Fog Computing, Mobile Edge Computing, Cloudlets - which one?

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Acknowledgement

1.This overview is compiled and structured, based on several public documents belonging to different authors and groups, on Cloud/Fog, Mobile Edge Computing, 4G/5G networking, SDN, NFV, etc. : conferences material, studies, research papers, standards, projects, overviews, tutorials, etc. (see specific references in the text and Reference list).

2. Given the topics extension, this presentation is a high level overview only.

Fog Computing, Mobile Edge Computing, Cloudlets - which one?

Motivation of this talk

Facts:

- **Internet and Telecom convergence → Integrated networks**: **Future Internet**
- **Novel services, applications and communication paradigms**
  - **Internet of Things (IoT) and Smart cities, M2M and Vehicular communications, Content/media oriented communications, Social networks,**
  - **Internet of Everything (IoE), etc.**
- **Novel, emergent technologies** are changing networks and services architectures :
  - ***Supporting technologies***
    - ***Cloud Computing***
    - ***Fog/Edge Computing /Mobile Edge Computing /Cloudlets***
      defined independently, but they can cooperate
    - ***Software Defined Networks (SDN)***
    - ***Network Function Virtualization (NFV)***
    - ***Advances in wireless technologies: 4G-LTE, LTE-A, WiFi, 5G***

Fog Computing, Mobile Edge Computing, Cloudlets - which one?

Motivation of this talk

Trends:

- **Cloud computing (CC)** is more and more used, including private/local and mixed cloud development
- However, traditional CC **centralization** (processing ,storage,..) may lead to some **limitations**
- **Novel services and applications like IoT, mobility-related, .. would be better served by decentralized systems**
- **Edge networking devices and even user terminals – more powerful** in terms of processing, storage, communication capabilities

- **Result**: recent attempts to push CC capabilities to the network edge:
  - Fog/Edge Computing
  - Mobile Edge Computing
  - Cloudlets, ..
- **To discuss:**
  - **What are their fundamentals? their relationship?**
  - **Competition? Cooperation? Complementary?**

CONTENTS

CONTENTS

1. Introduction

- **Fog Computing, Mobile Edge Computing, Cloudlets, Microdata centers, ..**
- **Fog Computing (FC)** - (*CISCO* ~ 2011) extends the CC to the edge of networks, in particular wireless networks for the Internet of Things (IoT)
  - FC nodes (FCNs) are typically located away from the main cloud data centers, i.e., at the network edge
- **Mobile Edge Computing (MEC)** – *ETSI* - an industry spec. ~2014
  - MEC pushes the CC capabilities close to the **Radio Access Networks** in 4G, 5G
  - ETSI is developing a system architecture and std. for a number of APIs
- **Cloudlet** – developed by *Carnegie Mellon University* ~2013
  - A cloudlet is middle tier of a 3-tier hierarchy: 'mobile device – cloudlet – cloud'
  - Cloudlet ~ "data center in a box" whose goal is to "bring the cloud closer to the users"
- **Micro data center** – developed by *Microsoft Research- ~2015*
  - Is an extension of today's hyperscale cloud data centers (as Microsoft Azure)
  - to meet new application demands like lower latency and new demands related to devices (e.g. lower battery consumption)
- **The above approaches include partially overlapping concepts and are also complementary**

CONTENTS

2. Fog/Edge Computing

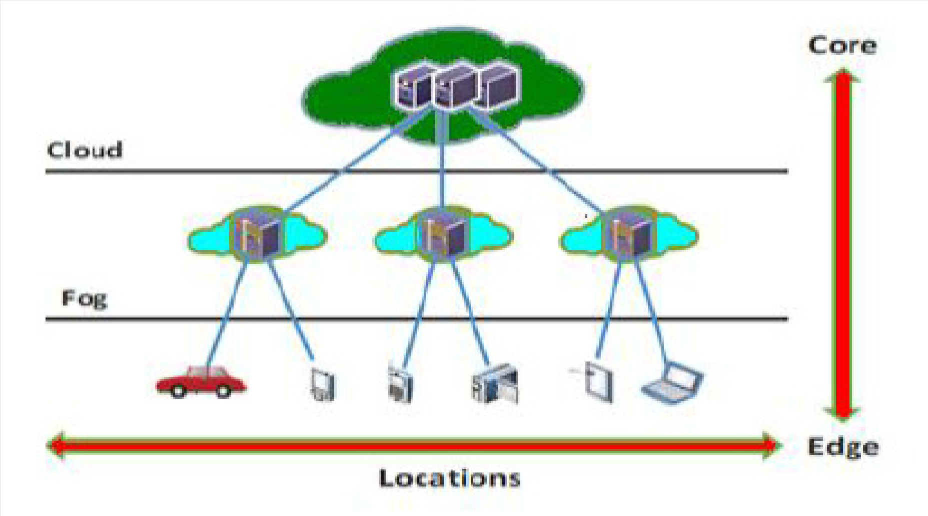
- **Fog Computing (FC) definitions**
  - **Initial (FC) – term coined by Cisco** to make the data transfer more easy in wireless and distributed environment
    - Rationale : *„fog" means that „cloud" is closer to the ground* →
      - **FC = Cloud Computing (CC)** carried out closer to the end users' networks
    - FC = virtualized platform, located between cloud data centers (hosted within the Internet) and end user devices
    - **FC offers strong support for Internet of Things**
    - **FC is not intended to replace CC; they are complementary**

    - *Source [1] : F.Bonomi, R.Milito, J.Zhu, and S.Addepalli, "Fog computing and its role in the Internet of Things," in ACM SIGCOMM Workshop on Mobile cloud Computing, Helsinki, Finland, 2012, pp. 13--16.*
- **Fog computing/networking**
  - decentralized computing infrastructure
  - computing resources and appl. services are distributed in the most logical, efficient places, at any point along the continuum from the data source to the cloud

  - Higher efficiency: lower amount of data to be transported to the cloud for data processing, analysis and storage
    - Reasons: efficiency, security and compliance

2. Fog/Edge Computing

- **Fog Computing (FC) definitions (cont'd)**
- FC performs/offers significant amount of
  - *storage at or near the end-user (avoid* primarily to store in large-scale data centers)
  - *communication at or near the end-user (avoid* routing through the backbone network)
  - *management, including network* measurement, control and configuration, is performed at or near the end-user



Deployment of IoT applications in a 2-tiered way (Cloud- things) does not meet the requirements related to low latency, mobility of the "things" and location awareness

Solution : a multi-tiered architecture (at least 3 tiers) → Fog computing

Source[2]: I. Stojmenovic, S.Wen," The Fog Computing Paradigm: Scenarios and Security Issues", Proc. of the 2014 Federated Conf. on Computer Science and Information Systems pp. 1–8

2. Fog/Edge Computing

- **Fog Computing (FC) definitions (cont'd)**
- **OpenFog Consortium (2015)** definition
- *http://www.openfogconsortium.org/resources/#definition-of-fog-computing*

- "**Fog computing is** a **system-level horizontal architecture** that distributes resources and services of computing, storage, control and networking **anywhere along the continuum from Cloud to Things**"

  - **Horizontal architecture**: Support multiple industry verticals and apps. domains, delivering intelligence and services to users and business

  - **Cloud-to-Thing continuum of services:** services and apps. can be distributed closer to Things, and anywhere along the continuum between Cloud and Things

  - **FC concept is at system-level:** spanning between the Things and the Cloud
    - over the network edges
    - across multiple protocol layers
    - not dependent on specific radio systems, protocol layer
    - it is not just at one part of an E2E system

2. Fog/Edge Computing

- **Fog Computing (FC) definitions (cont'd)**

- FC focuses processing efforts at the LAN end of the chain
  - Data are gathered, processed, and stored within the network, by way of an IoT GW or **FC node (FCN)**
    - Information is transmitted to this GW from various sources in the network
    - it is processed in FCN: then pertinent data + additional commands, are transmitted back, towards the necessary devices
- FC(+) :
  - enable a single, powerful processing device to
    - process data received from multiple end points
    - and send information exactly where it is needed
  - offers lower latency than centralized CC processing

  - FC is scalable ← it gives to a centralized processing body a more big-picture view of the network as it has multiple data points feeding it information

2. Fog/Edge Computing

- **Fog Computing (FC) definitions (cont'd)**
  - **More comprehensive FC definition:**
    - **FC -** scenario where
      - a huge number of heterogeneous (wireless and sometimes autonomous) ubiquitous and decentralised devices,
      - *communicate* and potentially *cooperate* among them and with the network to perform storage and processing tasks without the intervention of third-parties
    - tasks performed: basic network functions or new services and applications that run in a sandboxed environment.
    - *Source [3] :L.M. Vaquero, L.Rodero-Merino, "Finding your Way in the Fog: Towards a Comprehensive Definition of Fog Computing", ACM SIGCOMM Computer Comm. Review, Vol. 44, No 5, October 2014*

2. Fog/Edge Computing

- **Fog Computing (FC) definitions (cont'd)**
- **Related term to FC – having a larger scope**
  - **Edge Computing** (EC) - pushes the computing applications, data, and services *away from centralized nodes to the network edge,* enabling analytics and knowledge generation to occur close to the data sources
  - **Edge Computing (EC)** deals with resources that might not be continuously connected to a network : laptops, smartphones, tablets and sensors
  - EC covers a wide range of technologies and services:
    - wireless sensor networks
    - mobile data acquisition and mobile signature analysis
    - cooperative distributed P2P adhoc networking and processing also classifiable as Local Cloud/Fog computing and Grid/Mesh Computing
    - mobile edge computing
    - cloudlets
    - distributed data storage and retrieval
    - autonomic self-healing networks
    - remote cloud services
    - augmented reality, etc.

2. Fog/Edge Computing

- **Fog/Edge (FC) computing- summary of characteristics** [4]:
  - **Fog computing nodes (FCN)** are typically located away from the main cloud data centres, at the network edge
  - FC enables *low and predictable latency*
  - **FCNs**
    - are *wide-spread* and geographically available *in large numbers*
    - provide applications with *awareness of device geo location* and device context
    - *can support mobility of devices*
      - i.e. if a device moves far away from the in- service FCN, the fog node can redirect the app. on the mobile device to associate with a new app. instance on a FCN that is currently closer to the device
    - *offer special services that may only be required in the IoT context* (e.g. translation between IP to non-IP transport)
    - are typically accessed over wireless network
  - Fog app. code runs on FCNs as part of a distributed cloud application

Source[4] : Guenter I. Klas "Fog Computing and Mobile Edge Cloud Gain Momentum", Open Fog Consortium, ETSI MEC and Cloudlets , Version 1.1 Nov 22, 2015

2. Fog/Edge Computing

- **Comparison : Cloud Computing versus Fog Computing**
- **FC provides**
  - **light-weight cloud-like facility** close of mobile users
  - users with a **direct short-fat** connection versus long-thin mobile cloud connection
  - customized and engaged **location-aware** services
- **FC is still new and there is still lack of a standardized definition**

- **Comparison between Fog/Edge (FC) and Conventional Cloud Computing** [5]:

	Fog Computing	Cloud Computing
Target User	Mobile users	General Internet users.
Service Type	Limited localized information services related to specific deployment locations	Global information collected from worldwide
Hardware	Limited storage, compute power and wireless interface	Ample and scalable storage space and compute power
Distance to Users	In the physical proximity and communicate through single-hop wireless connection	Faraway from users and communicate through IP networks
Working Environment	Outdoor (streets, parklands, *etc.*) or indoor (restaurants, shopping malls, *etc.*)	Warehouse-size building with air conditioning systems
Deployment	Centralized or distributed in reginal areas by local business (local telecommunication vendor, shopping mall retailer, *etc.*)	Centralized and maintained by Amazon, Google, *etc.*

Source [5] T H. Luan et.; al. , "Fog Computing: Focusing on Mobile Users at the Edge" arXiv:1502.01815v3 [cs.NI] 30 Mar 2016

2. Fog/Edge Computing

- **Comparison: Cloud Computing versus Fog Computing**
  - **Comparisons on different parameters** [6]:

Parameters	Cloud Computing	Fog Computing
Server nodes location	Within the Internet	At the edge of the local network
Client and server distance	Multiple hops	Single/multiple hop
Latency	High	Low
Delay Jitter	High	Low
Security	Non-locally controllable	Locally controllable
Location awareness	No	Yes
Vulnerability	Higher probability	Lower probability
Geographical distribution	Centralized	Dense and Distributed
Number of server nodes	Few	Very large
Real time interactions	Not fully supported	Supported
Usual last mile connectivity	Leased line /wireless	Mainly wireless
Mobility	Limited support	Supported

See also [6] K.P.Saharan A.Kumar " Fog in Comparison to Cloud: A Survey", Int'l. Journal of Computer Applications (0975 – 8887) Volume 122 – No.3, July 2015

2. Fog/Edge Computing

- **Comparison: Cloud Computing versus Fog Computing [3]**

	Cloud	Fog
Latency	High (eventual consistency)	Low (locality)
Access	Fixed and wireless	Mainly wireless
Explicit mobility	NA	Lispmob[8]
Control	Centralised/hierarchical (full control)	distributed/hierarchical (partial control)
Service access	through core	at the edge/ on handheld device
Availability	99.99%	Highly volatile/ highly redundant
# of users/devices	Tens/Hundreds of millions	Tens of billions
Price per server device	$1500-3000	$50-200
Main content generator	Humans	Devices/sensors
Content generation	Central location	Anywhere
Content consumption	End devices	Anywhere
Software virtual infrastructure	Central corporate servers	User devices

Source [3] :L.M. Vaquero, L.Rodero-Merino, "Finding your Way in the Fog: Towards a Comprehensive Definition of Fog Computing", ACM SIGCOMM Computer Comm. Review, Vol. 44, No 5, October 2014

2. Fog/Edge Computing

- **Fog/Edge (FC) computing applications areas**

- Fog is considered to be an appropriate platform for a number of critical Internet of Things (IoT) services and applications:
  - Connected Vehicle
  - Smart Grid
  - Smart Cities
  - Wireless Sensors and Actuators Networks (WSANs)
  - ….

- Note: no yet exists a globally accepted unique definition of Fog Computing versus Edge Computing

2. Fog/Edge Computing

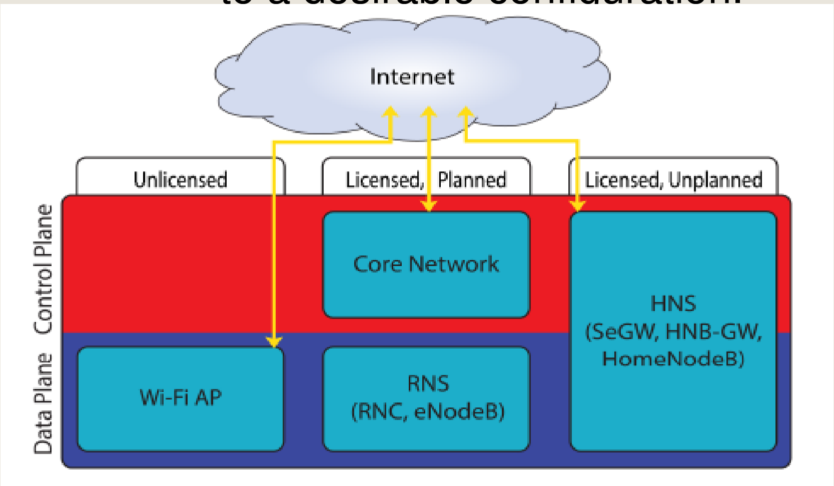
- **Fog/Edge (FC) computing enabled applications**
- **Data plane (DPl)*:***
  - **Pooling of clients idle computing/storage/bandwidth resources and local content**
  - **Content caching at the edge** and bandwidth management at home
  - Client-driven distributed beam-forming
  - **Client-to-client direct** communications (e.g., FlashLinQ, LTE/WiFi Direct, Air Drop)
  - **Cloudlets** (mobility-enhanced small-scale cloud data center located at the edge of the Internet) and micro data-centers
- **Control plane (CPl)**
  - Over the Top (OTT) content management
  - **Fog-RAN: Fog driven radio access network**
  - **Client-based HetNets control**
  - Client-controlled Cloud storage
  - **Session management and signaling load at the edge**
  - Crowd-sensing inference of network states
  - Edge analytics and real-time stream-mining

- **On top of CPl + DPl - appls. as: 5G Mobile, IoT, Cyber-Physical, Data analytics**

Source[7]: M.Chiang, "Fog Networking: An Overview on Research Opportunities“, December 2015, https://arxiv.org/ftp/arxiv/papers/1601/1601.00835.pdf

2. Fog/Edge Computing

- **Fog/Edge (FC) use cases examples** *[7]*
  - ***1. OTT network provisioning and content management***
    - Network services can be innovated faster : FC can directly leverage the "things" and phones, thus removing the need of introducing new boxes-in-the-network
    - SDKs sitting behind apps on client devices, allow tasks such as URL wrapping, content tagging, location tracking, behaviour monitoring
  - ***2. Client-based HetNets control (in 3GPP standards)***
    - In a HetNet (e.g., LTE, femto, WiFi) a client could observe its local conditions and decide on which network to join (in contrast to traditional network operator control)
    - Through randomization and hysteresis, such local actions may converge globally to a desirable configuration.



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2. Fog/Edge Computing

- **Fog/Edge (FC) use cases examples** *[7]*

- ***3. Crowd-sensing LTE states – for resource management***
  - A collection of client devices can combine
    - passive measurement (e.g., Reference Signal Received Quality-RSRQ)
    - with active probing (e.g., packet train)
    - appl. throughput correlation and historical data mining,
  - in order to infer in real-time the states of an eNB (e.g., the number of Resource Blocks used)

- ***4. Client-controlled Cloud storage***
  - Combined storage (in the Cloud) with Fog control (from client side control) can offer better data privacy
    - E.g., by spreading the bytes (of a given file), in a client shim layer, across multiple Cloud storage providers → better data privacy (even if encryption key is leaked by any given Cloud provider)

2. Fog/Edge Computing

- **Fog/Edge (FC) use cases examples** *(cont'd)*

- ***5. Sharing bandwidth/resources with neighbors***
  - A terminal device can ask the neighbors to share their LTE/WiFi (idle) bandwidth by downloading other parts of the same file and transmitting, via WiFi Direct, client to client
  - Some neighbours become helpers of a given device

- ***6. Bandwidth management at home gateway***
  - In a home set-top box/gateway, the limited broadband capacity can be allocated among competing users and application sessions,
  - according to each session's priority and individual preferences

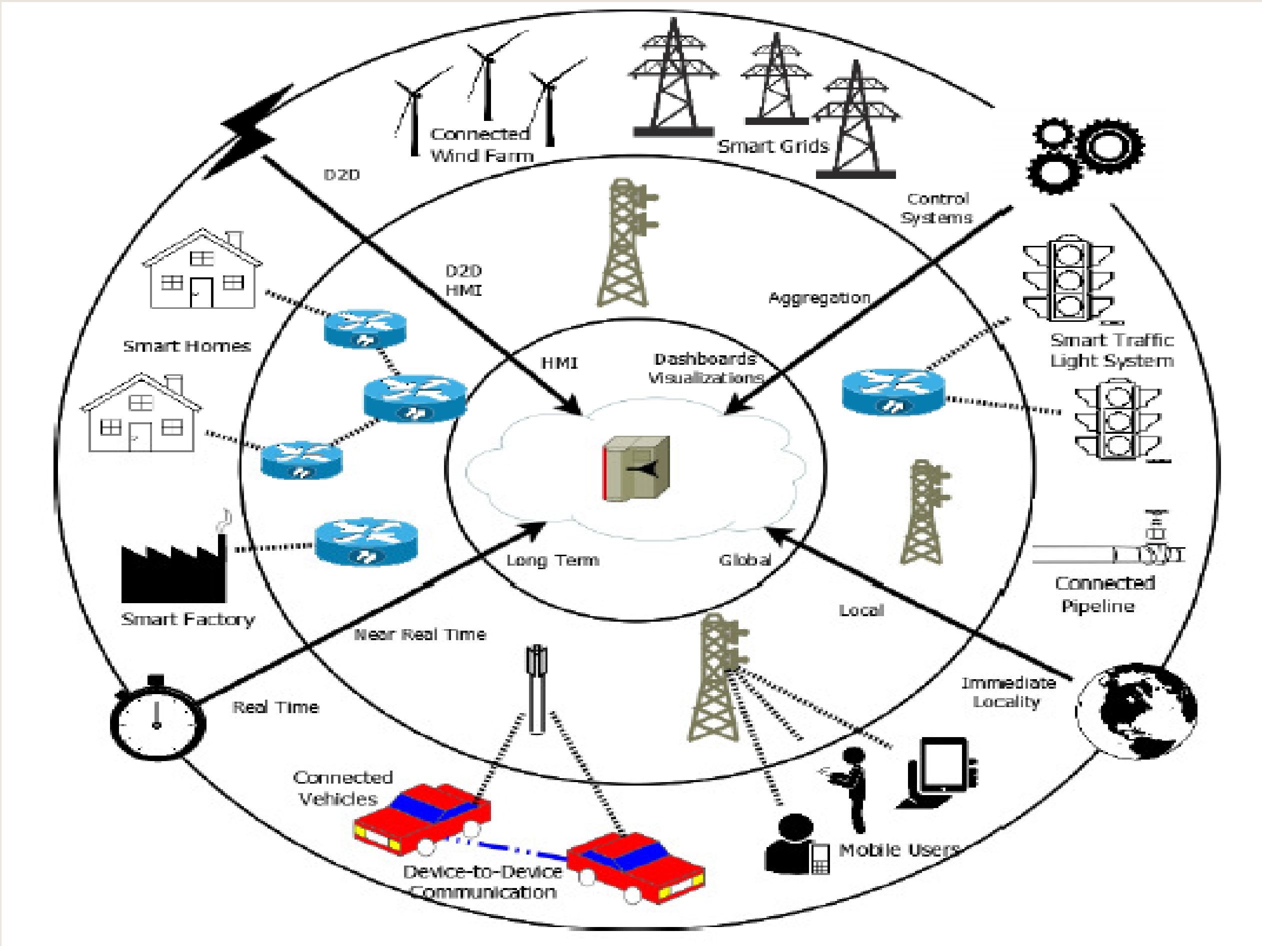
2. Fog/Edge Computing

- **Fog/Edge (FC) use cases examples** *(cont'd)*
- 7. ***A Smart Traffic Light System (STLS) in*** urban scenario
  - The STLS is a component in a Smart Connected Vehicle (SCV) and Advanced Transportation Systems (ATS)
  - **STLS goals/functions:**
    - local, real-time (rt) : accidents prevention
    - global, near - rt: efficient traffic management
    - global, non - rt : collection of relevant data to evaluate and improve the system
  - **Key STLS requirements examples:**
    - Local subsystem latency, Middleware orchestration platform
    - Distributed Networking infrastructure; Interplay with the Cloud
    - Consistency of a highly distributed system; Multi-tenancy; Multiplicity of providers
  - The STL
    - is deployed at each intersection.
    - has sensors measuring the vehicles' distance and speed and detects the presence of pedestrians and cyclists crossing the street.
    - can also issue "slow down" warnings to vehicles at risk to crossing in red, and even modifies its own cycle to prevent collisions.

Source [9]: F.Bonomi, R.Milito, P.Natarajan and J.Zhu, "Fog Computing: A Platform for Internet of Things and Analytics", in N. Bessis and C. Dobre (eds.), "Big Data and Internet of Things": 169
A Roadmap for Smart Environments, Studies in Computational Intelligence 546, Springer Int'l Publishing 2014

2. Fog/Edge Computing

- **Fog/Edge (FC) use cases examples** (cont'd)



Source [8]: A.V. Dastjerdi, et.al., "Fog Computing: Principles, Architectures, and Applications", 2016, Book Chapter in Internet of Things: Principles and Paradigms, http://arxiv.org/abs/1601.02752

CONTENTS

3. Fog Computing Architectures and IoT

- From CISCO: view on idealized **information and computing architecture** supporting the future IoT applications; Fog distributed infrastructure for IoT/IoE

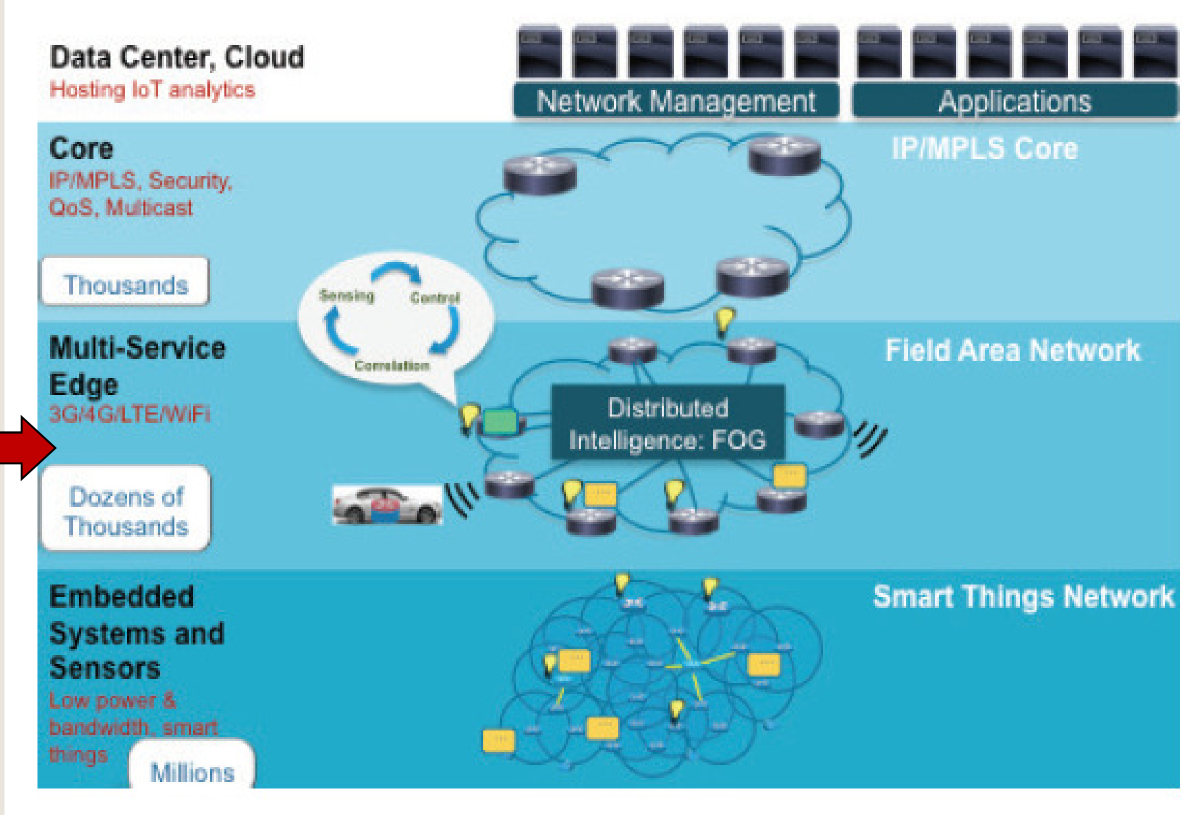
•Edge location, location awareness, low latency

•Geographical distribution
•Large-scale sensor networks to monitor the environment, and the Smart Grid
•Very large number of nodes

•Support for mobility
•Real-time interactions
•Predominance of wireless access

•Heterogeneity
•Interoperability and federation

•Support for on-line analytic and interplay with the Cloud



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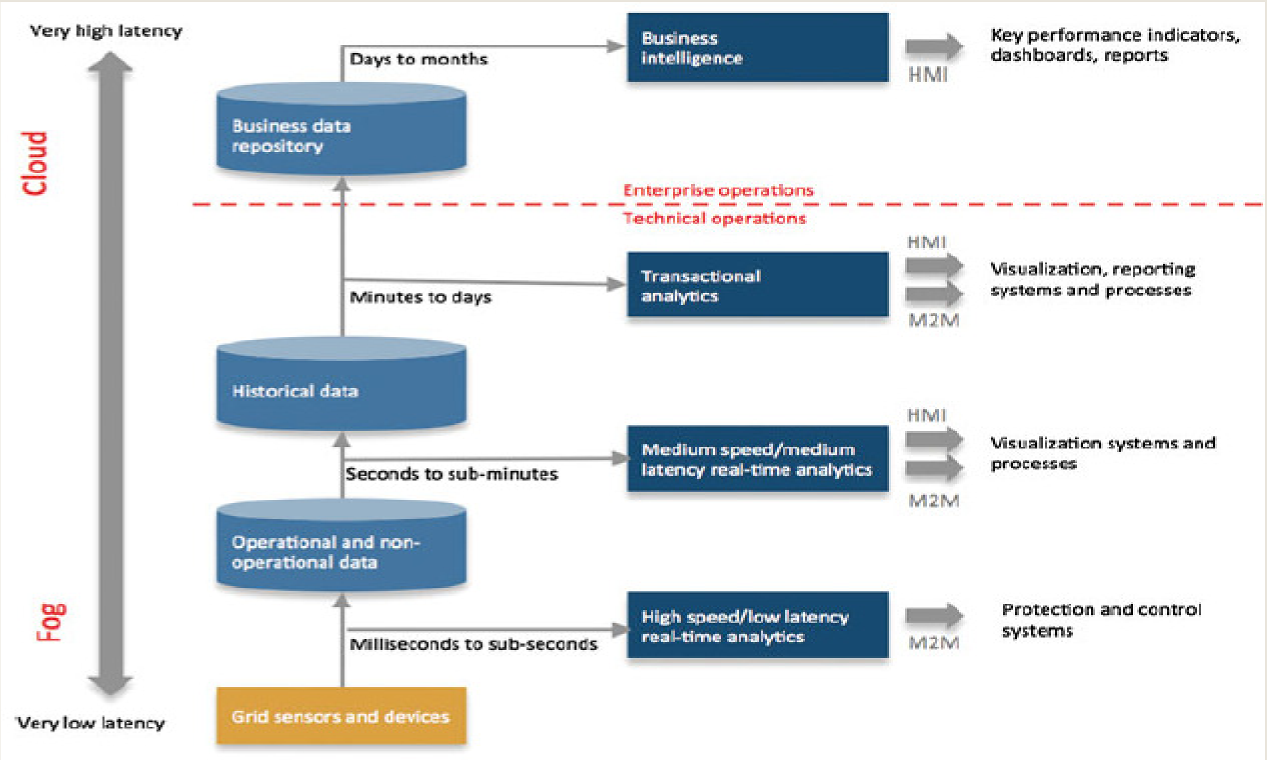
3. Fog Computing Architectures and IoT

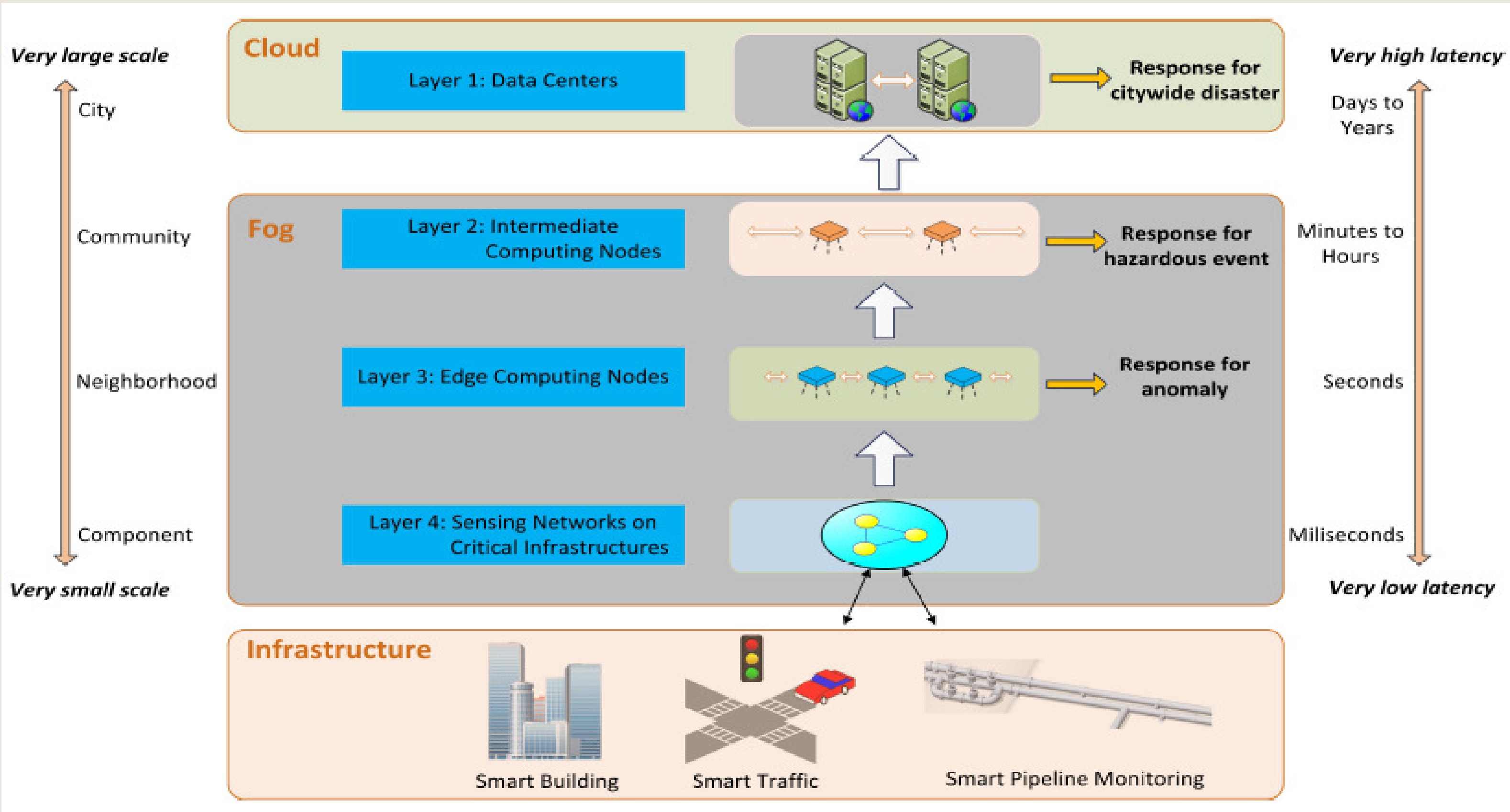
- **Fog and Big Data**
  - Big Data : characterized by Volume, Velocity, Variety and
    - *geo-distribution* – in case of Fog applications
    - data are processed in several layers



Source [9]: F.Bonomi, R.Milito, P.Natarajan and J.Zhu, "Fog Computing: A Platform for Internet of Things and Analytics", in N. Bessis and C. Dobre (eds.), "Big Data and Internet of Things": 169 A Roadmap for Smart Environments, Studies in Computational Intelligence 546, Springer Int'l Publishing ,2014

3. Fog Computing Architectures and IoT

- **FC in future smart cities**
  - **Example: Hierarchical distributed FC layered architecture for smart cities**



Source [10]: B.Tang, et.al., „A hierarchical distributed fog computing architecture for big data analysis in smart cities", ASE BD&SI 2015, October 07-09, 2015, Kaohsiung, Taiwan, ACM, https://www.researchgate.net/publication/281287012, ISBN 978-1-4503-3735-9

3. Fog Computing Architectures and IoT

- **FC in future smart cities (cont'd)**

- **Example : Hierarchical distributed FC architecture**

- It realizes a quick response at neighborhood-wide, community-wide, and city-wide levels, providing high computing performance and intelligence in future smart cities
  - Integrating massive number of infrastructure components and services [10]
  - Geo-distributed system, having to process big data generated by massive number of sensors
  - The intelligence is distributed at the edge of a 4-layer FC network.
  - The FCNs at each layer perform latency-sensitive applications and provide quick control loop to ensure the safety of critical infrastructure components

  - **Layer 4 (bottom)**
    - the sensing network (numerous non-invasive, highly reliable, and low cost, sensory nodes)
    - they are distributed at various public infrastructures to monitor condition changes over time
    - massive sensing data streams are generated, geospatially distributed, which should be processed as a coherent whole

3. Fog Computing Architectures and IoT

- **FC in future smart cities**
- **Hierarchical distributed FC architecture (cont'd)**

- **Layer 3: Edge computing nodes**
  - Many low-power and high-performance computing nodes or edge devices
  - Each edge device controls a local group of sensors that usually cover a neighborhood or a small community, performing data analysis in a timely manner
  - An edge device output has two parts:
    - reports of the results of data processing sent to the next upper layer intermediate computing node
    - simple and quick feedback control to a local infrastructure to respond to isolated and small threats to the monitored infrastructure components

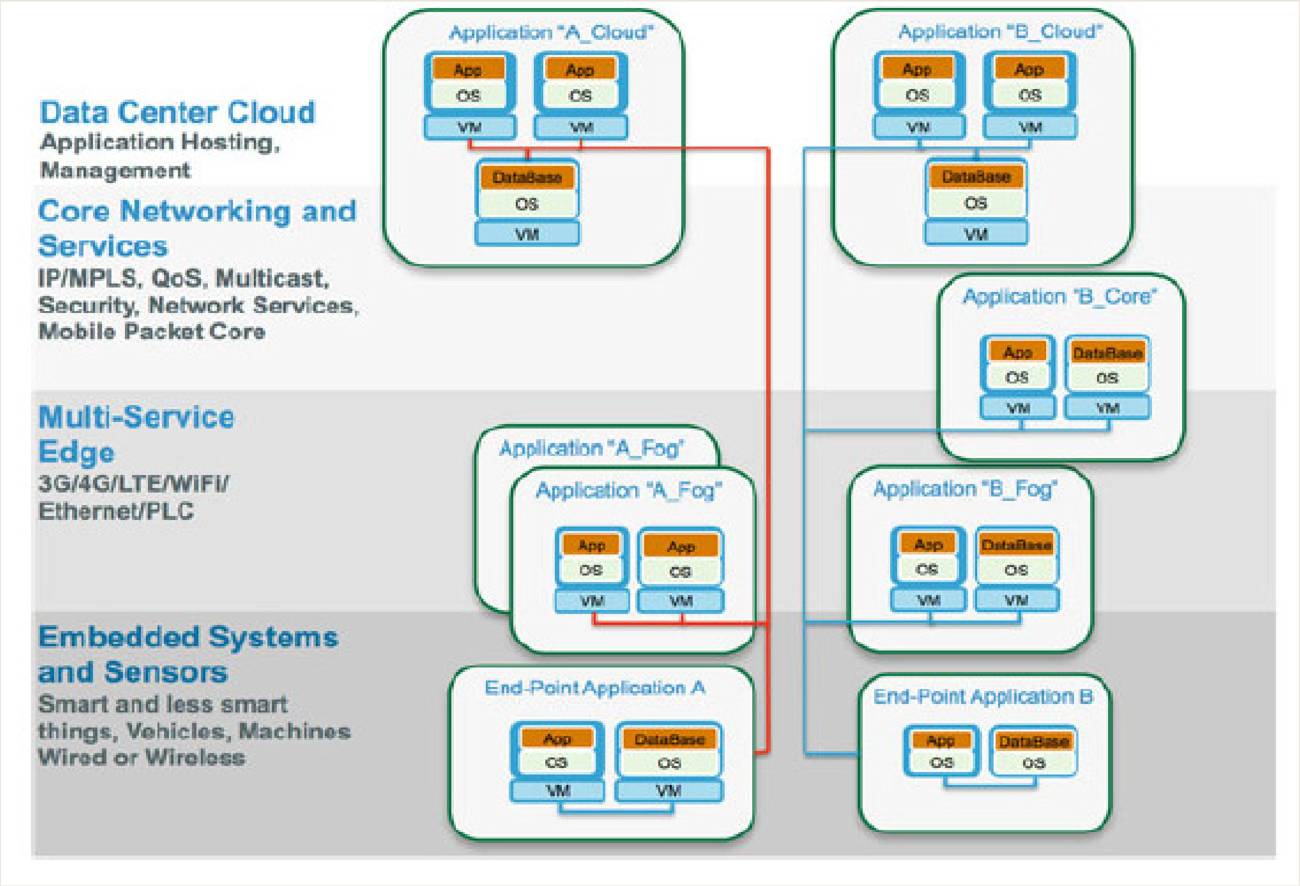
3. Fog Computing Architectures and IoT

- **FC in future smart cities**
- **Hierarchical distributed FC architecture (cont'd)**
- **Layer 2 : intermediate computing nodes**
  - Each node controls an L3 group of edge devices and associates spatial and temporal data to identify potential hazardous events
  - It makes quick response to control the infrastructure when hazardous events are detected
  - The quick feedback control provided at L2 and L3 acts as localized "reflex" decisions to avoid potential damage
  - The data analysis results at L2 & L3 are reported to the top L1, for large-scaled and long-term behavior analysis and condition monitoring

- **Layer 1(top) : Cloud Computing data center**
  - L1 provides city-wide monitoring and centralized control
  - Complex, long-term, and city-wide behavior analyses can be performed
    - E.g., large-scale event detection, long-term pattern recognition, relationship modeling, to support dynamic decision making
  - L1: city-wide response and resource management in the case of a natural disaster or a large-scale service interruption

3. Fog Computing Architectures and IoT

- **Distributed IoT/IoE applications on the fog infrastructure**



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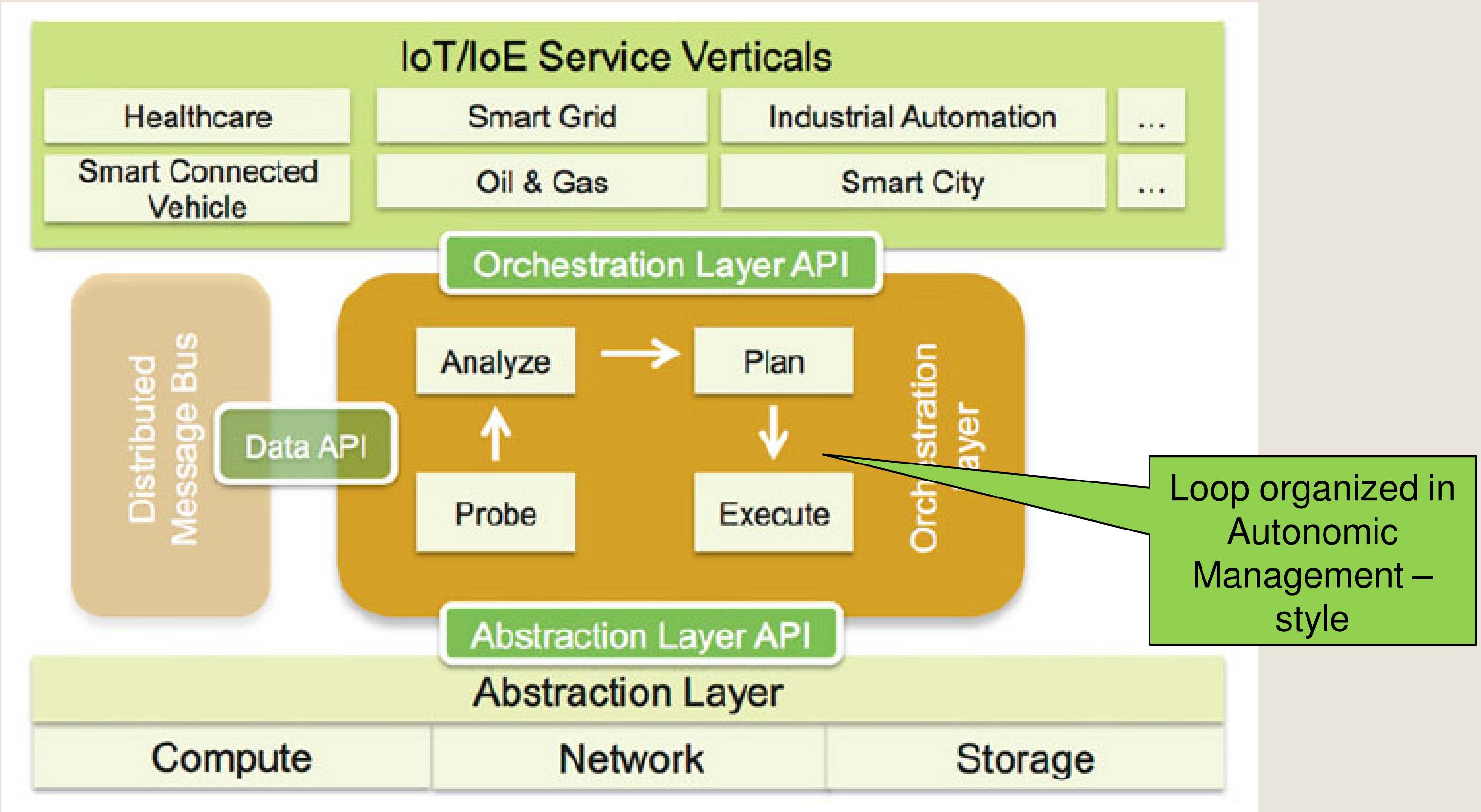
3. Fog Computing Architectures and IoT

- **Technology components needed for scalable virtualization of the resource classes:**
  - **Computing**, requiring the selection of hypervisors, to virtualize both the computing and I/O resources
  - **Storage -** needs a Virtual File System and a Virtual Block and/or Object Store
  - **Networking** - needs a Network Virtualization Infrastructure (e.g., SDN+ NFV)
  - Fog leverages (similar to CC) a policy-based orchestration and provisioning mechanism on top of the resource virtualization layer for scalable and automatic resource management
  - Fog architecture should expose APIs for application development and deployment

3. Fog Computing Architectures and IoT

- **Example of HW/SW Components in Fog architecture**



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3. Fog Computing Architectures and IoT

- **HW/SW Components in Fog architecture (cont'd)**
- ***Heterogeneous Physical Resources***
- **FCNs are heterogeneous**
  - Large range: high end servers, edge routers, access points, set-top boxes, .. to end devices such as vehicles, sensors, mobile phones etc.
  - Various HW/SW resources: processing, storage, capability to support new functionalities, OSes, software applications, etc.
- **The Fog net infrastructure is heterogeneous :**
  - High-speed links connecting enterprise data centers and the core ….to multiple wireless access technologies (ex: 3G/4G, LTE, WiFi, etc.)
- **Need an abstraction layer on top of these**

3. Fog Computing Architectures and IoT

- **HW/SW Components in Fog architecture (cont'd)**

- ***Fog Abstraction Layer***
  - hides the platform heterogeneity and exposes a uniform and programmable interface for seamless resource Management and Control (M&C)
  - provides generic APIs
    - for monitoring, provisioning and controlling PHY resources
    - to monitor and manage various hypervisors, OSes, service containers, and service instances on a PHY machine
    - to specify security, privacy and isolation policies for OSes or containers belonging to different tenants on the same physical machine.
  - includes support for virtualization,
    - e.g., the ability to run multiple OSes or service containers on a PHY machine and support multi-tenancy

- **Specific multi-tenancy features:**
  - data and resource isolation
  - expose a single, consistent model across PHY machine to provide these isolation services
  - exposes both the physical and the logical (per-tenant) network to administrators, and the resource usage per-tenant

3. Fog Computing Architectures and IoT

- **HW/SW Components in Fog architecture (cont'd)**

- ***Fog Service Orchestration Layer***
  - provides dynamic, policy-based life-cycle management of Fog services
  - the orchestration functionality is as distributed as the underlying Fog infrastructure and services

- **Managing services** – is done with technology and components as :
  - a **SW agent, *Foglet*** to bear the orchestration functionality and perf. requirements that could be embedded in various edge devices.
  - a distributed, persistent storage to store policies and resource meta-data (capability, performance, etc) that support high transaction rate update and retrieval
  - a scalable messaging bus to carry control messages for service orchestration and resource management.
  - a distributed policy engine with a single global view and local enforcement

3. Fog Computing Architectures and IoT

- **HW/SW Components in Fog architecture (cont'd)**

- **Foglet Software Agent (FSA)**
  - The **distributed Fog orchestration framework** – includes several FSAs, one running on every node in the Fog platform.
  - The FSA uses abstraction layer APIs to monitor the health and state associated with the PHY machine and services deployed on it
  - This information is both locally analyzed and also pushed to the distributed storage for global processing

  - Foglet also performs life-cycle mgmt. activities (standing up/down guest OSes, service containers, and provisioning and tearing down service instances, etc.)
  - Thus, Foglet's interactions on a Fog node span over a range of entities starting from the PHY machine, hypervisor, guest OSes, service containers, and service instances
  - Each of these entities implements the necessary functions for programmatic M&C
  - Foglet invokes these functions via the abstraction layer APIs.

3. Fog Computing Architectures and IoT

- **HW/SW Components in Fog architecture (cont'd)**

- **Distributed Database (DDB)**
  - increases Fog's scalability and fault-tolerance
  - provides fast storage and retrieval of data
  - stores both application data and meta-data to aid in Fog service orchestration.

- **Sample meta-data examples:**
  - Fog node's HW/SW capabilities to enable service instantiation on a platform with matching capabilities
  - Health and other state info of Fog nodes and running service instances for load balancing, and generating performance reports
  - Business policies that should be enforced throughout a service's life cycle

- **Policy-Based Service Orchestration**
  - The orchestration framework provides policy-based service routing, i.e., routes an incoming service request to the appropriate service instance that confirms to the relevant business policies
  - The policy manager is responsible of this
  - The policy framework is extensible

3. Fog Computing Architectures and IoT

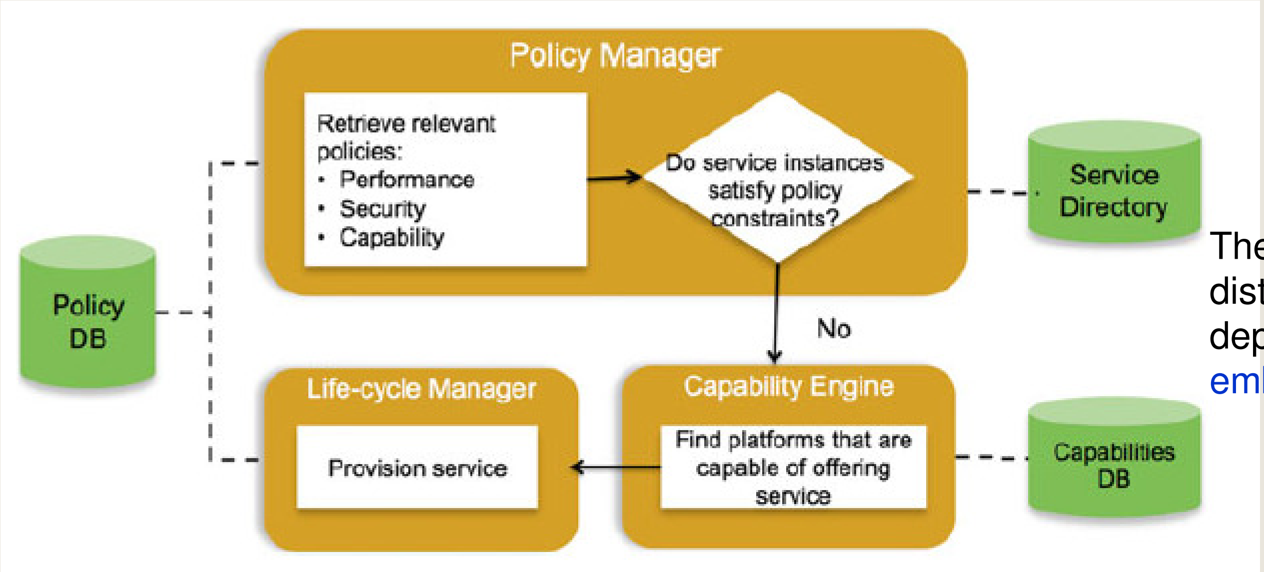
- **Policy-Based Service Orchestration Framework (cont'd)**

- **Administrators**
  - interact with the orchestration framework (intuitive dashboard-style user interface -UI)
  - enter business policies, manage, and monitor the Fog platform through this UI
  - The UI offers policy templates that admins can refine based on needs

- **Examples of policies** :
  - specify thresholds for load balancing such as maximum number of users, connections, CPU load etc.
  - specify QoS requirements (network, storage, compute) with a service
  - configure device, service instance in a specific setting
  - associate power management capabilities with a tenant/Fog platform
  - specify security, isolation and privacy during multi-tenancy
  - specify how and what services must be chained before delivery
    - E.g., firewall before video service

3. Fog Computing Architectures and IoT

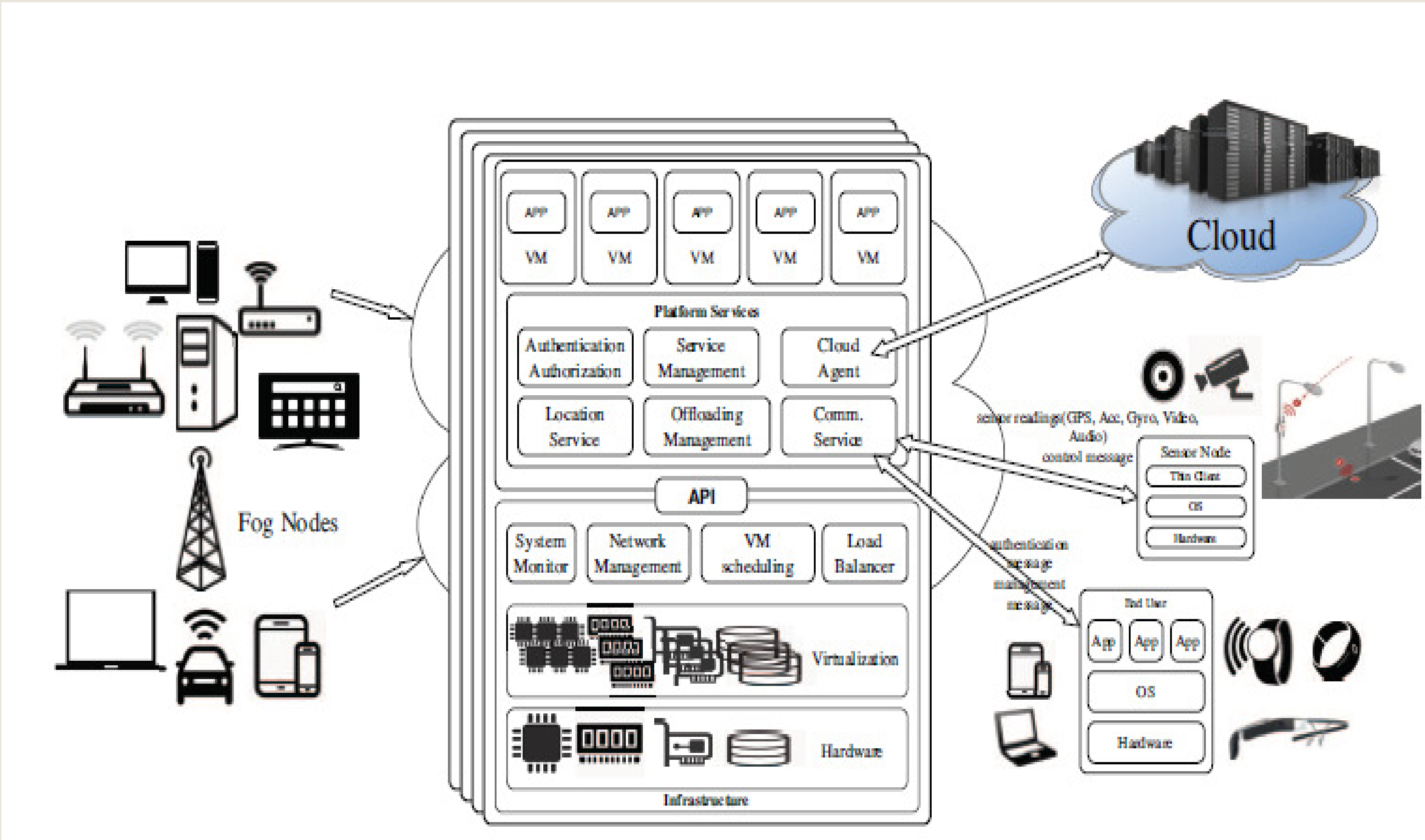
- **Policy-Based Service Orchestration Framework (cont'd)**
- Business policies are pushed to a distributed policy database
- The policy manager
  - is triggered by an incoming service request
  - gathers (from the policy repository) the relevant policies i.e., those pertaining to the service, subscriber, tenant etc.
  - retrieves (from the services directory) meta-data about active service instances
  - tries to find an active service instance that satisfies the policy constraints, and forwards the service request to that instance
  - If no such instance is available, then a new instance must be created.



The orchestration functionality is distributed across the Fog deployment such that the logic is embedded in every Foglet

3. Fog Computing Architectures and IoT

- **Another view of Fog Computing architecture**



Source [11]: Shanhe Yi, et.al., "Fog Computing: Platform and Applications", 2015 Third IEEE Workshop on Hot Topics in Web Systems and Technologies, https://www.computer.org/csdl/proceedings/hotweb/2015/9688/00/9688a073.pdf

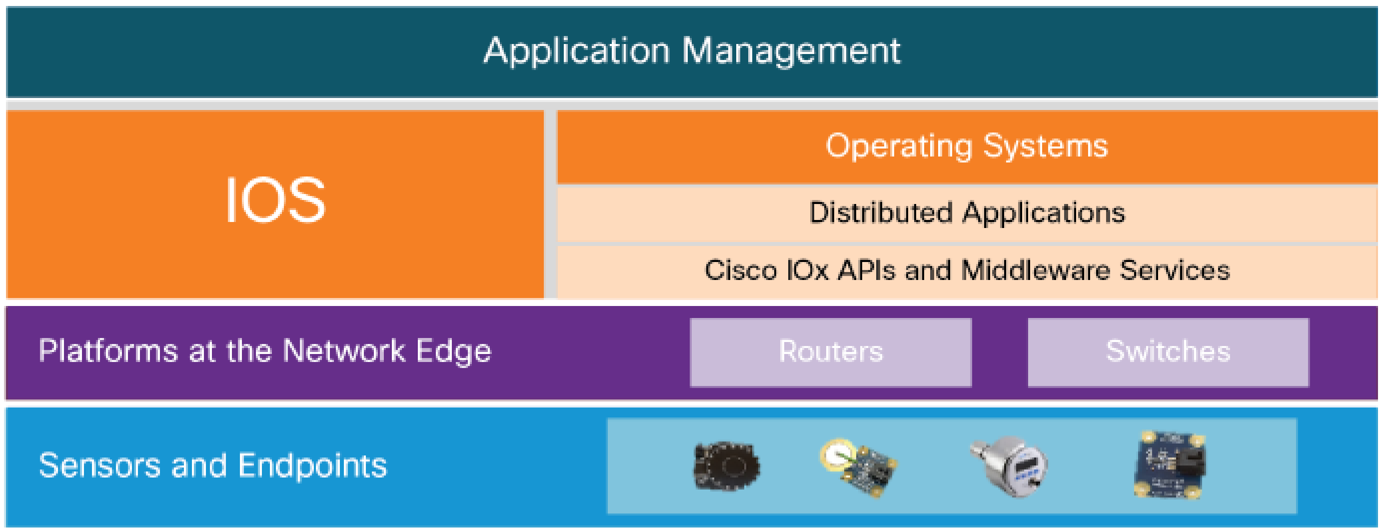
3. Fog Computing Architectures and IoT

- **Fog Computing Infrastructure as a Service- architecture example**

How Cisco IOx Works

Cisco IOx hosts applications in a Guest Operating System (GOS) that runs on a hypervisor on a Cisco fog node (Figure 1). Cisco IOx comes with Yocto Linux, but developers can use any operating system.

Figure 1. Cisco IOx Makes It Possible to Offer Fog Infrastructure as a Service



Source [12]: White Paper, "Cisco Fog Computing Solutions: Unleash the Power of the Internet of Things", https://www.cisco.com/c/dam/en_us/solutions/trends/iot/docs/computing-solutions.pdf

CONTENTS

4. Fog/Edge Computing in 4G and 5G

- **5G Key Drivers, Requirements, Technologies**

- **Driving factors for cellular network evolution 3G→ 4G→ 5G**
  - Data transfer rates growth, hetereogeneous RATs, QoE/QoS needs, mobility, …
  - Applications : IoT(~ 50 billion connected devices until 20202), M2M, Smart cities, Smart grid, vehicular, media, …
- **Three views for 5G:** user-centric, service-provider-centric, network-operator-centric
- **Three main 5G features**: Ubiquitous connectivity, ~ Zero latency (ms), High-speed Gigabit connection
- **Additional requirements (and objectives) :**
  - Sustainability, scalability, cost reduction, ecosystem features
- **Application fields**:
  - **IoT , IoE**
    - energy- smart grids
    - food and agriculture
    - smart city management
    - automotive, vehicular and public transportation
  - mission critical services
  - manufacturing
  - government
  - education, healthcare
  - …….

4. Fog/Edge Computing in 4G and 5G

- **Key Drivers, Requirements, Technologies** [16][17]
- **5G disruptive capabilities**
  - **x 10 improvement** in performance : capacity, latency, mobility, accuracy of terminal location, reliability and availability
  - **simultaneous connection of many devices** + improvement of the terminal battery capacity life
  - **lower energy consumption** w.r.t. 4G networks of today ; energy harvesting
  - **Better spectral efficiency**
  - help **citizens to manage their personal data**, tune their exposure over the Internet and protect their privacy
  - **reduce service creation time** and facilitate integration of various players delivering parts of a service
  - built on **more efficient hardware**
  - **flexible and interworking in heterogeneous** environments

4. Fog/Edge Computing in 4G and 5G

Key Drivers, Requirements, Technologies (cont'd)

- 5G will integrate: heterogeneous networking (RATs) + computing + storage resources into one programmable and unified infrastructure
  - optimized and more dynamic usage of all distributed resources
  - convergence of fixed, mobile and unicast/mcast/broadcast services.
  - support multi tenancy models, enabling players collaboration
  - supported by cloud computing technologies
  - ultra-dense networks with numerous small cells

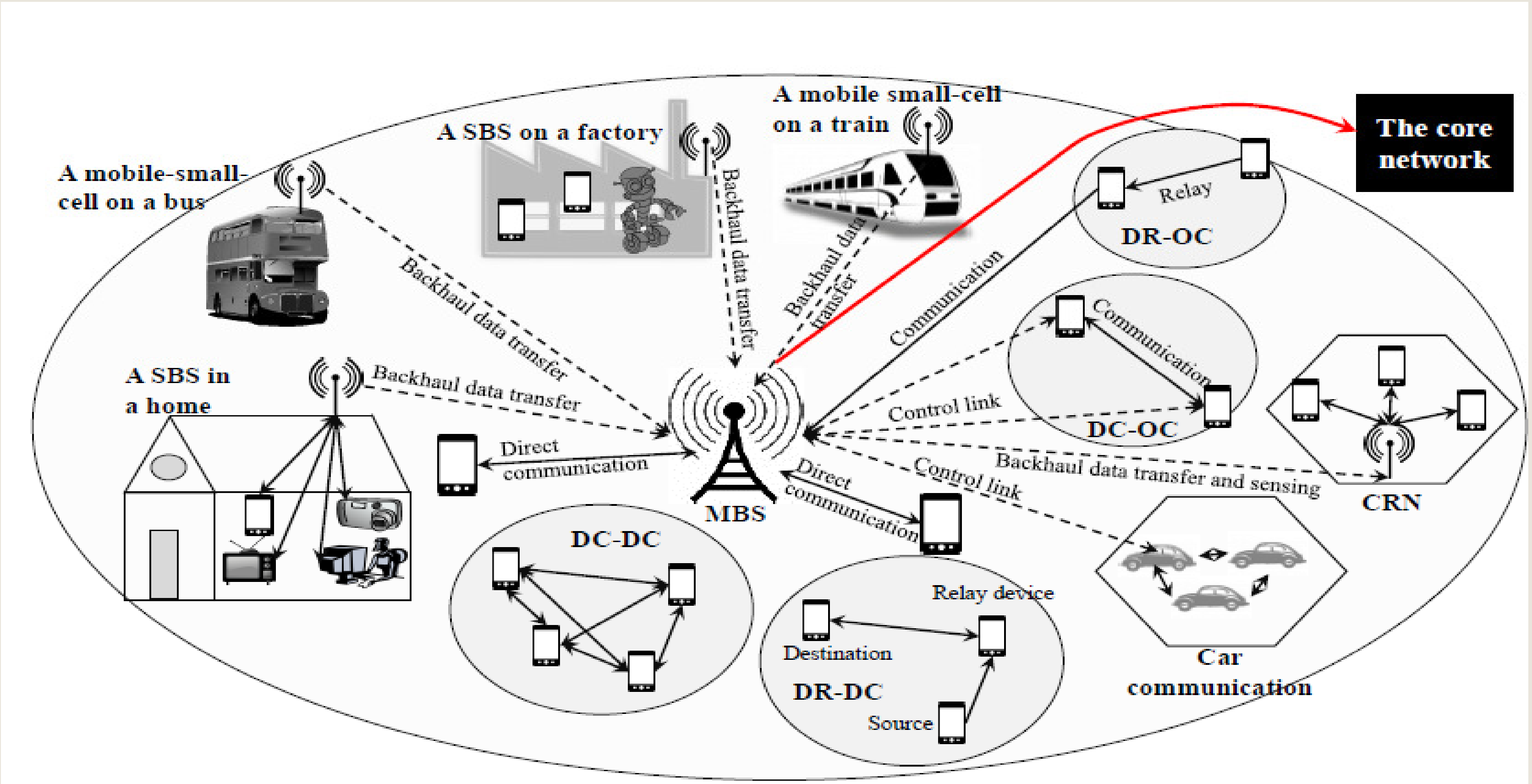
- Driven by SW
  - unified OS in a number of PoPs, especially at the network edge

- To achieve the required performance, scalability and agility it will rely on
  - Software Defined Networking (SDN)
  - Network Functions Virtualization (NFV)
  - Mobile Edge Computing (MEC)
  - Cloud/Fog Computing (CC/FC)

- Ease and optimize network management operations, through
  - cognitive features
  - advanced automation of operation through proper algorithms
  - Data Analytics and Big Data techniques -> monitor the users' QoE

4. Fog/Edge Computing in 4G and 5G

- **5G Overall view**
  - multi-tier architecture: small-cells, mobile small-cells, D2D, CRN-based comm.



Source[13]: Panwar N., Sharma S., Singh A. K. 'A Survey on 5G: The Next Generation of Mobile Communication'. Accepted in Elsevier Physical Communication, 4 Nov 2015, http://arxiv.org/pdf/1511.01643v1.pdf

4. Fog/Edge Computing in 4G and 5G

- **Cellular systems evolution towards 5G**
  - **CRAN Cloud Radio Access Networks- solution proposed for 5G** [14]
  - **CRAN (interest from academia and industry)**
    - Components
      - large number of low-cost **Remote Radio Heads (RRHs),** randomly deployed and connected to
      - the **Base Band Unit (BBU)** pool through the fronthaul links
    - **Advantages:**
      - **RRHs closer to the users → higher system capacity, lower power consumption**
      - the **baseband processing centralized at the BBU pool** → possible to apply cooperative processing techniques to mitigate interferences
    - **Drawbacks:**
      - **High traffic on the fronthaul BBU-RRH → constraints**
      - accessing the same BBU pool is limited and could not be too large due to the implementation complexity

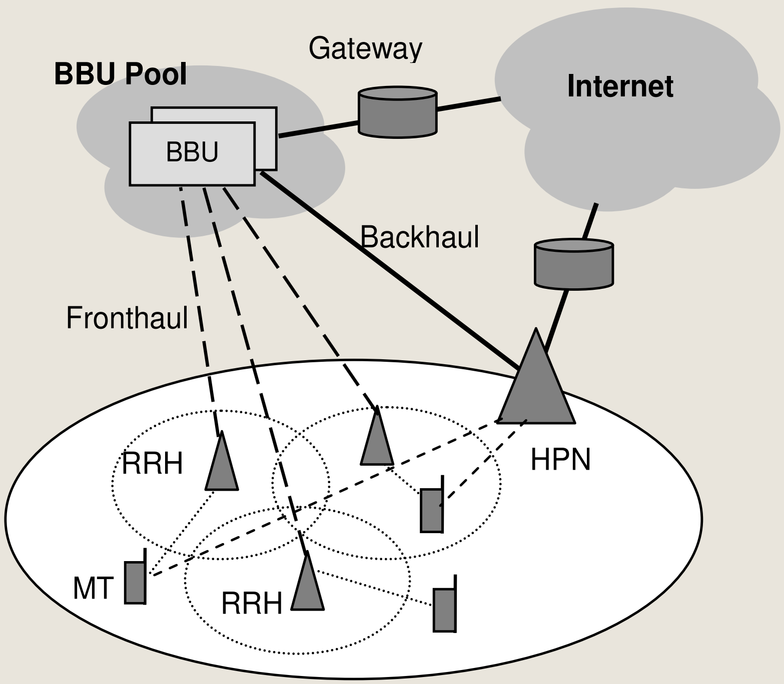
Source [14]: A.Checko , et al. 'Cloud RAN for Mobile Networks—A Technology Overview‘, IEEE Communications Surveys & Tutorials, VOL. 17, NO. 1, First Quarter 2015, 405

4. Fog/Edge Computing in 4G and 5G

- **Cellular systems evolution towards 5G (cont'd)**
  - **H-CRAN Heterogeneous Cloud Radio Access Networks (**HetNet)
    - Solve heterogeneity and some CRAN drawbacks
    - **Components**
      - **Low Power Nodes (LPN) (** e.g., pico BS, femto BS, small BS , etc to increase capacity in dense areas with high traffic demands.
      - **High power node (HPN),** (e.g., macro or micro BS) combined with LPN to form a HetNet
    - **Problem: too dense LPNs - >interferences, → need to control interferences**
      - Method : advanced DSP techniques
      - 4G solution: The coordinated multi-point (CoMP)
      - (-) in real networks because CoMP performance gain depends heavily on the backhaul constraints
      - Conclusion: cooperative processing capabilities is needed in the practical evolution of HetNets
  - **H-CRAN-based 5G system:** CC based cooperative processing and networking techniques are proposed to tackle the 4G challenges alleviating inter-tier interference and improving cooperative processing gains
    - The baseband data path processing + LPNs radio resource control are moved to the cloud server

4. Fog/Edge Computing in 4G and 5G

- **5G System Architecture in H-CRAN approach**
- Simplified H-CRAN architecture

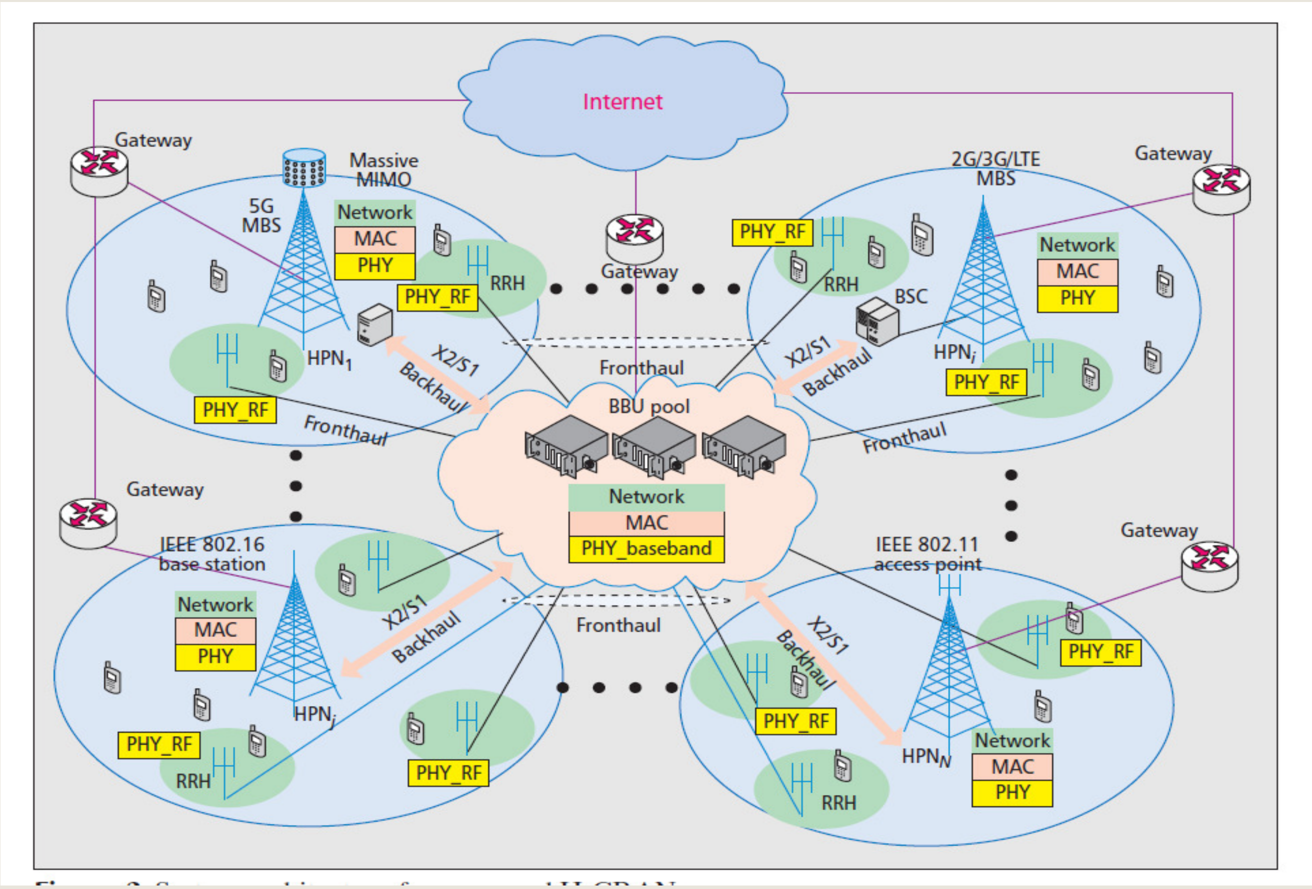


BBU- baseband (processing) unit
HPN – High Power Node
LPN- Low Power Node
RRH – Remote Radio Head

RRHs include only partial PHY functions ;
The model with these partial functionalities is denoted as PHY_RF

4. Fog/Edge Computing in 4G and 5G

- **Example of 5G System Architecture in H-CRAN approach**



RRH – Remote Radio Head;
X2/S1 – 3G imported interfaces
HPN – High Power Node
LPN- Low Power Node
BBU- baseband (processing) unit
BSC- Base Station Controller (2G/3G)
MIMO – Multiple Inputs – Multiple Outputs
LTE – Long Term Evolution (4G)

Source [15]: M. Peng, et al., "Heterogeneous cloud radio access networks: a new perspective for enhancing spectral and energy efficiencies," IEEE Wireless Communications, Dec. 2014

4. Fog/Edge Computing in 4G and 5G

- **C-RAN limitation in 5G context**
  - strong fronthaul network requirements - to access the centralized (BBU) pool
  - high bandwidth and low latency inter-connection fronthaul is necessary (expensive - in practice)
- **H-CRAN limitation in 5G context**
  - **(+) H-CRAN solves some C-RAN problems**
    - user /data (DPl) and control planes (CPl) are decoupled
    - the centralized control functions are shifted from the BBU pool (like in C-RANs) to the HPNs
    - (HPNs) are mainly used to provide seamless coverage and CPl functions
    - RRHs provide high speed data rate for DPl
    - HPNs <--→ BBU pool : backhaul links for interference coordination
  - **(-)**
  - **H-CRAN still has some challenges in practice**
    - popular location-based social applications → data traffic peaks appear over the fronthaul (RRHs <-->BBU pool) → high transient load for the fronthaul
    - deploying of a high number of fixed RRHs and HPNs in H-CRANs to meet traffic peak requirements is not efficient (traffic is low for long time intervals)
    - do not take full advantage of processing and storage capabilities in edge devices (e.g., RRHs and "smart" user equipments (UEs))

4. Fog/Edge Computing in 4G and 5G

- **Fog/Edge Computing in 5G context**

- extends the traditional CC paradigm to the network edge
  - a high amount of storage, comm., control, configuration, measurement and management is performed at the network edge

- collaboration radio signal processing (CRSP) can be executed in H-CRANs centralized BBU pool, **but also in RRHs and even "smart" UEs**

- UEs might download packets from closer points (other UEs or RRHs)

- integration possibility of on-device processing and cooperative radio resource management (CRRM) on new types of "smart" UEs

- **Fog computing based RAN (F-RAN) architecture**
  - real-time CRSP and flexible CRRM –executed at the edge devices
  - F-RANs can adapt to the dynamic traffic and radio environment
  - lower burden on the fronthaul and BBU pool
  - achievable user-centric objectives : adaptive technique among (D2D), wireless relay, distributed coordination, and large-scale centralized cooperation

4. Fog/Edge Computing in 4G and 5G

- **Fog/Edge Computing in 5G context (cont'd)**

- **Fog computing based RAN (F-RAN) architecture**
  - mobile FC and edge cloud can offer new services for information sciences and Internet of Things (IoT)
  - design of mobile fog as a programming model for large-scale, latency sensitive applications in the IoT
  - **FC in 5G environments- open research issue**

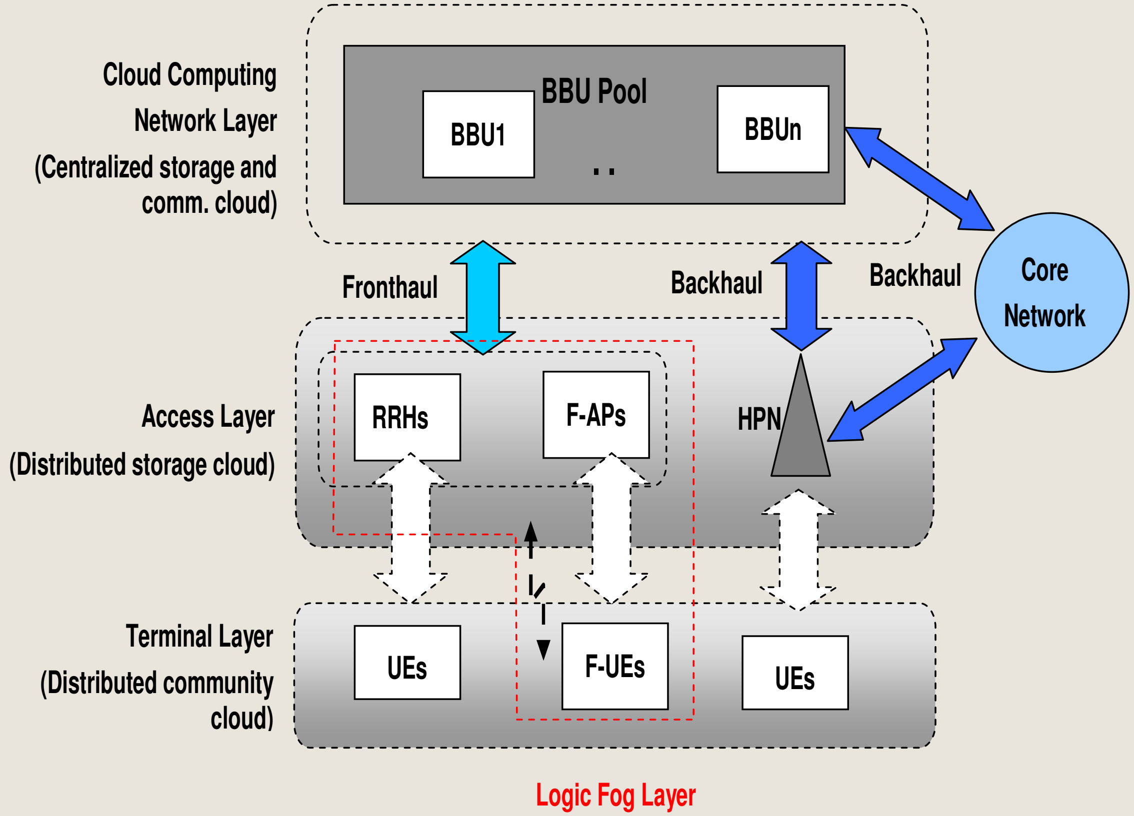
- **F-RAN architectures**
  - three layers: cloud computing, network access and terminal layer
  - F-RAN takes full advantages of the convergence of CC, heterogeneous networking, and FC
  - The FC network is actually composed of
    - **F-APs** (residing in the network access layer) and
    - **F-UEs** (placed in the terminal layer)
      - F-UEs can inter-communicate (direct -D2D mode or through additional F-UEs playing the role of mobile relays)
    - The **network access layer is composed by F-APs, HPNs and RRHs**

4. Fog/Edge Computing in 4G and 5G

F-RAN simplified architecture

BBU – BaseBand Unit
F-AP   Fog Access Point
RRH – Remote Radio Head
HPN – High Power Node
(Base Station)

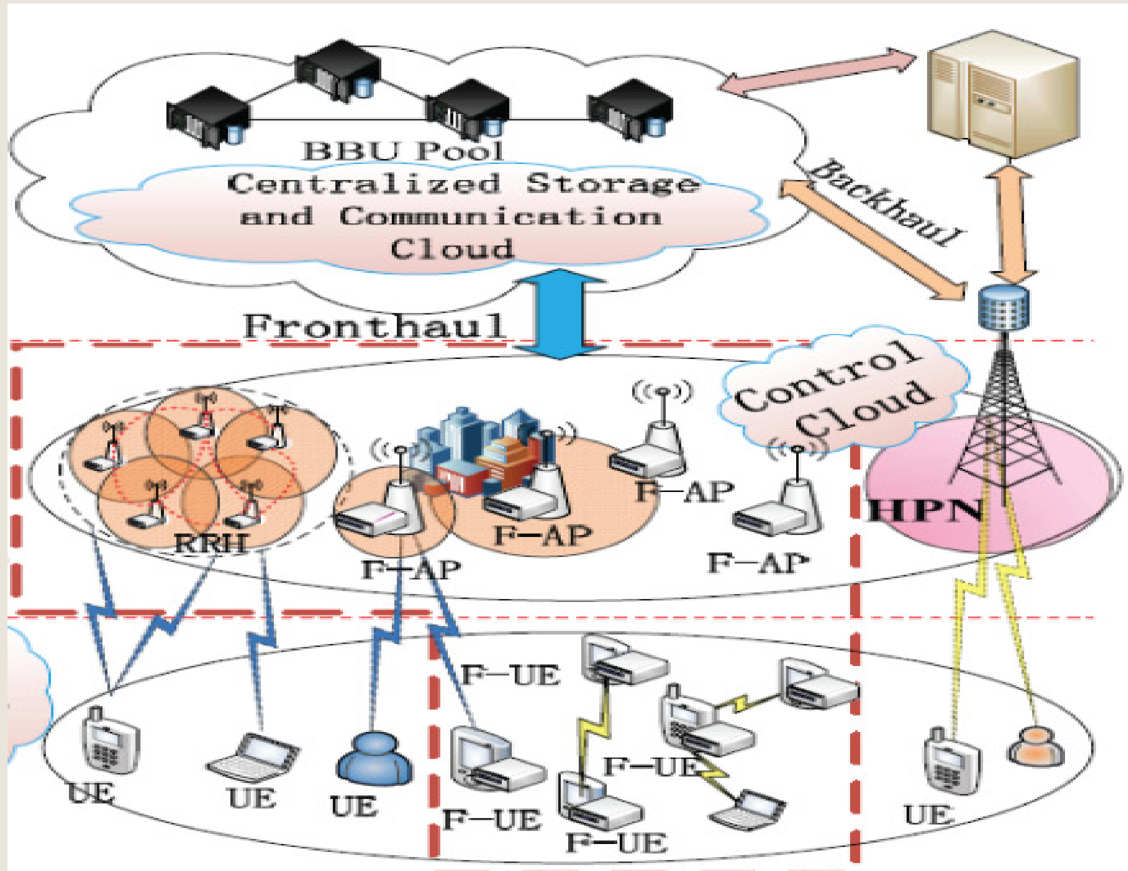
F-UE - Fog capable user equipment



4. Fog/Edge Computing in 4G and 5G

- **F-RAN architecture- example**

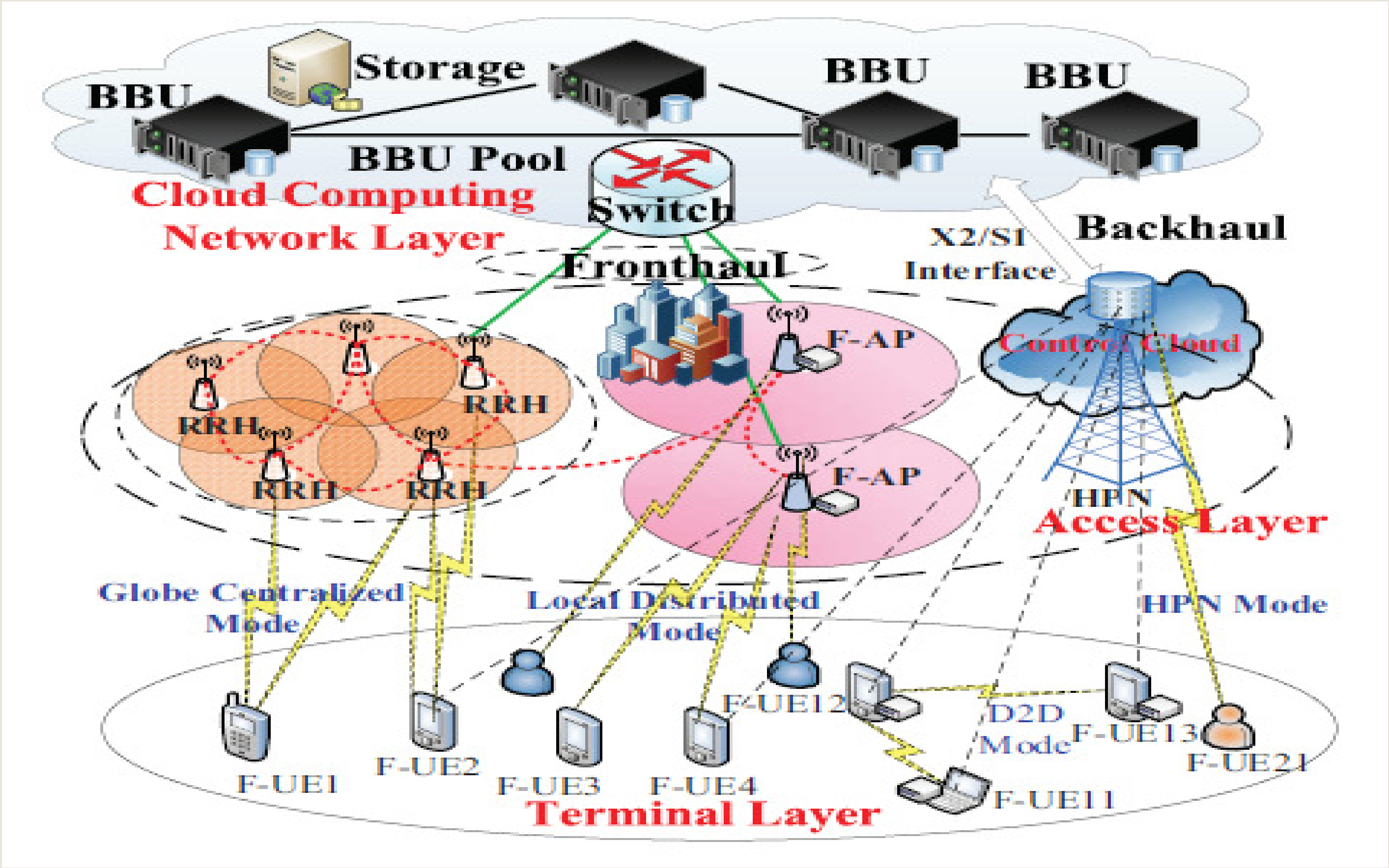
BBU – BaseBand Unit
F-AP Fog Access Point
RRH – Remote Radio Head
HPN – High Power Node
(Base Station)
F-UE Fog capable user equipment



Source [19]: M.Peng,S.Yan, K.Zhang, and C.Wang, "Fog Computing based Radio Access Networks:Issues and Challenges", IEEE NETWORK,2015, http://arxiv.org/abs/1506.04233

4. Fog/Edge Computing in 4G and 5G

- **F-RAN architecture- example (cont'd)**



Source [19]: M.Peng,S.Yan, K.Zhang, and C.Wang, "Fog Computing based Radio Access Networks:Issues and Challenges", IEEE NETWORK,2015, http://arxiv.org/abs/1506.04233

4. Fog/Edge Computing in 4G and 5G

- **F-RAN Architecture features**
- F-APs
  - used in the Data Plane to forward and process the traffic data
  - communicate with BBU pool through the fronthaul links and HPN through backhaul links

- The signals over fronthaul links are large-scale processed in the BBU pool, while over the backhaul links only control information is exchanged between the BBU pool and HPN

- The BBU pool plays a similar role as in H-CRANs (can also make centralised caching)

- F-RAN alleviates the tasks of the BBU pool and fronthaul links, given that a large number of CRSP and CRRM functions are shifted towards F-APs and F-UEs

- F-APs and F-UEs may perform limited caching

4. Fog/Edge Computing in 4G and 5G

- **Architectures comparison: C-RAN, H-CRAN and F-RAN**
- **BBU pool and fronthaul burden**:
  - C-RAN –highest; H-CRAN – medium; **F-RAN- lowest**
- F-RAN : Lowest latency

- **Decoupling between the CPI and DPI** : only in H-CRAN and F-RAN

- **Caching and collaboration radio signal processing (CRSP) functions**
  - centralized in CRAN and H-CRAN
  - F-RAN- it can be mixed, i.e., centralized/ distributed

- **Cooperative radio resource management (CRRM) functions**
  - centralized in CRAN
  - H-CRAN, F-RAN : mixed solution can be used

- **Complexity**
  - CRAN or H-CRAN put high complexity in BBU pool and low complexity in RRHs and UEs
  - F-RAN exposes medium complexity in BBU pool, F-APs and F-UEs.

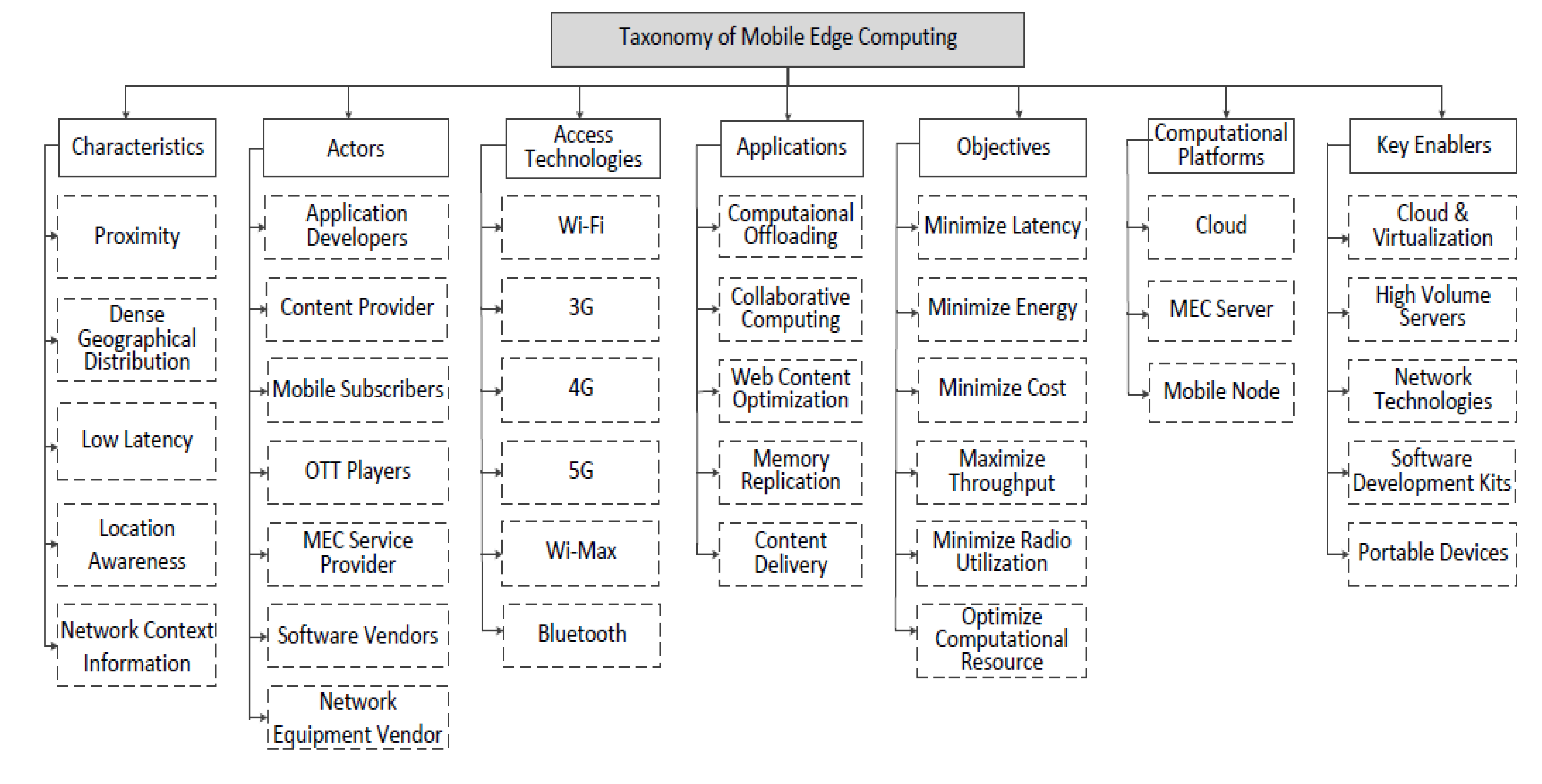
CONTENTS

5. Mobile Edge Computing

- **Why MEC?**
  - **MEC provides IT and cloud-computing capabilities within the RAN in close proximity to mobile subscribers** [20-25]
  - MEC accelerates content, services and applications responsiveness from the edge
  - **Main standardization actors:** ETSI, 3GPP, ITU-T
  - RAN edge offers a service environment with ultra-low latency and high-bandwidth as well as direct access to real-time RAN information
    - (subscriber location, cell load, channels load, etc.) useful for applications and services to offer context-related services
  - **Operators can open the radio network edge to third-party partners**
  - Proximity, context, agility and speed can create value and opportunities for mobile operators, service and content providers, Over the Top (OTT) players and Independent Software Vendors (ISVs)

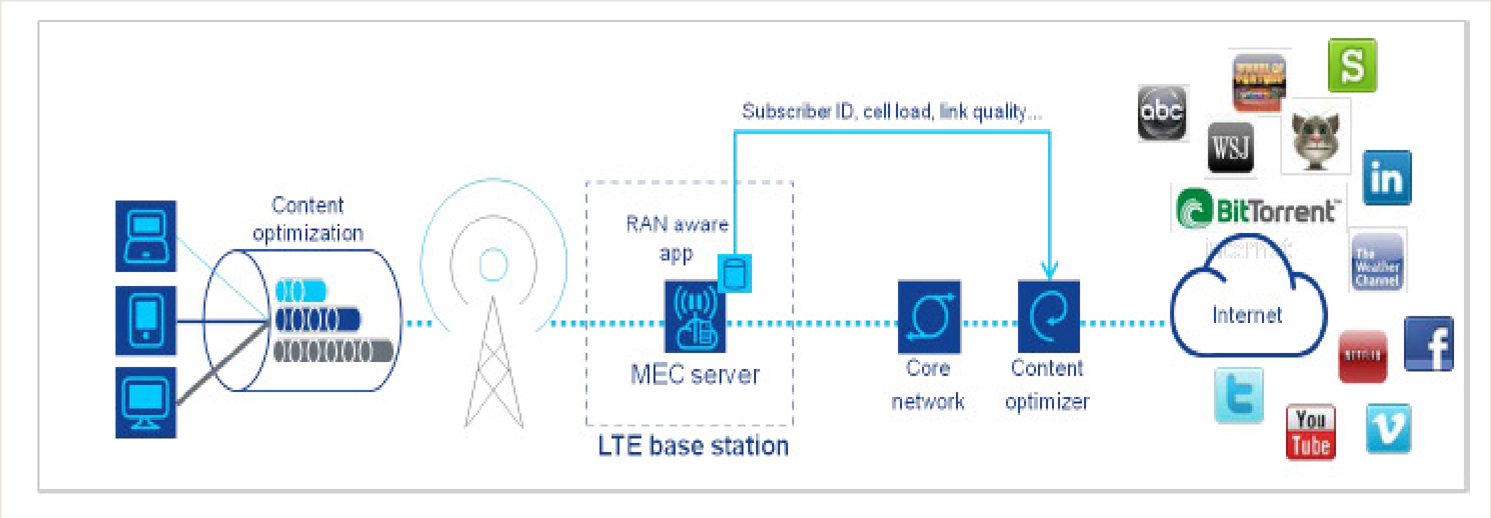
5. Mobile Edge Computing

▪ MEC Taxonomy



Source [20]: A. Ahmed, E. Ahmed, "A Survey on Mobile Edge Computing" IEEE, Int'l Conf. on Itelligent System and Control ISCO 2016
https://www.researchgate.net/publication/285765997

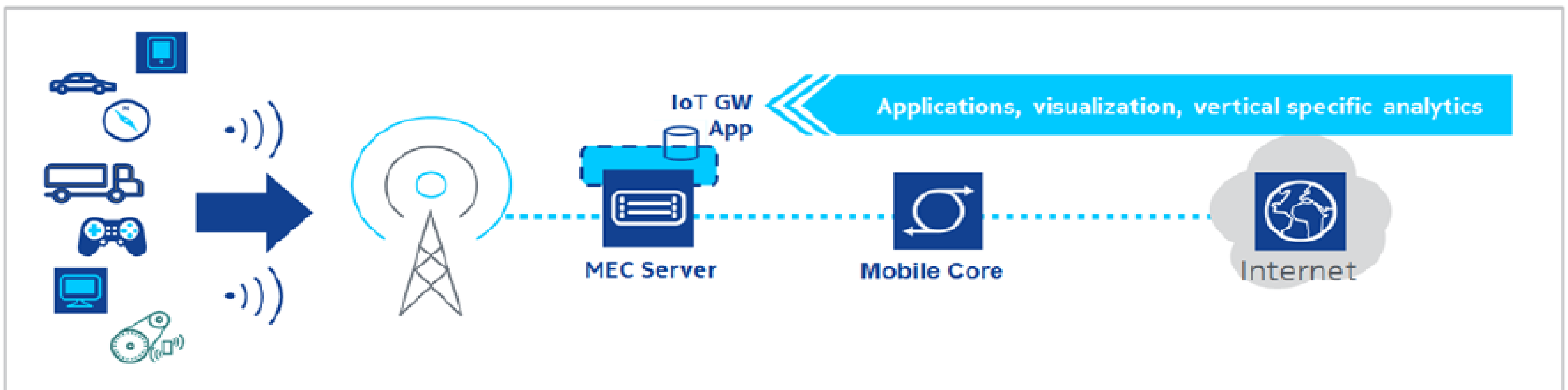
- **MEC Use Cases examples (content- oriented)**
  - **RAN-aware Content Optimization**
    - The application exposes accurate cell and subscriber radio interface information (cell load, link quality) to the content optimizer, enabling dynamic content optimization, improving QoE, network efficiency and enabling new service and revenue opportunities.
    - Dynamic content optimization enhances video delivery through reduced stalling, reduced time-to-start and 'best' video quality.



Source[24]: https://portal.etsi.org/Portals/0/TBpages/MEC/Docs/Mobile-edge_Computing_-_Introductory_Technical_White_Paper_V1%2018-09-14.pdf
Mobile-Edge Computing – Introductory Technical White Paper

5. Mobile Edge Computing

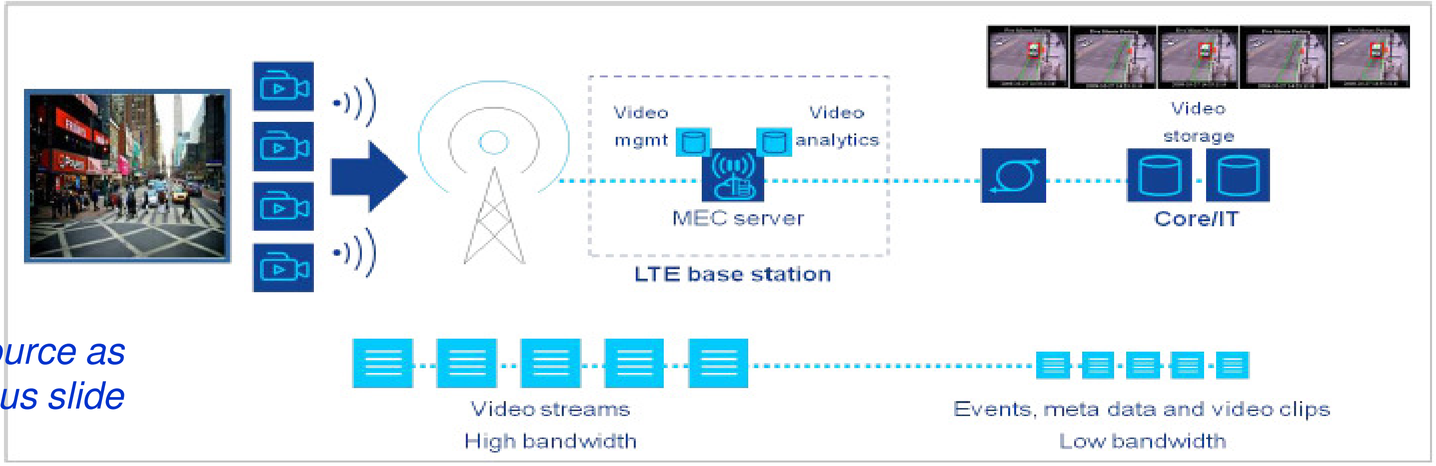
- **MEC Use Cases examples**
- Internet of Things (IoT)
  - IoT generates additional messaging on telecoms networks, and requires gateways to aggregate the messages and ensure security and low latency
  - Required: real time capability; grouping of sensors and devices is needed for efficient service
  - IoT devices are often low (processor, memory capacity)→ need to aggregate various IoT messages connected through the mobile network close to the devices
  - This also provides an analytics processing capability and a low latency response time.



Source [25]: Yun Chao Hu et.al., "Mobile Edge Computing A key technology towards 5G" ETSI White Paper No. 11 September 2015, ISBN No. 979-10-92620-08-5

5. Mobile Edge Computing

- **MEC Use Cases examples (content- oriented) (cont'd)**
  - **Video Analytics**
    - distributed video analytics solution: efficient and scalable mobile solution for LTE
    - The video mgmt. application transcodes and stores captured video streams from cameras, received on the LTE uplink
    - The video analytics application processes the video data to detect and notify specific configurable events e.g. object movement, lost child, abandoned luggage, etc.
    - The application sends low bandwidth video metadata to the central operations and management server for database searches. Applications : safety, public security to smart cities



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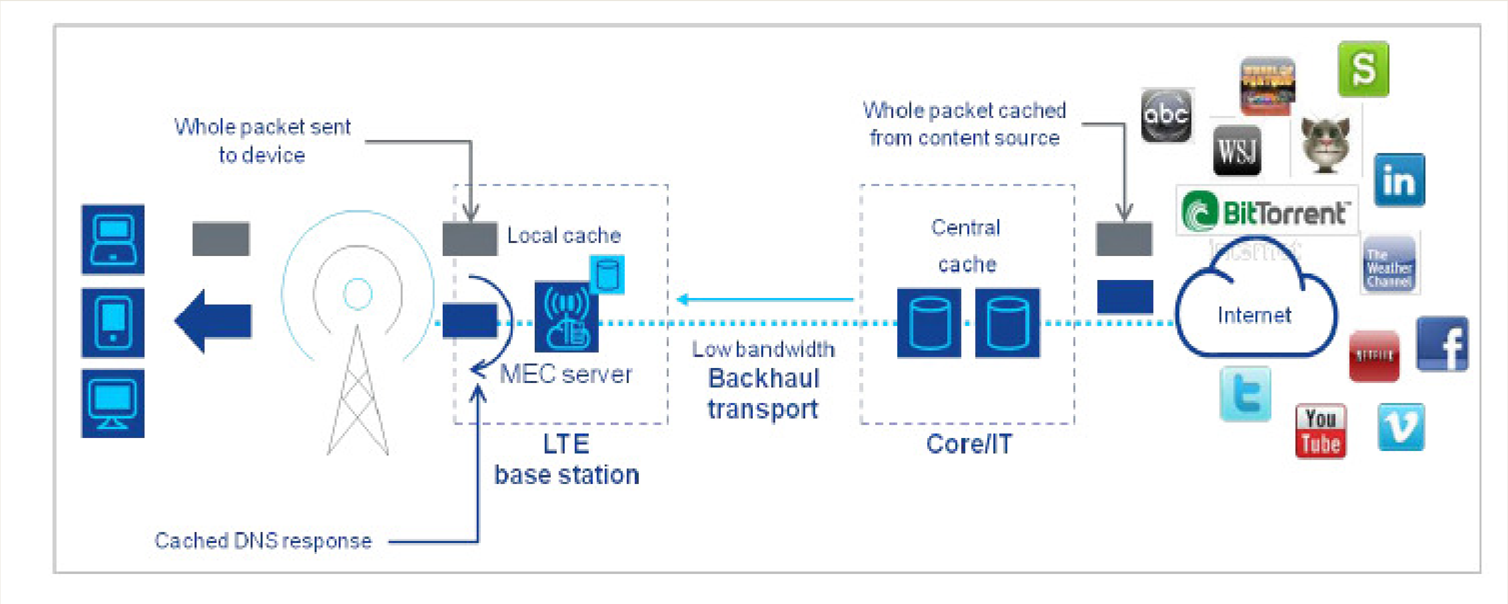
5. Mobile Edge Computing

- **MEC Use Cases examples (content- oriented) (cont'd)**
  - **Distributed Content and DNS Caching**
    - A distributed caching technology can provide backhaul and transport savings and improved QoE.
    - Content caching could reduce backhaul capacity requirements by ~35%
    - Local DNS caching can reduce web page download time by ~20%



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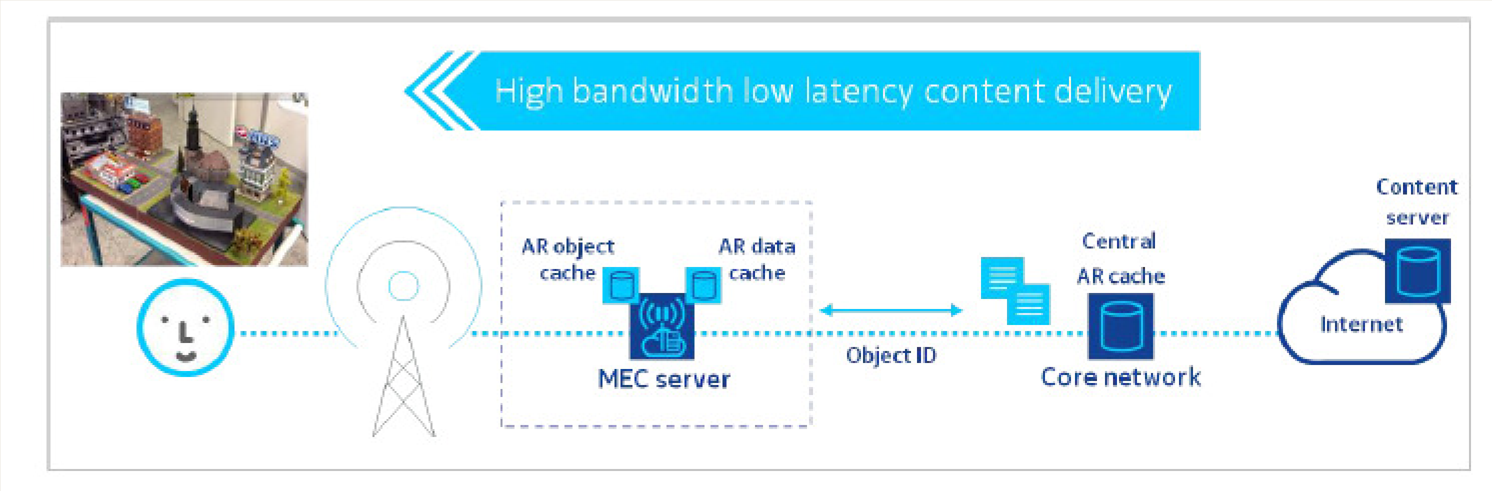
5. Mobile Edge Computing

- **MEC Use Cases examples (content- oriented)**
- **Augmented Reality (AR) content delivery**
  - An AR application on a smart-phone or tablet - overlays augmented reality content onto objects viewed on the device camera
  - Applications on the MEC server can provide local object tracking and local AR content caching;
    - RTT is minimized and throughput is maximized for optimum QoE
    - Use cases: offer consumer or enterprise propositions, such as tourist information, sporting event information, advertisements etc.



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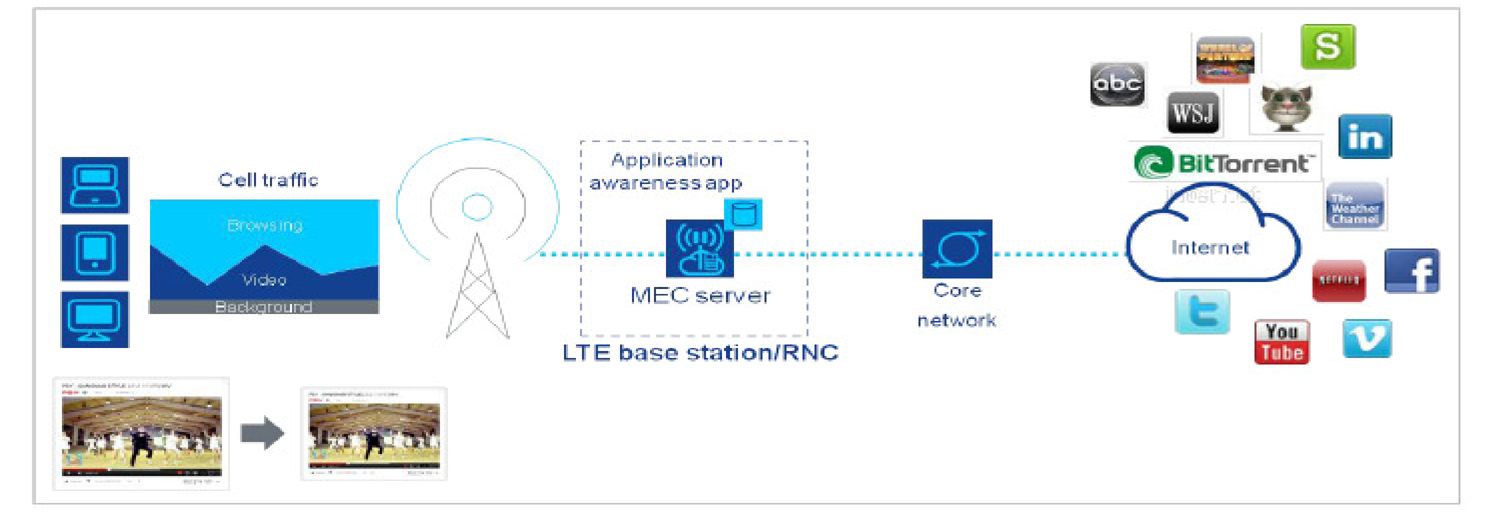
Mobile-Edge Computing – Introductory Technical White Paper

5. Mobile Edge Computing

- **MEC Use Cases examples**
- **Application-aware cell performance optimization**
  - Applied for each device in real time can improve network efficiency and customer experience
  - It can reduce video stalling and increase browsing throughput
  - Reduce latency
  - Provide independent metrics on application performance (video stalls, browsing throughput, and latency) for enhanced network management and reporting



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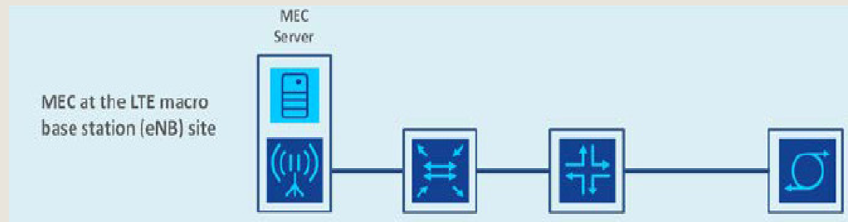
Mobile-Edge Computing – Introductory Technical White Paper

5. Mobile Edge Computing

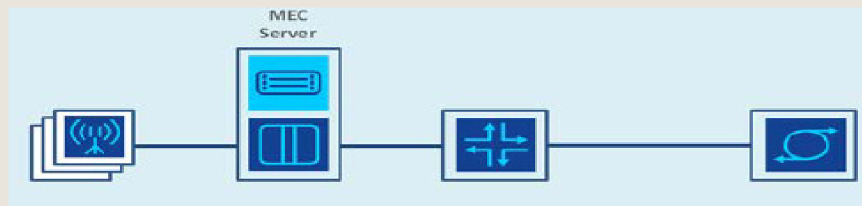
Possible Deployment Scenarios (ETSI)

- The MEC server can be deployed in several variants
- Note: the multi-technology (LTE/3G) cell aggregation site can be indoor or outdoor

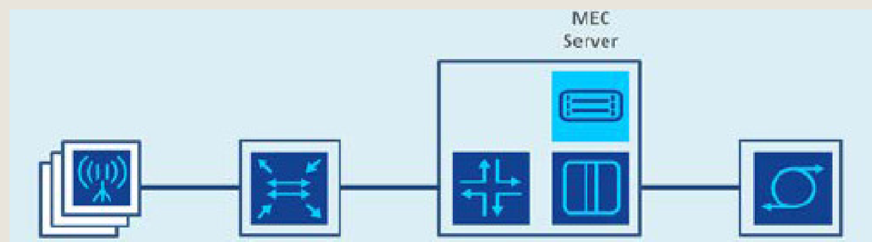
MEC at the LTE macro base station (eNB) site



MEC at the multi-technology (3G/LTE) cell aggregation site



MEC at the 3G Radio Network Controller (RNC) site



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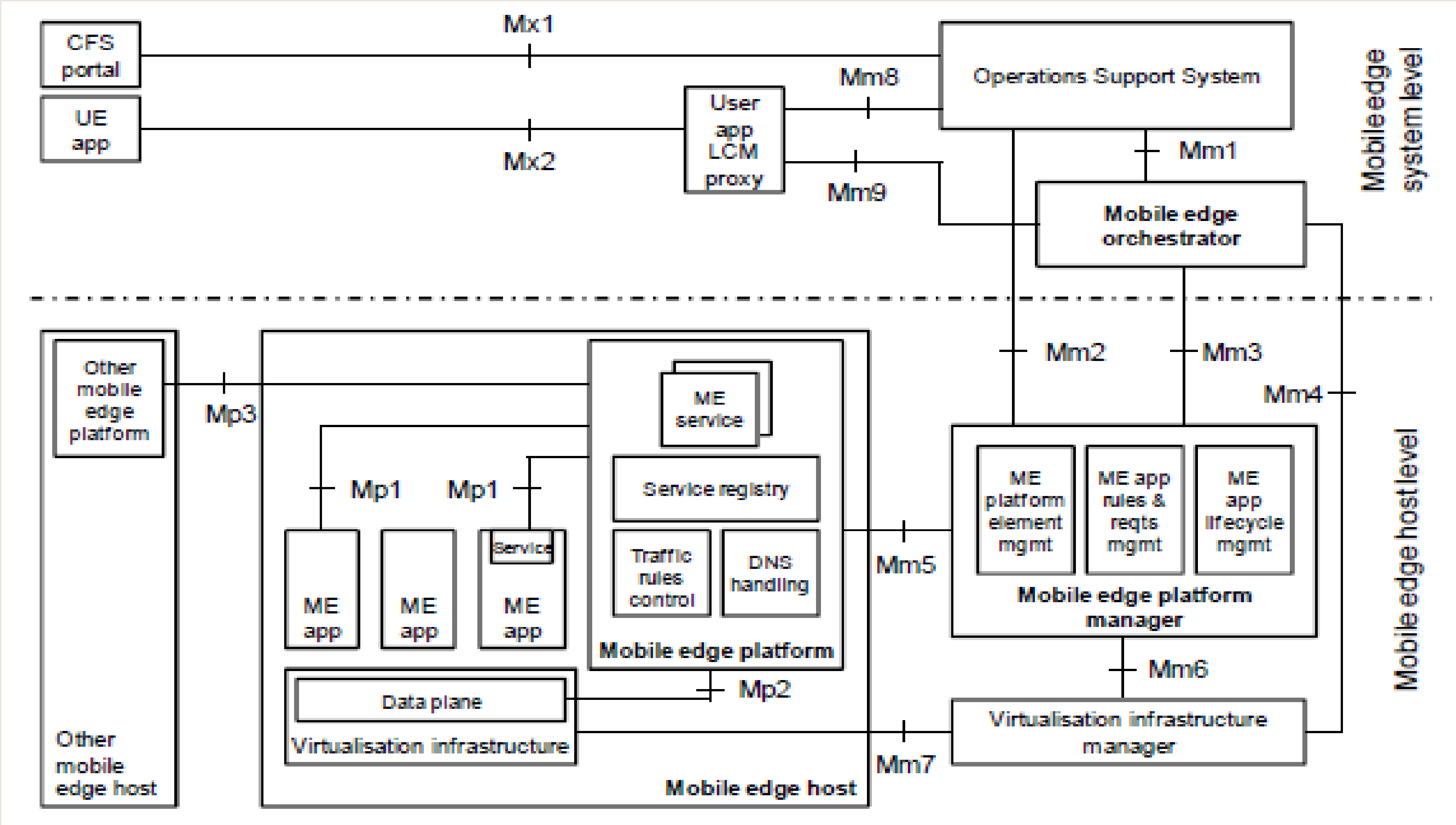
Mobile-Edge Computing – Introductory Technical White Paper

5. Mobile Edge Computing

- **MEC Architecture**
  - MEC provides a highly distributed computing environment that can be used to deploy applications and services as well as to store and process content in close proximity to mobile users.
  - Applications can benefit from real-time radio and network information and can offer a personalized and contextualized experience to the mobile subscriber.
  - The mobile-broadband experience is more responsive and opens up new monetization opportunities. This creates an ecosystem where new services are developed in and around the BS
  - **Key element : (MEC) IT application server** which is integrated in RAN (as above)
    - **The MEC server provides computing resources, storage capacity, connectivity, and access to user traffic and radio and network information**

5. Mobile Edge Computing

MEC Reference Architecture -ETSI



Source [21]:) ETSI GS MEC 003 V1.1.1 (2016-03), "Mobile Edge Computing (MEC); Framework and Reference Architecture"

5. Mobile Edge Computing

- **MEC Architecture**

- **ETSI MEC Terminology -** ETSI GS MEC 001 V1.1.1 (2016-03)

  - **ME application:** appl. instantiable on a ME host within the ME system and can potentially provide or consume ME services

  - **ME host:** entity containing a ME platform and a virtualization infrastructure to provide compute, storage and network resources to ME apps.

  - **ME platform:** set of functionalities
    - required to run ME apps. on a specific ME host virtualization infrastructure
    - and to enable them to provide and consume ME services, and that can provide itself a number of ME services

  - **ME host level management:** components handling the management of the ME specific functionality of a particular ME platform, ME host and the ME applications running on it

Source [21]:) ETSI GS MEC 003 V1.1.1 (2016-03), "Mobile Edge Computing (MEC); Framework and Reference Architecture"

5. Mobile Edge Computing

- **MEC Architecture**

- ETSI MEC Terminology ETSI GS MEC 001 V1.1.1 (2016-03)

  - **ME management:** mobile edge system level management and mobile edge host level management

  - **ME service:** service provided via the ME platform either
    - by the mobile edge platform itself
    - or by a ME application

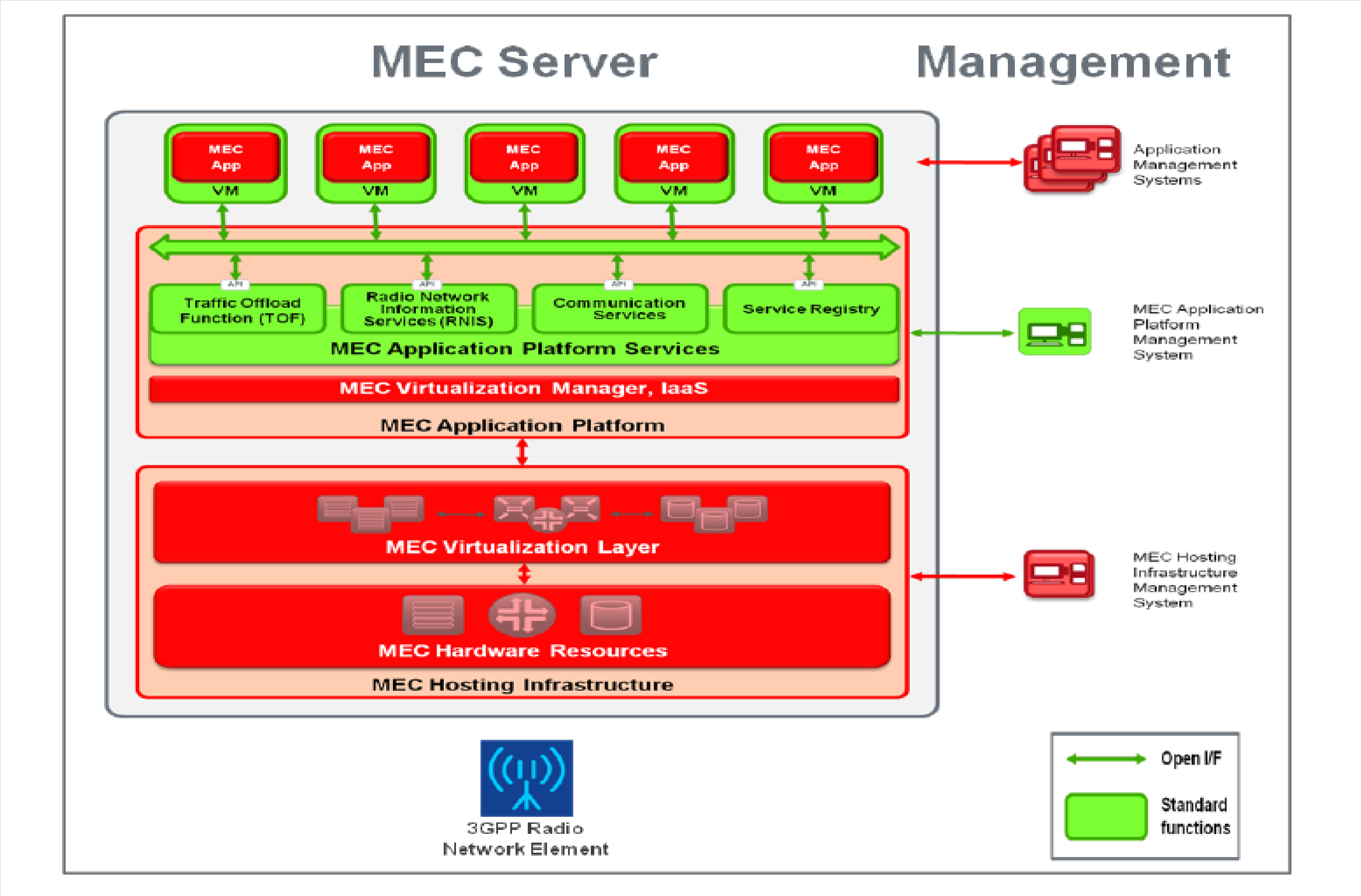
  - **ME system:** collection of ME hosts and ME management necessary to run ME apps. within an operator network or a subset of an operator network

  - **ME system level management:** management components which have the overview of the complete ME system

Source [21]:) ETSI GS MEC 003 V1.1.1 (2016-03), "Mobile Edge Computing (MEC); Framework and Reference Architecture"

5. Mobile Edge Computing

- MEC Platform Overview (*source: ETSI*)- *NFV inspired arch*



CONTENTS

6. Cloudlets

- **What is a Cloudlet?**
- **Carnegie Mellon University (CMU)** has developed ***Cloudlets*** *[26, 27]*
- A cloudlet
  - represents the **middle tier of a 3-tier hierarchy**: “mobile device – cloudlet – cloud”
  - can be viewed as a "data center in a box“, with no hard state, whose goal is to "bring the cloud closer"’
  - CMU have also implemented various mechanisms as open source code which is e.g. available at [27]

- Related proposal- Microsoft Research [28]:
  - concept of micro datacentre as an extension of today’s hyperscale cloud datacentres (as Microsoft Azure)
  - to meet new application demands like lower latency and new demands related to devices (e.g. lower battery consumption).

Source [26] :Cloudlets: all about cloudlet-enabled mobile computing. http://elijah.cs.cmu.edu/

Source [27] M.Satyanarayanant, et.al., "Cloudlets: at the Leading Edge of Mobile-Cloud Convergence", 2014 6th International Conference on Mobile Computing, Applications and Services (MobiCASE)http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7026272

Source [28]: Victor Bahl, Microsoft, interview about micro datacentres, Sept 2015. http://www.networkworld.com/article/2979570/cloud-computing/microsoft-researcher-why-micro-datacenters-really-matter-to-mobiles-future.html

6. Cloudlets

- **Cloudlet – short overview**
- Cloudlet: architectural element realizing convergence between CC and mobile computing, middle tier of the hierarchy [Cloud-cloudlet-device]
- Cloudlet ~ "data center in a box"
- **Main characteristics**
  - **Technology:**
    - based on standard cloud technology
    - encapsulates offload code from mobile devices in virtual machines (VMs)
    - may have specific role and functionality
    - Similar infrastructure to clouds based on Openstack
  - **Soft state only**
    - no hard state, but may contain cached states from the cloud
    - may buffer data originating from a mobile device and going to the cloud
    - after installation it is entirely self-managing
  - **Location**
    - "Logical proximity" of the mobile devices, i.e., capable to have low E2E latency and high bandwidth (e.g., one-hop Wi-Fi)
  - **Resources and connectivity**
    - sufficient CPU, RAM, etc. to offload resource-intensive computations from several mobile devices
    - good connectivity (bandwidth) to the cloud
    - not limited by electric power supply

6. Cloudlets

Cloudlet – achievements

- **Carnegie Mellon University** has created an open source platform
- *Open- Stack++ (http://elijah.cs.cmu.edu)*
  - derivative of the widely used OpenStack platform for cloud computing (http://openstack.org).
  - The "++" refers to the unique extensions necessary for use of OpenStack in cloudlet environments.
- Some key components of OpenStack++ such as cloudlet discovery and just-in-time provisioning have already been developed and are available as open source.

CONTENTS

7. Fog computing - MEC - Cloudlet

- **Initial promotion of these technologies**
  - Fog Computing (FC)- Cisco
  - Mobile Edge Computing (MEC)- ETSI ISG MEC founders: Nokia, Huawei, IBM, Intel, NTT DoCoMo, Vodafone
  - Cloudlet - Carnegie Mellon University; later supported by Intel, Huawei, Vodafone,
- **Support from Organizations**
  - **FC - Open Fog Consortium** website: http://www.openfogconsortium.org
    - drive industry/academic leadership in FC architecture, testbed development, interoperability and composability deliverables that seamlessly leverage CC and edge architectures to enable E2E IoT scenarios
  - **ETSI MEC**
    - http://www.etsi.org/technologies-clusters/technologies/mobile-edge-computing
    - aims to unite the telco and IT-cloud worlds, providing IT and cloud-computing capabilities within the RAN;
    - ISG MEC will specify the elements required to enable apps. to be hosted in a multi-vendor MEC environment

  - **Cloudlet :** OpenEdgeComputing.org: http://openedgecomputing.org/about-oec.html
    - OEC offers open source code for Cloudlets (extension to OpenStack)
    - Targets any industry that benefits from low-latency edge CC, whith products of IoT, Tactile Internet, 5G, web content delivery, or on-line gaming, etc.
    - while limited itself to focus on a few key enablers, the spectrum of use is open

7. Fog computing - MEC - Cloudlet

- **General note:**
  - many common characteristics
  - synergy is possible
- **General characteristics (FC, MEC, Cloudlets)**
  - Location, access
    - Geo-distributed and usually located between end device and main data center
    - Cloudlets and even some FC may run on terminal devices
    - Usually located in BSs, APs, aggregation points, routers, switches, GWs
    - Generally – wireless access, but not excluding the fixed one
    - Enabling low latency and jitter
    - Ruggedized for outdoor usage- possible
  - Multi-tenancy of apps at the edge and use of virtualized IaaS platform
  - **Typically they are extensions of the cloud** (MEC might be independent)
  - **IoT – is a driving factor** (services requiring distributed computing and storage)
    - Essentially for Fog computing, less for MEC and Cloudlets)
  - End device mobility support
  - **Context awareness** of the applications
    - Yes for FC and MEC, it can be added for cloudlets

7. Fog computing - MEC - Cloudlet

- **General characteristics (FC, MEC, Cloudlets) (cont'd)**
  - **Federation of services across domains of different edge node ownership and providers**
    - FC- yes, however need interoperability features (Open Fog Consortium)
    - MEC (specified in stds.)
    - Cloudlet – yes , need API included in OpenStack
  - **On-line data analytics** and interaction with cloud
    - FC – yes
    - MEC, Cloudlets- N.A
  - Support for appl. developed on N-tier hierarchy- yes, N = 3-FC, (2,3)-MEC, 3-Cloudlet
  - **Near-real-time interaction** amongst same apps on different edge nodes
    - FC- yes, inter-fog node communication is supporting a fully distributed application
    - MEC, Cloudlets – Partial (so far only to support device mobility: the device disassociates from edge node 1 and associates with a new edge node 2)
  - **Specify the need of efficient communication between edge nodes**
    - FC- yes, MEC, Cloudlet - No

Notes: *Data analytics :examining raw data , to draw conclusions about that information*
DA focuses on inference, the conclusion are derived based solely on what is already known
Data mining - to sort through huge data sets using sophisticated algorithms to identify undiscovered patterns and establish hidden relationships

7. Fog computing - MEC - Cloudlet

- **General characteristics (FC, MEC, Cloudlets) (cont'd)**
  - **Providing APIs for provisioning and monitoring virtual resources** for compute, storage, network
    - **FC** – Fog Abstraction Layer - provides such APIs. Foglet SW agents use such APIs and constitute a distributed fog orchestration framework
    - **MEC-** this is done via a Mobile Orchestrator (borrowing from ETSI network function virtualization (NFV) MANO and service orchestration for NFV
    - **Cloudlets** - such APIs are exposed via OpenStack and extensions to OpenStack
  - **Life-cycle management** of distributed cloud apps
    - **FC-** Fog Service Orchestration Layer
    - Mobile Orchestrator and OSS/BSS of the telecoms network operator
    - **Cloudlets**- partially specified
  - **Support for different use cases** from multiple vertical industries
    - **FC**- yes, e.g., smart cities with smart traffic lights, energy (wind farms)
    - **MEC**- yes, e.g., security industry, content delivery industry
    - **Cloudlet**- yes , e.g. health sector, security sector, consumer services discretionary with cognitive assistance

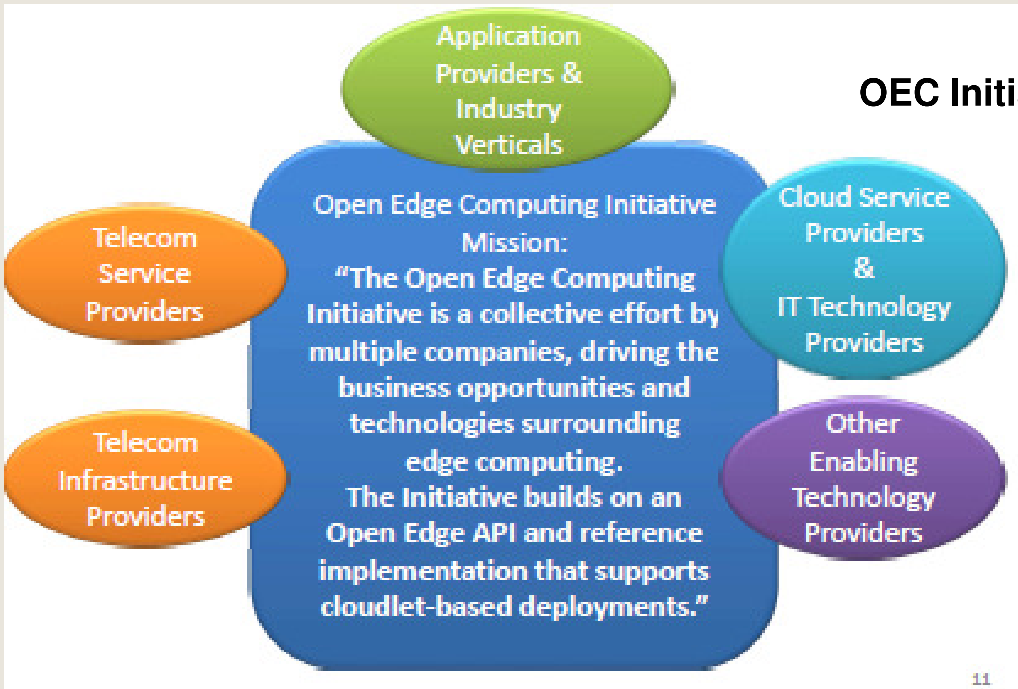
7. Fog computing - MEC - Cloudlet

- **Open Edge Computing (OEC) – novel general approach**
  - **Edge Computing:** small data centers at the network edge offering computing and storage resources next to the user
- Carnegie Mellon University- early work on Cloudlets at the edge
- **2015: overlapping interests in MEC → a few parties joined research efforts under the open source banner of Open Edge Computing (OEC)**
  - Curently, OEC ecosystem includes CMU, Intel, Huawei, and Vodafone
- **Main goals :**
  - To promote Cloudlets as enabling technology
  - **To drive**
    - The necessary technology for various use cases (low latency and computation at the edge) (e.g. extensions to OpenStack, KVM, QEMU).
    - prototyping of applications that leverage edge CC (ECC) pushing the boundaries and demonstrating benefits.
    - the eco system development for OEC and use current IT solutions
  - Engaging with
    - target service industries/sectors through demonstrators and joint projects
    - developer communities, seeking feedback and driving ECC acceptance
  - Synchronising work with other efforts incl. ETSI ISG MEC and OPNFV.

Source [31] http://openedgecomputing.org/about-oec.html

7. Fog computing - MEC - Cloudlet

- **Open Edge Computing (OEC)** : OEC status **– (cont'd)**
  - **Basic Edge Server** technology – market-available from several telco vendors (~2013); ~ All vendors work on edge solutions.
  - Many telecom operators : - perform trials with edge technology
  - Some operators have already launched edge services (e.g. edge caching)
  - EC initiatives in several industries
    - ETSI Industry Specification Group **MEC** - develops req., arch. and specs
    - IT industry initiatives: **OpenStack Foundation, OpenFog**



OEC Initiative: Mission

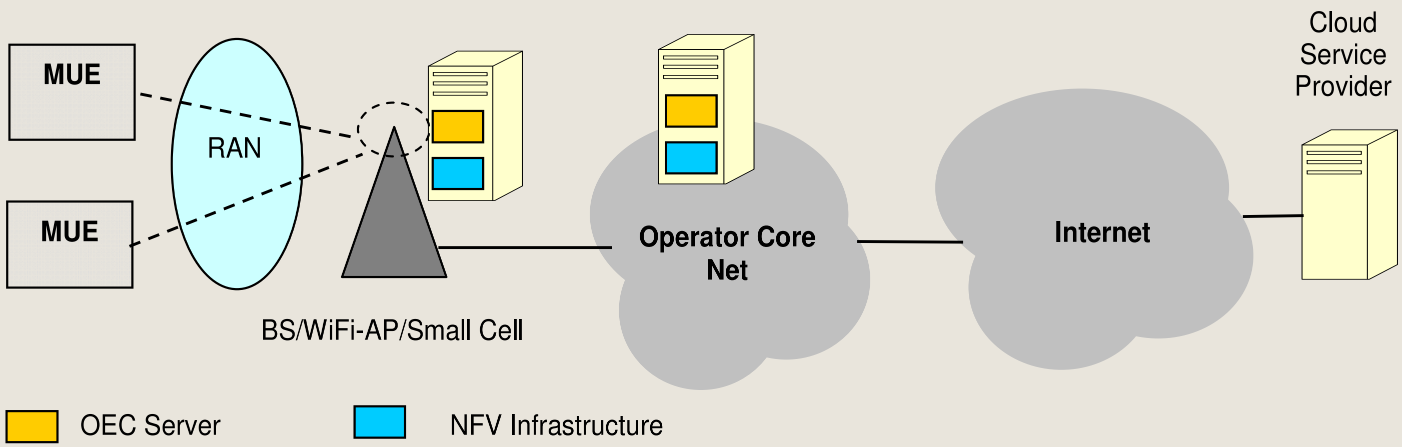
Main target: provide an OE API and reference platform for OEC and align it with the IT industry and the telecoms industry

Source [32] : R.Schuster, P. Ramchandran, OPEN EDGE COMPUTING – FROM VISION TO REALITY -2016, OPNFV Design Summit, Berlin, Germany

7. Fog computing - MEC - Cloudlet

Open Edge Computing (OEC) - general approach

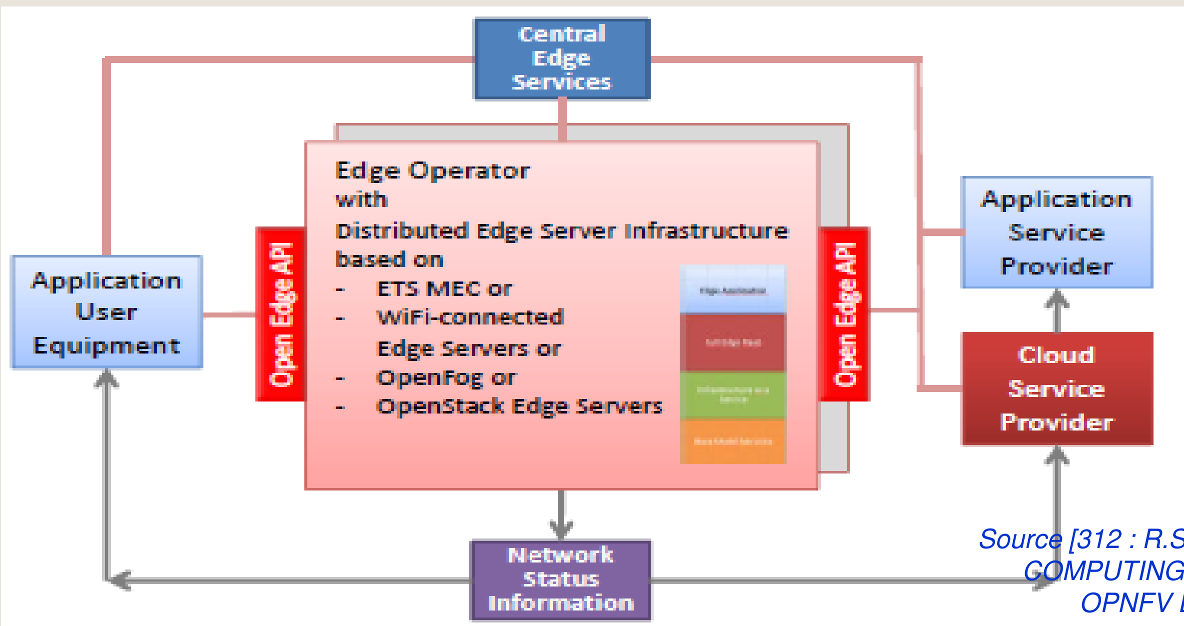
- The OEC servers can be located close/associated to Base Stations, Access Points, Small Cells, …or even in the Operator Core Network
- Edge Computing will utilize the Network Function Virtualization (NFV) infrastructure wherever possible
- This will reduce deployment cost of EC significantly



Adapted from Source [32] : R.Schuster, P. Ramchandran, OPEN EDGE COMPUTING – FROM VISION TO REALITY -2016, OPNFV Design Summit, Berlin, Germany

7. Fog computing - MEC - Cloudlet

- **OEC (cont'd): Open Edge Services main Requirements**
  - to have a globally agreed structure and to be available everywhere
  - to be independent of
    - the communication bearer and network provider
    - the underlying technology and its provider
  - open to all application categories + technologies
  - to support all relevant business scenarios
- **Edge Operator –novel** business entity, placed between the users and **App. Service Provider** or **Cloud Provider**

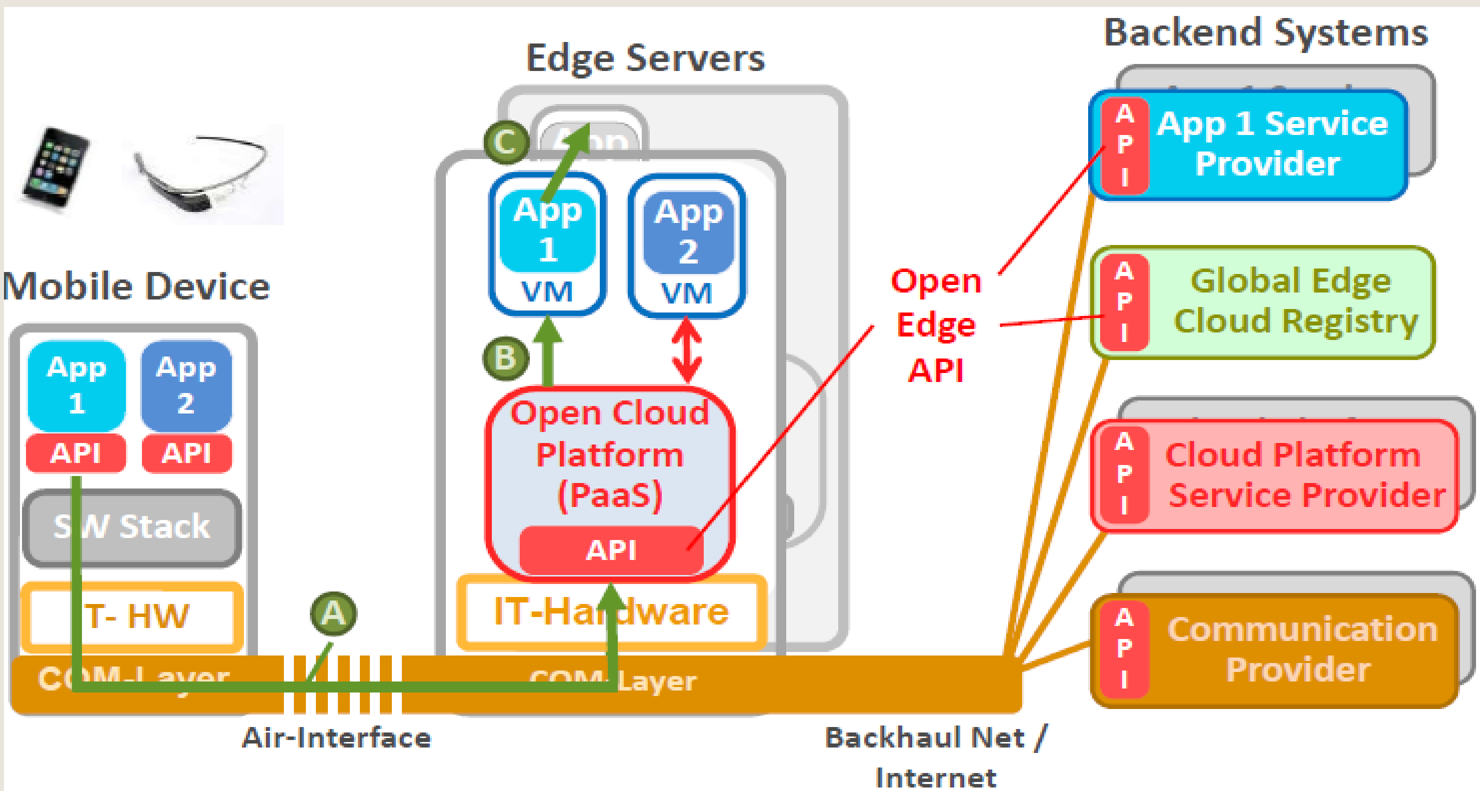


OEC:
OpenEdge API

Source [312 : R.Schuster, P. Ramchandran, OPEN EDGE COMPUTING - FROM VISION TO REALITY -2016 OPNFV Design Summit, Berlin, Germany

7. Fog computing - MEC - Cloudlet

- **OEC (cont'd):** Key Reference Platform **Functions** and **API**
  - A -Edge Server (Cloudlet) Discovery – discover the best and closest edge server
  - B- VM Provisioning – fast provisioning of VM and app on selected edge server
  - C-VM Handoff – handoff of application to next edge server in case of movement



Source [32] : R.Schuster, P. Ramchandran, OPEN EDGE COMPUTING - FROM VISION TO REALITY -2016, OPNFV Design Summit, Berlin

CONTENTS

8. Open topics – cooperation and research

- **Business level cooperation needs**
  - Stronger cooperation between
    - Fog and Edge Cloud Computing interested players and traditional CC big players
    - ETSI ISG MEC and traditional CC big players (Microsoft, Amazon, ..) and also with OEC
  - **Bridging the gap** between "the novel concept" FC, MEC, Cloudlet) and the industrial corporate clients/actors
    - e.g. to sell the concept to industry leaders in CC, and convince such leaders to promote and introduce the new technology to their clients
  - Conventional Cloud – to migrate towards Intelligent Cloud (including IoT, IoE)

  - **Specific steps already started-** examples
    - Expanding the coverage of the public cloud data centers into more regions
    - Adding cloud GWs close to the IoT data sources and inject data into the main cloud
    - Adding PaaS or SaaS features (e.g., machine learning software - Microsoft Azure ML)
    - Adding real-time analytics engines to the clouds
    - Adding tools for corporate clients to deploy IoT applications across the Cloud.
    - Partnering with key players in the IoT device platform market

8. Open topics – cooperation and research

- **Technical/research open topics**
  - Interworking between edge clouds
    - (in FC, ETSI MEC server, Cloudlet) and main clouds (e.g., Microsoft, HP, IBM, Google etc.).
    - belonging to different domains (operated by different providers)
  - Design techniques for cloud-native applications (e.g. , for IoT) to be deployable in a distributed cloud environment (e.g., IoT device, a fog platform or Cloudlet of provider X, and a main cloud).
    - Example use case: smart traffic light
  - Extension of
    - IP routers to become fog nodes (e.g. Cisco IOX),
    - LTE base stations to become MEC nodes (e.g. NOKIA)
    - hyperscale cloud data center to reach out to the edge as well (e.g. Microsoft Azure
  - Design of distributed cloud applications for deployment across the chain :
    - a main data center + multiple FC nodes + end points (the "things" in the Internet)
  - Develop methodology to deploy edge/fog appl. in a 3+ tier way , similar to the smooth way, as for today's cloud offerings (e.g. Amazon EC2, Microsoft Azure etc.)
    - Fog/edge architectures have to further develop APIs for application development and deployment

8. Open topics – cooperation and research

- **Technical/research open topics (cont'd)**

  - Determining the needs/requirements and constraints of vertical industries for security and privacy in the context of distributed cloud, edge cloud and fog.

  - Studying possible operational /business models:
    - Who would operate E2E appl. ?
    - Where/which part of the application is hosted
      - in a big public or hybrid cloud,
      - in edge cloud computing nodes and fog nodes
      - on the devices?

    - What are the service guarantees, who provides them (SLAs?)
      - how do service guarantees fit together
      - which party is responsible for the E2E quality of the distributed cloud application?

8. Open topics – cooperation and research

- **Technical/research open topics (cont'd)**
- **Fog Computing specific issues**

- **Communications between Mobile User Equipment and Fog Servers**
  - **Cross-layer Design:**
    - The fog server manages an autonomous, network by providing both service applications and wireless communications to mobile users.
    - It can manage all layers and enable the cross-layer design to provide the best service quality to users (e.g., caching a number of videos)
  - **Predictable User Feature and Demand:**
    - A Fog server needs to adapt to RAN interfaces to fully explore the localized user features and service demand.
    - It may run specific prediction algorithms (e.g., for shopping malls, bus, V2X, etc.) to evaluate estimate the demand.

8. Open topics – cooperation and research

- **Technical/research open topics (cont'd)**
- **Fog Computing specific issues (cont'd)**

- **Fog Servers – Central Cloud Communications**

  - The cloud is the central controller - it manages and coordinates the distributed Fog servers

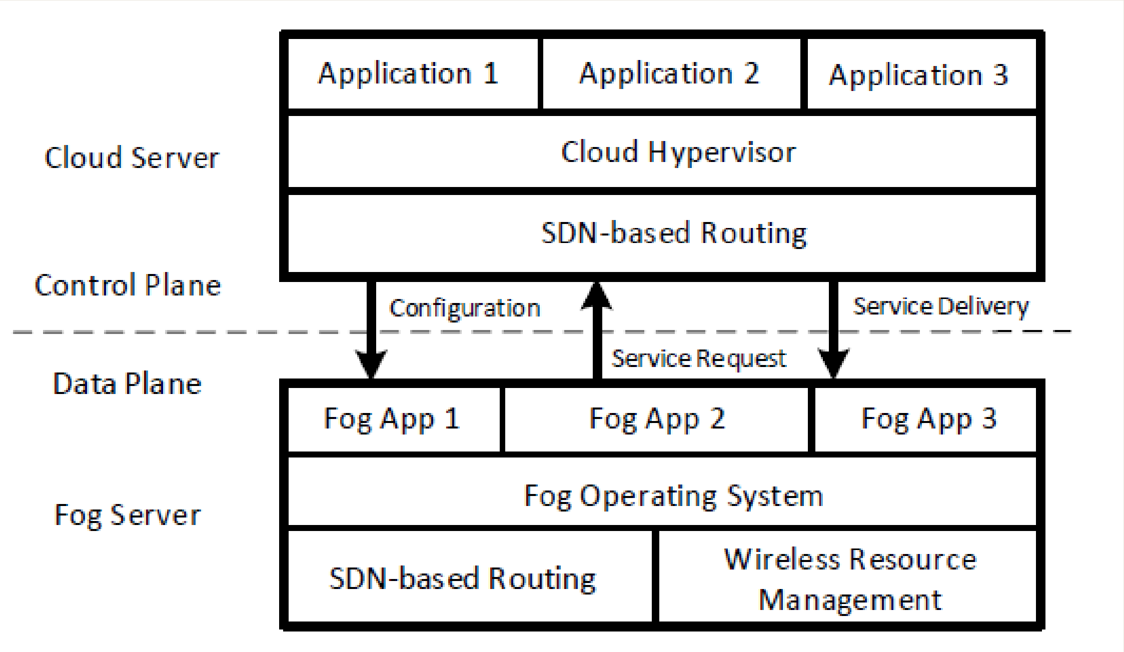
  - The cloud is the central information store.
  - Different Fog servers select the information contents from the cloud and then deliver the replicas from its cache to the mobile users

  - A cloud server manages the applications and contents for the entire system

  - At a particular Fog server, selective localized applications should be provisioned and synchronized with the cloud

8. Open topics – cooperation and research

- **Technical/research open topics**
- **Fog Computing specific issues (cont'd)**
  - **Fog - Cloud Communications (cont'd)**
  - If SDN approach is adopted then the cloud
    - manages the network with a global (SDN principle) view
    - the cloud establish the routing path of data to update the geo-distributed Fog servers (+ control plane and data plane separation).



Source [5]: T H. Luan et.; al. , "Fog Computing: Focusing on Mobile Users at the Edge", arXiv:1502.01815v3 [cs.NI] 30 Mar 2016

8. Open topics – cooperation and research

- **Technical/research open topics (cont'd)**
- **Fog Computing specific issues (cont'd)**
- **Communications between Fog Servers**
  - A Fog Server (FS) manages a pool of resources locally → need of collaborative service provision and content delivery among peered FSs
  - The data routing among FSs can be managed
    - either by a centralized manner using the SDN-based approach,
    - or, by a fully distributed manner ~ traditional routing mechanism (e.g., OSPF).
- **Data transmission challenges:**
  - **Service policy:**
    - the FSs at different locations may belong to different business actors
    - they may conform to different policies defined by owners → data routing among FSs needs to address the heterogeneous service policies.
  - **Topology:**
    - If FSs co-located in the same region are connected to the Internet through the same ISP with the high-rate low-cost connections,
    - then direct communications via Internet can alleviate the traffic between cloud and FSs
  - **Connection:**
    - Optimization problem is open - the data routing among FSs (wired connections over Internet or wireless connections through opportunistic connections)

8. Open topics – cooperation and research

- **Technical/research open topics (cont'd)**
- **Fog Computing specific issues (cont'd)**

- **Fog Computing Deployment**
  - Additional computing and storage resources at the edge
  - The FS needs to adapt its services → extra management and maintenance cost.

  - The FC operator Should address challenges
    - **Application:** customize the applications embedded in each of the FS based on the local demand.

    - **Scaling:** anticipate the demand of each of the FSs and deploy adequate fog resources so as to sufficiently provision.

    - **Placement:** A group of FS can collaboratively provide service applications to mobile users nearby.

8. Open topics – cooperation and research

- **Technical/research open topics**
- **Fog Computing specific issues**

- **Supporting Technologies: 5G, SDN, NFV**
  - 5G: The Fog layers can be adapted by using the existing accessing networks, e.g., WiFi,or emerging 5G wireless technologies with a virtualized architecture
  - Network Function Virtualization (NFV) - enable VNFs inside network nodes, e.g., switches and routers
  - FC enable virtualized location-based applications at the edge device and providing desirable services to localized mobile users.
  - With a global network view, the cloud can manage the entire network using a SDN approach

8. Open research topics

- **Technical/research open topics (cont'd)**
- **Specific topics in C-RAN/H-CRAN/Fog**

  - two major problems in both CRANs and H-CRANs
    - high transmission delay and heavy burden on the fronthaul
    - C-RAN s H-CRANs do not take benefit from processing and storage capabilities in edge devices, such as RRHs and even 'smart' mobile terminals / user equipments (UEs

  - **use SDN style of control in F-RAN environment?**
    - The combination of the MAC functions and L1 functions for edge devices in F-RANs is still not yet clarified
    - SDN is centralisation-based (for control), while the F-RAN has a distributed characteristic, based on edge devices
    - using SDN control for F-RANs-> need to carefully define slices to isolate the signal processing from resource management in edge devices, as to provide non-interfering networks to different coordinators.

  - If SDN controllers are located in cloud computing network layer -> control traffic overhead appears (CPI --DPI) to be transported over fronthaul links -> decreasing the advantages of F-RANs.

8. Open topics – cooperation and research

- **Technical/research open topics (cont'd)**
  - **Mobile Edge computing – specific issues**
    - Standardized open environment is needed to be further developed to allow seamless and proficiently integration of traditional applications across the MEC platform
    - simulation platform to experiment for various MEC scenario can cut costs of development
    - implementing a mobility management (vertical and horizontal) allowing users to seamlessly access edge applications
    - Heterogeneous access management : 3G, 4G, 5G, WiFi, WiMAX, BlueTooth, ..
    - **Combining MEC with Fog in CRAN/H-CRAN architectures**
    - Pricing models
    - Scalability assurance (application migration, load balancing, ..)
    - Security problems for applications running in MEC
  - **Cloudlet specific issues:**
    - optimal cloudlet selection and seamless cloudlet handoff ?
    - OpenStack++
      - effort to become a universally deployable cloudlet platform
      - above and below which many proprietary HW/SW and service innovations can emerge

8. Open topics – cooperation and research

- **Technical/research open topics (cont'd)**
- **Identified by OEC Initiative**
- **ETSI ISG MEC to continue work on**
  - Requirements for MEC , Edge arch. focusing on mobile BS
  - Standard API´s for telecom related edge applications
- **Current Gaps:**
  - **Customer Facing Service**
  - **mobile edge system level management**
    - **Mobile edge orchestration, OSS Operations Support System**
    - **User application life cycle management proxy**
  - **mobile edge host**
    - Deployment model [one instance per /user or host or edge] – topology, cost etc.
    - Latency and location requirements
    - connectivity or mobility requirements (e.g. app. state relocation, app. instance relocation);
  - **mobile edge platform**
    - offering an environment where the mobile edge applications can discover, advertise, consume and offer mobile edge services
    - receiving traffic rules from the mobile edge platform manager, appls, or services, and instructing the data plane accordingly
    - hosting mobile edge services
    - providing access to persistent storage and time of day information

8. Open topics – cooperation and research

- **Technical/research open topics**
- **Identified by OEC Initiative (cont'd)**

  - **Mobile edge platform management**
    - managing the life cycle of applications including informing the mobile edge orchestrator of relevant application related events;
    - providing element management functions (site, cluster, fog) to the mobile edge platform;
    - managing the application rules and requirements including service authorisations, traffic rules, DNS configuration and resolving conflicts.

CONTENTS

9. Conclusions

- There are some differences, however FC, MEC, Cloudlets share a similar vision
- Main domain of applications and fields:
  - Internet of Things, Internet of Everything, Smart cities
  - Tactile Internet, and existence of appropriate wireless connectivity (low data rate minimal power consumption at a device)
  - 5G networks and related services
  - Big data wit near real-time response
- The current paradigm of bigger and more consolidated, more hyperscale cloud computing data centers will fall short of future industry needs
- It is required an extension of cloud computing to the edge of networks

- Many players have recognized this, as reflected in the existence of concepts like
  - **Fog Computing, Mobile Edge Computing and Cloudlets (Open Edge Computing)**

- For the time being - the trend is less supported less by big public cloud providers like HP, IBM, Google, Microsoft, or Amazon.

- However, cooperation Cloud- Middleware – devices seems to be the best tradeoffs to take benefit of powerful CC and also solve the scalability, real-time and bandwidth problems of a lot of applications

9. Conclusions

- **FC, MEC, Cloudlet** approaches can well serve and play a role in specific domain of Future Internet and especially in IoT, IoE, ..:

- Connected vehicles, V2V, V2X. Automotive safety services (like ice on motorway real-time warning, platooning, coordinated lane change manoeuvres etc.)

- Services in infotainment (e.g. in automotive)
- Safety and emergency systems
- Mission critical systems

- Smart city system components like smart traffic lights (beyond what's available today)
- Big data and analytics for sectors like industrial: real-time analytics at the edge, long-term analytics in the main cloud, for purposes like predictive maintenance and others.

- Smart grid, closed loop system (a degree of central processing occurs at the edge with special requirements on stability and rapid response).
- Efficient operation of wind farms: semi-autonomous controllers at each wind turbine are orchestrated on the level of the wind farm by software at the edge
- Robotics for various sectors including assisted living, remote diagnostics etc.

- Any sector that makes use of wireless sensor systems, (e.g. oil & gas or building industry)

- Thank you !
- Questions?

List of Acronyms

- ACE Ancestral Communication Entity
- AVC Audio Video Conference
- BBU Baseband Processing Unit
- BS Base Station
- BSC Base Station Controller (2G/3G)
- BSS Business Support System
- CC Cloud Computing
- CCN Content Centric Networking
- CDN Content Delivery Network
- COTS Commercial-off-the-Shelf
- CoMP Coordinated multi-point
- CP Content Provider
- CRAN Cloud RAN
- DASH Dynamic adaptive streaming over HTTP
- DRM Digital Rights Management
- EC Edge Computing
- EPC Evolved Packet Core
- ETSI European Telecommunications Standards Institute
- FC Fog Computing
- FCN Fog Computing Node
- HCRAN Heterogeneous CRAN
- HPN High Power Node
- HSPA High Speed Packet Access
- HTTP Hyper Text Transport Protocol
- IaaS Infrastructure as a Service

List of Acronyms (cont'd)

▪	IMS	IP Multimedia System
▪	ISG	Industry Specification Group.
▪	IT	Information Technology
▪	KVM	Kernel-based Virtual Machine
▪	LPN	Low Power Node
▪	LTE	Long Term Evolution
▪	MEC	Mobile Edge Computing
▪	MBMS	Multicast Broadcast Media Service
▪	M&O	Management and Orchestration
▪	MME	Mobility Management Entity
▪	NF	Network Function
▪	NFV	Network Functions Virtualization
▪	NFVI	Network Functions Virtualization Infrastructure
▪	NO	Network Operator
▪	NP	Network Provider
▪	NS	Network Service
▪	OEC	Open Edge Computing
▪	OSS	Operations Support System
▪	OSPF	Open Shortest Path First
▪	PaaS	Platform as a Service
▪	PoC	Proof of Concept
▪	RAN	Radio Access Network
▪	RRH	Remote Radio Head

List of Acronyms (cont'd)

▪	RNC	Radio Network Controller
▪	QEMU	Quick Emulator
▪	SaaS	Software as a Service
▪	SDN	Software Defined Network
▪	SLA	Service Level Agreement
▪	S/P-GW	Serving and Packet Data Networks Gateway
▪	SP	Service Provider
▪	TCP	Transmission Control Protocol
▪	UDP	User Datagram Protocol
▪	VM	Virtual Machine
▪	VNF	Virtual Network Function

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Backup slides

1.1 SDN main objectives and features

- **Recent industry/research effort - results:**
  - **SDN** –new networking architecture
  - **Open Networking Foundation** (ONF- non-profit industry consortium) → several OpenFlow I/F specs for SDN

- **Promises for enterprises, data centres, carriers** :
  - higher programmability, automation, and network control
  - highly scalable, flexible networks
  - fast adaptation to changing business needs

- **SDN objectives:**
  - **Control Plane (CPl) and Data Plane (DPl) separation**
  - A centralized logical control and view of the network
    - underlying network infrastructure is abstracted from the applications
    - common APIs
  - Open I/Fs between the CPl (controllers) and DPl elements.
  - Network programmability: by external applications including network management and control
  - Independency of operators w.r.t. network equipment vendors
  - Technology to be used in Cloud data centers as well in WANs
  - Increased network reliability and security

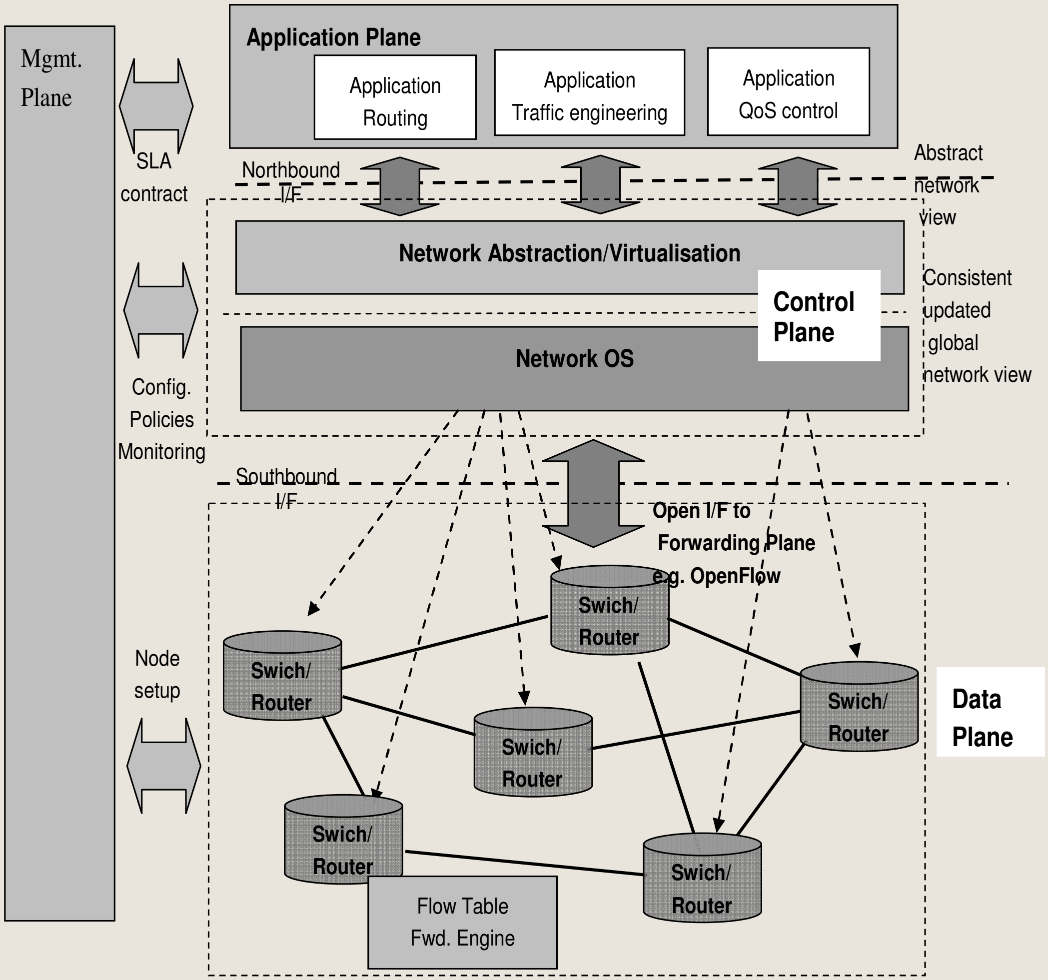
  - ***OpenFlow*** : typical ("vertical") protocol DPl ---CPl

1. Software Defined Networking- short overview

1.2 SDN Basic Architecture

- **Network OS:**
  - Distributed system that creates a consistent, updated network view
  - Executed on servers (controllers) in the network
  - Examples: NOX, PoX, ONIX, HyperFlow, Floodlight, Trema, Kandoo, Beacon, Maestro,..

- **SDN controller uses forwarding abstraction in order to:**
  - Collect state information from forwarding nodes
  - Generate commands to forwarding nodes



2. Network Function Virtualization – short overview

2.1 Network Function Virtualization

- **NFV objectives**:
  - Improved capital efficiencies vs. dedicated HW implementation solutions, by:
    - Using COTS computing HW to provide **Virtualized Network Functions (VNFs)** through **SW virtualization techniques**
    - Sharing of HW and reducing the number of different HW architectures
- **Improved flexibility in assigning VNFs to HW**
  - better scalability
  - decouples functionality from location
  - enables time of day reuse
  - enhance resilience through **Virtualization**, and facilitates resource sharing
- **Rapid service innovation** through SW -based service deployment
- Common automation and operating procedures ⇒ **Improved operational efficiencies**
- **Reduced power consumption**
  - (migrating workloads and powering down unused HW)
- **Standardized and open I/Fs**: between VNFs infrastructure and mgmt. entities

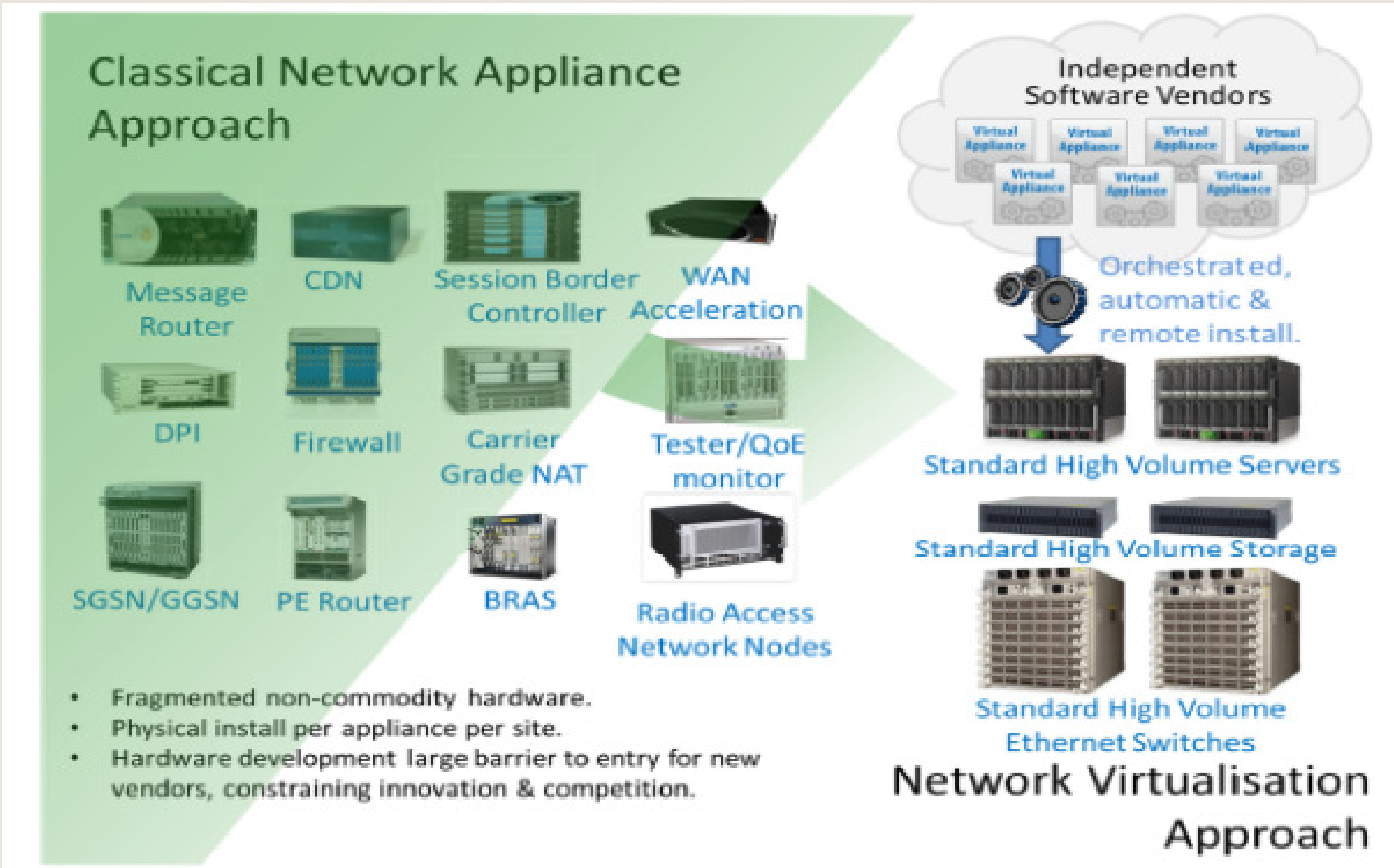
2. Network Function Virtualization (NFV)

- **2.1.Network Function Virtualization (cont'd)**
- Network services are provisioned differently w.r.t current networks practice
  - **Decoupling SW from HW**
    - network element is no longer a collection of integrated HW@SW entities ⇒ they may ***evolve independently***
  - **Flexible network function deployment:**
    - The SW/HW detachment allows to reassign and share the infrastructure resources
    - HW and SW can perform different functions at various times
    - The pool of HW resources is already in place and installed at some **NFVI-PoPs** ⇒ the actual NF SW instantiation *can be automated.*
      - leverages the different cloud and network technologies currently available
      - helps NOs to *faster deploy new network services* over the same physical platform.
  - **Dynamic operation**
    - network function are performed by ***instantiable SW components*** ⇒
      - greater flexibility to scale the actual VNF performance in a dynamic way
      - finer granularity, for instance, according to the actual traffic

2. Network Function Virtualization

2.2 Network Function Virtualization (cont'd)

- NFV vision (source : ETSI)



2. Network Function Virtualization

- ## 2.3 NFV Architecture (ETSI)

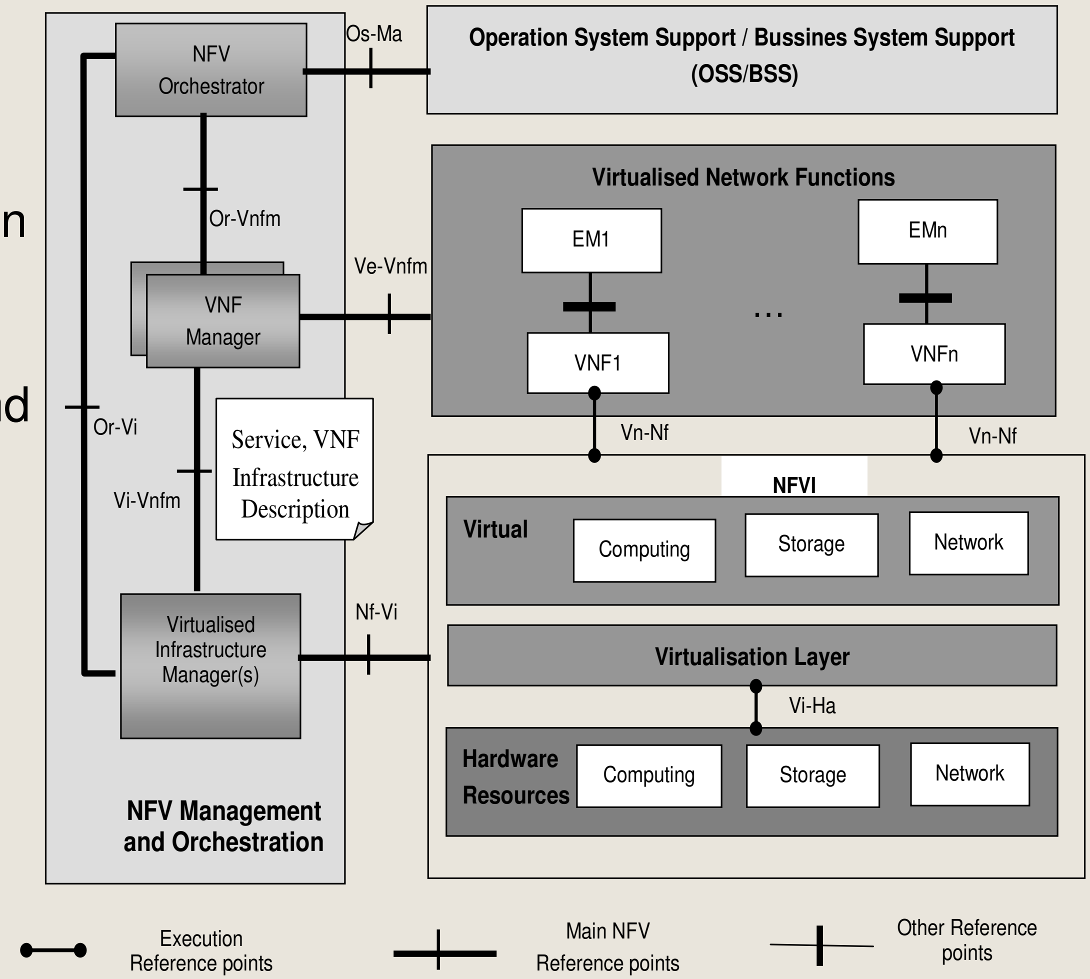
- **High level view of NFV framework**

- **Working domains**
- **VNF,** as the SW implementation of a NF

- **NFV Infrastructure (NFVI)** includes the PHY resources and how these can be virtualized
  - NFVI supports the execution of the VNFs.

- **NFV Management and Orchestration (NFV-MANO)**
  - orchestration and lifecycle management of physical and/or SW resources

  - NFV MANO focuses on all virtualization-specific management tasks



3. SDN and NFV cooperation

- **NFV SDN-Cooperation**
- ONF: NFV and SDN – industry view on architecture
- *Source: ONF*

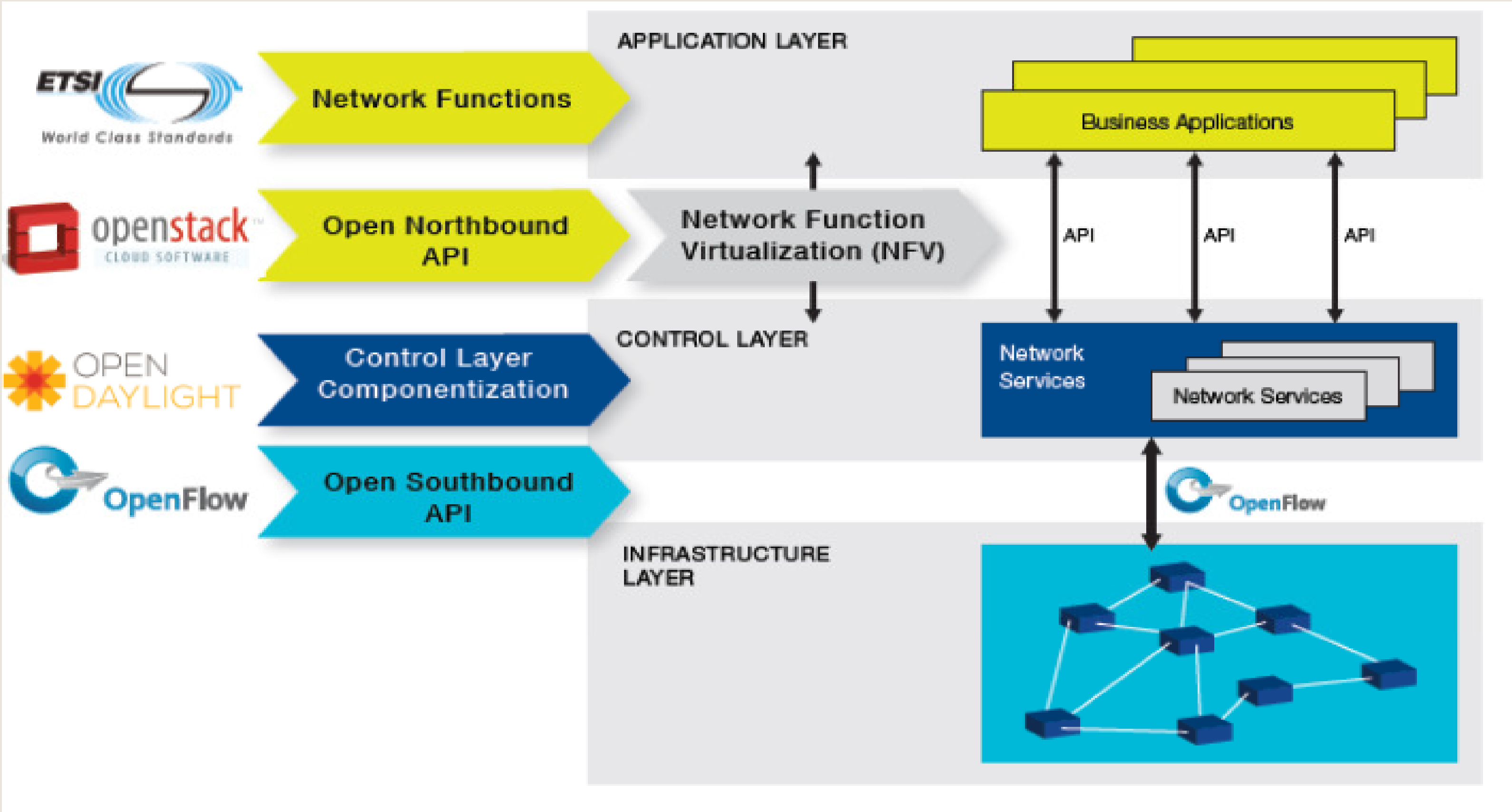


FIGURE 2: NFV and SDN Industry Map