

Mobile Systems M

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

Mobile Systems M course (8 ECTS)
II Term – Academic Year 2019/2020

05 – 5G and Mobile Edge Computing

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http://lia.disi.unibo.it/Courses/sm1920-info/

5G and Mobile Edge Computing - Mobile Systems M

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5G converged world



Voice (VoIP)



Audio/Video Conference



Chat and messagging



Video on Demand



And many more...



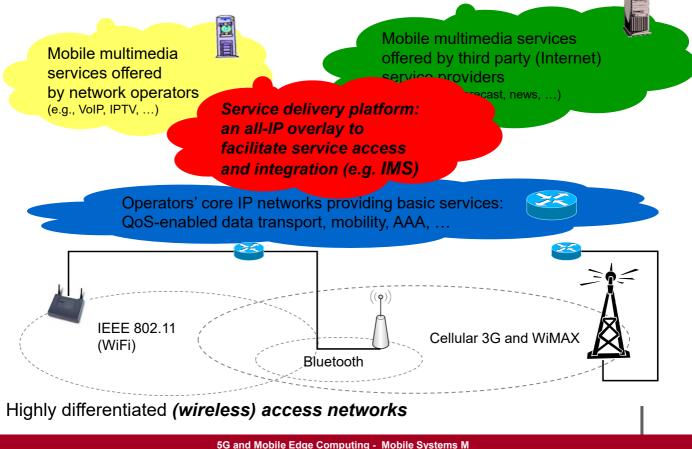
- IPTV
- Video sharing
- ...

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

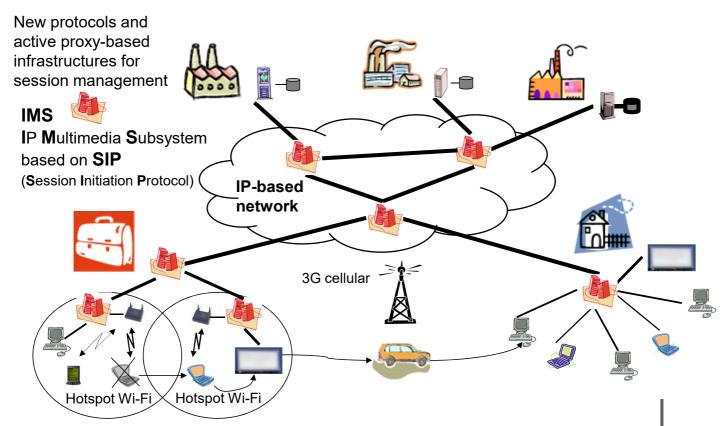


5G converged service delivery scenario





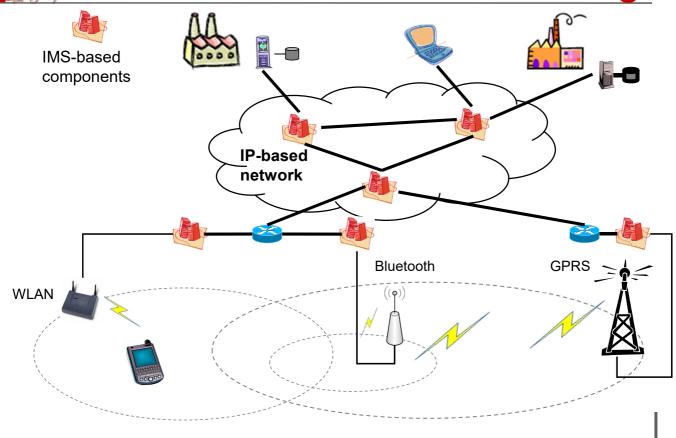
5G service & network management: a proxy-based approach



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New 5G service scenarios: mobile multimedia handoff mngm

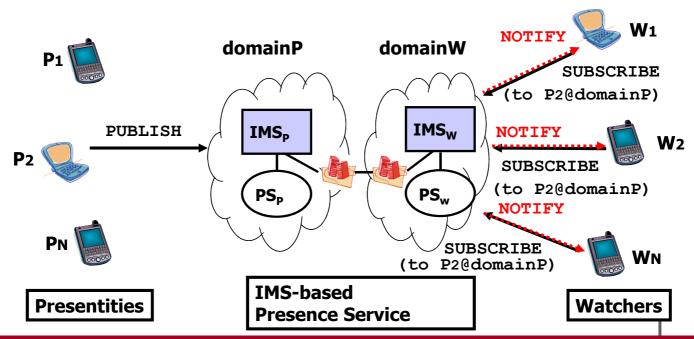




New support services in 5G: presence service

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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_i)**



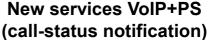


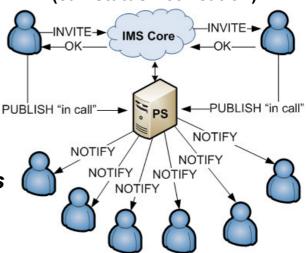
Scalability issues at a glance

High mobility & context changes



- 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

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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

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SIP in a nutshell

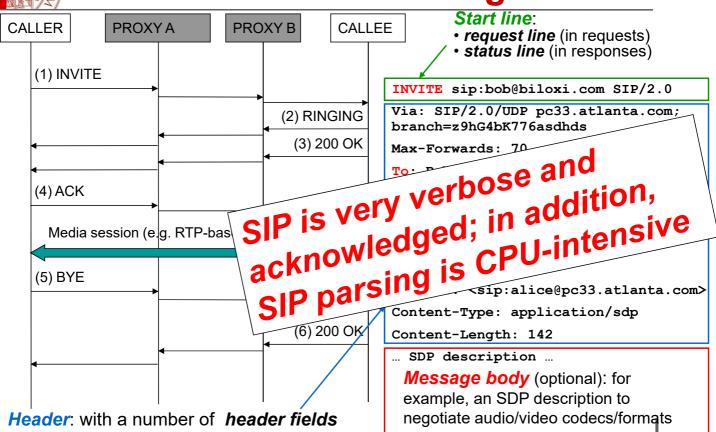
- SIP core signaling
 - HTTP-like text-based protocol and email-like SIP identifiers (addresses)
 - Client/server protocol (request/response protocol)
 - Standardized session control messages
 - INVITE, REGISTER, OK, ACK, BYE, ...
- SIP proxy-based framework and main entities
 - User agents: end points, 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

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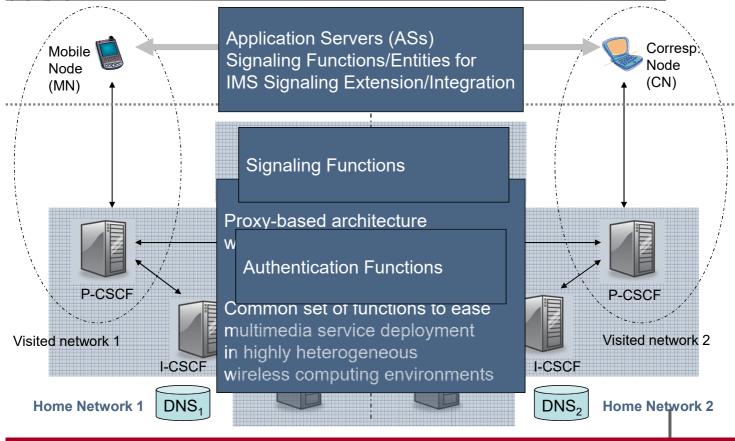
SELDIORUM

SIP VoIP call initiation example: INVITE dialog





Some background: IMS – IP Multimedia Subsystem





IMS functional entities: DNS and HSS

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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* ② (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

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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

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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 ©

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IMS functional entities: AS

Application Server (AS):

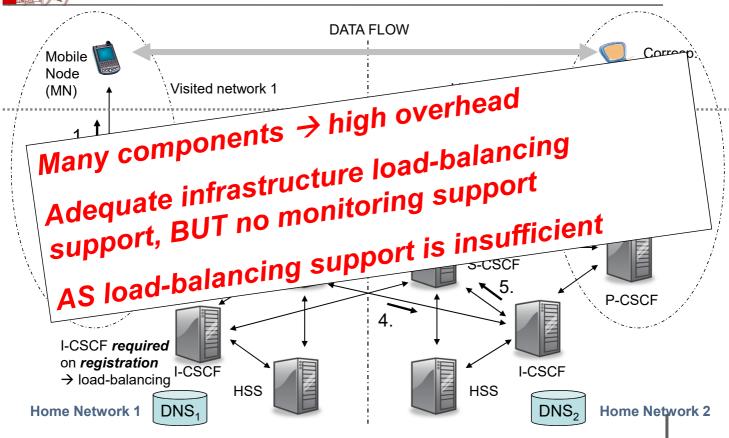
- Host services and execute services
- Communicates using SIP: very costly!! ⊗
 - Each interposed AS generates 2 msgs (processed+ACK)
 - Complex coordination for stateful and distributed ASs

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





IMS scalability: (partial) solutions

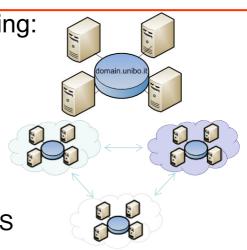
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- Single host (local) optimizations w/out (or with minimal) coordination:
 - Selective message dropping
 - SIP message compression and incremental parsing techniques
 - Stateful vs Stateless SIP proxies

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)



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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, intradomain, 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

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IHMAS: emerging design guidelines for IMS scalability

IMS-compliant Handoff Management Application Server

- 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

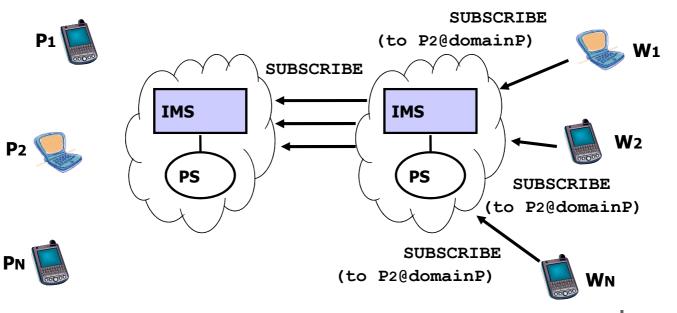
P: Presentity

PS: Presence Server

Inter-domain PS scenario

W: Watcher

DOMAIN P DOMAIN W

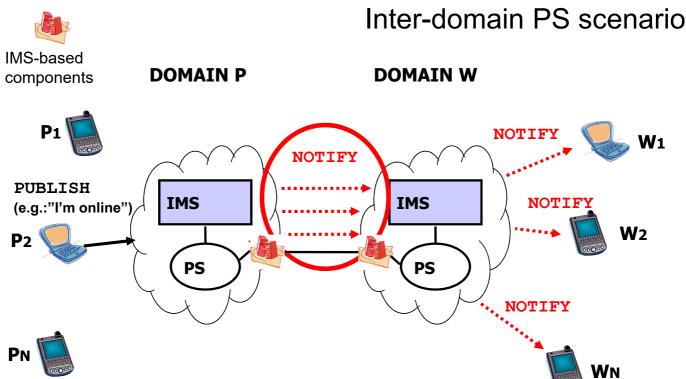


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IHMAS PS scalability use case



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

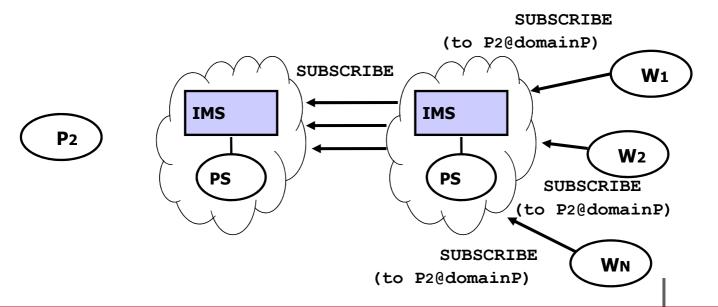
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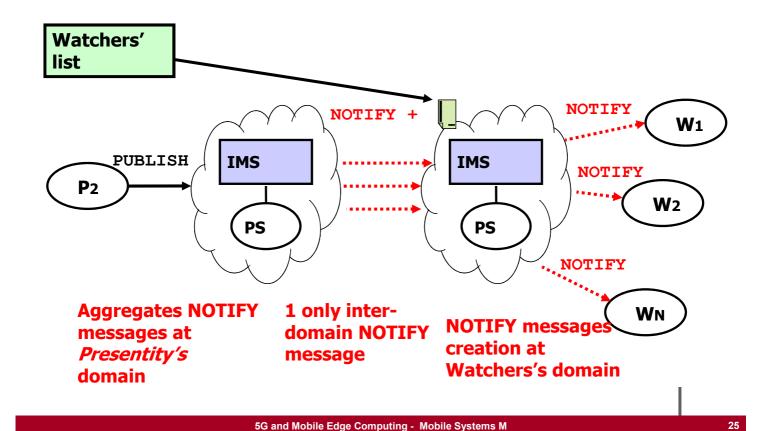
Common NOTIFY

"Several watchers subscribed to one presentity"





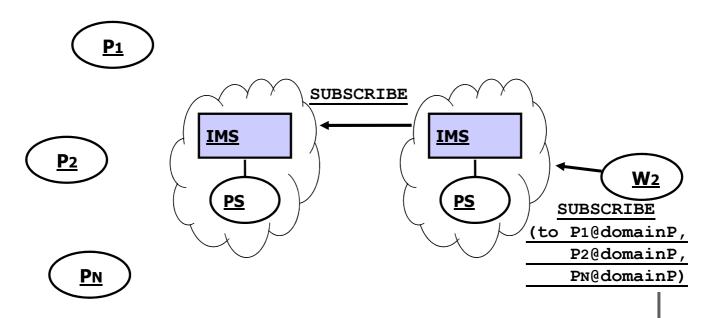
Common NOTIFY





Batched NOTIFY

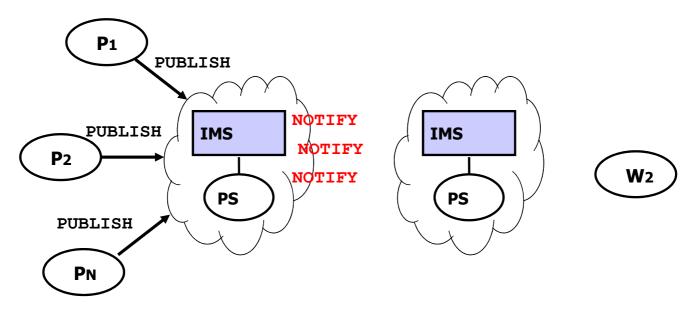
"One single watcher subscribed for multiple presentities"



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Batched NOTIFY



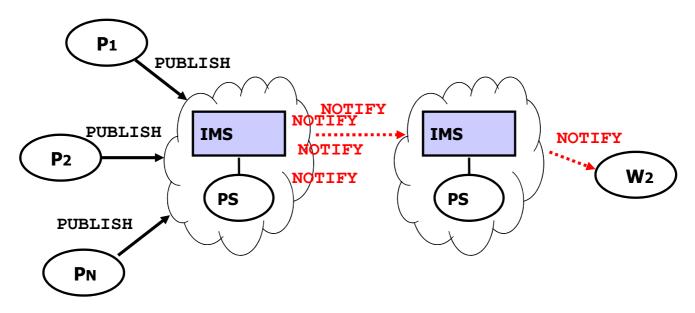
Time-based (periodic)
NOTIFY message batching

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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 loadbalancing actions
 - → dynamic de-/activation of distributed components and DNS (de-)registration actions
- integrates seamlessly with existing infrastructures
 - → full compliancy with IMS standard

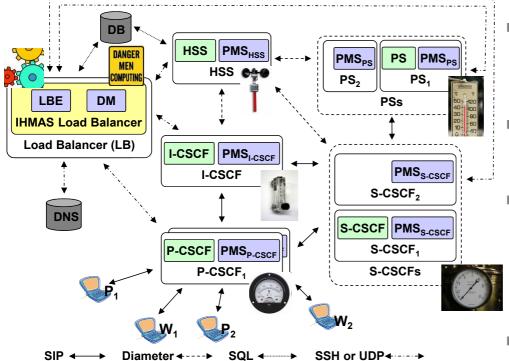
P. Bellavista, A. Corradi, L. Foschini, "Enhancing the Scalability of IMS-based Presence Service for LBS Applications", IEEE COMPSAC, 2009

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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

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IHMAS intra-domain PS scalability: service load balancing

IHMAS intra-domain service load-balancing

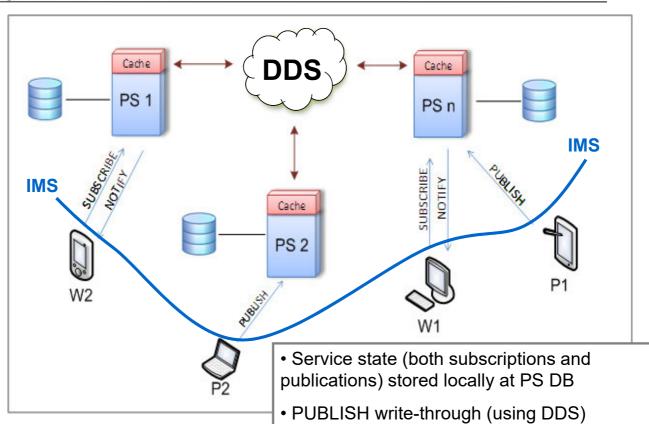
- extends IMS PS to support multiple AS service state storages and fast exchange of (and access to) shared session state among ASs
 - → novel PS intra-domain module to enable data distribution overlays and caching techniques within AS partition
- exploits existing standards for data distribution
 - → 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

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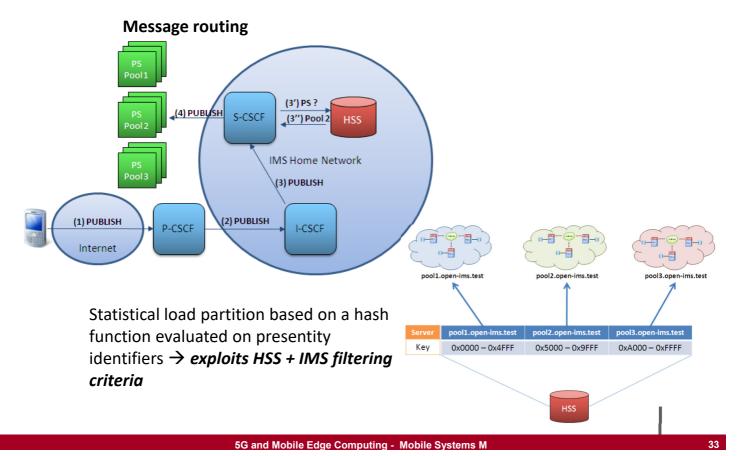


IHMAS intra-domain PS scalability: session data-centric management





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





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

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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

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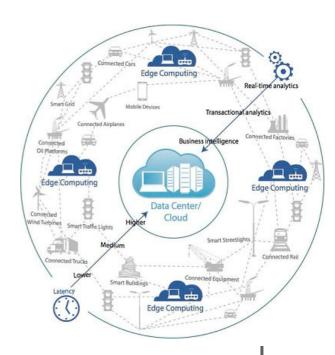
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Edge Computing: Definition (to be discussed...)

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, ...



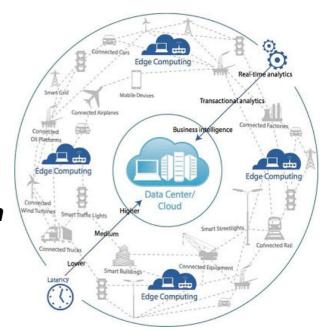


Edge Computing: Definition

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, ...



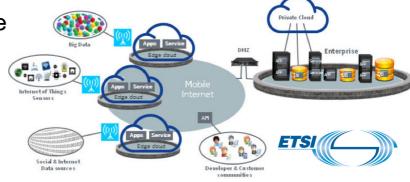
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Multi-access Edge Computing

- The MEC architecture is proposed to overcome the challenges of limitedresources 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

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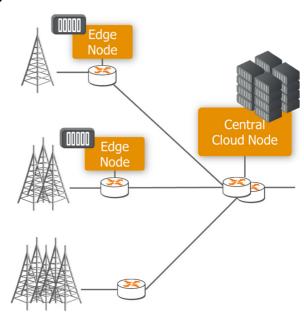
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Notable example: ETSI Multi-access Edge Computing (MEC)

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





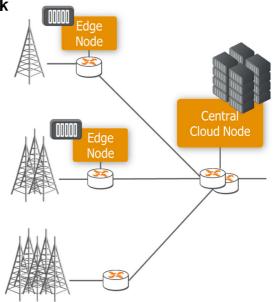
Local vs Global: the MEC Use Cases

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



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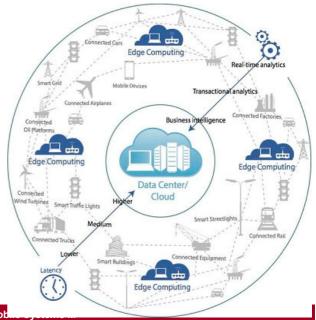
Edge Computing: Definition (again...)

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 (?)



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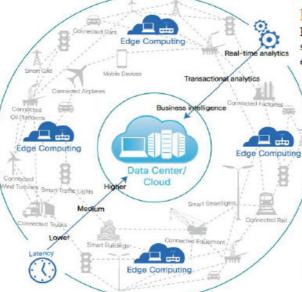
Edge Computing Applications



Application suitable at the Edge

Performance:

Is there a <u>low latency requirement?</u>
E.g. gaming, safety



Data preprocessing opportunities:

Does it make sense to compress or transmit selected data <u>before transferring</u>? 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 <u>edge is more</u> attractive?

E.g. smart city, monitoring, IoT?

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

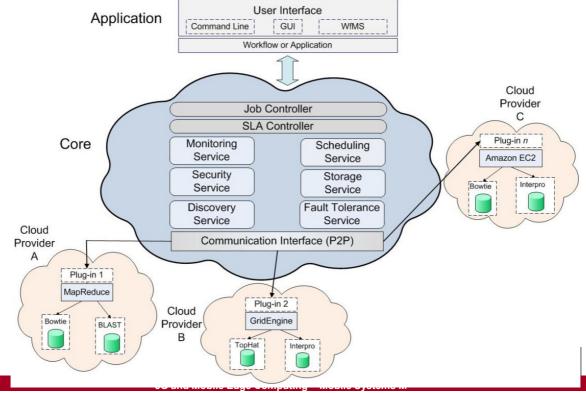
Attaining IoT Value: How To Move from Connecting Things to Capturing Insights Gain an Edge by Taking Analytics to the Edge. Andy Noronha Robert Moriarty Kathy O'Connell Nicola Villa. Cisco 2015

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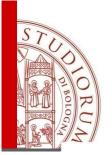
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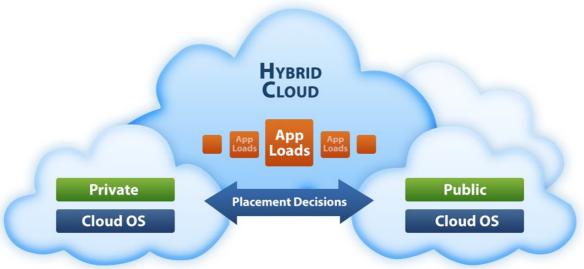
From traditional cloud to federated cloud...



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...to hybrid cloud

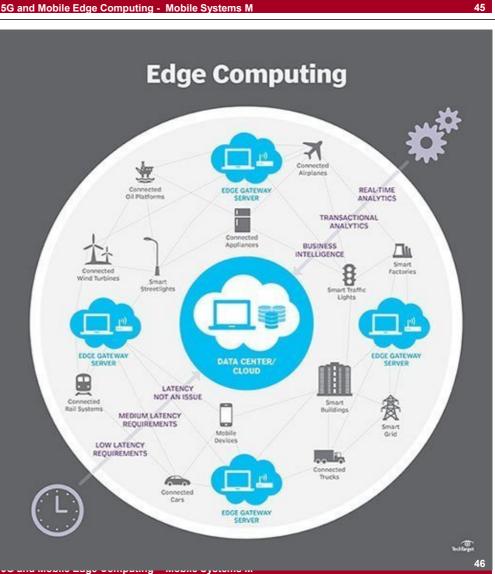


and of course towards the combination of federated and hybrid clouds



Growing relevance for:

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





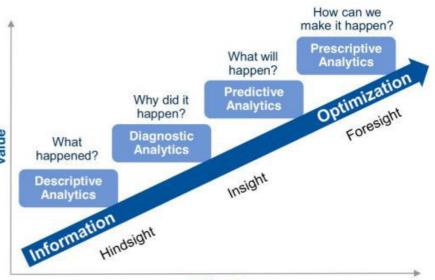
Use Case #1:

Predictive Diagnostics and Optimization of Production Processes

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

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

...



5G and

Difficulty

Robot

System

Industry 4.0

Smart Factory

INDUSTRIAL CLOUD

Sensor



Use Case #1: Predictive Diagnostics

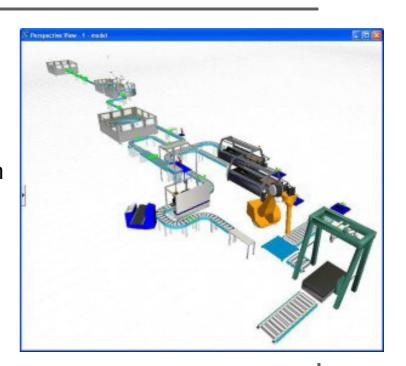
- Industrial cloud
- Compliance with standards and best practices





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



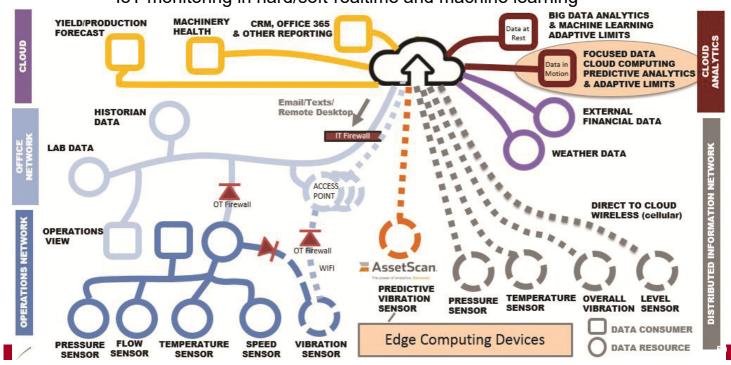
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Use Case #1: Prescriptive Analytics and Optimization of Manufacturing Processes

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

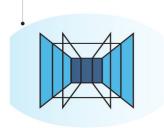


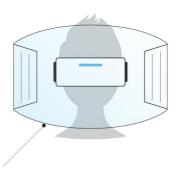


Use Case #2: Virtual and Augmented Reality

VIRTUAL REALITY (VR)

Completely digital environment





Fully enclosed, synthetic experience with no sense of the real world.

AUGMENTED REALITY (AR)

Real world with digital information overlay

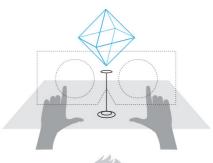


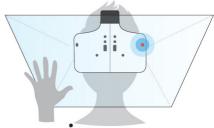


Real world remains central to the experience, enhanced by virtual details.

MERGED REALITY (MR)

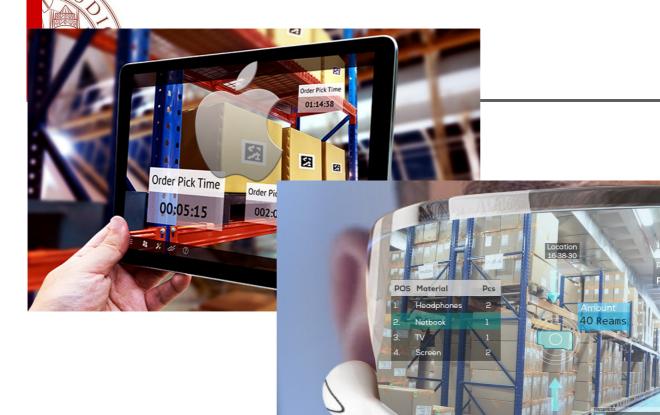
Real and the virtual are intertwined



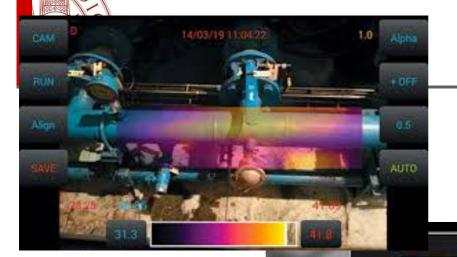


Interaction with and manipulation of both the physical and virtual environment.

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!!!

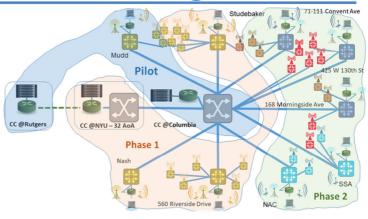


Edge Computing

COSMOS Deployment: NYC Coverage Areas

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











Phase 1 Columbia/CCNY - ~15-20 nodes

Phase 2 - ~40 nodes

Mudd

Broadway

Amsterdam

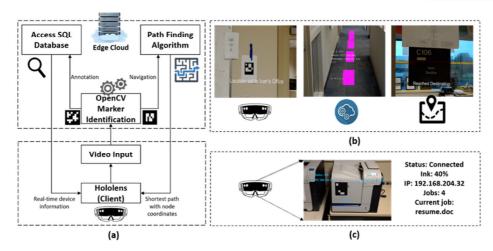
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Edge Computing

COSMOS Experiments: AR Applications



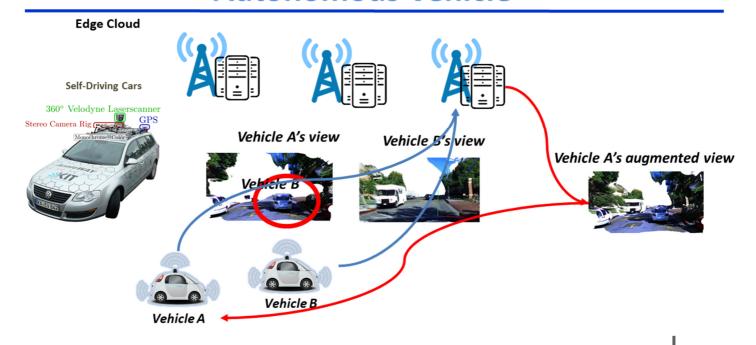
(a) AR application flow; (b) Smart meeting application using indoor navigation; (c) Annotation based assistance



Edge Computing

COSMOS Experiments: Cloud Assisted

Autonomous Vehicle



5G and Mobile Edge Computing - Mobile Systems M

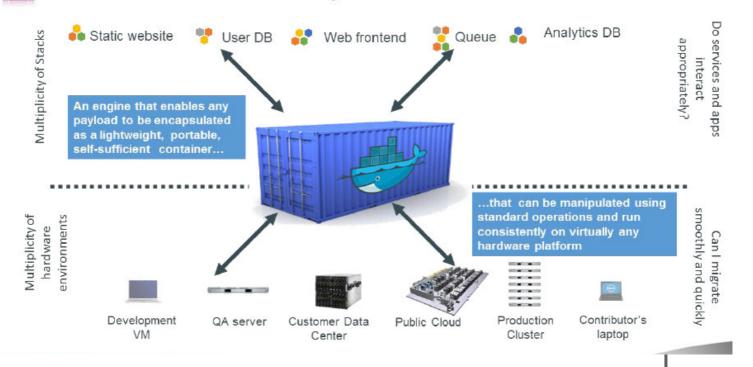
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Edge Computing & Docker



Docker as a Container System for code..





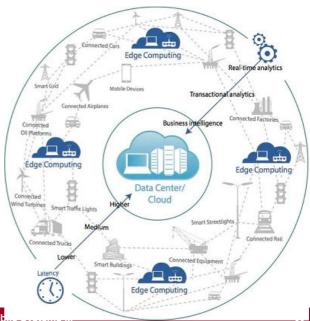
Edge Computing: Definition (again...)

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)

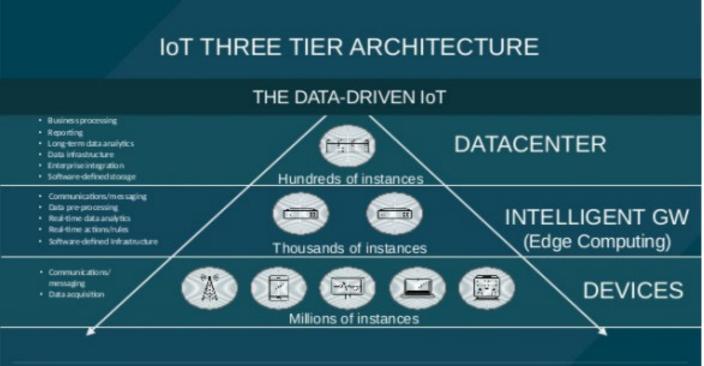
"Only" stronger accent on standard protocols (MEC), content caching (MEC), data aggregation (fog), distributed control (fog), orchestration of virtualized resources (both), mobile offloading (?)



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Edge Computing for Industrial IoT: Quality Requirements



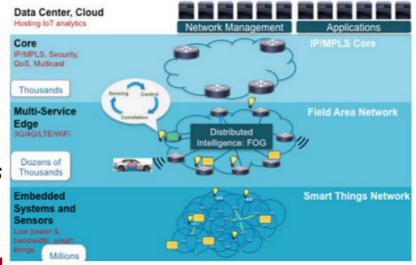


Edge Computing for Industrial IoT: Quality Requirements

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

The Internet of Thing Architecture and Fog Computing



5G and Mobile



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 IoT¹
- **URLLC² + mMTC³** 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









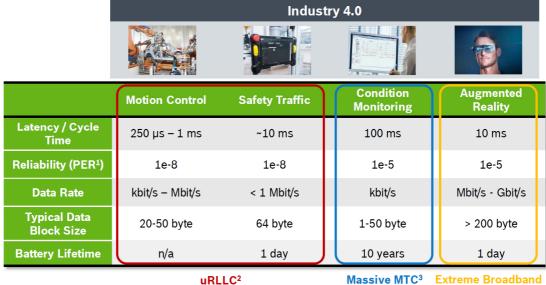
Images: BOSCH



For example, Edge and 5G for Constrained Latency

Selected Performance Requirements

Credits to Bosch



→ most challenging

Massive MTC³ Extreme Broadba + Low Latency

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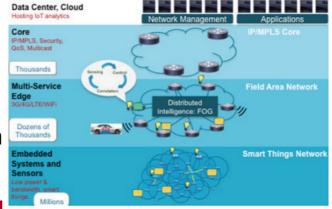
Edge Computing for IoT Apps: Research Directions

- 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

•



The Internet of Thing Architecture and Fog Computing

5G and Mobile Edge Computing

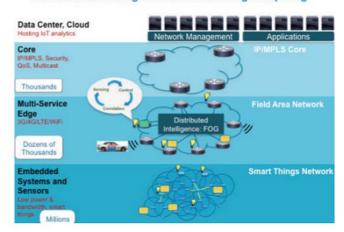


1) Architecture Modeling

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…

The Internet of Thing Architecture and Fog Computing



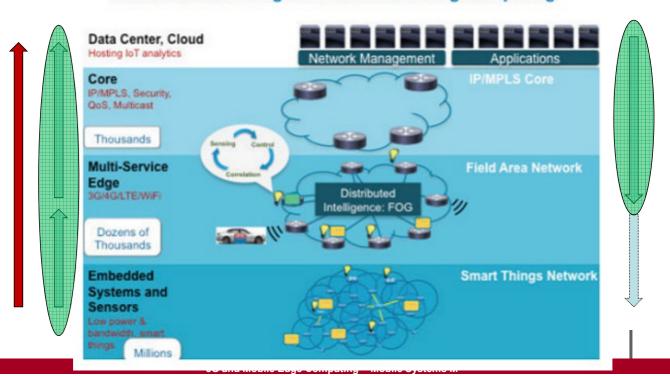
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1) Architecture Modeling Need for new models Offloading and Onloading

The Internet of Thing Architecture and Fog Computing



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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

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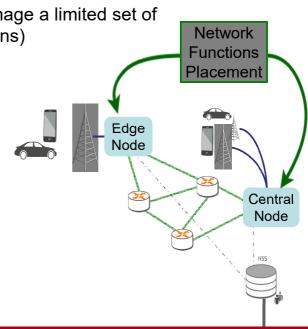
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For example, Network Function Placement

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





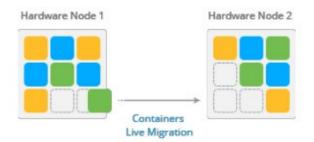
Edge computing empowered by containerization



Container live migration and state maintenance:

which tradeoff between state consistency and overhead?

Live Migration for Containers



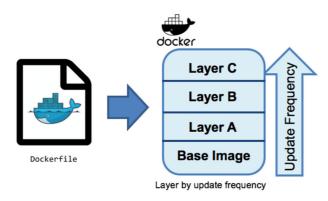




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Edge computing empowered by containerization

- 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)

′0



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

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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

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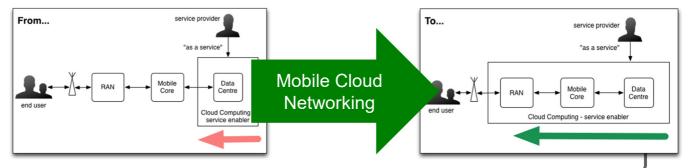
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U Mobile Cloud Networking Project: Network Functions as a Service

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







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

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ETSI Network Functions Virtualization (NFV)

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

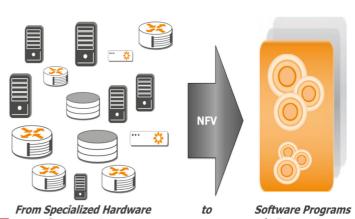
- Running on high volume servers with high volume storage
- Interconnected by generic high volume switches
- Automatically orchestrated and remotely installed

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



Components

in Datacenters

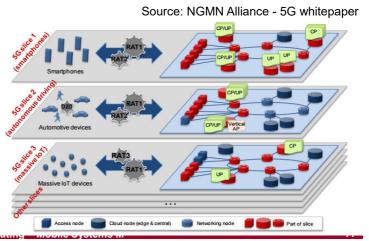


NFV and SDN as the support technologies for 5G

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



5G and Mobile Edge Comp

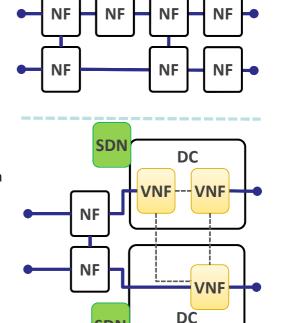


NFV and **SDN**

- 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.

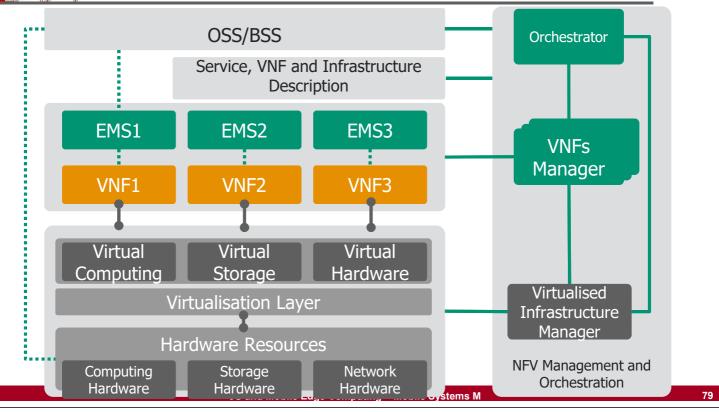
The main value added differentiator between different solutions is the *quality of the software*

how well it can solve the specific service needs

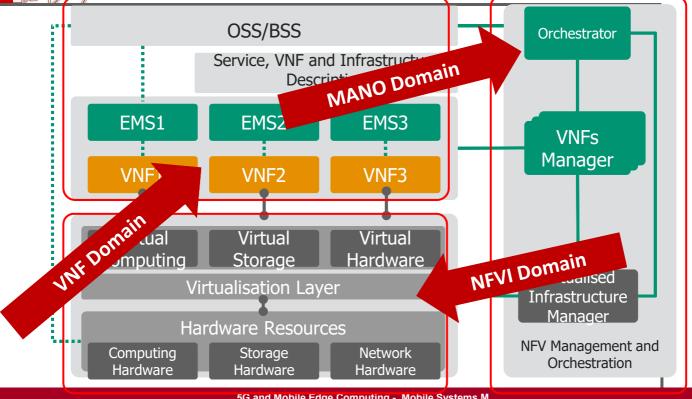




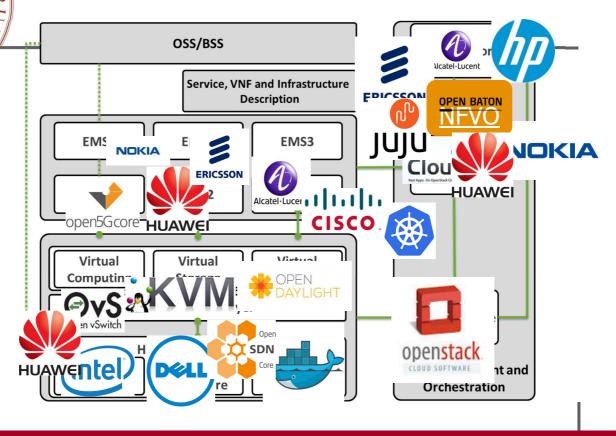
NFV Architecture Blue print is ready since Nov. 2012...



NFV Architecture Blue print is ready since Nov. 2012...







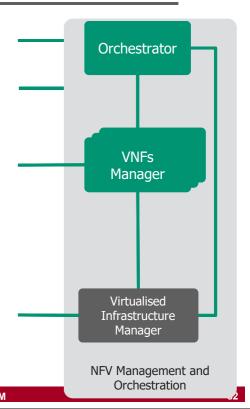
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Virtualized Infrastructure Manager (VIM)

- 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

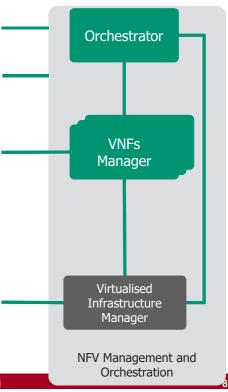


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VNF Manager (VNFM)

- 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

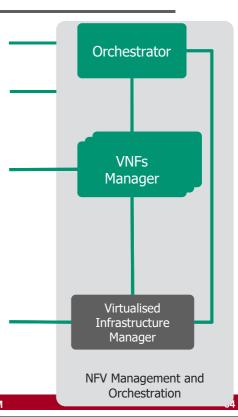


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Network Function Virtualization Orchestration (NFVO)

- 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

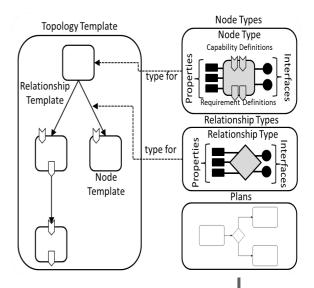




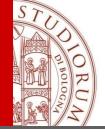
OASIS TOSCA

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



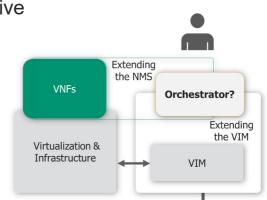
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A comprehensive MANO orchestrator was (still) missing...

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:

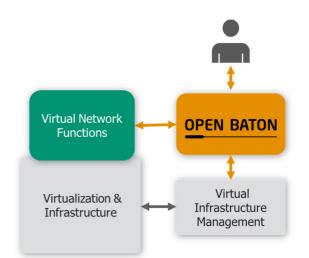
- Virtual Network Function providers
- Cloud Infrastructure providers

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



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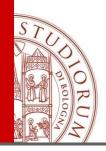


What OpenBaton stands for

- 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 87

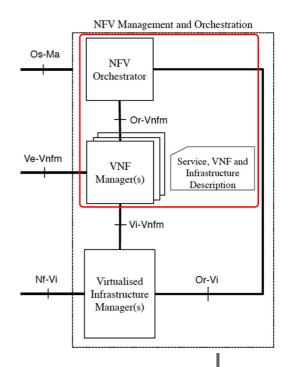


OpenBaton

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



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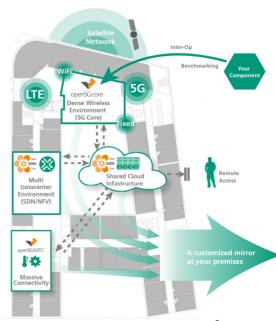
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The Fraunhofer FOKUS 5G Playground

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 endto-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

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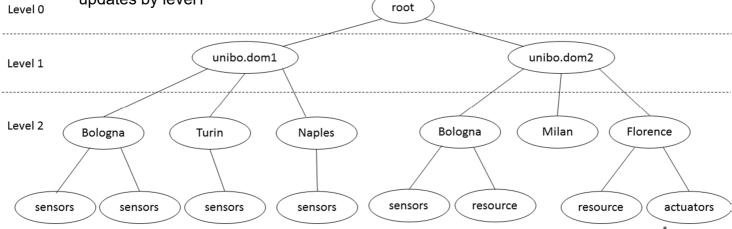
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3) Scalability via Hierarchical Locality Management

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

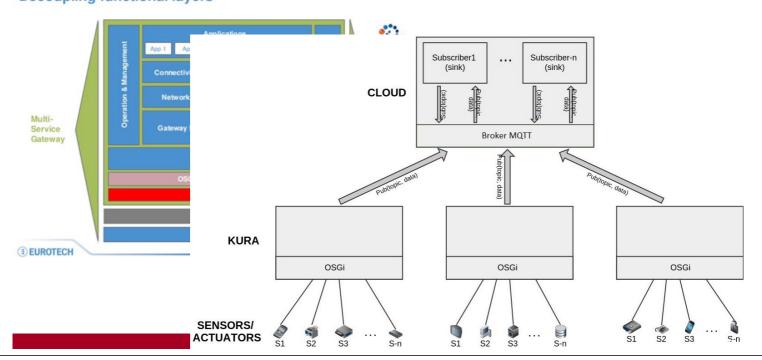
- Level0 includes the root node, enables inter-localities communications
- Level1 includes all the nodes belonging to a specific domain, updates level2 about hierarchy modification (quicker update)
- Level2 includes all the nodes of a given domain and (sub)group, receives periodically updates by level1





Industry-grade Integration with IoT Gateways: Eurotech Kura

Functional Architecture Decoupling functional layers





MQTT-CoAP Interworking in our Extended Kura Gateway

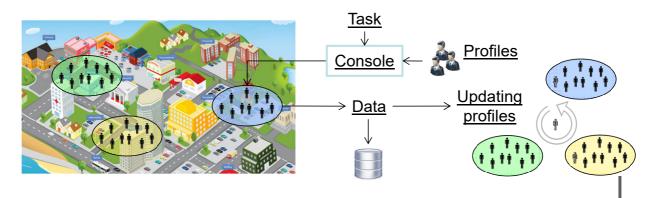
- Design and implementation of a scalable distributed architecture for the dynamic management of IoT resources via hierarchical localities
- Gateway coordination via integration of emerging standard protocols, i.e.,
 MQTT and CoAP:
 - MQTT natively integrated into Kura
 - MQTT non-negligible limitations 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

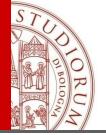
- Citizens are active (participactive) actors contributing to the collection of data along their usual routes/habits
- Smartphones as sensors used to opportunistically monitor phenomena in the Smart City

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



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Smart City Crowdsensing:

the Bologna use case

ParticipAct - http://participact.unibo.it

Bologna heatmap:

- 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 (M²EC) nodes* for serving local MCS computing/storage needs
- Ongoing implementation in the MCS ParticipAct framework through the integration of the MEC Elijah (OpenStack++) platform

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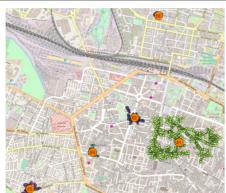


Human-driven Edge Computing (HEC)

- 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 (M²EC)
 - 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 M²EC



Human-driven Edge Computing (HEC)



FMEC nodes identified as DBSCAN clusters







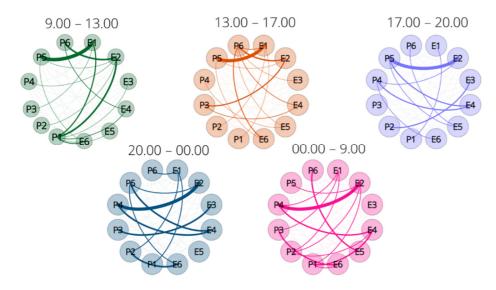
M²EC nodes identified as DBSCAN clusters

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Human-driven Edge Computing (HEC)



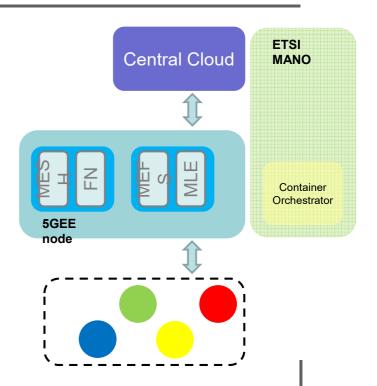
measurement of connectivity as temporal graphs between FMECs (E_i) and M²EC (P_i)

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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



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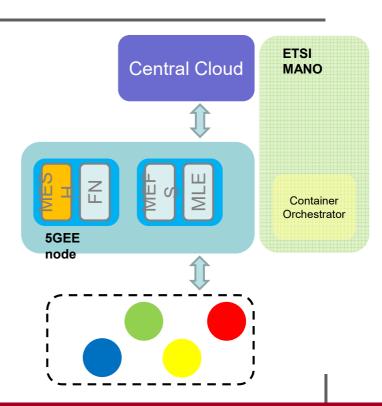
MEC Services Handoff (MESH) as an Example of Advanced Management Operations at the Edge

- 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

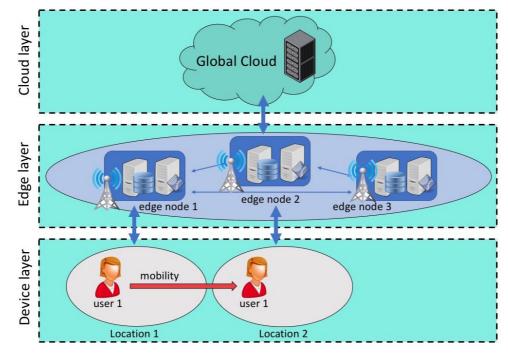


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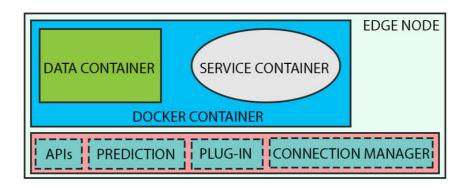


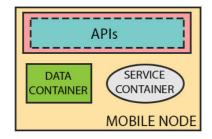
Edge-enabled Handoff

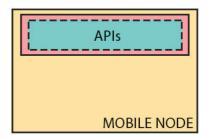




MESH – Architecture







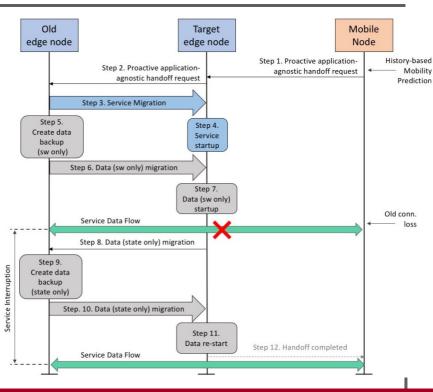
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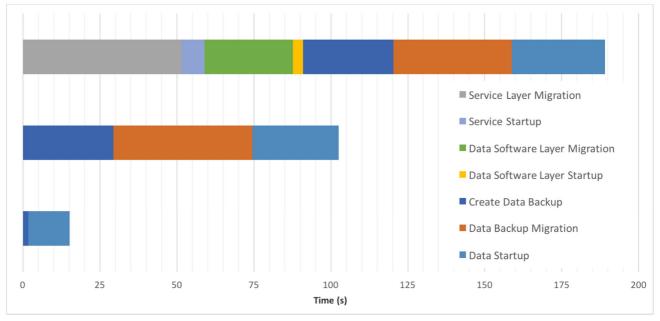
MESH – Proactive Handoff

- 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

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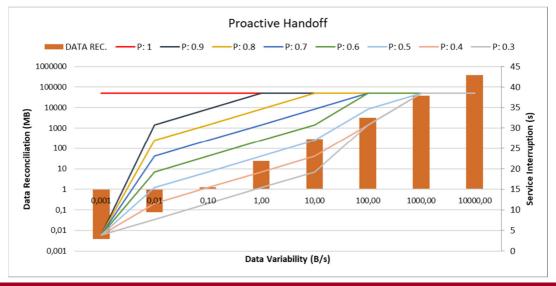
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Application-aware: Simulation Results

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



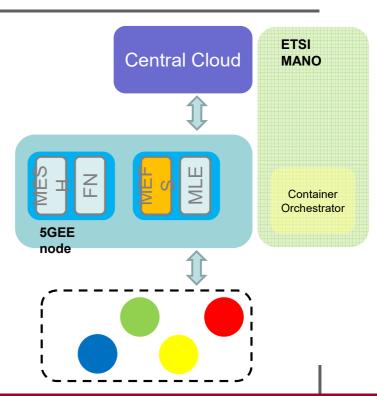
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Mobile Edge File System

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





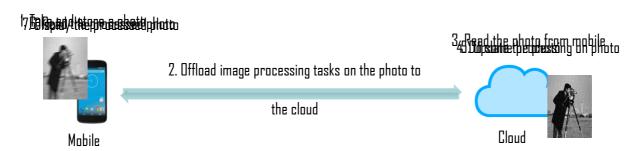
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Example of Cloud-assisted App

Photo Enhancement App

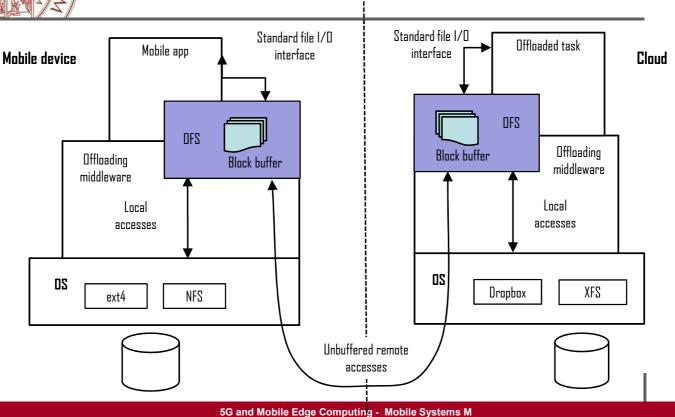


- Characteristics of file I/O in cloud-assisted mobile apps:
 - Read and write files on both mobile and cloud
 - Require strong consistency
 - Long I/O latency due to transferring the file over network

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OFS Architecure

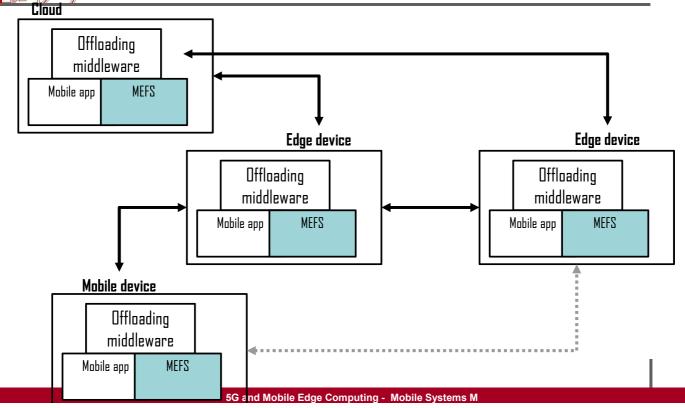




MEFS Architecture

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MEC Technical Challenges

1. Application portability

Transfer apps between MEC servers

2. Resilience

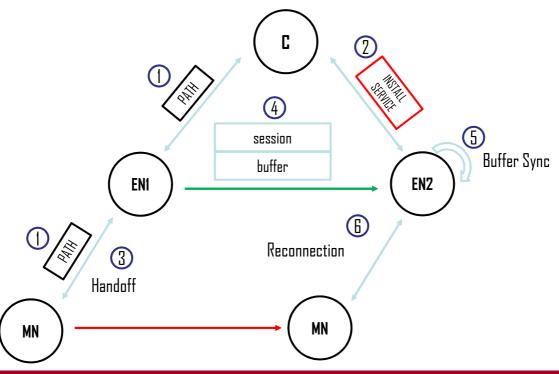
 Protect against node or communication failure

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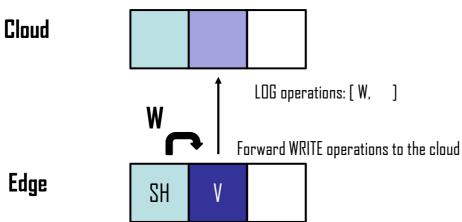


MEFS Handoff





MEFS Resilience



Edge node fails: Log-based FS approach

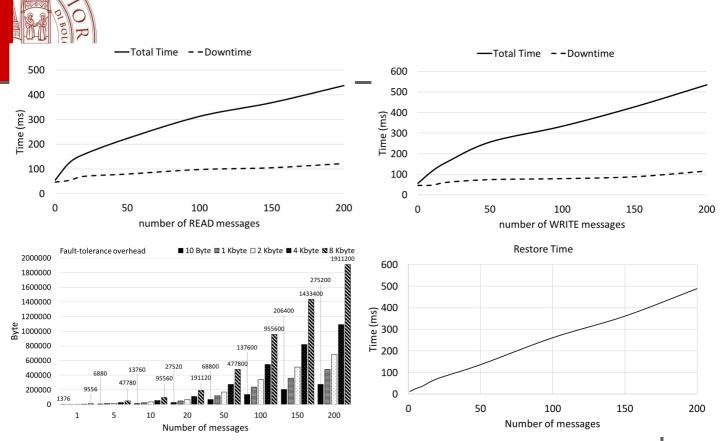
Mobile

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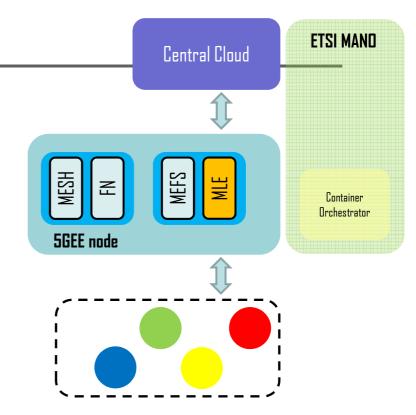
MEFS Performance





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

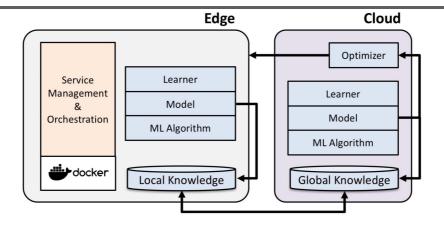


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Support architecture for ML

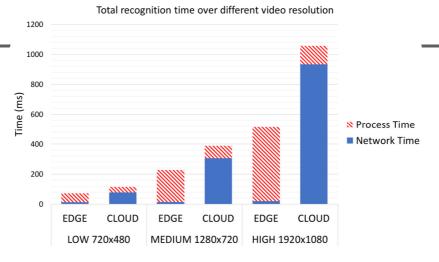


- A set of ML algorithms run at the edge for online analysis
- Learning module able to train model (Digital Twins)
- An Optimizer module that sends feedback to reinforce distributed models

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Experimental Results (Smart City scenario)



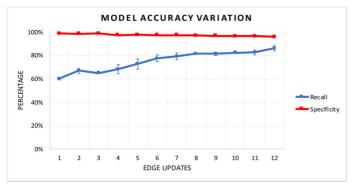
- Compared performance of face recognition app in two scenario: mobile/edge and mobile/cloud when the video quality grows
 - In the cloud the recognition time goes up rapidly as the video quality increases
 - Mobile/edge recognition performs better due to lower latency and higher throughput at the edge

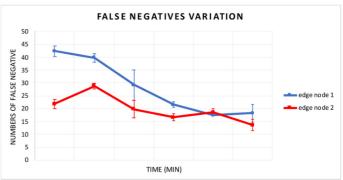
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Experimental Results (IIoT scenario)

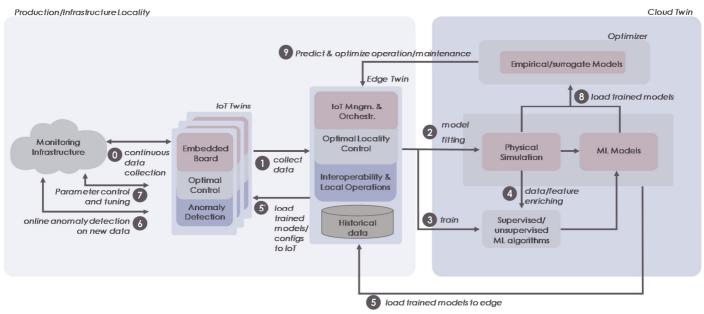




- By sending reinforced models from the edge towards the cloud:
 - the total model accuracy is more or less the same
 - more accuracy to predict negative instances



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



Still confidential...

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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 widescale 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...

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To conclude: Open Innovation Challenges for Industrial Exploitation

About immediate industrial applicability of solutions in the field, in several subareas with specific performance/functional constraints we are far from ready-todeploy 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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Some Primary References (1)

- ETSI's Mobile Edge Computing initiative https://portal.etsi.org/Portals/0/TBpages/MEC/Docs/Mobile-edge_Computing_-_Introductory_Technical_White_Paper_V1%2018-09-14.pdf
- IEEE Future Networks Initiative, https://futurenetworks.ieee.org/
- Open Fog Consortium, https://www.openfogconsortium.org/
- Open Edge Computing (OEC) open source project, http://openedgecomputing.org/
- Cisco IOx, https://developer.cisco.com/site/iox/
- M. Satyanarayanan, P. Bahl, R. Caceres, N. Davies, "The Case for VM-Based Cloudlets in Mobile Computing," IEEE journal on Pervasive Computing, vol.8, no.4, pp.14-23, Oct.-Dec. 2009



Some Primary References (2)

- F. Bonomi, R. Milito, J. Zhu and S. Addepalli, "Fog Computing and Its Role in the Internet of Things,"Proceedings of the first edition of the MCC workshop on Mobile cloud computing (MCC 2012), ACM, August 2012
- S. Singh, Yen-Chang Chiu, Yi-Hsing Tsai, Jen-Shun Yang, "Mobile Edge Fog Computing in 5G Era: Architecture and Implementation", Computer Symposium (ICS), 2016
- M. Tao, K. Ota, M. Dong, "Foud: Integrating Fog and Cloud for 5G-Enabled V2G Networks," IEEE Network, Vol. 31, No. 2, March/April 2017
- D. Keren, G. Sagy, A. Abboud, D. Ben-David, A. Schuster, I. Sharfman, A. Deligiannakis, «Geometric Monitoring of Heterogeneous Streams», IEEE Transactions on Knowledge and Data Engineering, Vol. 26, No. 8, 2014
- D. Keren, I. Sharfman, A. Schuster, A. Livne, «Shape Sensitive Geometric Monitoring», IEEE Transactions on Knowledge and Data Engineering, Vol. 24, No. 8, 2012

5G and Mobile Edge Computing - Mobile Systems M

127



Some Secondary © References (3)

- P. Bellavista, J. Berrocal, A. Corradi, S.K. Das, L. Foschini, A. Zanni, «A survey on fog computing for the Internet of Things», Elsever PMC, accepted, 2019
- P. Bellavista, C. Giannelli, T. Lagkas, P.G. Sarigiannidis, «Quality Management of Surveillance Multimedia Streams Via Federated SDN Controllers in Fiwi-Iot Integrated Deployment Environments», IEEE Access, 2018
- P. Bellavista, A. Corradi, L. Foschini, S. Monti, «Improved Adaptation and Survivability via Dynamic Service Composition of Ubiquitous Computing Middleware», IEEE Access, 2018
- P. Bellavista, S. Chessa, L. Foschini, L. Gioia, M. Girolami, «Human-Enabled Edge Computing: Exploiting the Crowd as a Dynamic Extension of Mobile Edge Computing», IEEE Communications Magazine, 2018
- L. Tartarini, M. Gerla, P. Bellavista, et al., «Software-defined handover decision engine for heterogeneous cloud radio access networks», Computer Comm., 2018



Some Secondary © References (4)

- R. Venanzi, B. Kantarci, L. Foschini, P. Bellavista, «MQTT-Driven Sustainable Node Discovery for Internet of Things-Fog Environments», IEEE ICC, 2018
- L. Scalzotto, K.E. Benson, G. Bouloukakis, P. Bellavista, V. Issarny, S. Mehrotra, N. Venkatasubramanian, «An Implementation Experience with SDN-enabled IoT Data Exchange Middleware», ACM Middleware (Posters), 2018
- A. Zanni, S. Forsström, U. Jennehag, P. Bellavista, «Elastic Provisioning of Internet of Things Services Using Fog Computing: An Experience Report», IEEE Mobile Cloud, 2018
- R. Venanzi, B. Kantarci, L. Foschini, P. Bellavista, «MQTT-Driven Node Discovery for Integrated IoT-Fog Settings Revisited: The Impact of Advertiser Dynamicity», IEEE SOSE, 2018
- L. Acquaviva, P. Bellavista, F. Bosi, A. Corradi, L. Foschini, S. Monti, A. Sabbioni, «NoMISHAP: A Novel Middleware Support for High Availability in Multicloud PaaS», IEEE Cloud Computing, 2017

5G and Mobile Edge Computing - Mobile Systems M

129



Some Secondary © References (5)

- J. De Benedetto, P. Bellavista, L. Foschini, «Proximity discovery and data dissemination for mobile crowd sensing using LTE direct», Computer Networks, 2017
- P. Bellavista, A. Corradi, A. Zanni, «Integrating mobile internet of things and cloud computing towards scalability: lessons learned from existing fog computing architectures and solutions», IJCC, 2017
- H. Kim, H. Oh, P. Bellavista, J. Ben-Othman, «Constructing event-driven partial barriers with resilience in wireless mobile sensor networks», J. Network and Computer Applications, 2017
- P. Bellavista, C. Giannelli, S. Lanzone, G. Riberto, C. Stefanelli, M. Tortonesi, «A Middleware Solution for Wireless IoT Applications in Sparse Smart Cities», Sensors, 2017
- A. Zanni, S.-Y. Yu, P. Bellavista, R. Langar, S. Secci, «Automated selection of offloadable tasks for mobile computation offloading in edge computing», CNSM, 2017



Some Secondary © References (6)

- P. Bellavista, L. Foschini, D. Scotece, «Converging Mobile Edge Computing, Fog Computing, and IoT Quality Requirements», FiCloud, 2017
- A. Zanni, S.-Y. Yu, S. Secci, R. Langar, P. Bellavista, D.F. Macedo, «Automated offloading of android applications for computation/energy optimizations», IEEE INFOCOM Workshops, 2017
- I. Aljawarneh, P. Bellavista, A. Corradi, R. Montanari, L. Foschini, A. Zanotti, «Efficient spark-based framework for big geospatial data query processing and analysis», IEEE ISCC, 2017
- P. Bellavista, A. Zanni, M. Solimando, «A migration-enhanced edge computing support for mobile devices in hostile environments», IWCMC, 2017
- G.A. Carella, M. Pauls, T. Magedanz, M. Cilloni, P. Bellavista, L. Foschini, «Prototyping nfv-based multi-access edge computing in 5G ready networks with open baton», NetSoft, 2017

5G and Mobile Edge Computing - Mobile Systems M

131



Some Secondary © References (7)

- A. Edmonds, G. Carella, F. Zarrar Yousaf, C. Goncalves, T.M. Bohnert, T. Metsch, P. Bellavista, L. Foschini, «An OCCI-compliant framework for fine-grained resource-aware management in Mobile Cloud Networking», IEEE ISCC, 2016
- P. Bellavista, A. Zanni, «Scalability of Kura-extended Gateways via MQTT-CoAP Integration and Hierarchical Optimizations», Mobilware, Springer, 2016
- P. Bellavista, invited keynote speech, «Mobile Cloud Networking: Lessons Learnt, Open Research Directions, and Industrial Innovation Opportunities», IEEE MobileCloud, 2016
- E. Cau, M. Corici, P. Bellavista, L. Foschini, G. Carella, A. Edmonds, T.M. Bohnert, «Efficient Exploitation of Mobile Edge Computing for Virtualized 5G in EPC Architectures». IEEE MobileCloud, 2016
- P. Bellavista, A. Zanni, «Towards better scalability for IoT-cloud interactions via combined exploitation of MQTT and CoAP», IEEE RTSI, 2016
- ... and several © others under review...