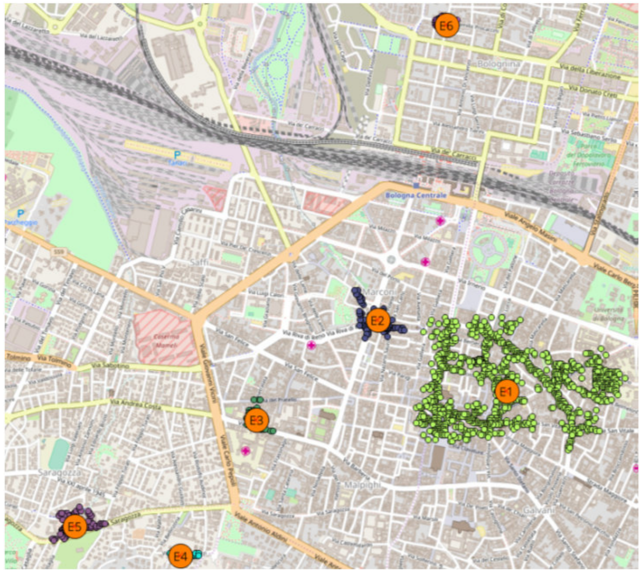
Human-driven Edge Computing (HEC)

- HEC potentially mitigates weaknesses of having only Fixed MEC entities (FMEC) by exploiting MCS
  - to continuously monitor humans and their mobility patterns
  - to ***dynamically re-identify hot locations*** of potential interest for the deployment of ***new edges***

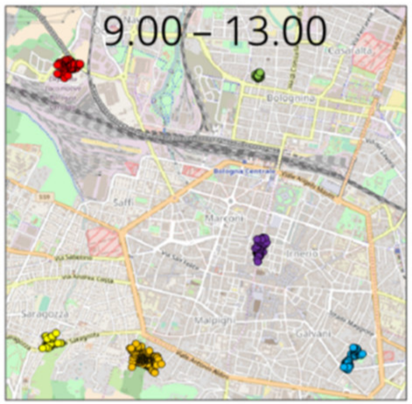
- Implementation and dynamic activation of ***impromptu and temporary Mobile MEC*** entities (M^2EC)
  - Leveraging resources of ***locally available mobile devices*** (in a logical bounded location where people tend to stay for a while in a repetitive and predictable way) -> ***participatory edge node***

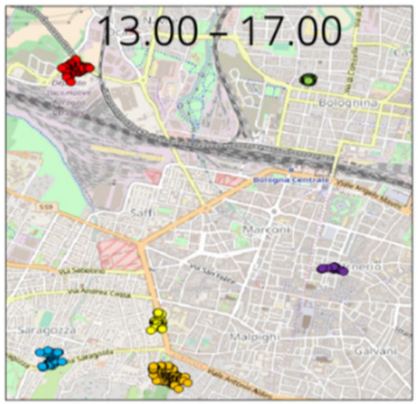
- HEC exploits ***local one-hop communications and the store-and-forward*** principle
  - by using ***humans as VM/container couriers*** to enable ***migrations*** between well-connected FMEC and local M^2EC

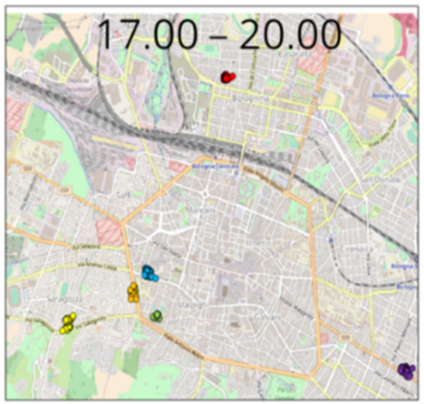
Human-driven Edge Computing (HEC)



FMEC nodes identified as DBSCAN clusters

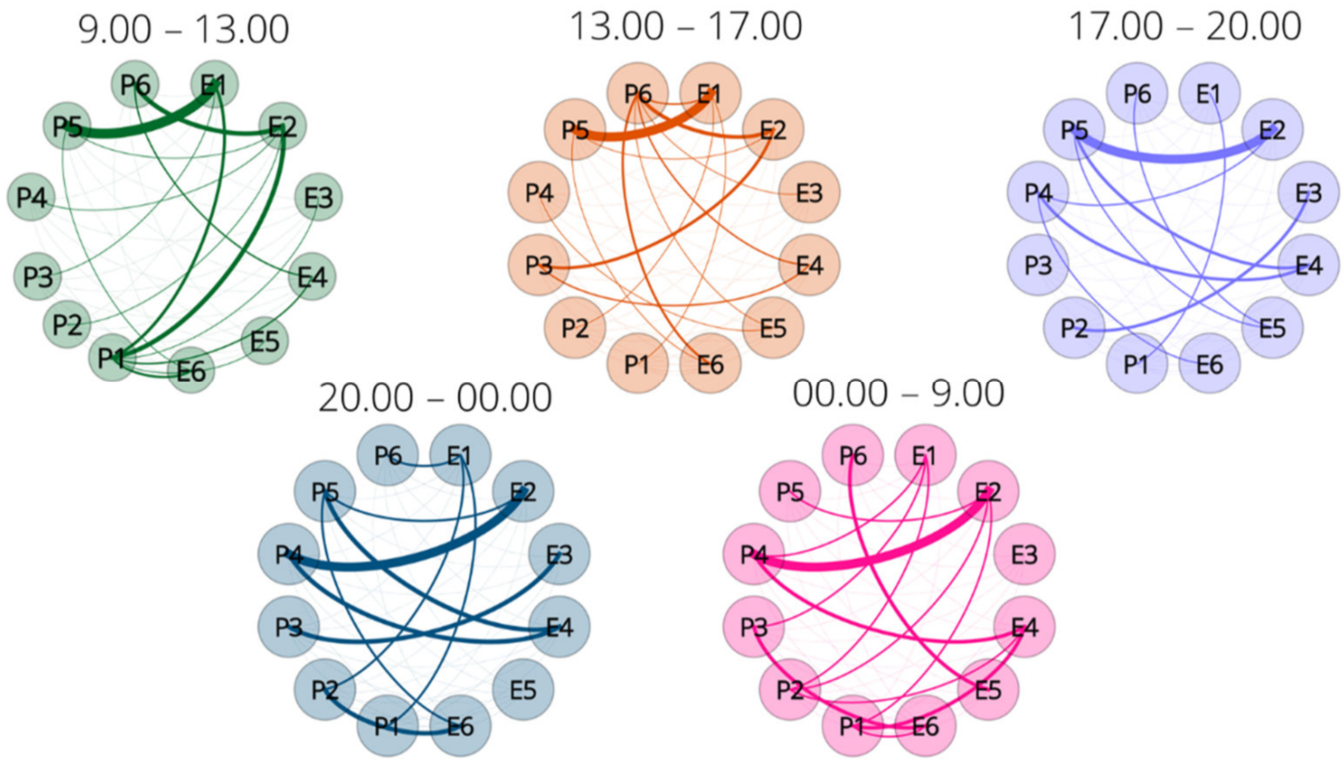






M^{2}EC nodes identified as DBSCAN clusters

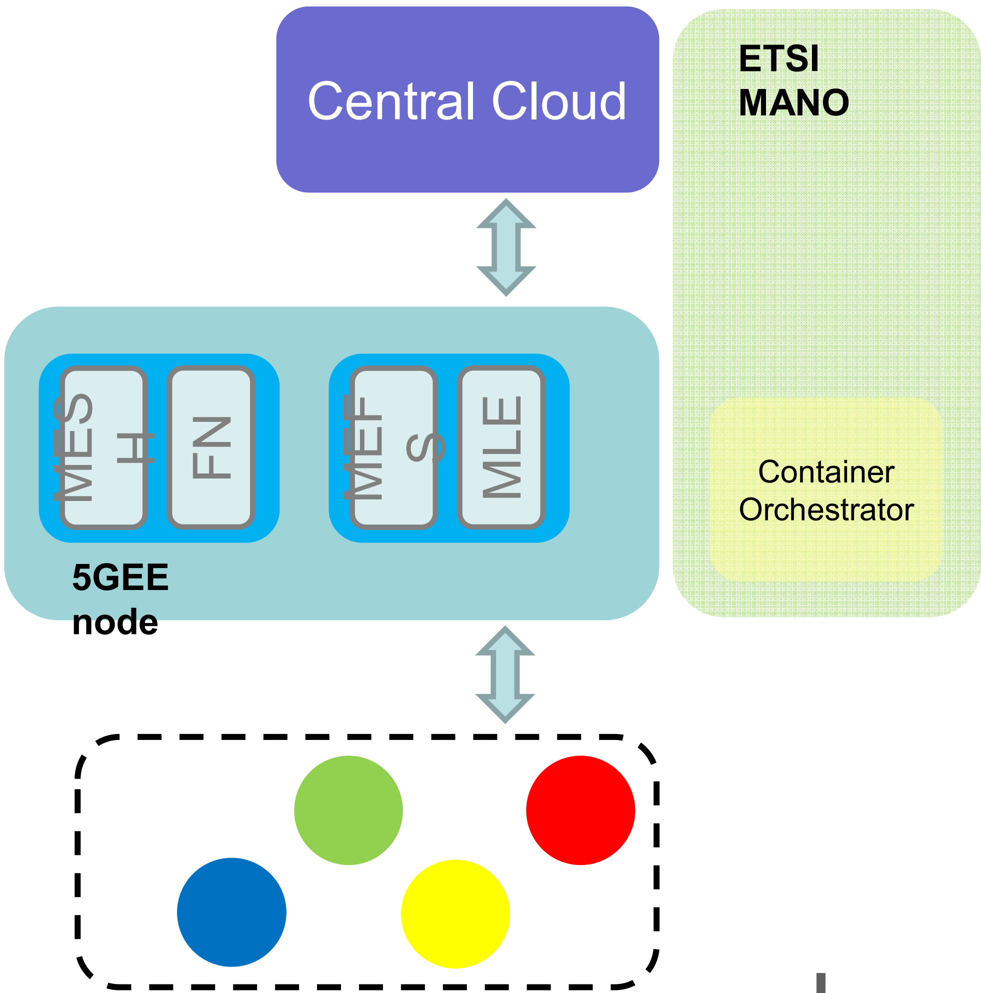
Human-driven Edge Computing (HEC)



measurement of connectivity as temporal graphs between FMECs (E_i) and M^2EC (P_i)

4) Advanced Management Operations at the Edge

- Architectural solution called 5G-Enabled Edge **(5GEE)** that aims at converging MEC and Fog while maintaining quality awareness and orientation
  - **Combination** of all the main MEC and Fog functions
  - Dynamic **management/(re-) configuration** of 5GEE entities
  - Implementation based on **ETSI MANO**

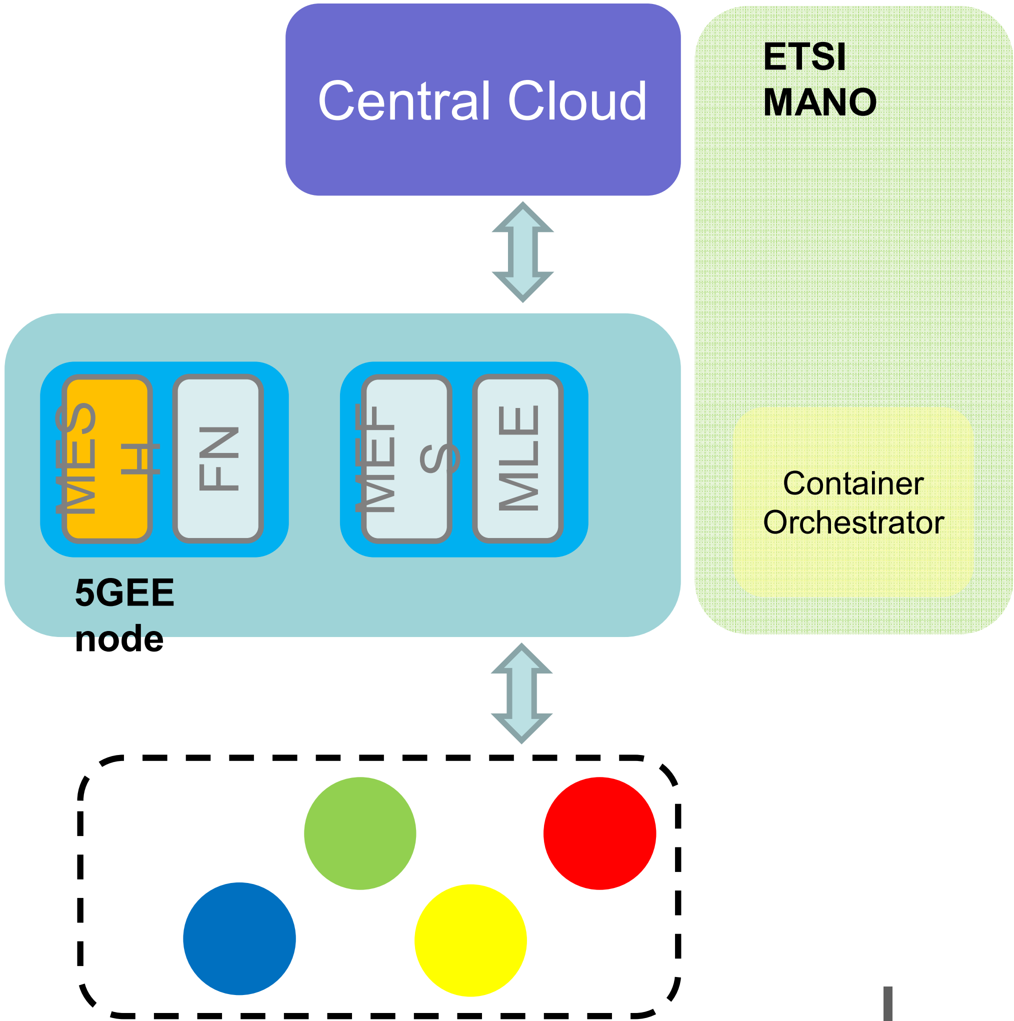


MEC Services Handoff (MESH) as an Example of Advanced Management Operations at the Edge

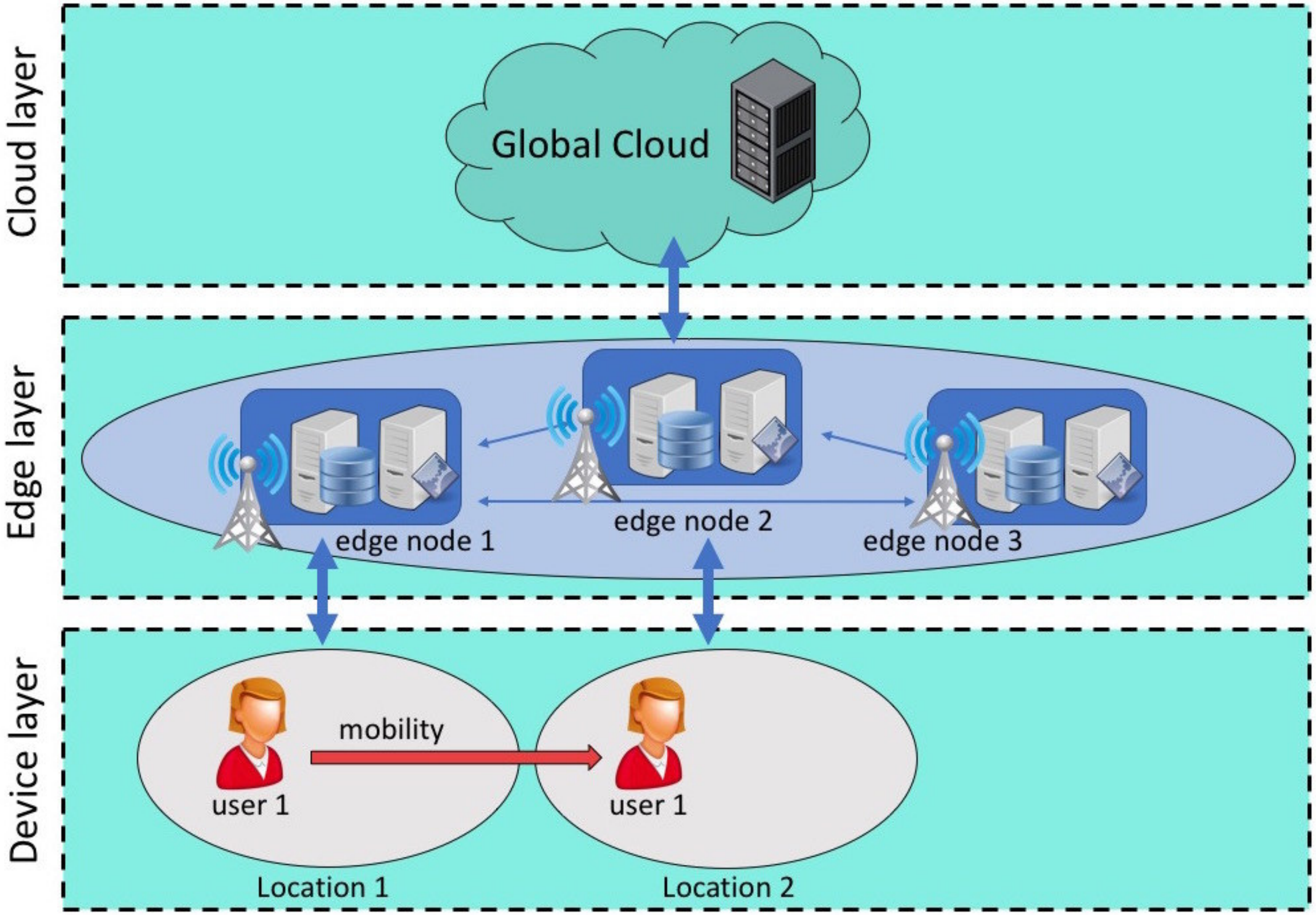
1. **MESH** is **proactive**
2. **MESH** enables either **application-agnostic** or **application-aware** handoff
3. **MESH** supports inter-edge migration of:
   - Virtual machine (VM)
   - **Docker container**
4. **MESH** runs on resource-poor edge devices such as **Raspberry Pi**
5. **MESH** is tailored on ETSI MEC specification

Edge-enabled Handoff

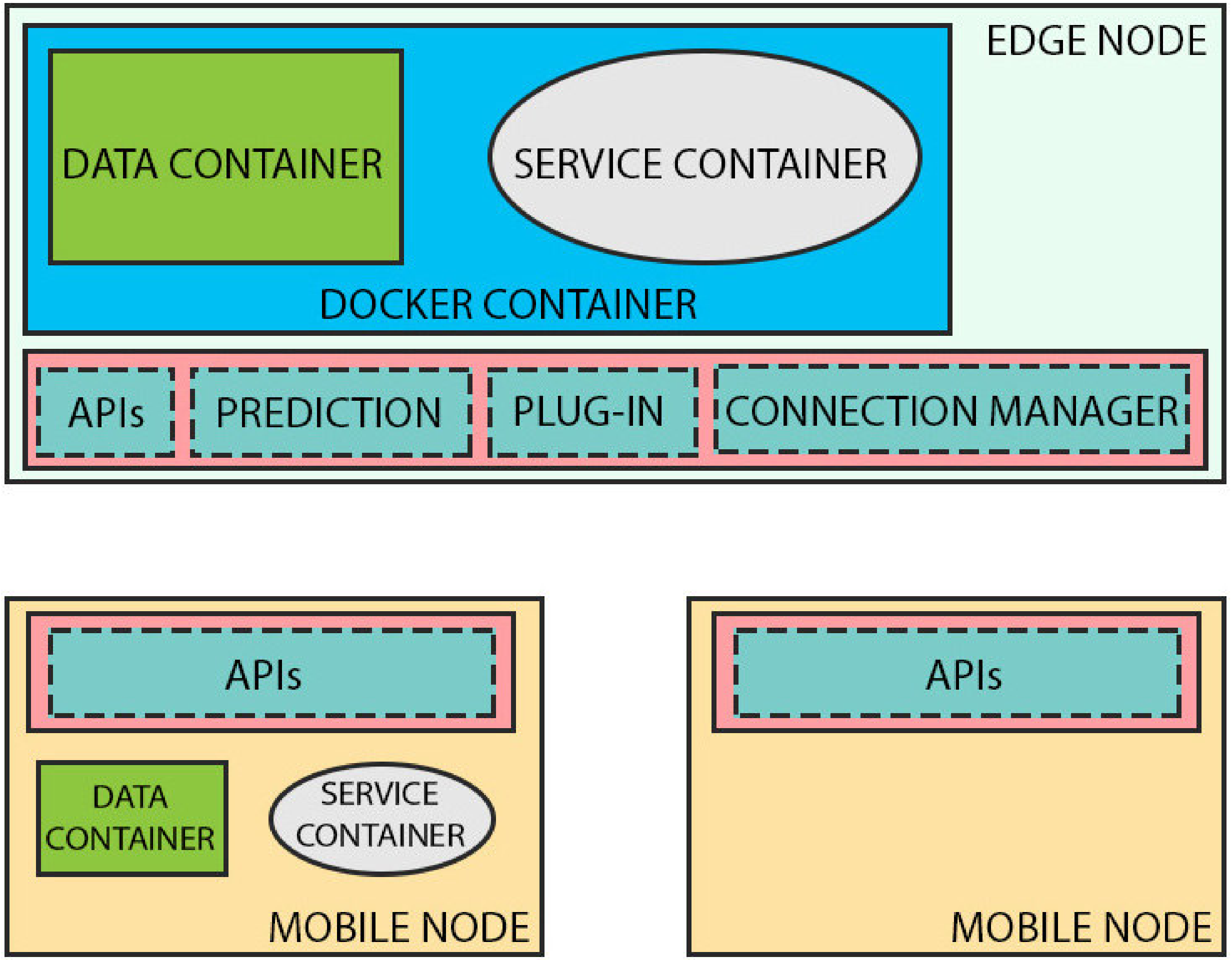
1. Background
2. Proposal of proactive application-aware service handoff protocol
3. Proposal of application-aware optimizations



Edge-enabled Handoff

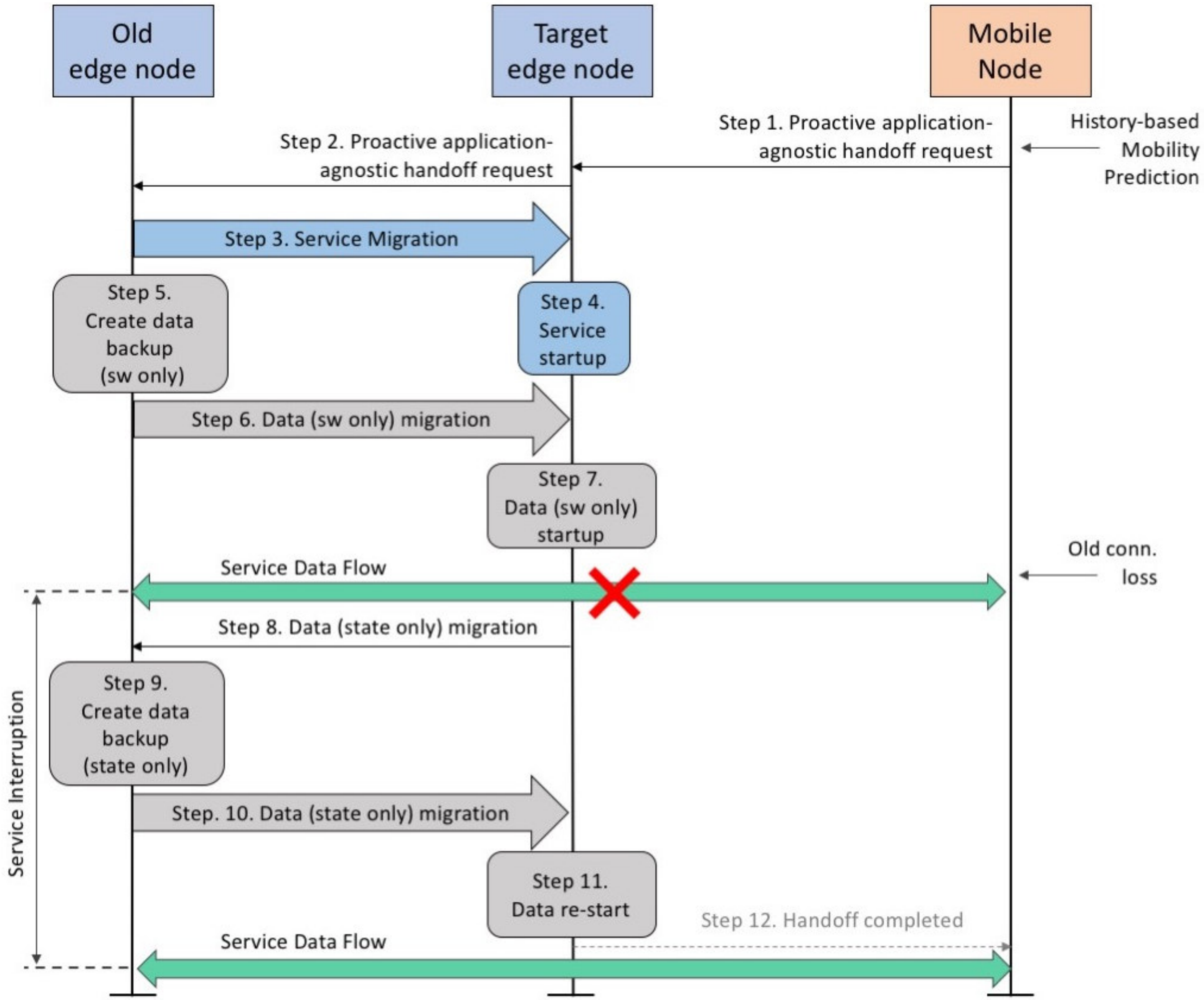


MESH – Architecture

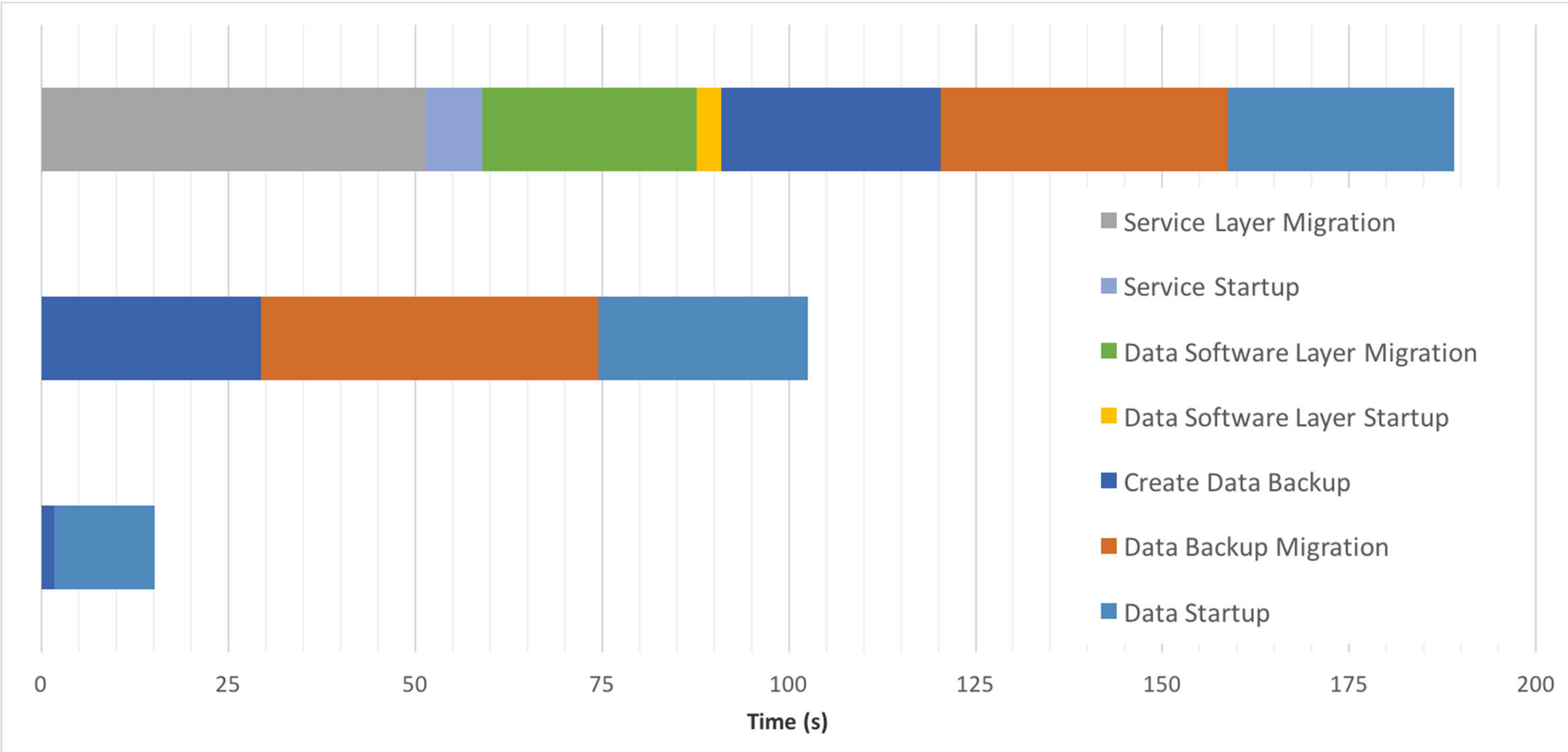


MESH – Proactive Handoff

- **service layer**: the stateless application logic.
- **data software layer**: software parts for managing the data storage.
- **data state**: the data stored in the physical disk.



MESH – Experimental Results

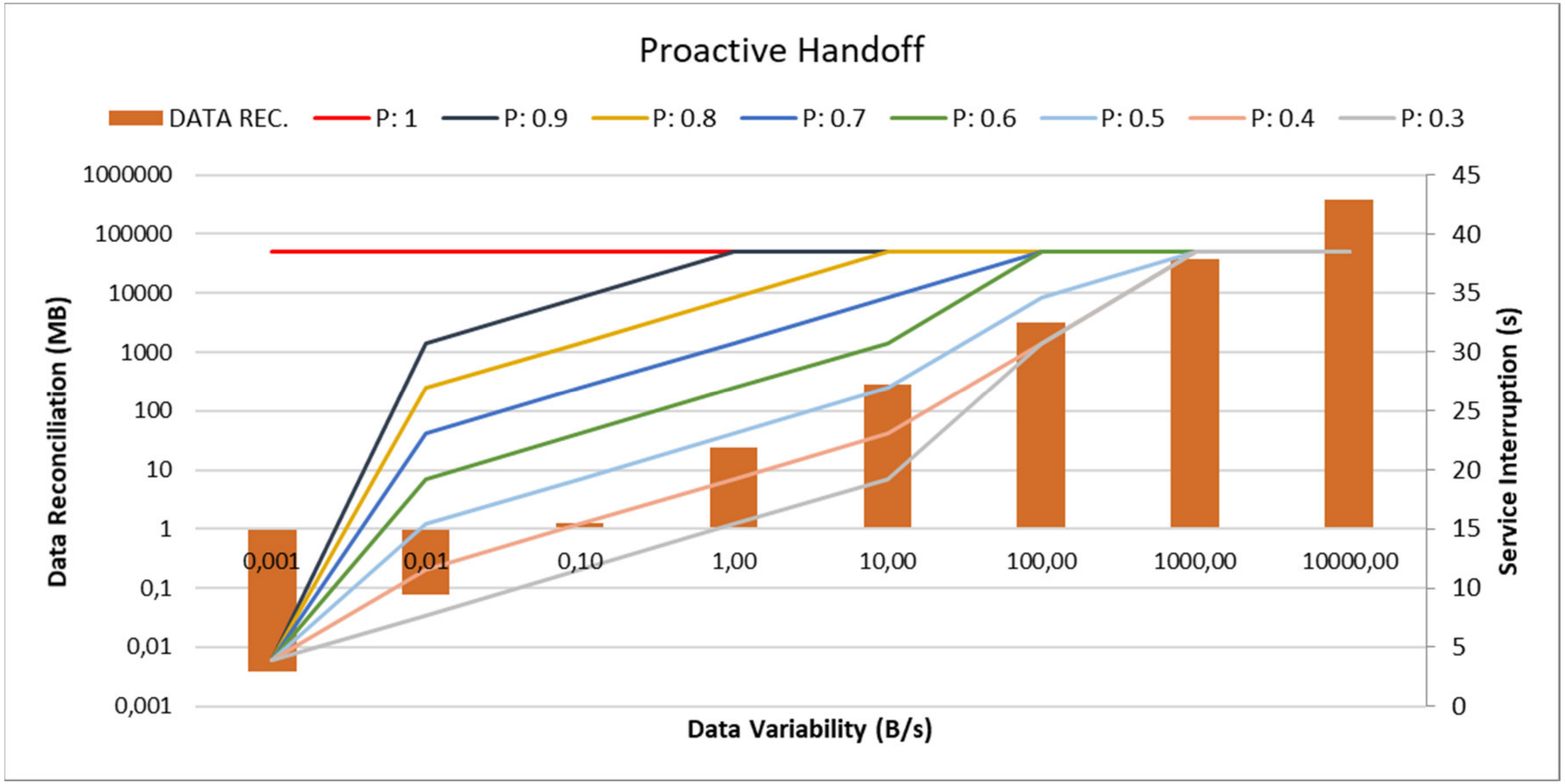


- **Raspberry Pi 3**

Application-aware: Simulation Results

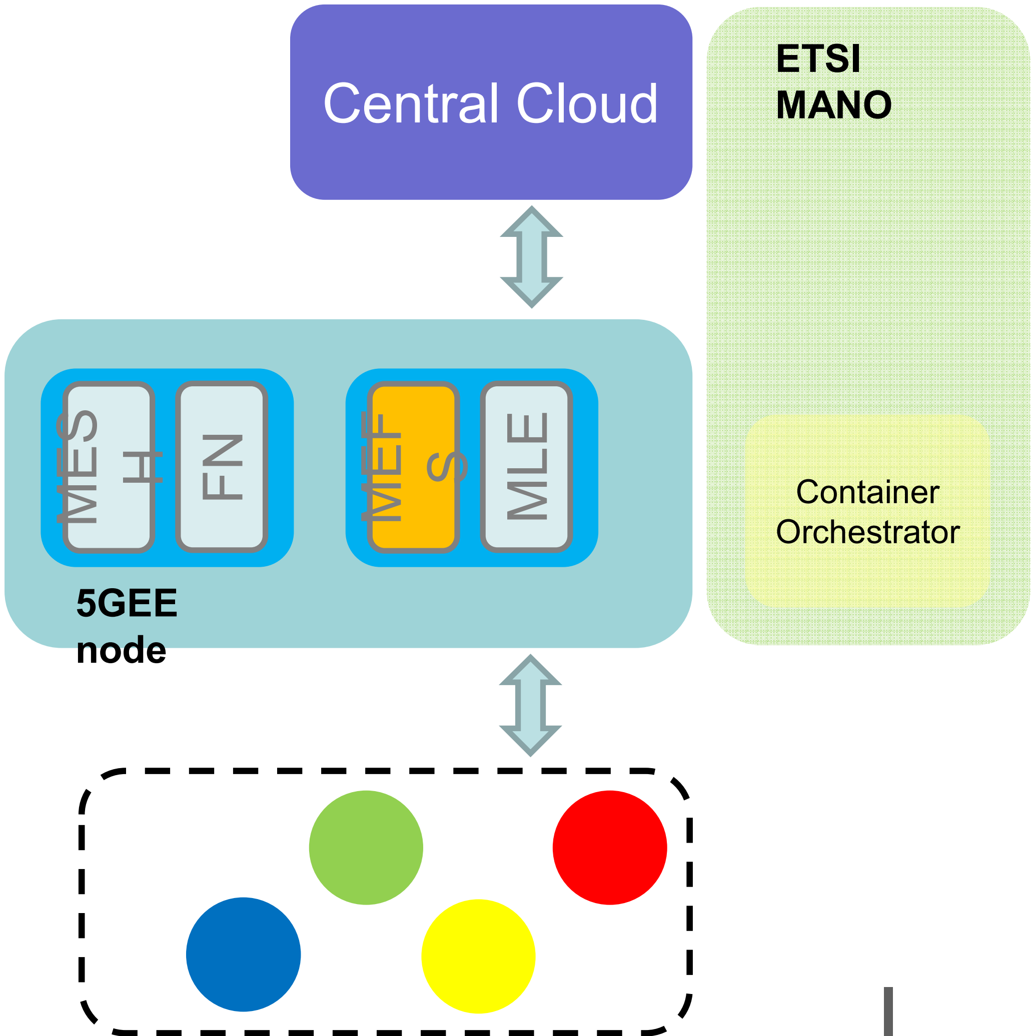
How to select the proper value of migration probability?

- This is a baseline guide to choose the best value of migration probability related to the data variability



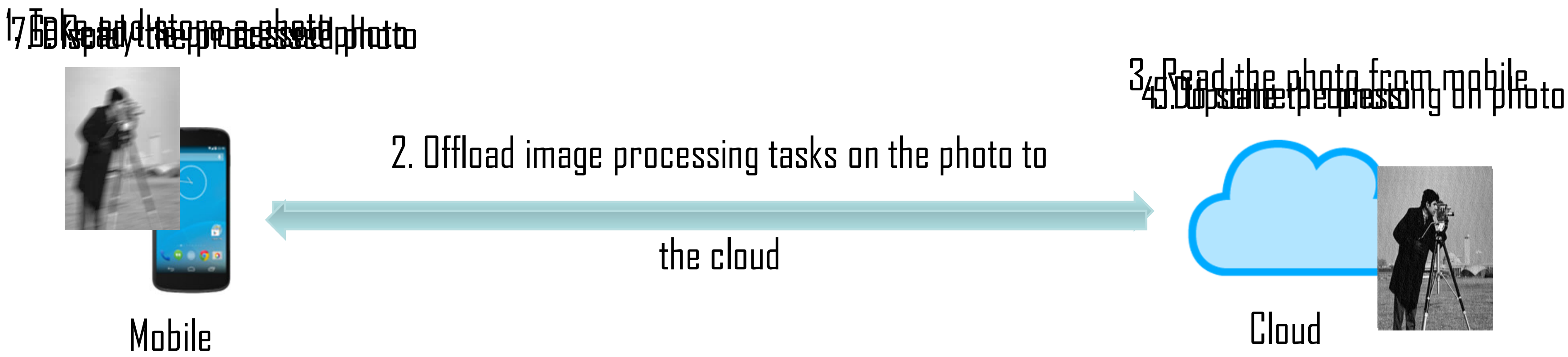
Mobile Edge File System

- **OFS**: An Overlay File System for Cloud-Assisted Mobile Applications
- Systems designed to offload resource-demanding tasks to cloud
  - Task offloaded in the form of **Objects**



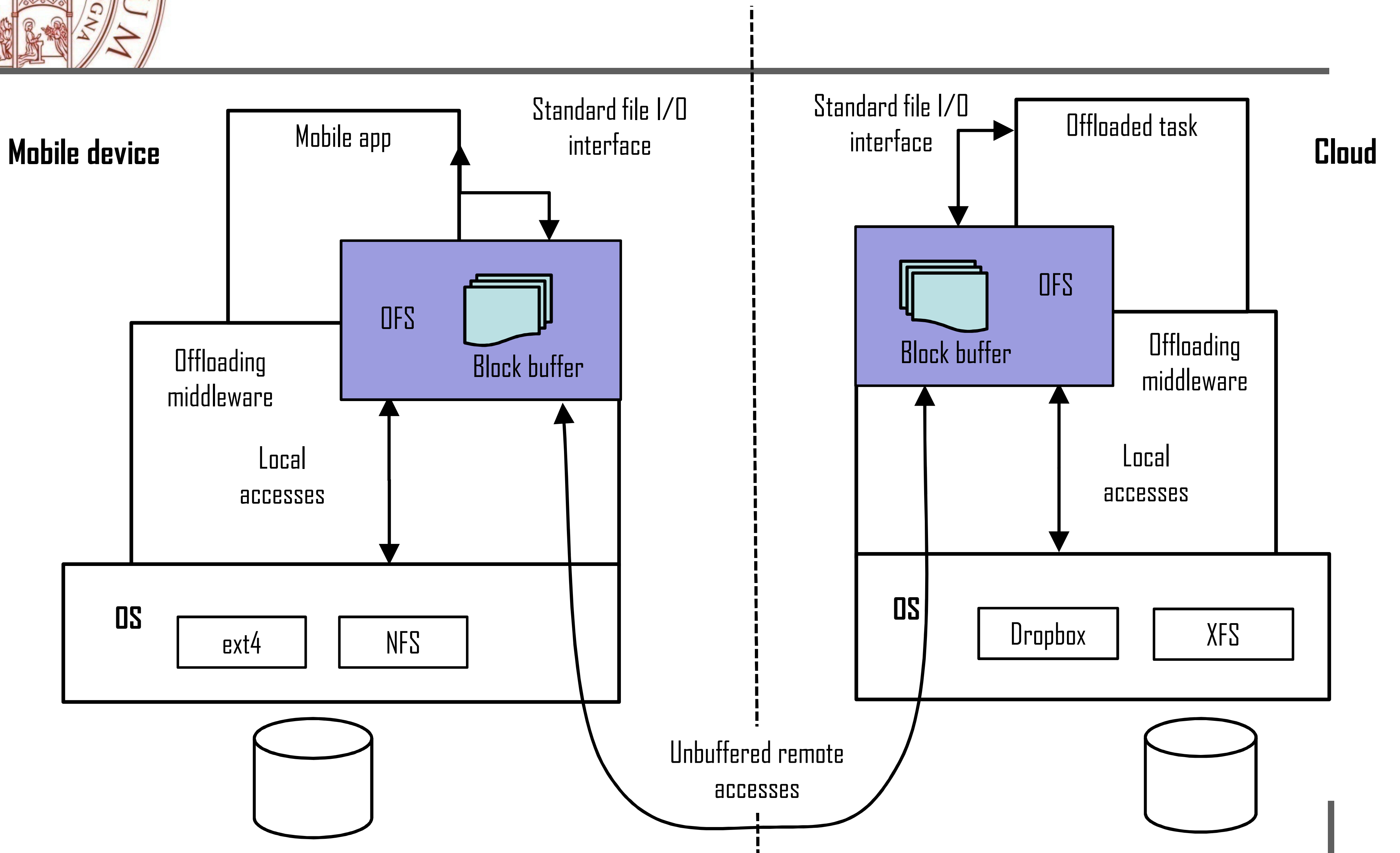
Example of Cloud-assisted App

- **Photo Enhancement App**

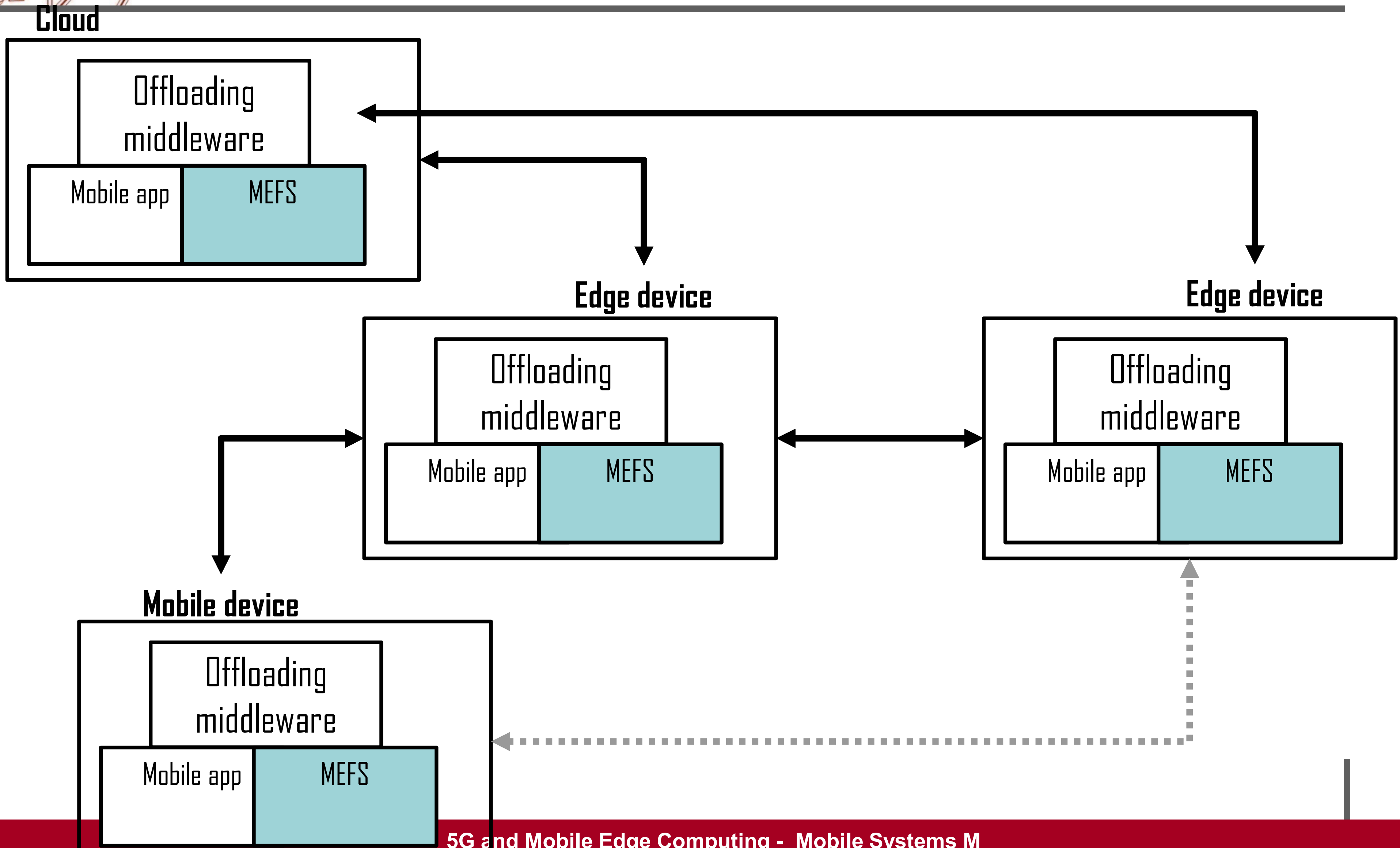


- Characteristics of file I/O in cloud-assisted mobile apps:
  - Read and write files on both mobile and cloud
  - Require strong consistency
  - Long I/O latency due to transferring the file over network

OFS Architecure



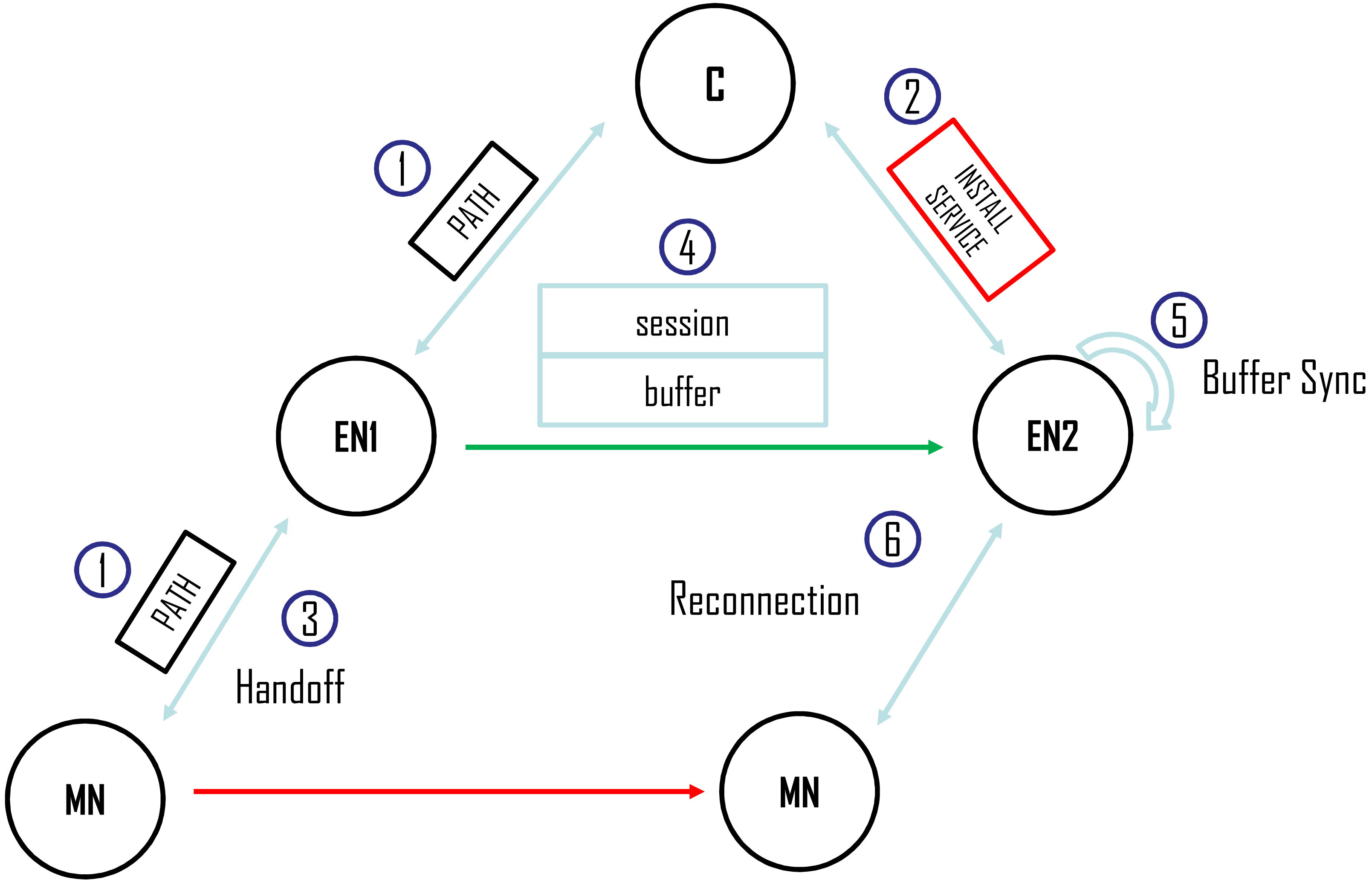
MEFS Architecture



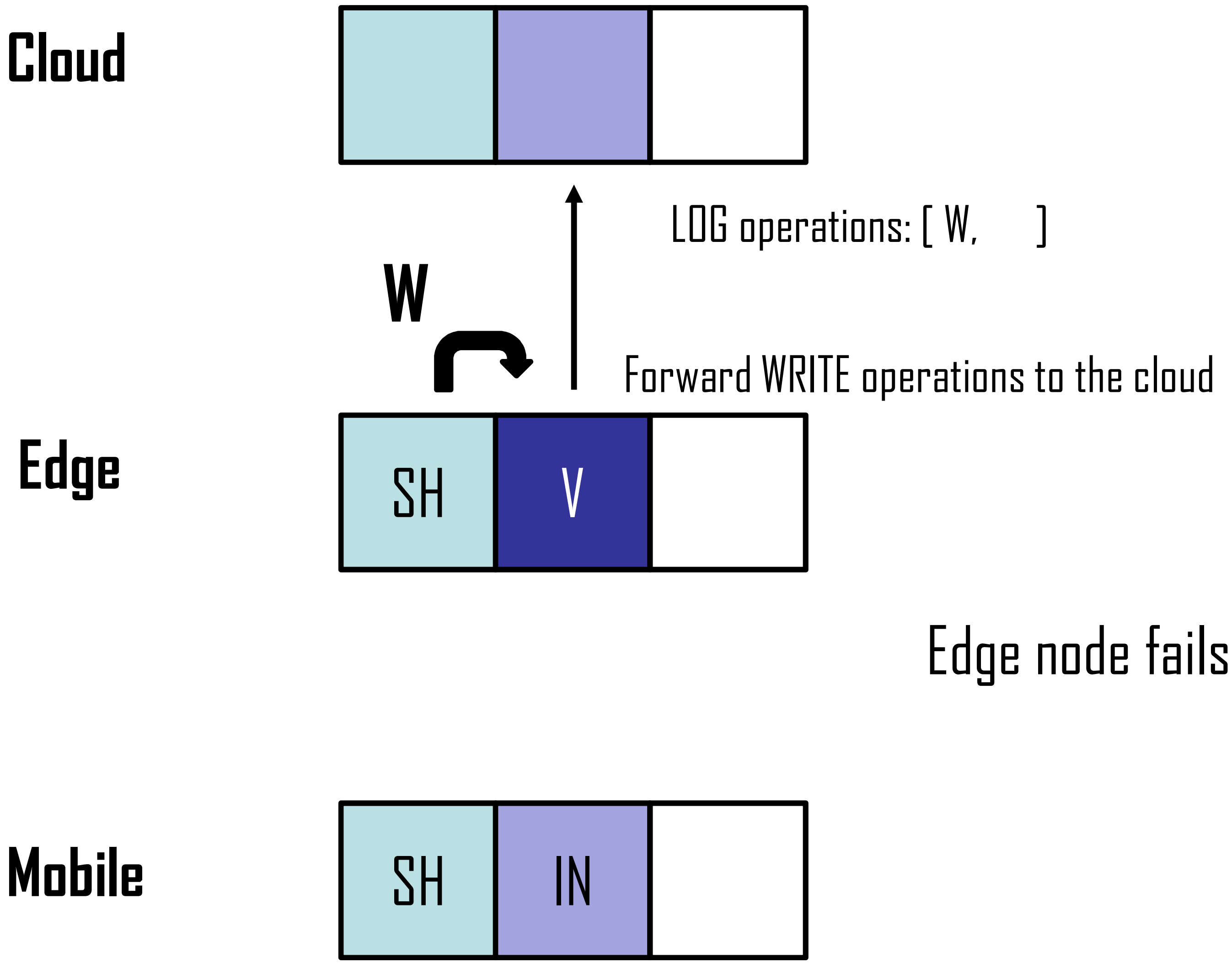
MEC Technical Challenges

1. **Application portability**
   - Transfer apps between MEC servers
2. **Resilience**
   - Protect against node or communication failure

MEFS Handoff

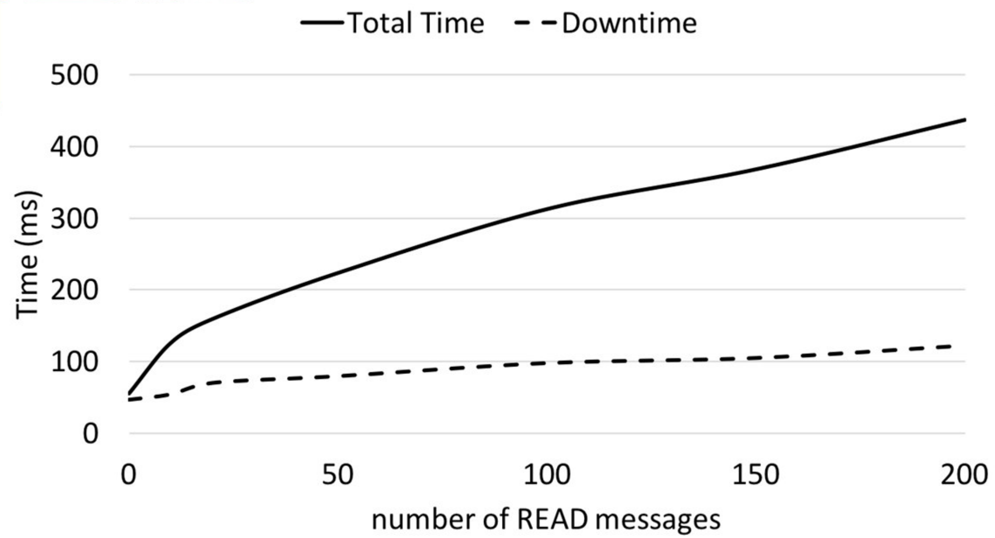


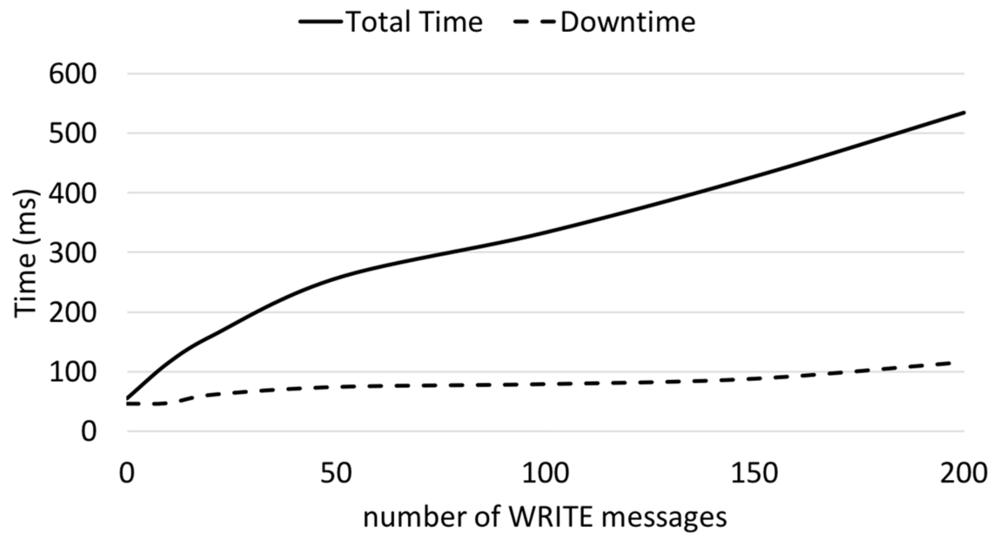
MEFS Resilience

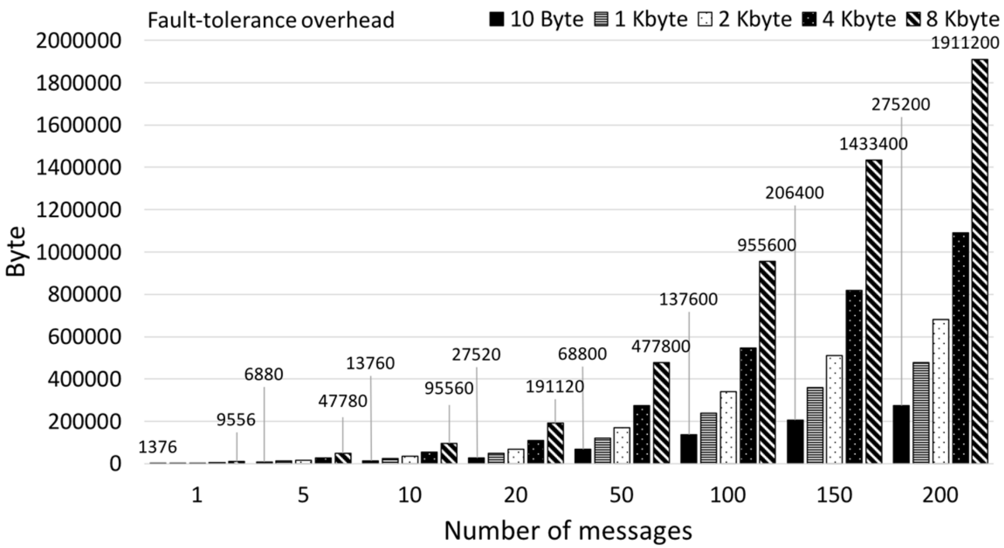


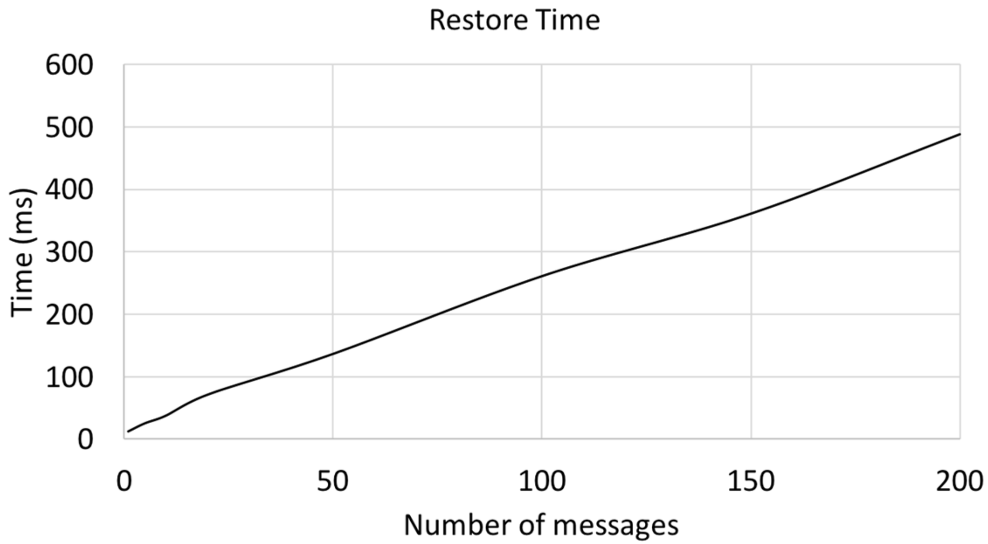
Edge node fails: **Log-based FS approach**

MEFS Performance



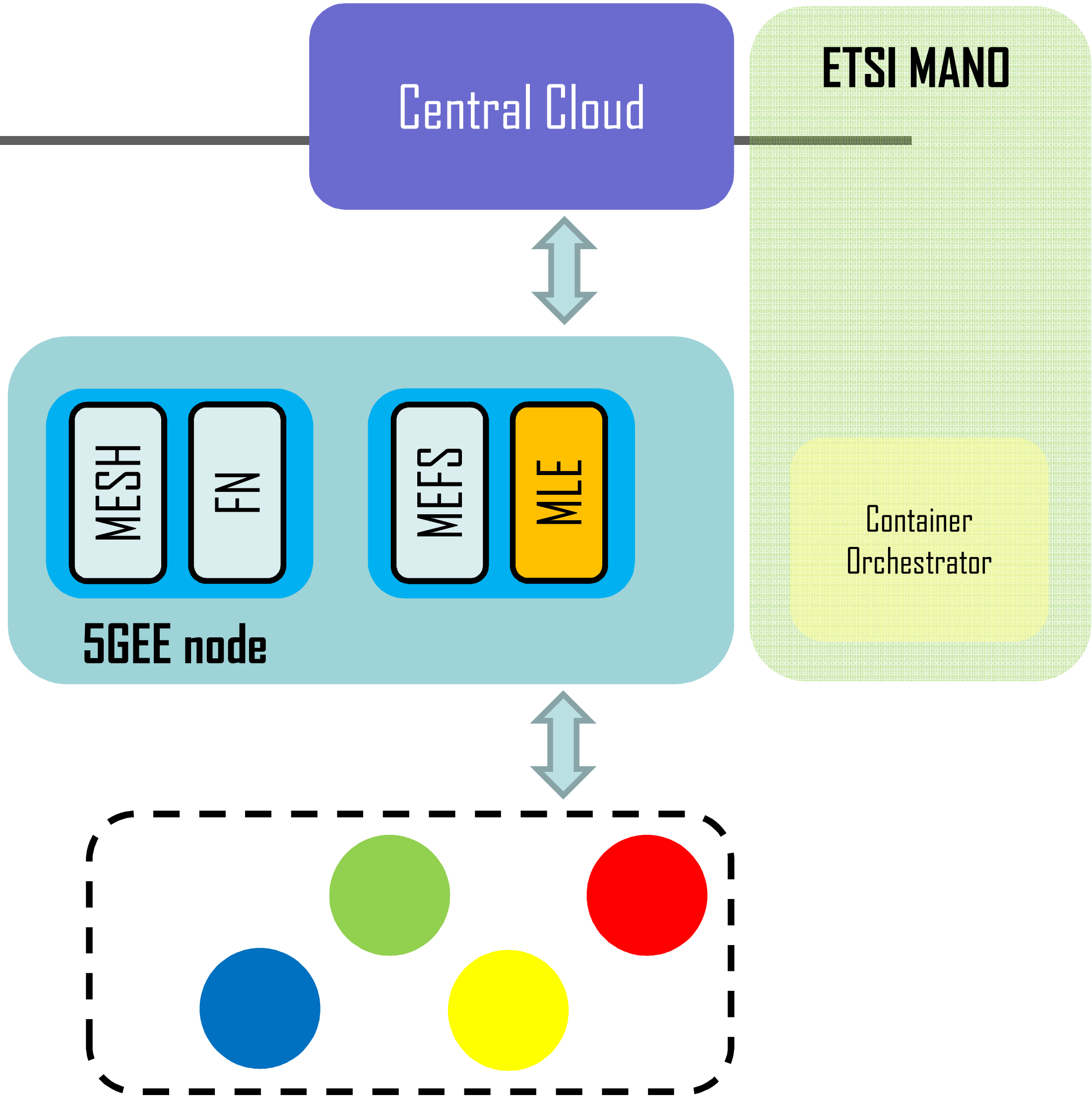




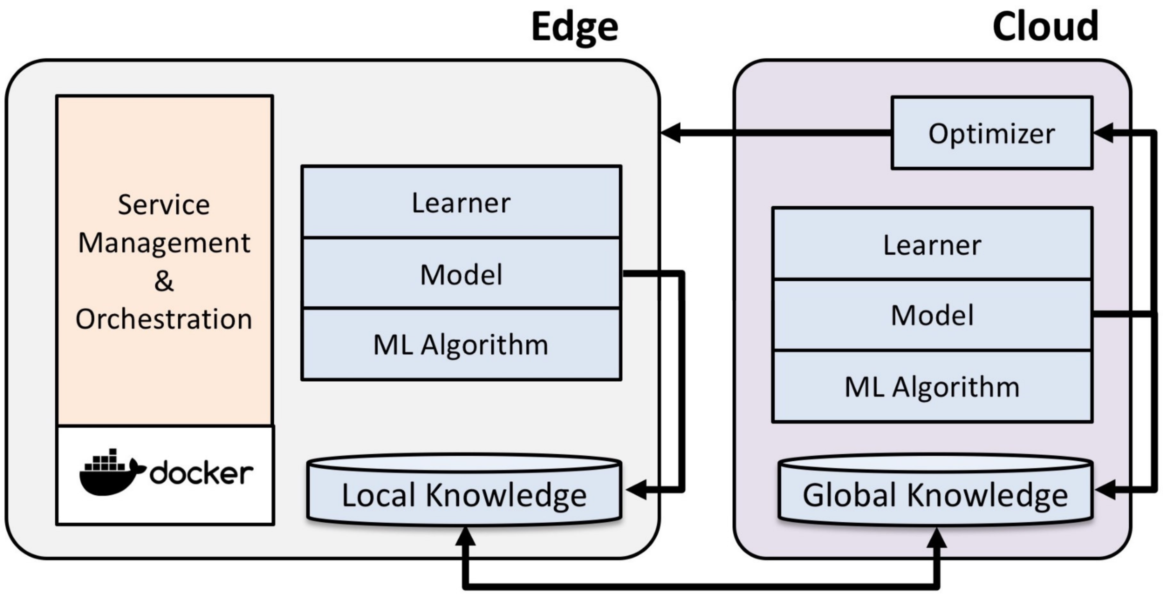


Machine Learning at the Edge

- IoT generates a huge quantity of data
- **Machine Learning** is often used to extract info from generated data
- Support infrastructure to perform ML on distributed EC

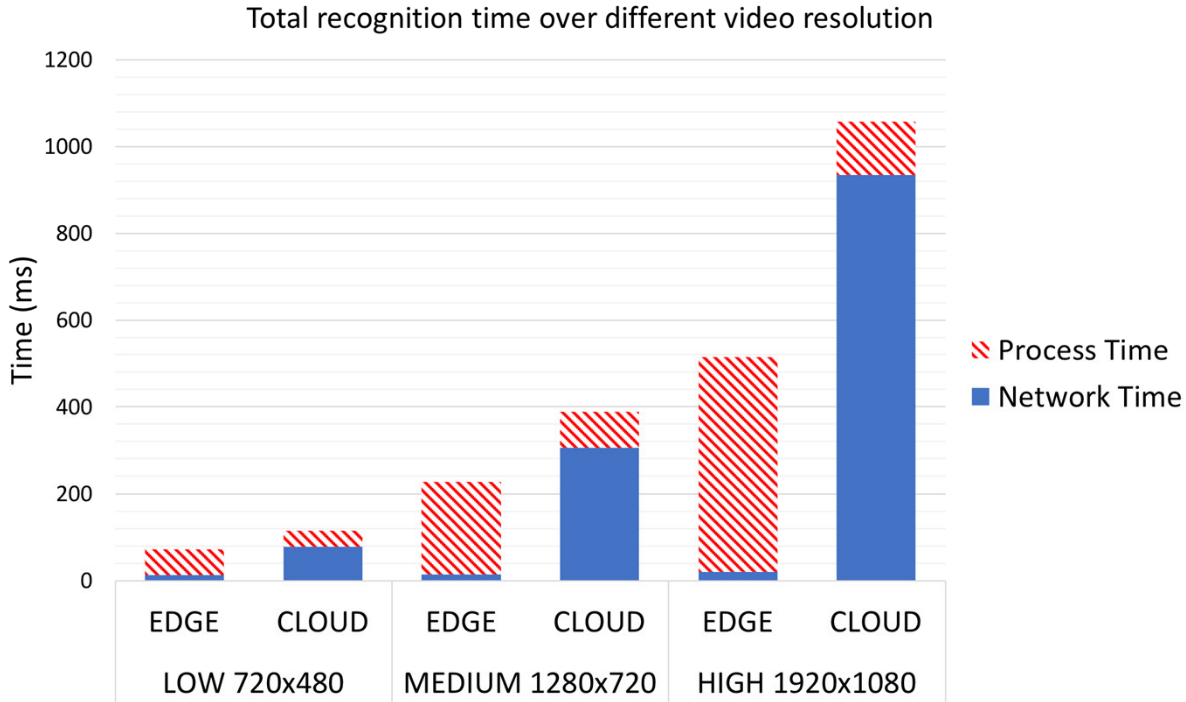


Support architecture for ML



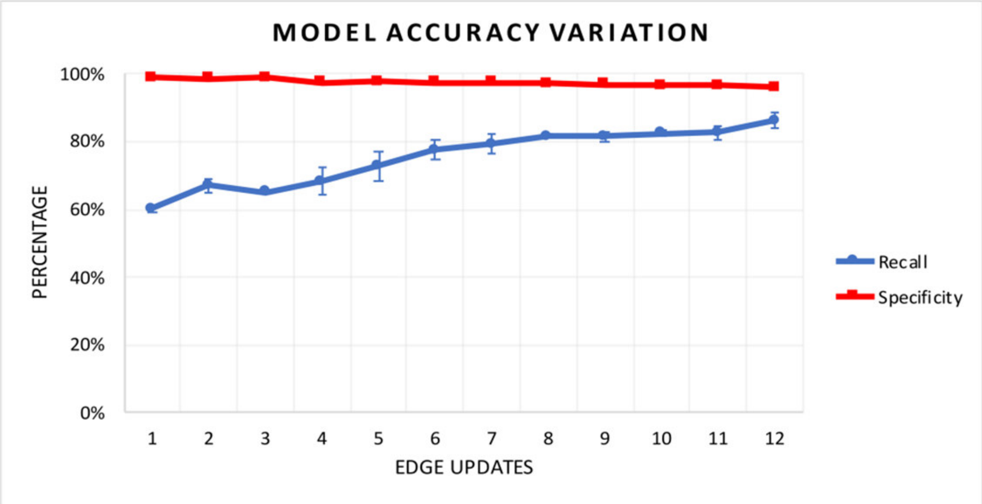
- A set of ML algorithms **run at the edge** for online analysis
- Learning module able to train model (**Digital Twins**)
- An **Optimizer** module that sends feedback to reinforce distributed models

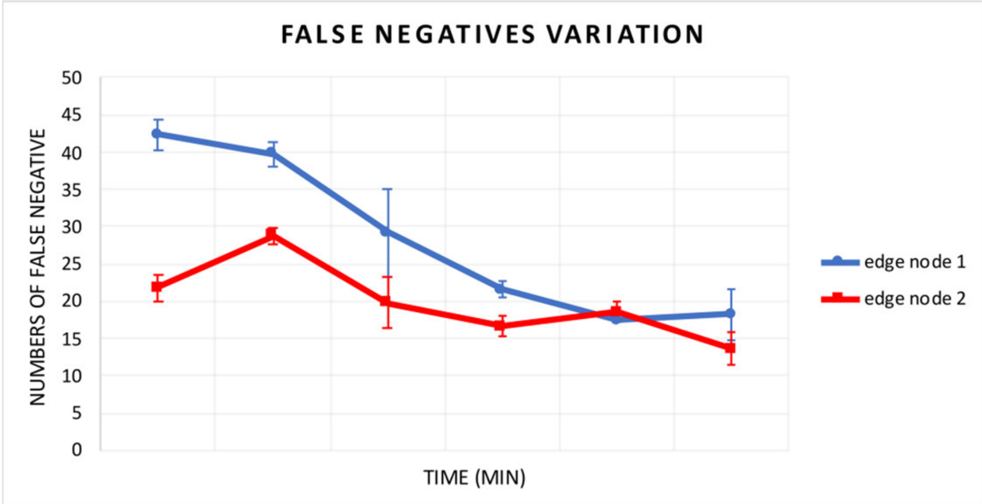
Experimental Results (Smart City scenario)



- **Compared performance of face recognition app in two scenario: mobile/edge and mobile/cloud when the video quality grows**
  - In the cloud the recognition time goes up rapidly as the video quality increases
  - Mobile/edge recognition performs better due to lower latency and higher throughput at the edge

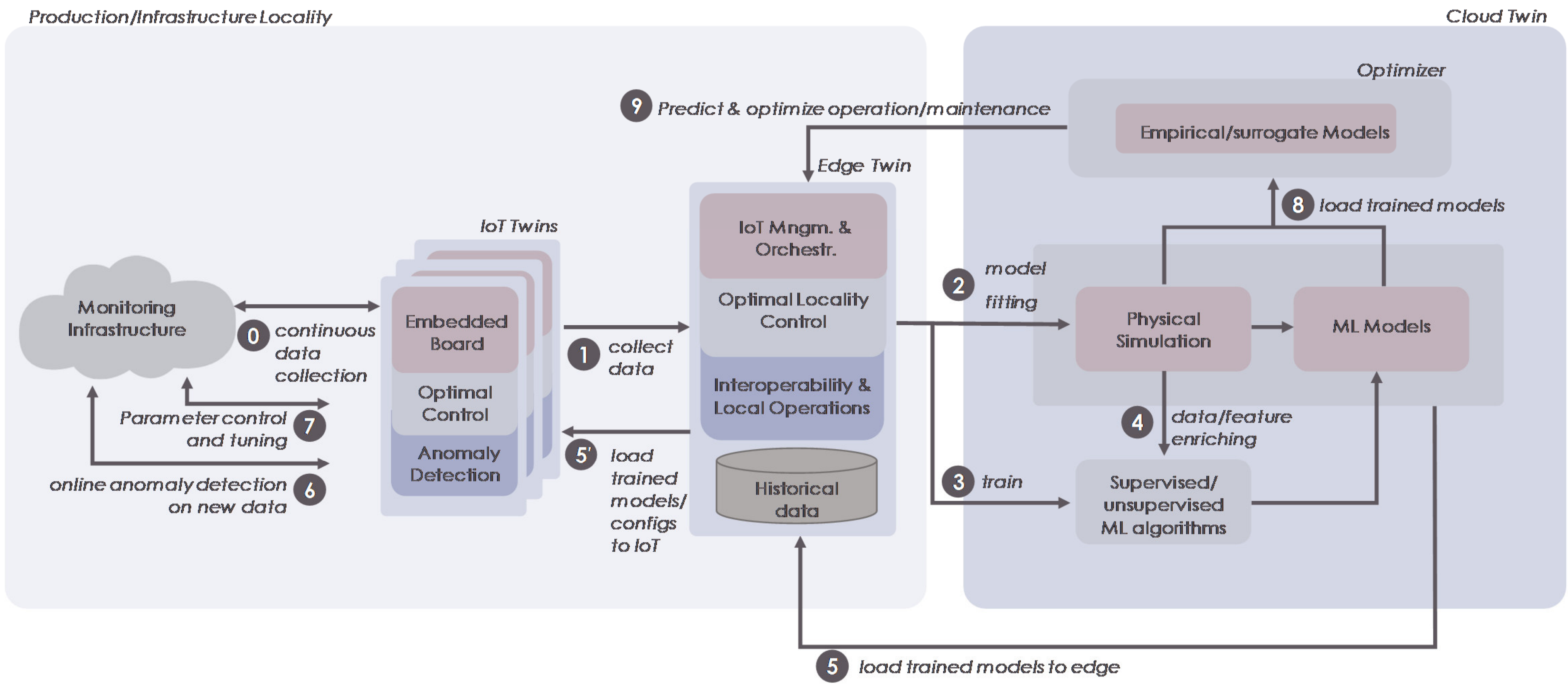
Experimental Results (IIoT scenario)





- **By sending reinforced models from the edge towards the cloud:**
  - the total model accuracy is more or less the same
  - more accuracy to predict negative instances

Off-/On-loading from/to the edge in the **Fog/Edge/Core-cloud Continuum** in the IoTwins RA



Still confidential…

To conclude:
Open Research Directions (1)

- ***Fog-enabled federated management*** - efficiently deploying and managing federations of dense inter-connected and decentralized cloud infrastructures, by dynamically moving (partial) MCN functions to the edge of the network by taking local decisions and optimizations
- ***Edge computing for extremely high availability*** - How to exploit mobile edge computing towards disaster resilient and emergency robust MCN solutions? How should it be efficiently combined with DC networking virtualization?
- ***Scalability and quality for data-intensive applications*** - Effective and efficient solutions for scale, quality, and privacy/security, in particular in data-intensive applications deployed over federated environments, such as in the case of MCN for smart cities or wide-scale IoT with dominant M2M communications

To conclude:
Open Research Directions (2)

- Efficient MEC solutions for industrial IoT ***Machine Learning*** – Local execution of ***partly learned models*** (cloud-based learning), ***federated learning***, online local refinement of partly learned models, cloud notification and update for offline model refinement only when needed, …
- ***State, state, state…*** - efficient state migration, replication, eventual consistency, proactive state management, etc
- Etc etc…

To conclude: Open Innovation Challenges for **Industrial Exploitation**

About immediate industrial applicability of solutions in the field, in several sub-areas with specific performance/functional constraints we are far from ready-to-deploy frameworks:

- ***high-availability by design***, in particular in the case of federated infrastructures
- ***cost-efficient scalability***
- ***QoS differentiation*** with reasonable guarantees under dynamically changing (in both time and space) load profiles
- Prototyping and demonstrating ***wide-scale pilots*** that show the advantages of edge computing techniques in “hard” application scenarios, such as ***federated mobile public safety networks***, with specific challenges in terms of reliability and privacy

Conclusions?

Still a lot of ***research & innovation work to complete*** to make edge computing solutions applicable in ***different application domains*** (e.g., machine learning for predictive diagnostics, online process quality optimization in manufacturing, …) and ***economically sustainable to leverage new business models*** (e.g., need for portable orchestration solutions for federated environments, especially container-based)

Opportunities for both academia & industries

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- … and several ☺ others under review…