Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

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Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

- **Eugen Borcoci : professor**

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- **Expertise:** telecommunications and computer networks architectures, technologies and services: network architectures and services, management/control/data plane, protocols, 4G/5G, SDN, NFV, virtualization, QoS assurance, multimedia services over IP networks

- **Our UPB team:**
  - **Recent research interest :** Software Defined Networking (SDN), Network Function Virtualization (NFV), Fog/edge computing, 5G networking and slicing, vehicular communications.
  - **Partners in many research European** and bilateral projects in the above domains

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

- **Acknowledgement**
  - This overview presentation **is compiled and structured based on several public documents**: conference proceedings, studies (overviews, tutorials, research papers), standards and specifications (Including 3GPP, 5GPPP, IETF, ETSI, GSMA, 5GAA, etc), research projects, etc. (see specific references in the text and the Reference list).
  - **The selection and structure of this material belong to the author.**

  - **Notes:**
    - Given the extension of the topics, this **presentation is limited to high level overview only**, mainly on conceptual, architectural, methods, challenges and open research.
    - **Some examples are selected** from the literature, projects, etc., to illustrate architectures and implementations of task offloading in edge computing support for V2X on top of 5G networks

This work has been partially supported by the NO Grants 2014-2021, under research project contract no. 42/2021, RO-NO-2019-0499 - "A Massive MIMO Enabled IoT Platform with Networking Slicing for Beyond 5G IoV/V2X and Maritime Services" SOLID-B5G, 2020-2023.

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

- **Motivation of this talk**

- **Vehicles and transportation systems** -essential parts of the today society
  - Significant development of vehicular networks and associated services
- **Traditional solutions**
  - **Intelligent Transport System (ITS) – mature set of standards and implementations**
    - initial applications : traffic safety and efficiency - only
    - ITS includes vehicular communication (VC) supported by specific communication technologies (wireless- WiFi, cellular; wireline, ..)

- **Recent extension: Vehicle to Everything (V2X) communications and services**

- **Global extension of V2X: Internet of Vehicles (IoV) –**
  - involves Internet and includes heterogeneous access networks
  - IoV – can be seen as a special/extended use case of **Internet of Things (IoT)**

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

- **Motivation of this talk** (cont'd)
- **The 5G (fifth generation) networks, in E2E architectures**
  - Driving forces for 5G and beyond (B5G): current and future networks and services needs (flexibility, bandwidth, traffic capacity, response time, number of terminals, energy saving, etc.)-
- **Application domains of 5G-B5G**: IoT, **IoV/automotive**, smart cities, industry, governance, safety/emergency, entertainment, environment, etc
  - **5G Network slices** –dedicated (to specific applications) logical, isolated networks, sharing the same physical network resources
  - **Standardization**/forums organizations –involved
    - 3GPP, 5GPP, ETSI, ITU-T, GSMA, ONF, NGNM, IETF, IEEE, etc.
- **Edge computing- (Fog/Multi-access Edge Computing) –moves the cloud-like capabilities in proximity of users**
  - strong support for V2X communications and services
  - better real time response
  - more efficient data processing
  - **Problem: mobility of vehicles → needs to offload computing tasks through the edge infrastructure**

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1. Vehicle to everything (V2X) communications - introduction

- **1.1 Vehicular communications and services – types**
  - **Basic vehicular (VC) communications**
    - vehicle-to-vehicle (**V2V**)-direct communications
    - vehicle-to-road/infrastructure (**V2R/V2I**)
  - **Extended communication models** :
    - **Vehicular-to-everything (V2X)** - (see 3GPP Release 14-17), adds several communication modes, i.e., vehicle-to:
      - pedestrian (**V2P**)- direct communication
      - vulnerable road user (**VRU**)
      - network (**V2N**)- including cellular networks and Internet
      - sensors (**V2S**)
  - **Typical use cases and services/applications**
    - **Active road safety**
      - Warnings, notifications, assistance
    - **Vehicular traffic** management
    - **Infotainment**

1. Vehicle to everything (V2X) communications - introduction

1.2 Traditional developments in vehicular communications and services

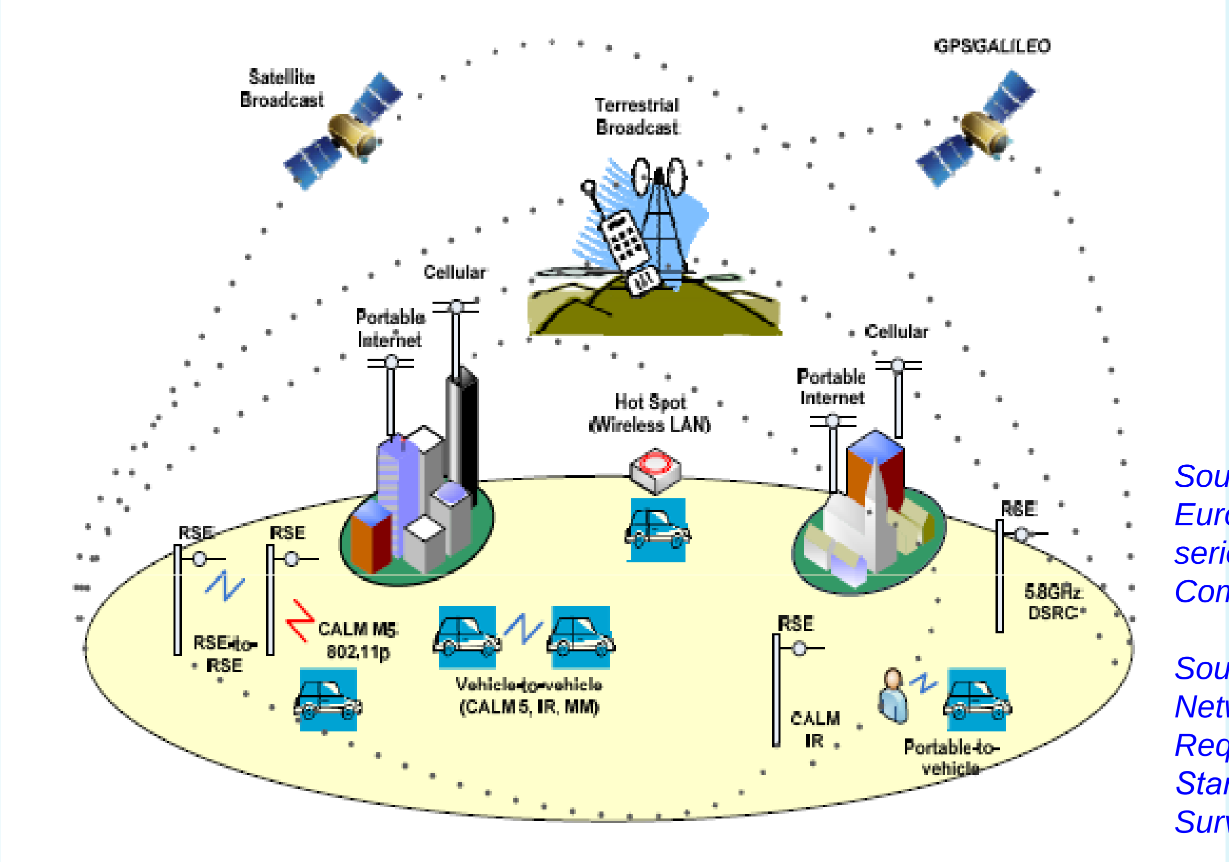
- **Intelligent Transport System (ITS)**
  - **Advanced technologies using IT&C,** to serve **transport systems**
    - innovative services for different modes of transport and traffic management
    - enable users to be informed and make safer, more coordinated, and 'smarter' use of transport networks
  - ITS targets all transport modes

  - **The EU directive (2010) defined ITS as systems in which IT&C are applied in the field of road transport,** including
    - infrastructure, vehicles and users
    - traffic management and mobility management
    - assistance for drivers with safety and other information
    - applications for passengers
    - interfaces with other modes of transport
  - **ITS: high interest for** companies, operators, government, academia, research; in many countries public and private sector bodies -work on ITS

1. Vehicle to everything (V2X) communications - introduction

1.2 Traditional developments in vehicular communications and services

- **Intelligent Transport System** (cont'd)
- Elements of ITS are standardized : on int'l level at e.g., ISO TC204, and on regional levels, e.g., in Europe at ETSI TC ITS and at CEN TC278



ITS Scenario illustration

Source : ETSI EN 302 665 V1.1.1 (2010-09, European Standard (Telecommunications series) Intelligent Transport Systems (ITS); Communications Architecture

Source : G.Karagiannis,et.al.,"Vehicular Networking:A Survey and Tutorial on Requirements,Architectures, Challenges, Standards and Solutions", IEEE Comm. Surveys and Tutorials, 2011

1. Vehicle to everything (V2X) communications - introduction

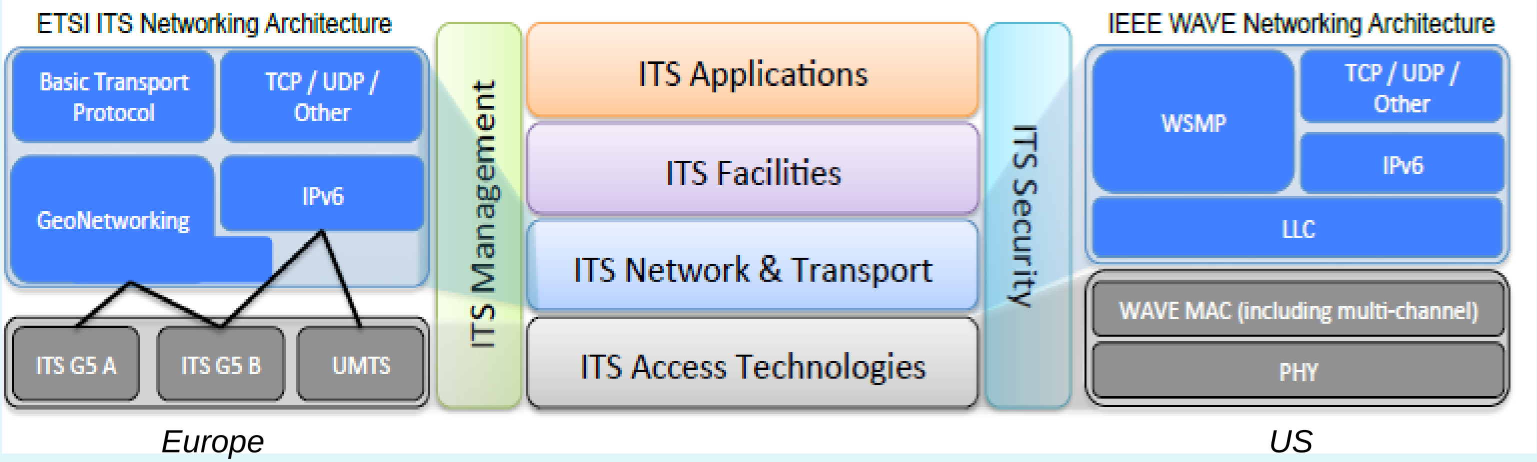
1.2 Traditional developments in vehicular communications and services

- **Intelligent Transportation System** (cont'd)
- **ITS Application categories**
  - Emergency notification systems, Automatic road enforcement, Variable speed limits, cCollision avoidance systems
- **Networks involved in the ITS architecture**
  - Ad-hoc network, Access Networks, Core networks
- **Technologies**
  - **DSRC (Dedicated Short Range Communication)**
    - spectrum dedicated for ITS communication (vehicles,infrastructure); two-way wireless system, 5.9 GHz licensed spectrum band
    - US *Federal Communications Commission* (FCC) : 75 MHz of spectrum in the 5.9 GHz band for ITS – 1999; ETSI : 30 MHz of spectrum in the 5.9 GHz band for ITS- 2008
  - **WAVE (Wireless Access in Vehicular Environment)**
    - Basic: MAC/PHY protocols and standards used for VC (including DSRC)
    - Extended: higher layers, such as **IEEE 1609.1-4**, included in WAVE
    - **WAVE : IEEE 802.11 (2012) + IEEE 1609.1-4 + SAE 2735** (*Society of Automotive Engineers*)

1. Vehicle to everything (V2X) communications - introduction

1.2 Traditional developments in vehicular communications and services

- **ETSI ITS versus IEEE WAVE layered architecture**



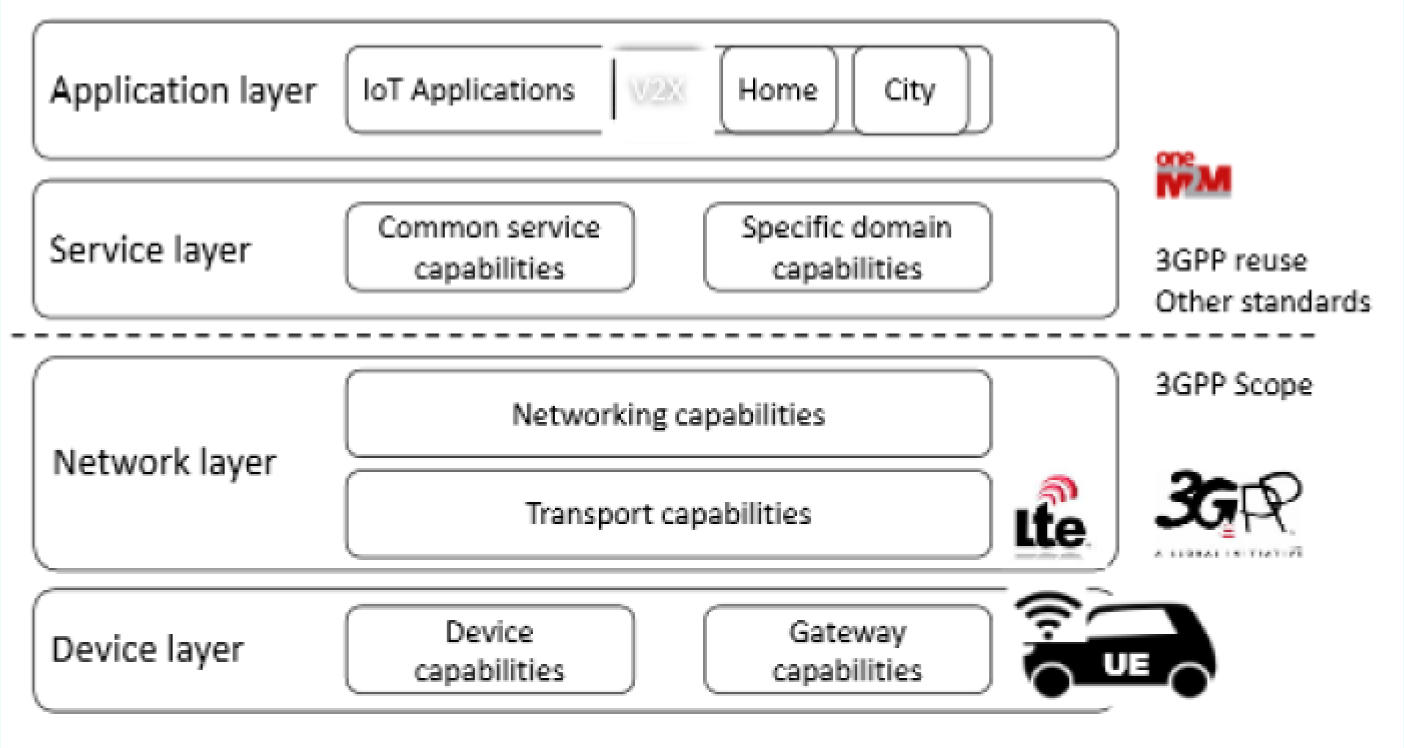
- *Wave Short Message Protocol (WSMP)* = network layer for ITS-specific traffic
  - WSMP is a single-hop broadcast, hence no routing protocol is employed, as no application requiring forwarding has been designed in WAVE architecture

Source: K.Katsaros and M.Dianati, "A Conceptual 5G Vehicular Networking Architecture", October 2017, https://www.researchgate.net/publication/309149571, DOI: 10.1007/978-3-319-34208-5_22

1. Vehicle to everything (V2X) communications - introduction

1.3 Recent developments in vehicular communications and services

- **Layered architecture overview for V2X**

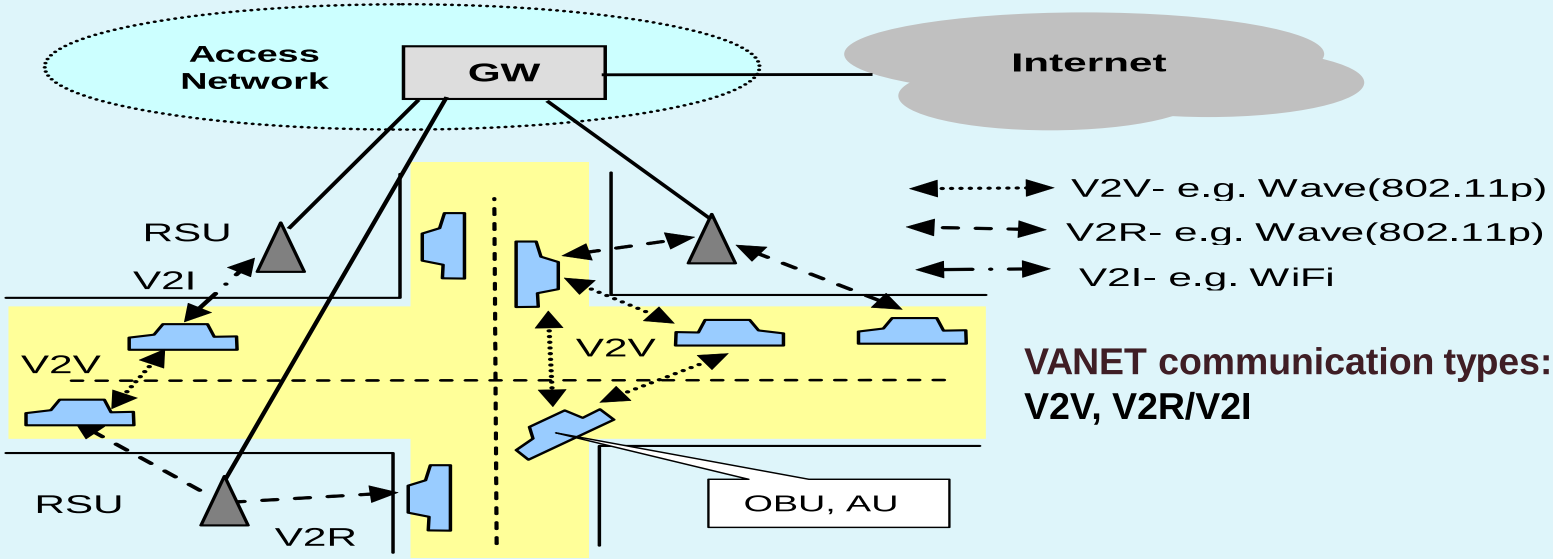


Source: U.S. Department of Transportation: "IEEE 1609 – Family of Standards for Wireless Access in Vehicular Environments (WAVE)". https://www.standards.its.dot.gov/Factsheets/Factsheet/80

1. Vehicle to everything (V2X) communications - introduction

1.3 Recent developments in vehicular communications and services

- **Vehicular ad-hoc Networks (VANET)**
- **Basic VANET system components**
  - **RSU- Road Side Unit, OBU On-board Unit, AU - Application Unit**
- **Typically**
  - RSU hosts apps. that provides services; OBU -peer device that uses the services
  - The apps. may reside in the RSU or in the OBU (provider/user model)
  - Vehicle: may host n≥1 AUs that use the apps. offered by the provider, supported by OBU connection capabilities
-

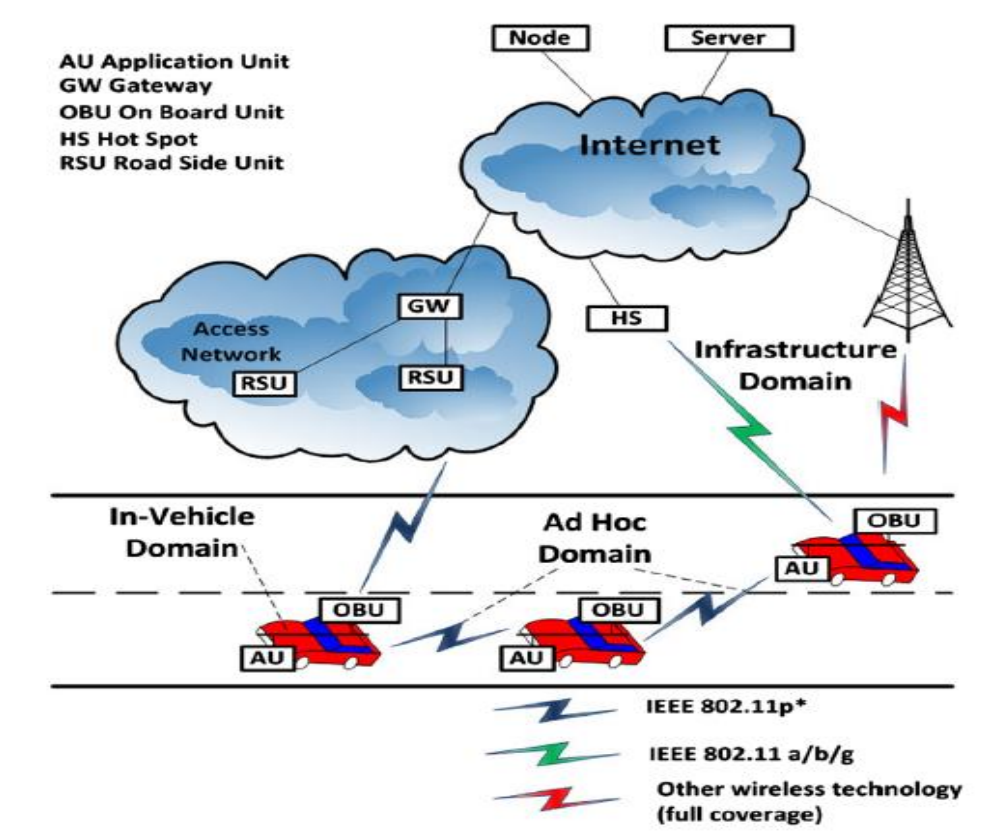


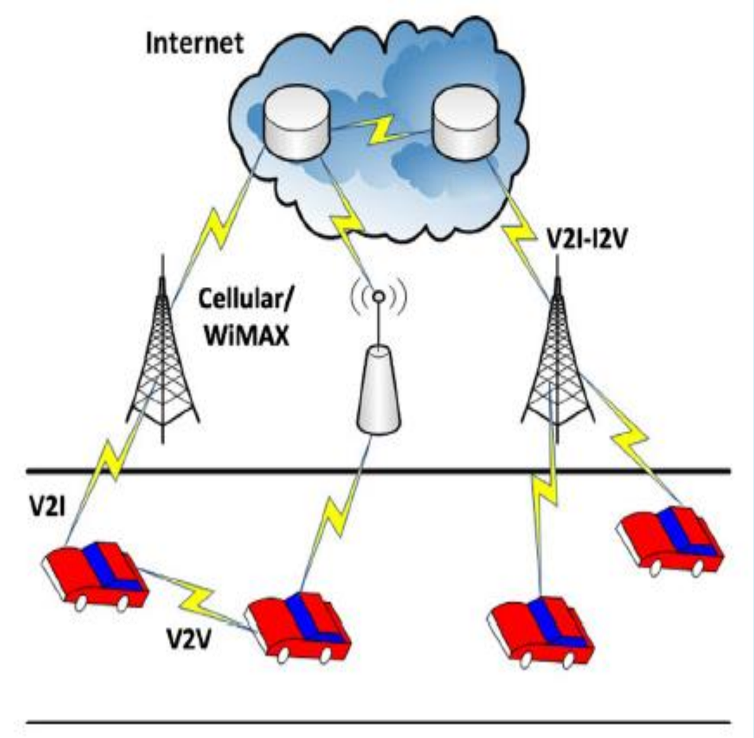
VANET communication types:
V2V, V2R/V2I

1. Vehicle to everything (V2X) communications - introduction

1.3 Recent developments in vehicular communications and services

- **Vehicular ad-hoc Networks (VANET)** (cont'd)
- **VANET – communication domains**





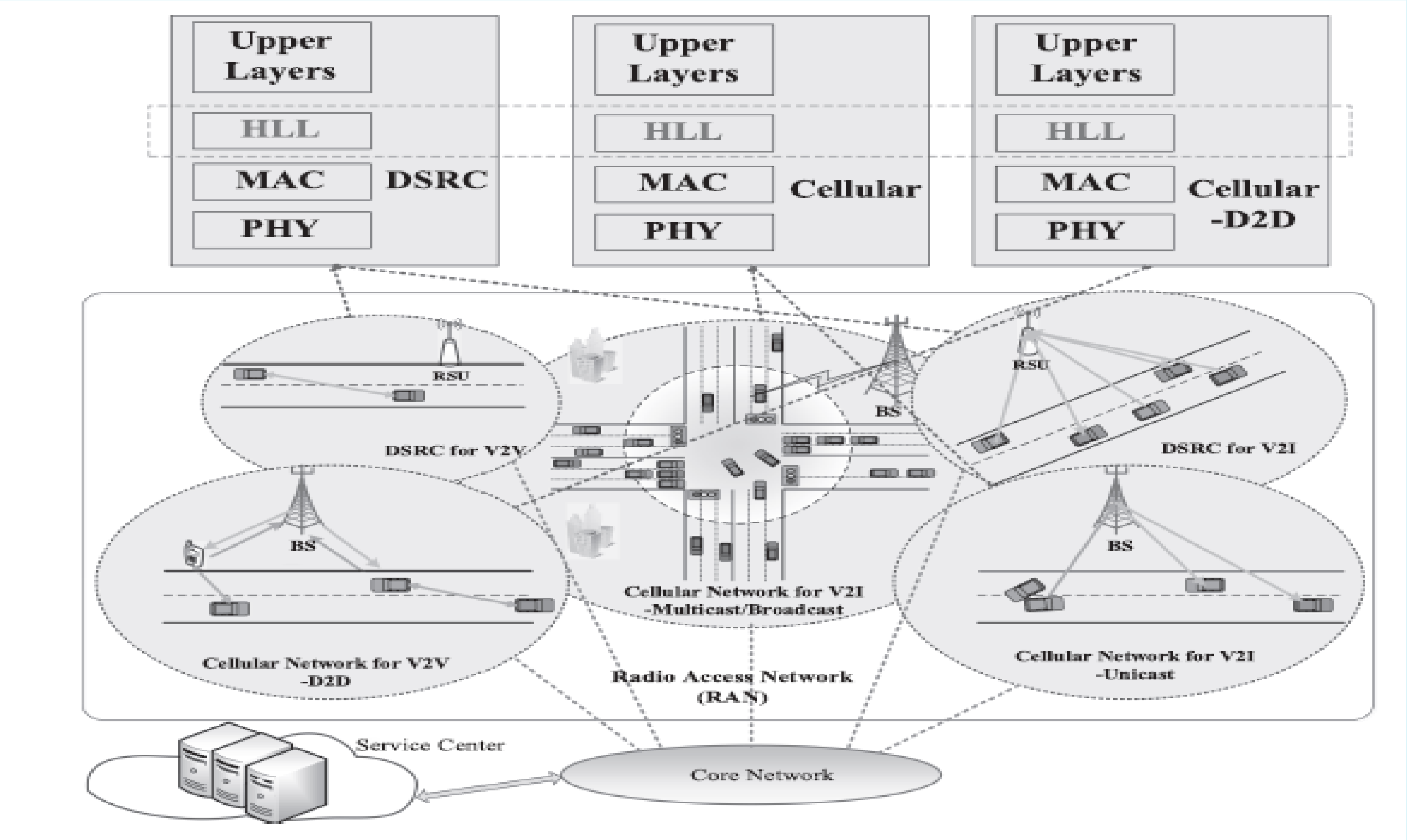
Combined DSRC, Cellular, Wi-Fi and WiMAX

Source: S. Sultan, M. Moath Al-Doori, A.H. Al-Bayatti, and H.Zedan "A comprehensive survey on vehicular Ad Hoc Network", J.of Network and Computer Applications, Jan. 2014

1. Vehicle to everything (V2X) communications - introduction

1.3 Recent developments in vehicular communications and services

- **Cellular alternative to IEEE 802.11-2012/DSRC**



Source : K.Zheng, et.al., "Architecture of Heterogeneous Vehicular Networks", Springer 2016, www.springer.com/cda/.../9783319256207-c1.pdf

1. Vehicle to everything (V2X) communications - introduction

1.3 Recent developments in vehicular communications and services

- **Cellular V2X (C-V2X)**
  - **C-V2X belongs to 3GPP advanced cellular systems (4G, 5G, …)**

  - **Early standardization**
    - LTE Broadcast (3GPP Rel. 9), LTE Direct (3GPP Rel.12), 3GPP Release 14
  - **LTE Direct**: V2V direct communications (< hundreds of meters) with low alert latency (~ 1 ms)
    - both in-coverage and out-of-coverage (of standard cellular infrastructure)

  - **LTE Broadcast** facilitates V2I and V2N, within traditional cellular infrastructure
    - The V2X servers can broadcast messages to groups while individual vehicles can unicast messages back to the server
      - Vehicle can - receive alerts about events a few miles ahead up the road; connect to smart parking systems to find open available spaces

  - V2V -> RAN modifications
    - Direct links over the sidelink PC5 (Rel.12, Rel.14) are based on the customization for the vehicular scenario of Proximity Services (ProSe)

1. Vehicle to everything (V2X) communications - introduction

1.3 Recent developments in vehicular communications and services

- **Cellular V2X (C-V2X)** (cont'd)
  - **C-V2X communications modes**
    - **D2D : V2V, V2R, V2I, V2I** - no mandatory network involvement for scheduling.
    - **Device-to-network (D2N): V2N**: uses cellular links to enable cloud services to be part of the E2E solution
  - **Two interfaces:** wide area network LTE interface (Uu); direct communications interface (PC5)
    - V2N occur over the cellular LTE-Uu I/F, operating in the traditional licensed spectrum, to support both unicast and multicast communications

1.4 Standardization- examples

- **3GPP (Third Generation Partnership Project)**
- **Standards for cellular V2X (C-V2X)**
  - **3GPP- C-V2X -**major target : autonomous driving
    - **Communication types**: V2V, V2R, V2I,V2P, wide area V2N, V2U, V2Cloud
    - One can replace the US -DSRC and the Europe-Cooperative ITS
- **Release 14 (2016)** - based on Long Term Evolution (LTE) – 4G technology (named LTE-V2X); basic safety services

1. Vehicle to everything (V2X) communications - introduction

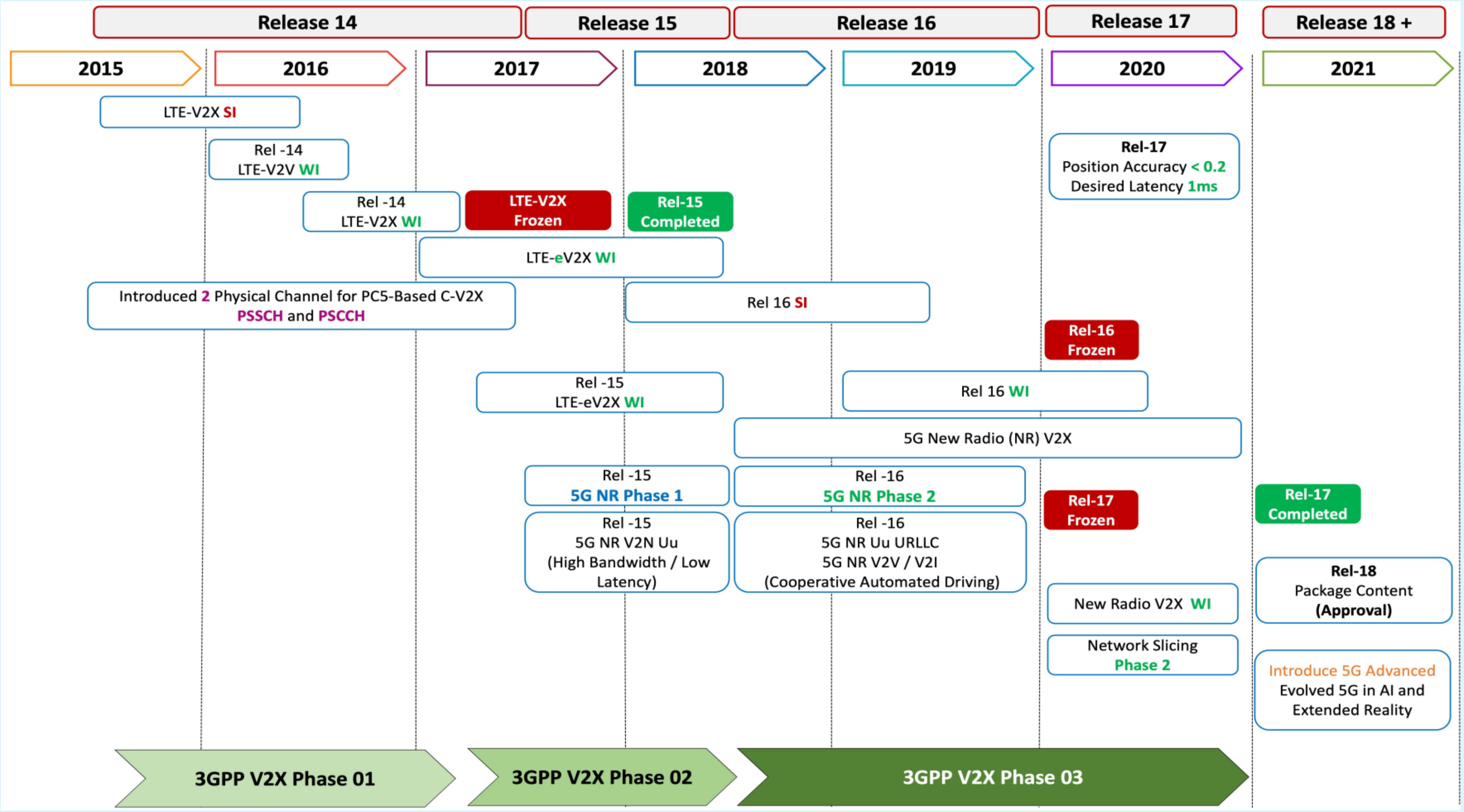
- **Release 15 (2017-18) 5G-V2X -**based on 5G (named **5G-V2X**)
  - New features: longer range, higher-order modulation (64QAM), lower latency (10ms min), higher reliability, and carrier aggregation (< eight component carriers)
  - Rel-15 phase 2 built a stable LTE-V2X (4G-V2X) ecosystem : services: platooning, extended sensors, advanced driving, and remote driving- support for eV2X services complementary to Rel-14
  - The 5G-NewRadio (NR)phase 1 started in Rel-15 and the 5G-NR phase 2 in Rel-16

- **Release 16** - further enhances the C-V2X functionality
  - The 5G updated version (5GS: 5G Phase 2) extends the 5G specs i.e., architectural aspects and service-oriented functionalities for V2X.
- **Release -17 NR** provides new sidelink communication relaying architecture
  - aiming to support some of the aV2X services
- **Release-18** aims to introduce new features and services such as 5G advanced, evolved 5G in Artificial Intelligence (AI) I and extended reality, etc.

Source: M.J.Khan, M.A.Khan, S.Malik, P.Kulkarni, N.Alkaabi , O.Ullah , H.El-Sayed, A.Ahmed and S.Turaev Advancing C-V2X for Level 5 Autonomous Driving from the Perspective of 3GPP Standards Sensors 2023, 23, 2261. https://doi.org/10.3390/s23042261. https://www.mdpi.com/journal/sensors Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Vehicle to everything (V2X) communications - introduction

- **1.4 Standardization examples**
- **3GPP (Third Generation Partnership Project)** (cont'd)



1. Vehicle to everything (V2X) communications - introduction

- **1.5 V2X Applications and services**
- The **5GAA** defined four **V2X** areas :
  - ***Safety*** – contribute to reducing vehicle collisions events
  - ***Convenience*** – help the management of vehicle status and offer special services (e.g. diagnostics, software updates, etc)
  - ***VRU*** **-** safe interactions between vehicles and non-vehicle road users
  - ***Advanced driving assistance***
    - strong interaction with (semi-) autonomous vehicle operation
    - **3GPP-refinement** 3GPP TR 21.915 V15.0.0 (2019-09)
      - Vehicles platooning, Advanced driving, Extended sensors Remote driving
- **Examples**
  - **Safety and traffic efficiency**
    - **V2V/V2P messages** sent/received (event-driven or periodic)
    - **applications** : forward collision warning, cooperative adaptive cruise control,VRU safety
  - **Autonomous driving**
    - higher requirements than V2V safety apps. (reasons: high speed, small inter-vehicle distances)
    - requires full road network coverage to be driverless in all geographies
    - network should support V2V/V2N communications under high vehicle density
    - video/data exchange over V2N links may be necessary

Sources: 3GPP TR 21.915 V15.0.0 (2019-09), TSG Services and System Aspects; Release 15
A.Molinaro and C.Campolo, "5G for V2X Communications", https://www.5gitaly.eu/2018/wp-content/uploads/2019/01/5G-Italy-White-eBook-5G-for-V2X-Communications.pdf

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2. 5G technology summary

2.1 5G Main characteristics

- **5G: evolution of mobile *broadband networks + new unique network and service capabilities***
- **Three main 5G features: *Ubiquitous connectivity for large sets of users, Very low latency, High-speed Gigabit connection***
- 5G - *user experience continuity* in various situations: high mobility, very dense or sparsely populated areas, heterogeneous access technologies
- **5G - key enabler for : IoT, M2M, IoV/V2X, Broadband/media services, ….**
- 5G integrates: *networking* + *computing* + *storage* resources

- **5G Key technological characteristics**
  - Heterogeneous set of integrated air interfaces; cellular and satellite solutions; different **Radio Access Technologies (RAT)**
    - **Seamless handover** between heterogeneous RATs
  - 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)
    - Cloud/**Mobile Edge Computing (MEC) /Fog Computing (FC)**
  - **Optimized network orchestration,management and control based on cognitive and AI/Machine learning technologies,** advanced **automation**

2. 5G technology summary

2.1 5G Main characteristics

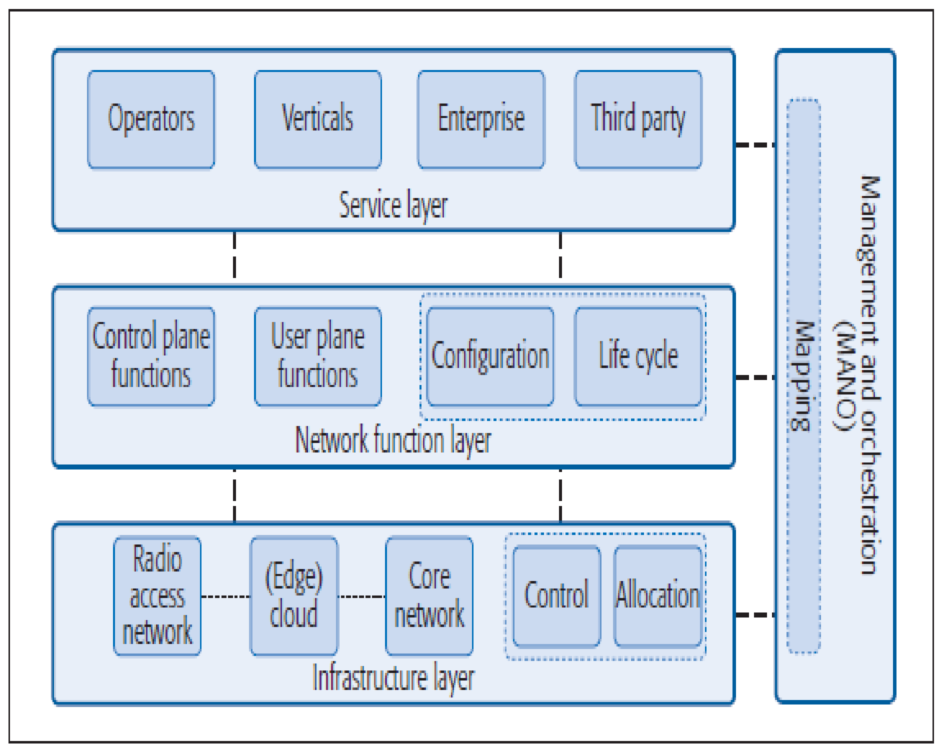
- **Summary of 5G figures - strong goals:**
  - **1,000 X in mobile data volume** per geographical area reaching a target ≥ 10 Tb/s/km2
  - **1,000 X in number of connected devices** reaching a density ≥ 1M terminals/km2
  - **100 X in user data rate** reaching a peak terminal data rate ≥ 10Gb/s
  - **1/10 X in energy** consumption compared to 2010
  - **1/5 X in E2E latency reaching 5 ms** for e.g. tactile Internet and radio link latency reaching a target ≤ 1 ms, e.g. for Vehicle to Vehicle (V2V) communication
  - **1/5 X in network management** OPEX
  - **1/1,000 X in service** deployment time, reaching a complete deployment in ≤ 90 minutes

- **Network softwarization:** represents sets of functions assuring **programmabil**ity of
  - network devices
  - **network functions (NF)-** virtual (VNF)–cooperating with physical (PNF)
  - **network slices** – logical, on demand, isolated customized networks
  - network services and applications- supported by slices
  - **Architectural planes**: Data/user, control, management

2. 5G technology summary

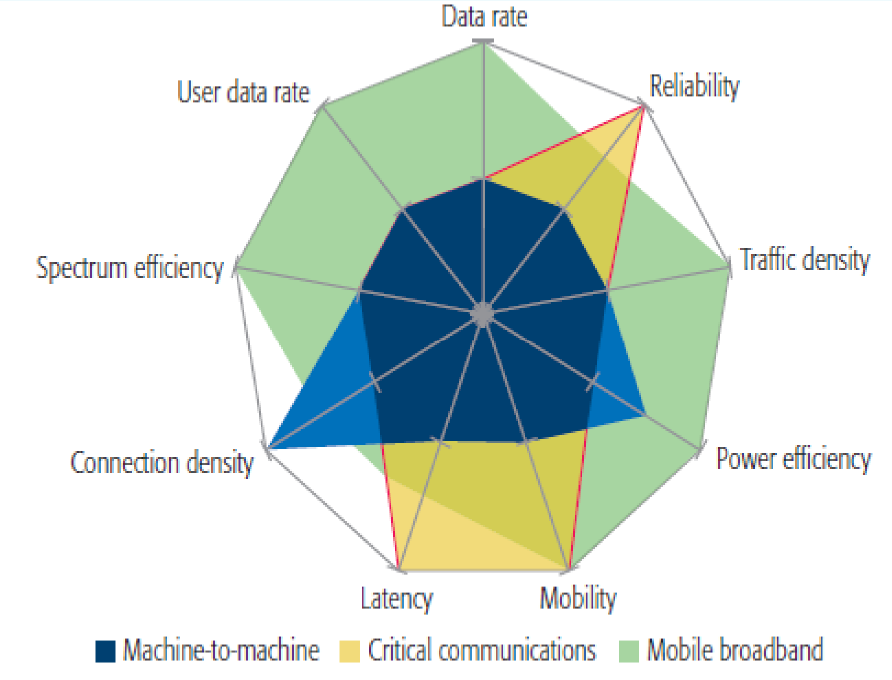
2.2 5G Layered Architecture

- **Generic layered architecture**
  - High level representation



Key 5G use cases and their requirements

- difficult for a traditional unique arch to meet all of them
- **dedicated slicing can be the solution**



Source: X. Foukas, G. Patounas, A.Elmokashfi, and M.K. Marina, Network Slicing in 5G: Survey and Challenges, IEEE Communications Magazine, May 2017, pp.94-100

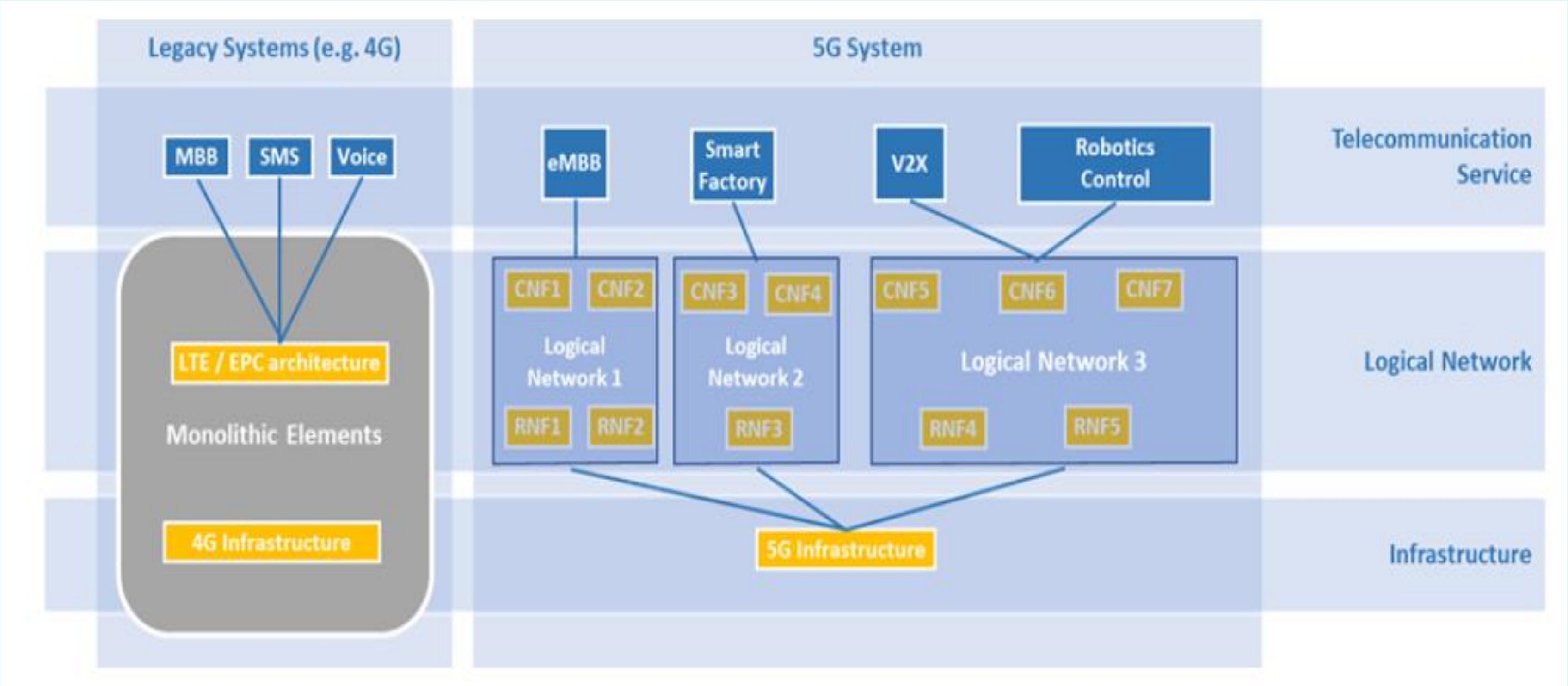
2. 5G technology summary

2.3 Network slicing concepts and architecture

- **Network Slicing** :
  - **E2E concept** covers all network segments : radio or wire access, edge, core, transport networks.
  - **concurrent deployment of multiple E2E logical, self-contained and independent shared or partitioned networks** on a common infrastructure platform
  - **Slices**
    - created **on demand or provisioned** (based on templates)
    - they run on a common underlying (PHY/V) network and are mutually isolated, each one having its own independent M&C
    - **composition** of adequately configured NFs/VNFs, network apps., and the underlying cloud infrastructure (PHY/virtual/ emulated resources, etc.)
    - **resources are bundled together** to meet specific UC reqs. (e.g., bandwidth, latency, processing, resiliency) coupled with a business purpose
- **SDN and NFV** –technologies providing virtualization, programmability, flexibility, and modularity to create **multiple network slices** each tailored for a given UC

2. 5G technology summary

- **2.3 Network slicing concepts and architecture**
- **4G versus 5G slicing concepts**



MBB - Mobile Broadband;
LTE - Long Term Evolution (4G) ;
V2X - vehicle to X ; **CNF**- Core Network Functions;

SMS - Short Messages service;
EPC- Evolved Packet Core
RNF- RAN network Functions

2. 5G technology summary

2.3 Network slicing concepts and architecture

- **Business model (**stakeholders**)-** variant of definition

  - **Infrastructure Provider (InP)**– owner of the PHY infrastructure (network/cloud/data center) and lease them to operators
    - It can become an ISLP if it leases the infrastructure in slicing fashion
  - **Infrastructure Slice Provider (ISLP) –** typically a telecom SP, **owner or tenant** of the infrastructures from which network slices can be created
  - **Infrastructure Slice Tenant (IST) -** the user of specific network/cloud/data centre slice, hosting customized services
    - ISTs can request creation of new infrastructure slice through a service model
    - **IST leases virtual resources from one or more ISLP** in the form of a virtual network, where the tenant can realize, manage and provide network services to its users
    - **A network service** is a **composition of NFs,** and it is defined
      - in terms of the **individual NFs**
      - and the **mechanism** used to **connect them**
  - **End user:** consumes (part of) the services supplied by the tenant, ***without providing them to other business actors.***

Source: A.Galis and K.Makhijani, Network Slicing Landscape: A holistic architectural approach, orchestration and management with applicability in mobile and fixed networks and clouds, v1.0, Network Slicing Tutorial – IEEE NetSoft 2018

2. 5G technology summary

2.4 Categories of 5G fundamental scenarios

- Massive Machine Type Communication (mMTC)
- Ultra Reliability Low Latency Communication (URLLC)
- Enhanced Mobile Broadband (eMBB)

Applicable to V2X

- **different requirements on 5G: functional** (e.g., priority, charging, policies, security, and mobility) and **performance** (e.g., latency, mobility, availability, reliability and data rates) -→ **dedicated slices can be constructed**

Characteristics	mMTC	URLLC	eMBB
Availability	Regular	Very High	Regular (baseline)
E2E latency	Not highly sensitive	Extremely sensitive	Not highly sensitive
Throughput type	Low	Low/med/high	Medium
Frequency of Xfers	Low	High	High
Density	High	Medium	High
Network coverage	Full	Localized	Full

Source: End to End Network Slicing – White paper 3 Outlook 21, Wireless World , Nov 2017

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3. Edge computing in 5G

3.1 Edge-oriented computing

- **Edge computing (EC) – generic definition**
  - **EC- autonomous computing model -**part of CC capabilities and operations are offloaded from **centralized CC Data Center (CCDC)** to the **network, edge and/or terminal devices**
  - EC provides context aware storage and distributed computing at the network edge

- **Specific definitions (Fog computing, Multi-access Edge Computing, Cloudlets, ..)**
  - **Fog Computing (FC)** - (*CISCO* ~ 2012)
    - FC is extended on a **continuum of devices from CCDC down to the edge of networks,** for secure management and control (M&C)
      - of domain specific HW/SW
      - and standard compute, storage and network functions within the domain
    - FC enable secure rich data processing applications across the domain
    - FC nodes (FCNs) are typically located away from the main cloud data centers

  - **Multi-access Edge Computing (MEC)** – *ETSI* - an industry spec. ~2014
    - MEC – edge CC platform within or close **the Radio Access Network (RAN)** to serve delay sensitive, context aware applications
    - **ETSI :** defined a system architecture and std. for a number of APIs
      - MEC means today – **multi-access…to include non-cellular actors**

3. Edge computing in 5G

3.1 Edge-oriented computing

- **Cloudlet –** developed by *Carnegie Mellon University* ~2013)
  - **Mobility-enhanced *micro data centers* located at the edge of a network to serve the mobile or smart device portion of the network**
    - takes the load off both the network and the CCDC and keeps computing close to the point of origin of information

- **Micro data centre** – developed by *Microsoft Research- ~2015*
  - extension of today's hyperscale cloud data centers (e.g., Microsoft Azure)
  - to meet new requirements: lower latency, new demands related to devices (e.g. lower battery consumption)

3.2. Different visions on Edge-oriented computing

Examples

- **OpenFog Consortium vision on FC and EC**
- **Fog computing** :
  - **A horizontal, system-level arch. that distributes computing, storage, control and networking functions closer to the users along <u>a cloud-to-thing continuum.</u>**
  - FC - extends the traditional CC model; implementations of the architecture can reside in multiple layers of a network topology
  - the CC benefits are extended to FC (containerisation, virtualisation, orchestration, manageability, and efficiency)
  - FC can cooperate with CC
  - **OpenFog reference arch**. includes security, scalability, openness, autonomy, RAS (reliability, availability and serviceability), agility, hierarchy, and programmability
- **EC is seen as different from FC**
  - FC works with the cloud, whereas EC is defined by the exclusion of cloud.
  - FC is hierarchical, where edge tends to be limited to a small number of layers
  - In addition to computation, FC also addresses networking, storage, control and acceleration.

Source: OpenFog Reference Architecture for Fog Computing, 2017, www.OpenFogConsortium.org

3. Edge computing in 5G

3.2 Different visions on Edge-oriented computing

- **Examples (cont'd)**
- **NIST visions of Fog Computing**
- **FC** : horizontal, physical or virtual resource paradigm that resides **between smart end-devices and traditional cloud or data centers.**
  - **FC** supports vertically-isolated, latency-sensitive applications by providing ubiquitous, scalable, layered, federated, and distributed computing, storage, and network connectivity

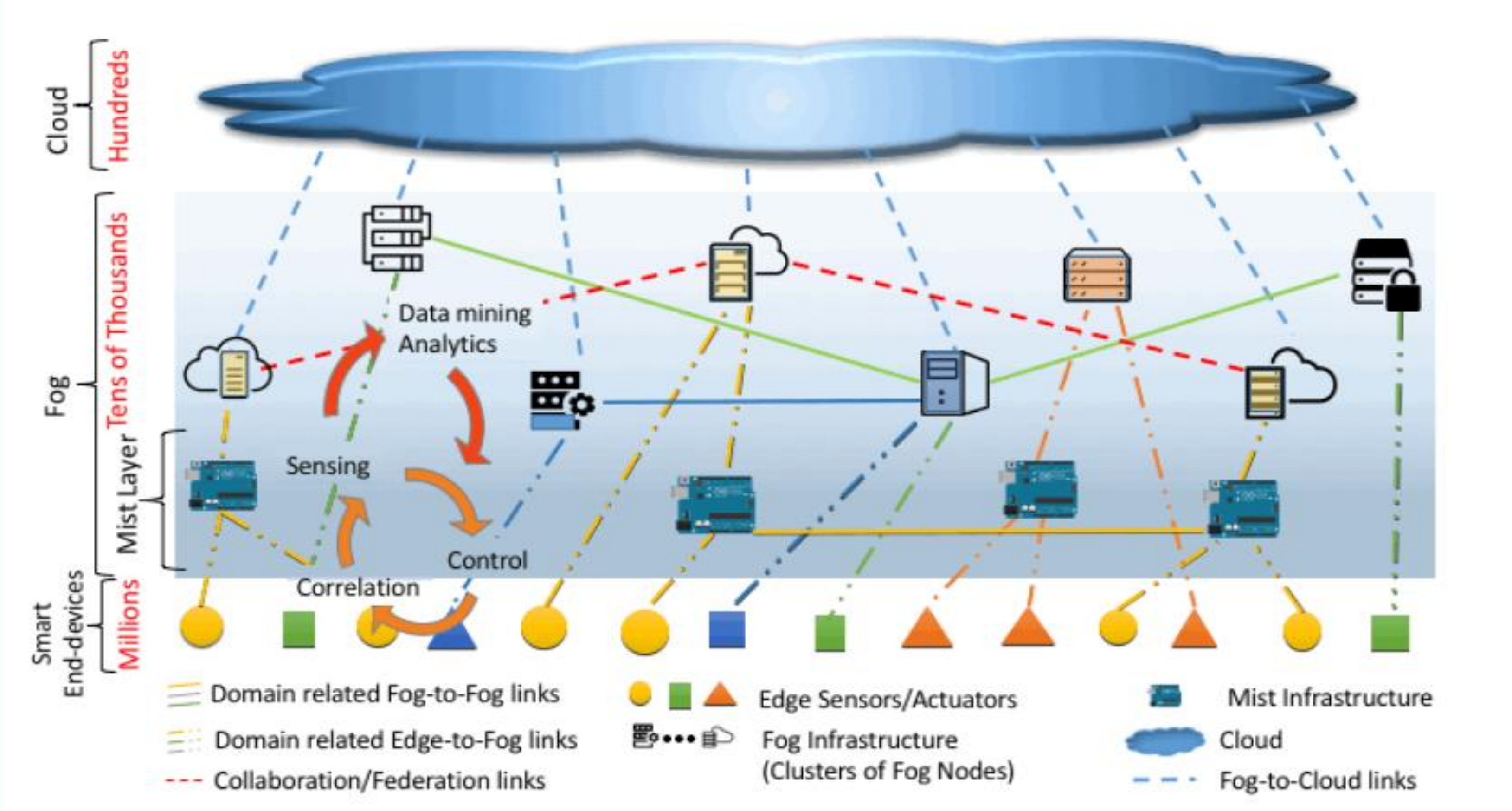
  - **Fog Computing Characteristics**
    - Contextual location awareness, and low latency
    - Geographical distribution with predominance of wireless access
    - Large-scale sensor networks
    - Very large number of nodes
    - Support for mobility
    - Real-time interactions
    - Heterogeneity
    - Interoperability and federation
    - Support for real-time analytics and interplay with the Cloud

Source : M.Iorga et. al., NIST Special Publication 800-191 (Draft) 1, The NIST Definition of Fog Computing, 2017

3. Edge computing in 5G

3.2 Different visions on Edge-oriented computing

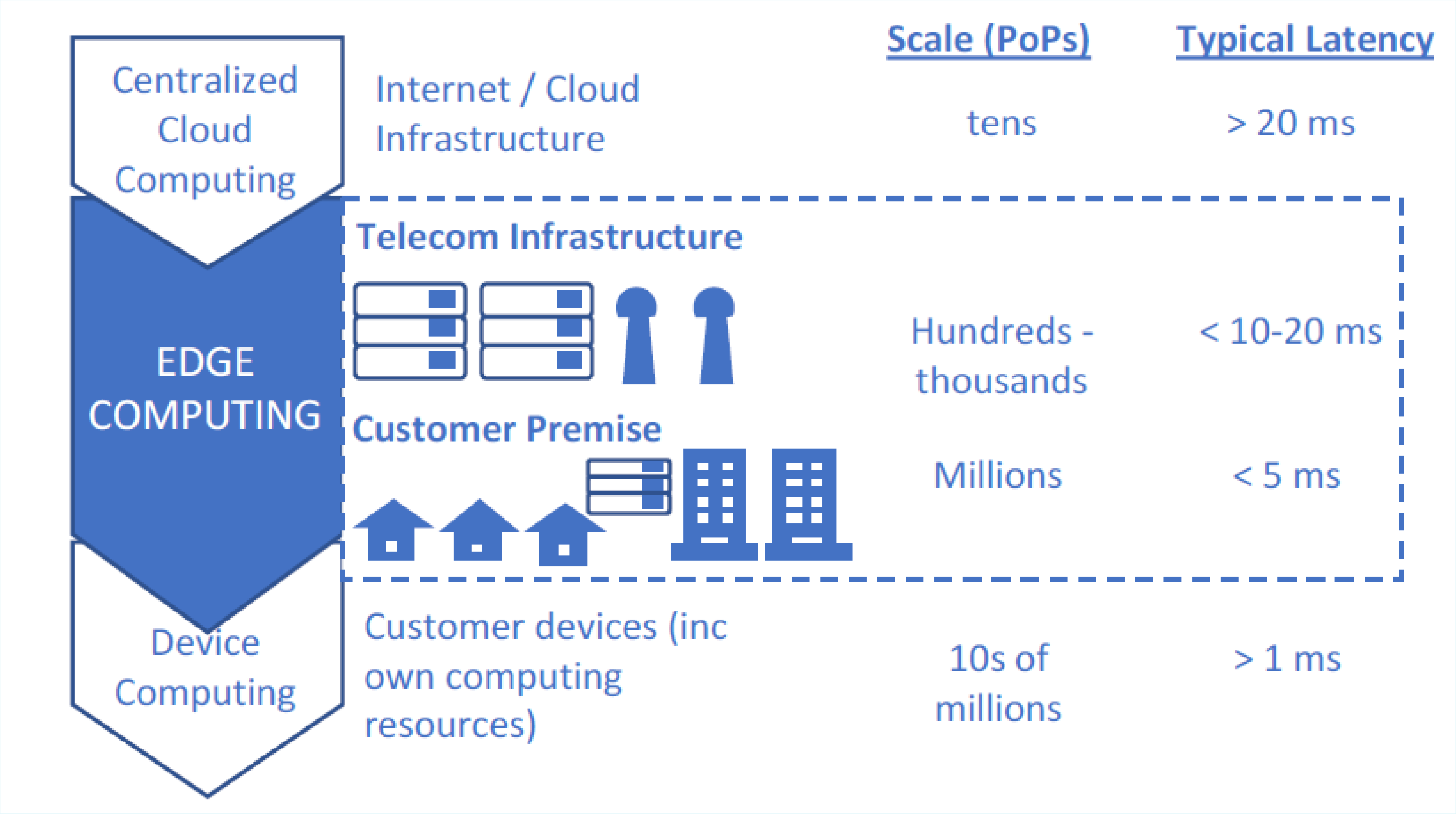
- **Examples (cont'd)**
- **NIST definition of Fog Computing**



Source : M.Iorga et. al., NIST Special Publication 800-191 (Draft) 1, The NIST Definition of Fog Computing, 2017

3. Edge computing in 5G

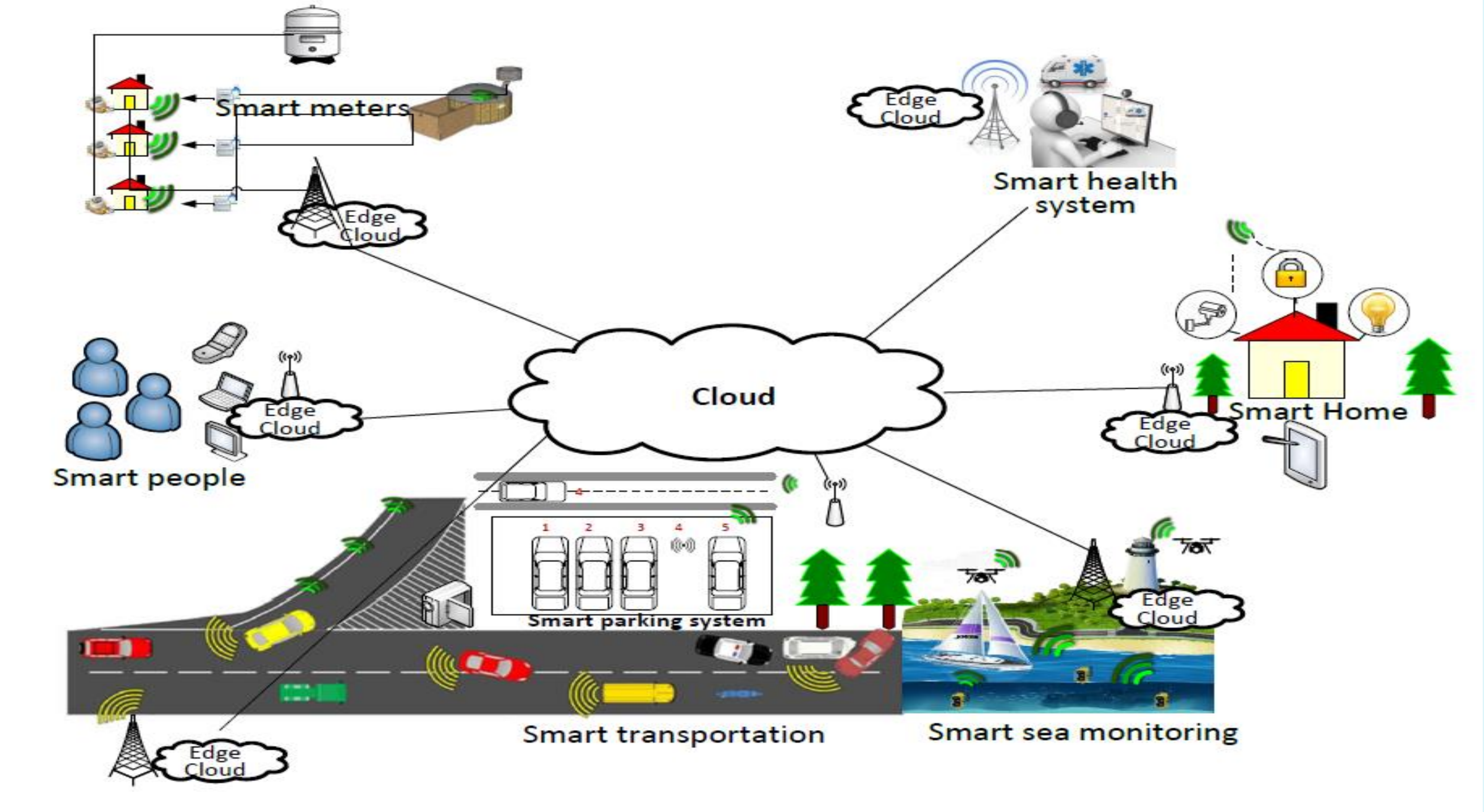
3.3 Edge Computing Location



Source: 5GPPP Technology Board Working Group, 5G-IA's Trials Working Group Edge Computing for 5G Networks, 2021

3. Edge computing in 5G

3.4 Edge computing applications- examples



Source: Wazir Zada Khan, et al., "Edge computing: A survey", in Future Generation Computer Systems, Feb. 2019, https://www.researchgate.net/publication/331362529

3. Edge computing in 5G

3.5 Multi-access Edge Computing (MEC)- ETSI Reference architecture

- **ETSI** : **Reference Architecture (RA)** to support the requirements (defined for MEC in ETSI GS MEC 002) and supporting several MEC services
- The RA describes the functional elements that compose the MEC system
  - **MEC platform**
  - **MEC management**
  - **Reference Points (RP)** between them
- MEC enables the **implementation of MEC applications** as software-only entities that run on top of a **Virtualization infrastructure,** which is located in or close to the network edge
- The MEC framework defines the general entities involved
  - these can be grouped into **system level, host level** and **network level entities**

- **MEC entities:**
  - **MEC host,** including : MEC platform, MEC applications, Virtualization Infrastructure
  - **MEC system level management**
  - **MEC host level management**
  - external related entities, i.e. network level entities

ETSI GS MEC 003 V2.2.1 (2020-12), Multi-access Edge Computing (MEC); Framework and Reference Arch.

3. Edge computing in 5G

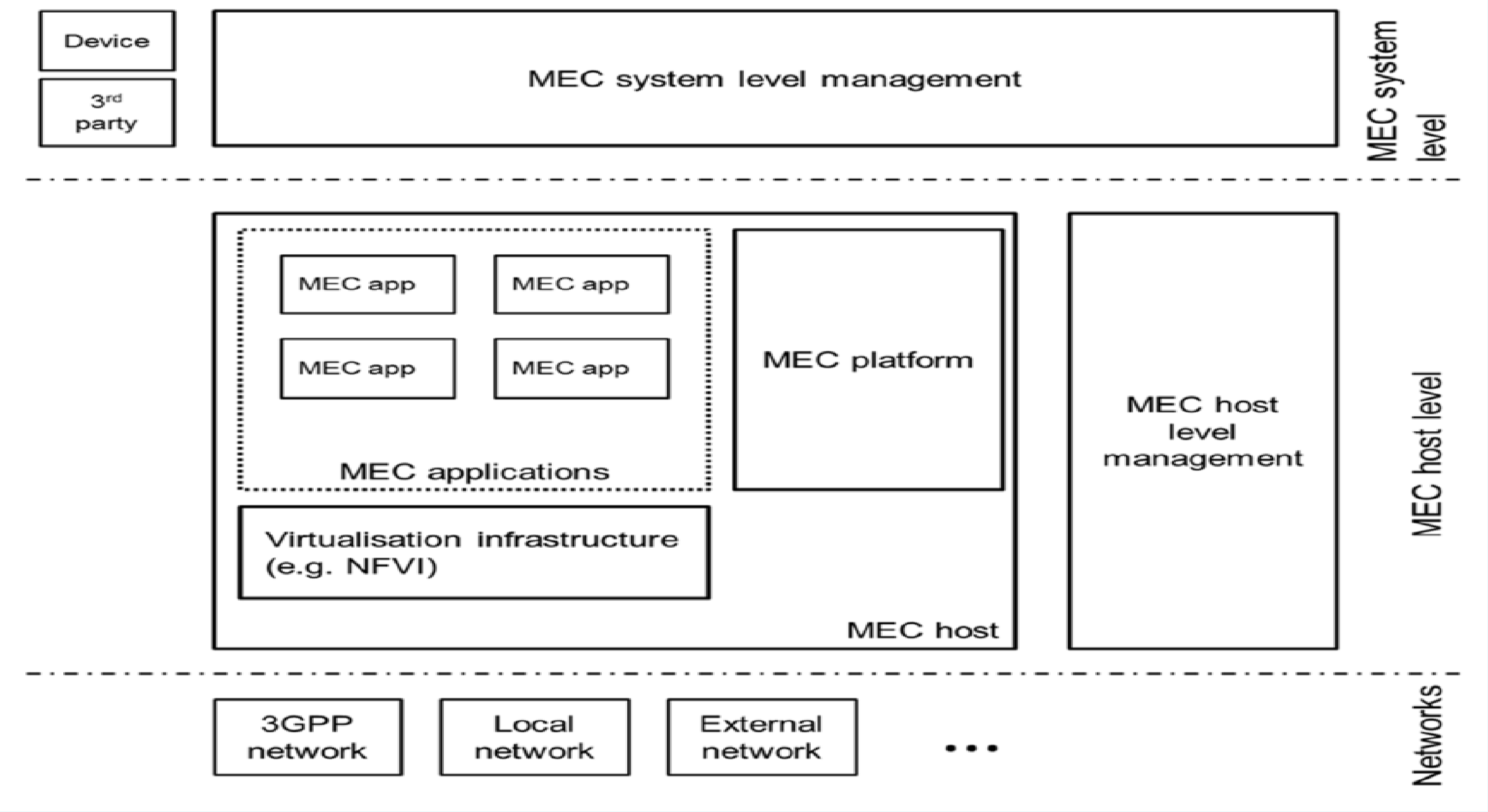
3.5 Multi-access Edge computing- ETSI Reference architecture

- **MEC main services**
  - **Radio Network Information (RNI)** service, provides authorized applications with radio network related information
  - **Location services** provides authorized applications with location-related info
  - **Traffic Management Services**- optional services are supported:
    - Bandwidth Management (BWM) service
    - Multi-access Traffic Steering (MTS) service
  - **Inter-MEC system communication-** addresses the requirements:
    - A MEC platform should be able
      - to discover other MEC platforms that may belong to different MEC systems
      - to exchange information in a secure manner with other MEC platforms that may belong to different MEC systems
    - A MEC application should be able to exchange information in a secure manner with other MEC applications that may belong to different MEC systems

Adapted from ETSI GS MEC 003 V2.2.1 (2020-12), MEC Framework and Reference Architecture

3.5 Multi-access Edge computing- ETSI Reference architecture

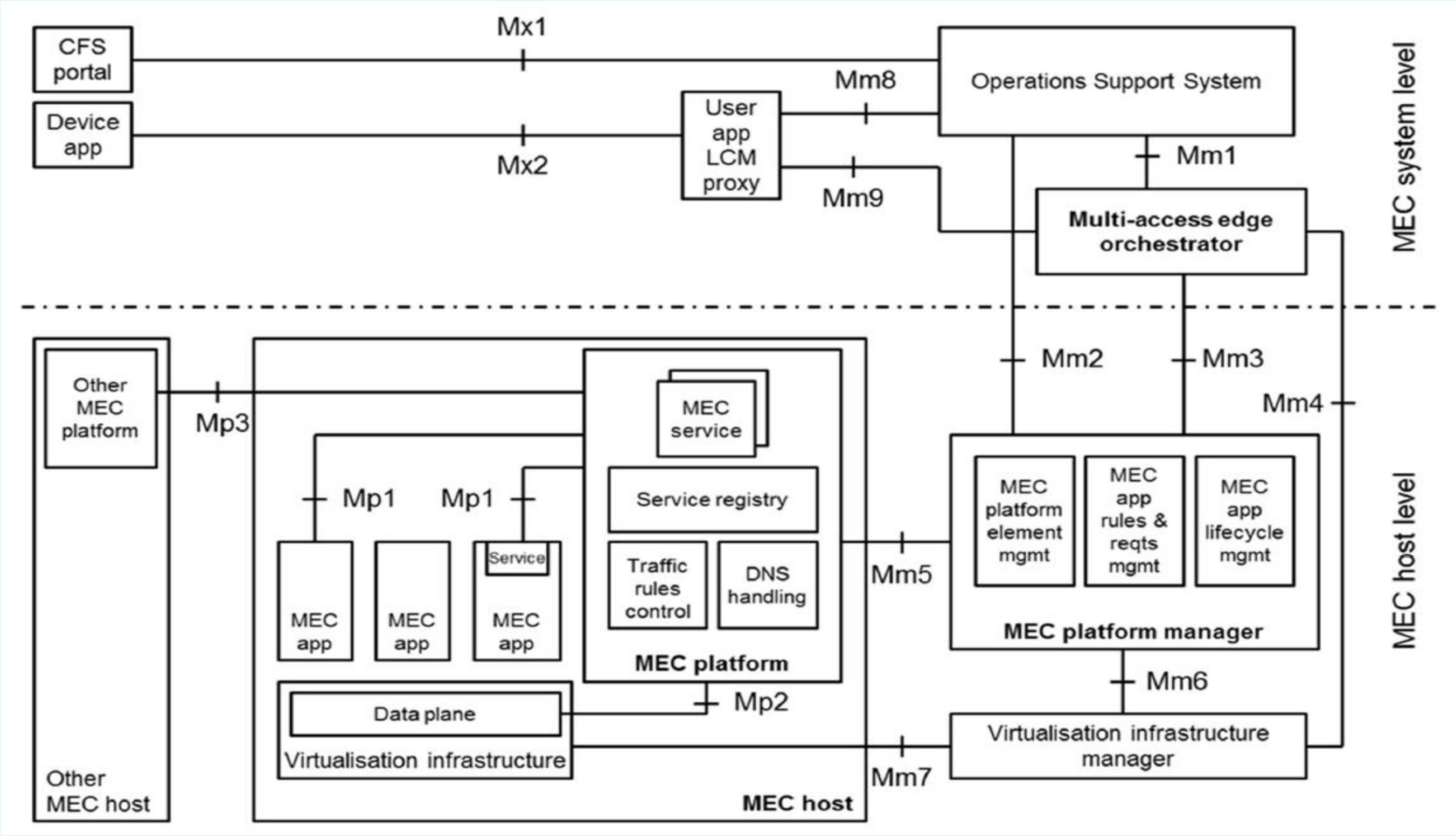
- **MEC framework**



Source: ETSI GS MEC 003 V2.2.1 (2020-12), MEC Framework and Reference Architecture

3. Edge computing in 5G

3.5 Multi-access Edge computing- ETSI Reference architecture



ETSI GS MEC 003 V2.2.1 (2020-12), MEC Framework and Reference Architecture

3. Edge computing in 5G

3.5 Multi-access Edge computing- ETSI Reference architecture

- **Previous slide elements**
  - **three groups of reference points (RP) defined between the system entities:**
    - RPs regarding the MEC platform functionality (Mp);
    - management RPs (Mm)
    - RPs connecting to external entities (Mx)

  - **MEC system** : **MEC hosts** and the **MEC management** (to run MEC apps) within an operator network or a subset of an operator network

    - **MEC host: MEC platform + Virtualization Infrastructure (VI)**
      - **MEC platform :** collection of essential functionality required to run MEC applications on a particular VI and enable them to provide and consume MEC services

        The MEC platform can also provide services
      - **Virtualisation Infrastructure** provides compute, storage, and network resources, for the purpose of running MEC applications
    - **MEC applications are instantiated on the VI** of the MEC host based on configuration or requests validated by the MEC management

Adapted from Source ETSI GS MEC 003 V2.2.1 (2020-12), MEC Framework and Reference Architecture

3. Edge computing in 5G

3.5 Multi-access Edge computing- ETSI Reference architecture

- **MEC management** : **MEC system level** and **MEC host level management**

  - ***MEC system level* management** includes the **MEC orchestrator** as its core component, which has an overview of the complete MEC system.
  - ***MEC host level* management :**
    - **MEC platform manager** and the **Virtualization infrastructure manager**
      - It handles the management of the MEC specific functionality of a particular MEC host and the applications running on it

- **Architectural levels specific aspects**
  - ***Network level entities*** comprising connectivity to LANs, cellular networks and external networks (e.g., Internet)
  - **Multi-access:** extension - to include non-cellular networks
  - ***MEC host level* -** where the MEC host sits along with its associated management

  - ***MEC system level management*** has a global view of the whole MEC system, i.e., the **collection of MEC hosts** and the associated management subsystem

Adapted from Source ETSI GS MEC 003 V2.2.1 (2020-12), MEC Framework and Reference Architecture

3. Edge computing in 5G

- **3.5 Multi-access Edge computing- ETSI Reference architecture**
- **Details about functional entities**
  - **ME application:** instantiable on a ME host; It can 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 functionality
    - required to run ME apps. on a specific ME host virtualization infrastructure
    - and to enable them to provide and consume ME services
    - It can provide itself a number of ME services
  - **ME management:**
    - **system level management:** components which have the overview of the complete ME system
    - and **mobile edge host level management:** handles the management of the ME specific functionality of a particular ME platform, ME host and the ME applications
  - **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 service:** service provided via the ME platform either
    - by the **ME platform** itself
    - or, by a **ME application**

Adapted from Source ETSI GS MEC 003 V2.2.1 (2020-12), MEC Framework and Reference Architecture

3. Edge computing in 5G

3.5 Multi-access Edge computing- ETSI Reference architecture

- **MEC system reference architecture variant for MEC in Network Function Virtualization (NFV)**
  - **MEC** and **NFV** are complementary concepts
  - The MEC architecture allows a number of different deployment options of MEC system
    - ETSI GR MEC 017 : analysis of solution details of the deployment of MEC in a NFV environment
  - **Presented here:**
    - **MEC applications and NFV Virtualized Network Functions (VNF) are instantiated on the same VI**
    - the architecture re-uses the ETSI NFV MANO components to fulfil a part of the MEC M&O tasks

Adapted from Source ETSI GS MEC 003 V2.2.1 (2020-12), MEC Framework and Reference Architecture

3.5 Multi-access Edge computing- ETSI Reference architecture

- **Multi-access edge system reference architecture variant for MEC in NFV** (cont'd)

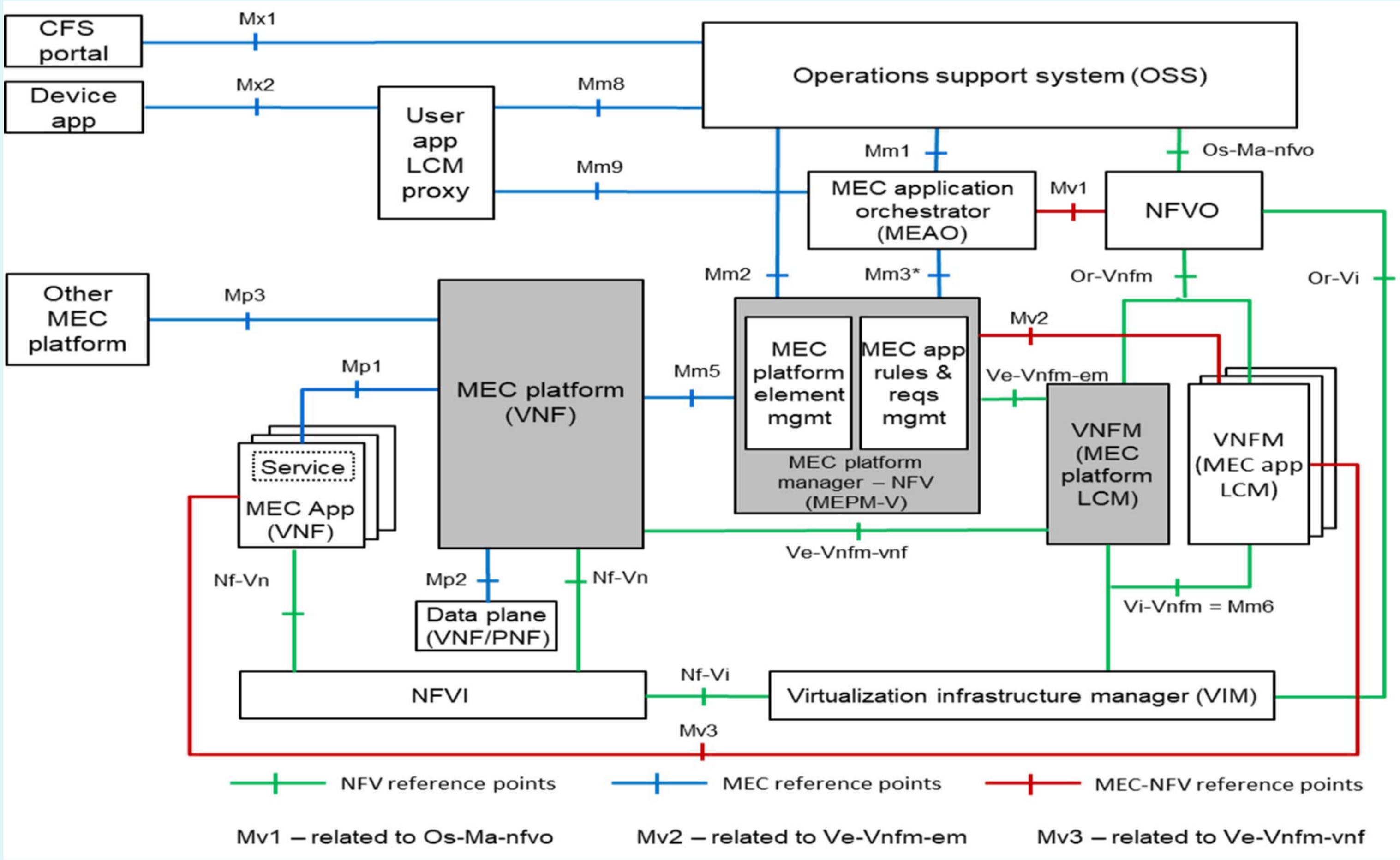
  - In addition to the definitions for the generic RA, the NFV – oriented architecture assumes that
    - The **MEC platform** is deployed as a **Virtualized Network Function (VNF).**
    - The **MEC applications appear as VNFs** towards the ETSI NFV MANO components
    - The **VI is deployed as an NFVI** and is managed by a **VI Manager (VIM)** as defined by ETSI GS NFV 002
    - The **MEC Platform Manager (MEPM)** is replaced by a **MEC Platform Manager - NFV (MEPM-V)** that delegates the VNF lifecycle management to one or more VNF Managers (VNFM).
    - The **MEC Orchestrator (MEO)** is replaced by a **MEC Application Orchestrator (MEAO)** that relies on the **NFV Orchestrator (NFVO)** for resource orchestration and for orchestration of the set of MEC application VNFs as one or more **NFV Network Services (NSs)**

Source ETSI GS MEC 003 V2.2.1 (2020-12), MEC Framework and Reference Architecture

3. Edge computing in 5G

3.5 Multi-access Edge computing- ETSI Reference architecture

- **Multi-access edge reference architecture variant based on NFV Framework**

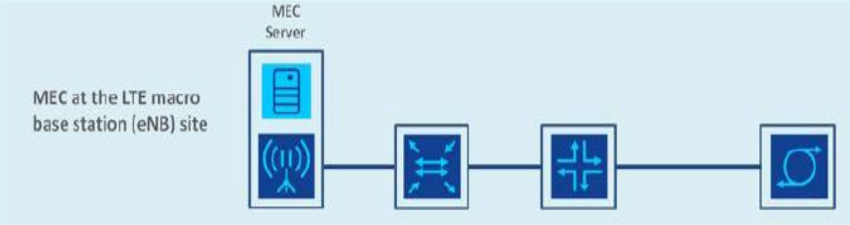


Source: ETSI GS MEC 003 V2.2.1 (2020-12), MEC Framework and Reference Architecture

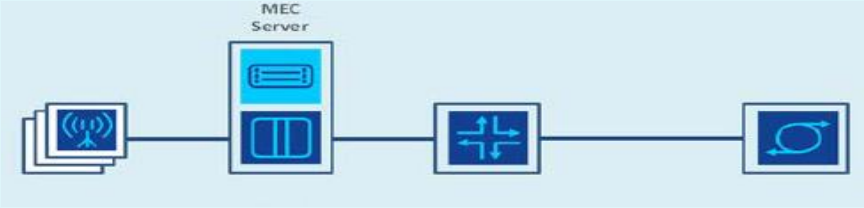
3.6 Possible Deployment Scenarios (ETSI)

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

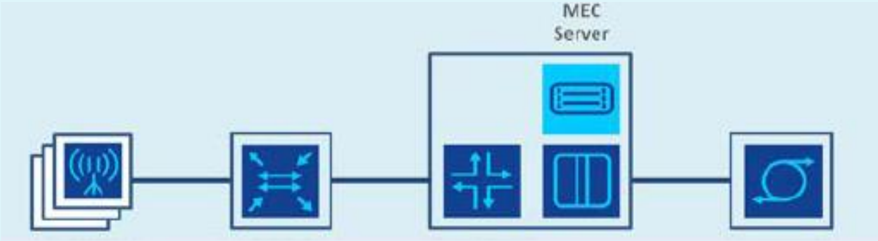
MEC at the LTE macro base station (eNB) site



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



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

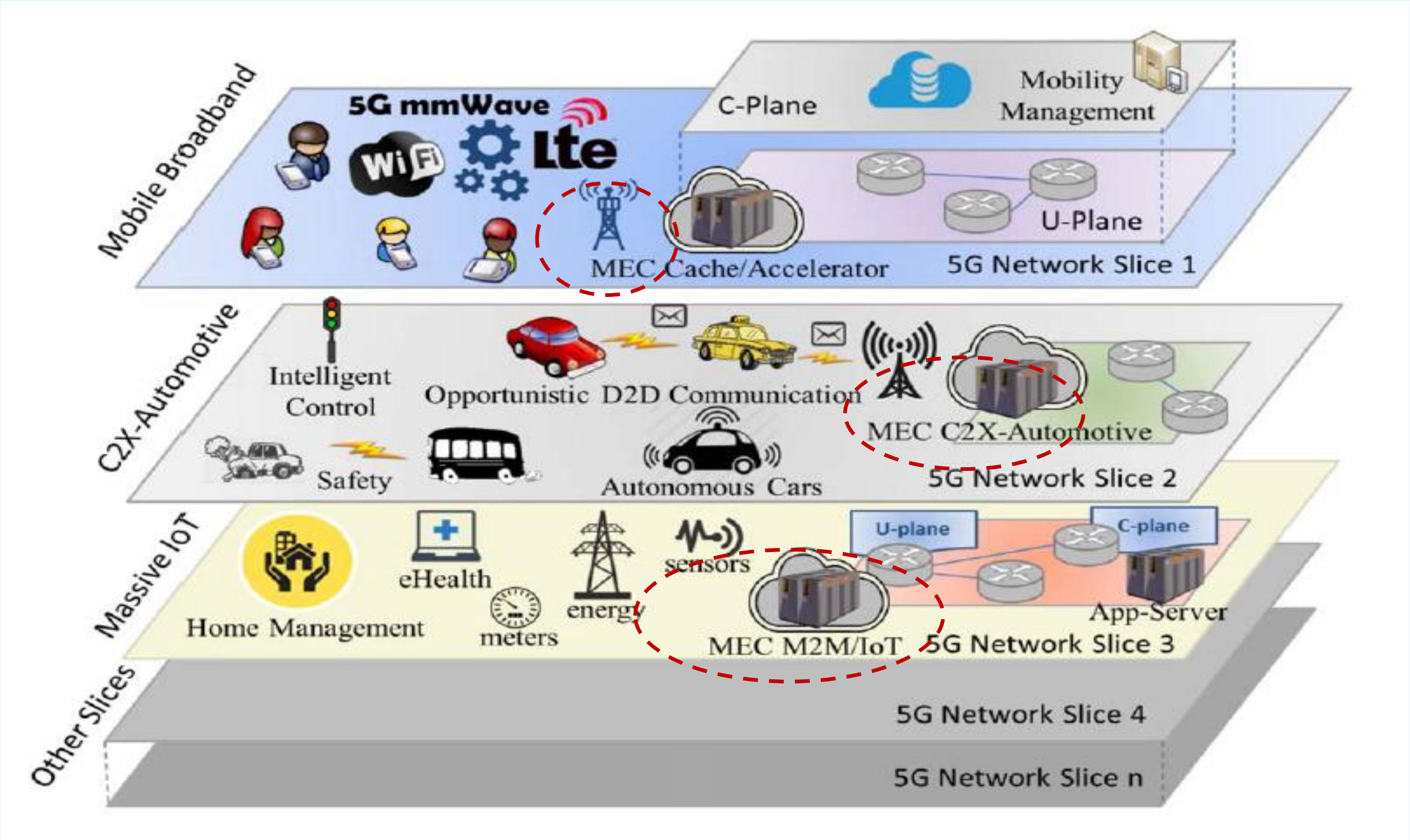


Source: https://portal.etsi.org/Portals/0/TBpages/MEC/Docs/Mobile-edge_Computing_-_Introductory_Technical_White_Paper_V1%2018-09-14.pdf
Mobile-Edge Computing – Introductory Technical White Paper

3. Edge computing in 5G

3.7 MEC in slicing context

- The **MEC role in different dedicated slices**



T.Taleb,et al., "On Multi-Access Edge Computing: A Survey of the Emerging 5G Network Edge Cloud Architecture and Orchestration", IEEE COMMUNICATIONS SURVEYS & TUTORIALS, VOL. 19, NO. 3, THIRD QUARTER 2017 1657

3. Edge computing in 5G

3.7 MEC in slicing context

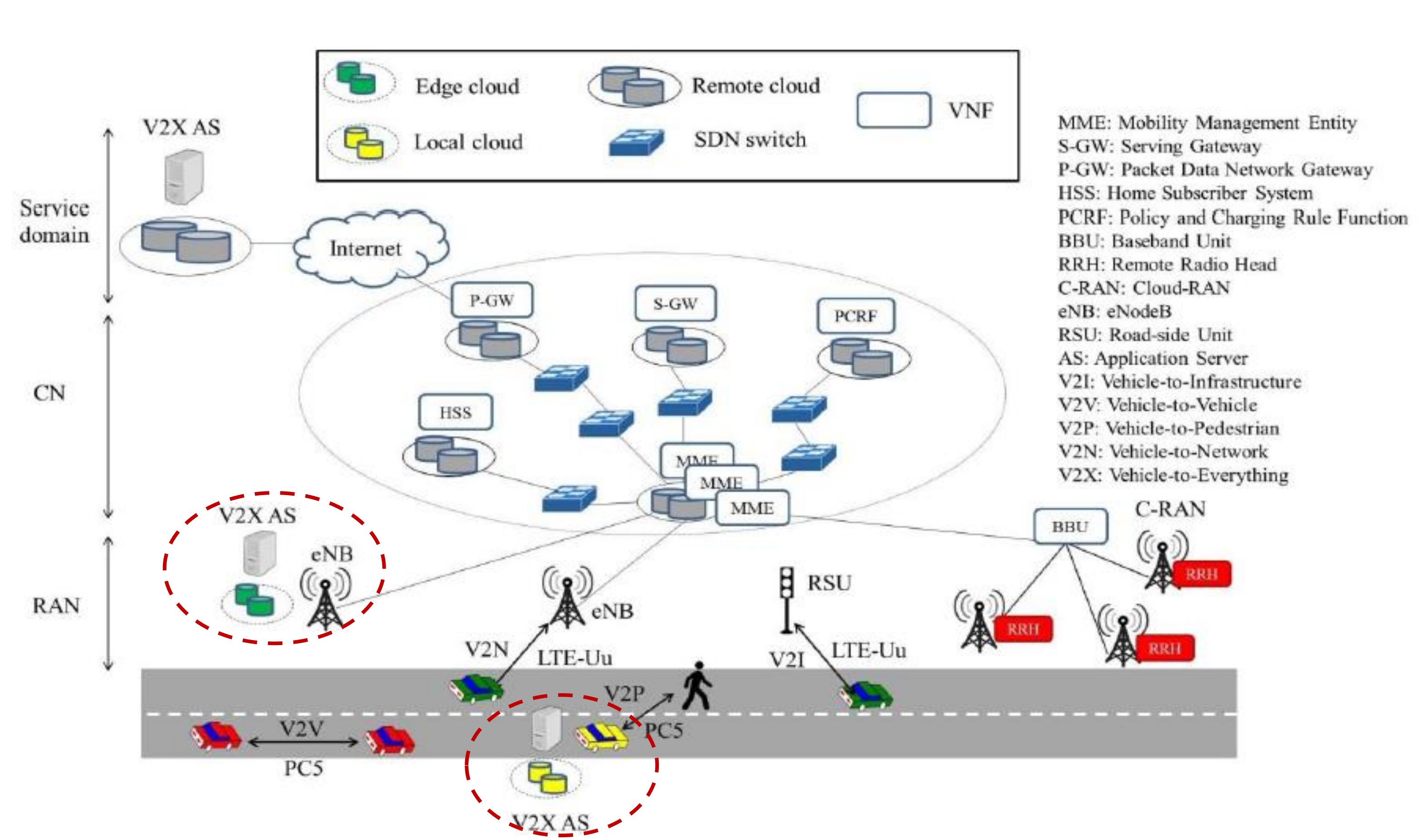
- The **MEC roles in different dedicated slices** (previous slide)
  - **MB slice :** the MEC platform
    - can cache content at the edge increasing the capacity of the mobile backhaul and core network via traffic offloading to the local edge
    - can provide a number of services including, e.g., video accelerator or application aware performance optimization
  - **Car-to-X/automotive slice**
    - needs strict latency and scalability with NFs instantiated at the edge
    - MEC may offer such capabilities
  - **Massive IoT slice**
    - scalability is important for handling efficiently huge amounts of small data
    - MEC can provide processing and storage for performing signaling optimizations
  - NFV and SDN technologies can cooperate (in M&C plane)
    - to achieve service customization in network slicing
    - to contribute to coordination for VNF allocation and service provisioning at the edge-cloud

CONTENTS

4. MEC support for V2X 5G systems

4.1 V2X in 5G network - general architecture

- network functional blocks are taken from 4G/LTE



Source: C.Campolo, A.Molinaro, A.Iera, F.Menichella, "5G Network Slicing for Vehicle-to-Everything Services", IEEE Wireless Communications, Volume: 24 Issue: 6, DOI: 10.1109/MWC.2017.160040

4. MEC support for V2X 5G systems

4.2 5G slicing for V2X

- **V2X services require complex features** which do not map exactly on the basic reference slice types: eMBB, URLLC and mMTC

- **Different V2X dedicated slicing** solutions have been proposed
  - **Traffic safety and efficiency** services –slice (V2V, V2P, V2I)
    - periodic and event-driven messages (carrying position and kinematics information of vehicle); broadcast messages to surrounding environment
    - **low latency and high reliability requirements**
  - **Autonomous driving** services –slice (V2V, V2I, V2N)
    - **ultra low-latency** V2V RAT connection mode
    - additional RAN/CN functions (e.g., for network-controlled resource allocation over the PC5I/F - in eNB)
    - mobility, authentication, authorization and subscription mgmt. (MEM and HSS).
    - low-latency and reliable video/data exchange : supported with a V2X AS, **deployed at the network edge**

Sources: J.Mei, X.Wang, and K.Zheng, "Intelligent Network Slicing for V2X Services Towards 5G", arXiv:1910.01516v1 [cs.NI] 3 Oct 2019
C.Campolo, A.Molinaro, A.Iera, F.Menichella, "5G Network Slicing for Vehicle-to-Everything Services", IEEE Wireless Communications, Volume: 24 Issue: 6, DOI: 10.1109/MWC.2017.160040

4. MEC support for V2X 5G systems

4.2 5G slicing for V2X

- Different V2X dedicated slicing solutions have been proposed (cont'd)

  - **Tele-operated driving slice**
    - **ultra-low latency and highly-reliable E2E** connectivity between the controlled vehicle and the remote operator (typically hosted outside the CN ; data flows passes through a P-GW).

  - **Vehicular Internet and Infotainment – slice**
    - use **multiple RATs** for a high throughput
    - the contents can be located in the remote/edge cloud (e.g., server co-located in eNodeBs- MEC technology)
    - **multiple MME instances** may be required depending on the users mobility degree

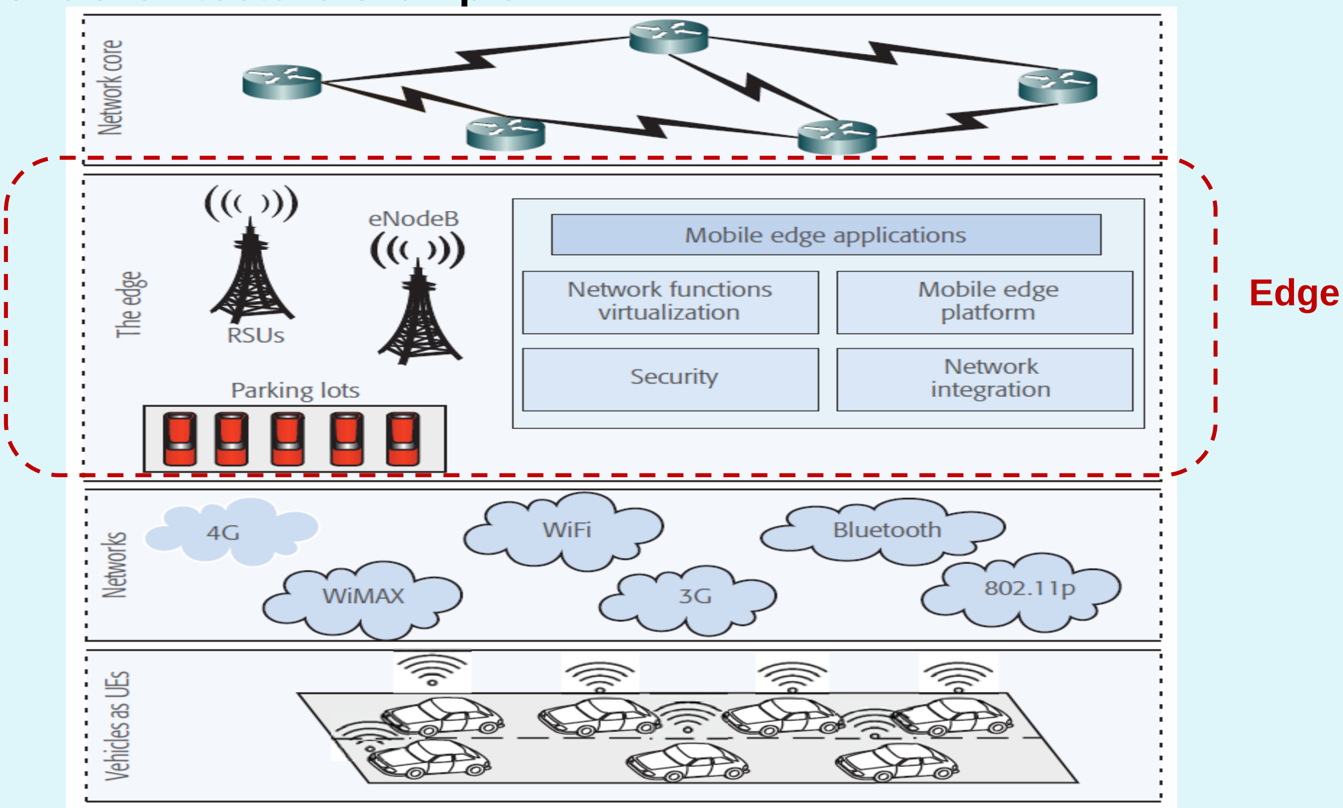
  - **Vehicle management and remote diagnostics** slice
    - support the exchange of low-frequency small amounts of data between vehicles and remote servers outside the core network
    - **DPI and CPI handle multiple interactions**

Sources: C.Campolo, A.Molinaro, A.Iera, F.Menichella, "5G Network Slicing for Vehicle-to-Everything Services", IEEE Wireless Communications, Volume: 24 Issue: 6, DOI: 10.1109/MWC.2017.160040

4. MEC support for V2X 5G systems

4.3 Multi-access Edge Computing in 5G V2X- architecture

- MEC - major technology in the 5G ecosystem, to ensure **URLLC** for **V2X communication** and also to deploy services at appropriate locations
- **Generic architecture-example**



Source: S.A.Ali Shah, E.Ahmed, M.Imran, and S.Zeadally, "5G for Vehicular Communications", IEEE Communications Magazine, January 2018, pp.111-117

4. MEC support for V2X 5G systems

4.4 Examples of MEC support for V2X Use Cases

- **V2X use case group "safety“**
  - includes several different types of UCs to support road safety, using the V2I and V2V communication
    - **Intersection Movement Assist (IMA)**
    - **Queue Warning (QW)**
- **MEC system services examples :**
  - Network to the vehicle feedback information)
  - Multi-operator operation
  - Interoperability:
    - **V2X information exchange among road users**
    - in a multi-operator scenario
      - **MEC apps** in different systems can securely
      - **MEC apps can securely communicate with the V2X-related 3GPP core** network logical functions

Source: ETSI GR MEC 022 V2.1.1 (2018-09), Multi-access Edge Computing (MEC);Study on MEC Support for V2X Use Cases

4. MEC support for V2X 5G systems

4.4 Examples of MEC support for V2X Use Cases

- **V2X use case group "convenience"**
  - **Software updates and other telematics** - can be implemented with existing access technology (partly is already supported by car manufacturers)
  - Needs communication between the vehicles to backend server (e.g., car OEM's server)
  - The MEC system can ***enable*** **multi-operator operation**
- **MEC system can :**
  - support for **locally aggregating the rt information** from the connected nodes with very low latency
  - support for **locally distributing rt information** to the connected nodes with very low latency
  - provide to the vehicle **predictive and updated quality related information** for connectivity parameters (like latency, PER, signal-strength …)
  - **interoperability**, by supporting V2X information exchange among road users connected through different access technologies or networks or mobile operators
  - **multi-operator operation** for V2X mobiles/users to provide service continuity across AN coverage nationwide and across borders of different operators' networks

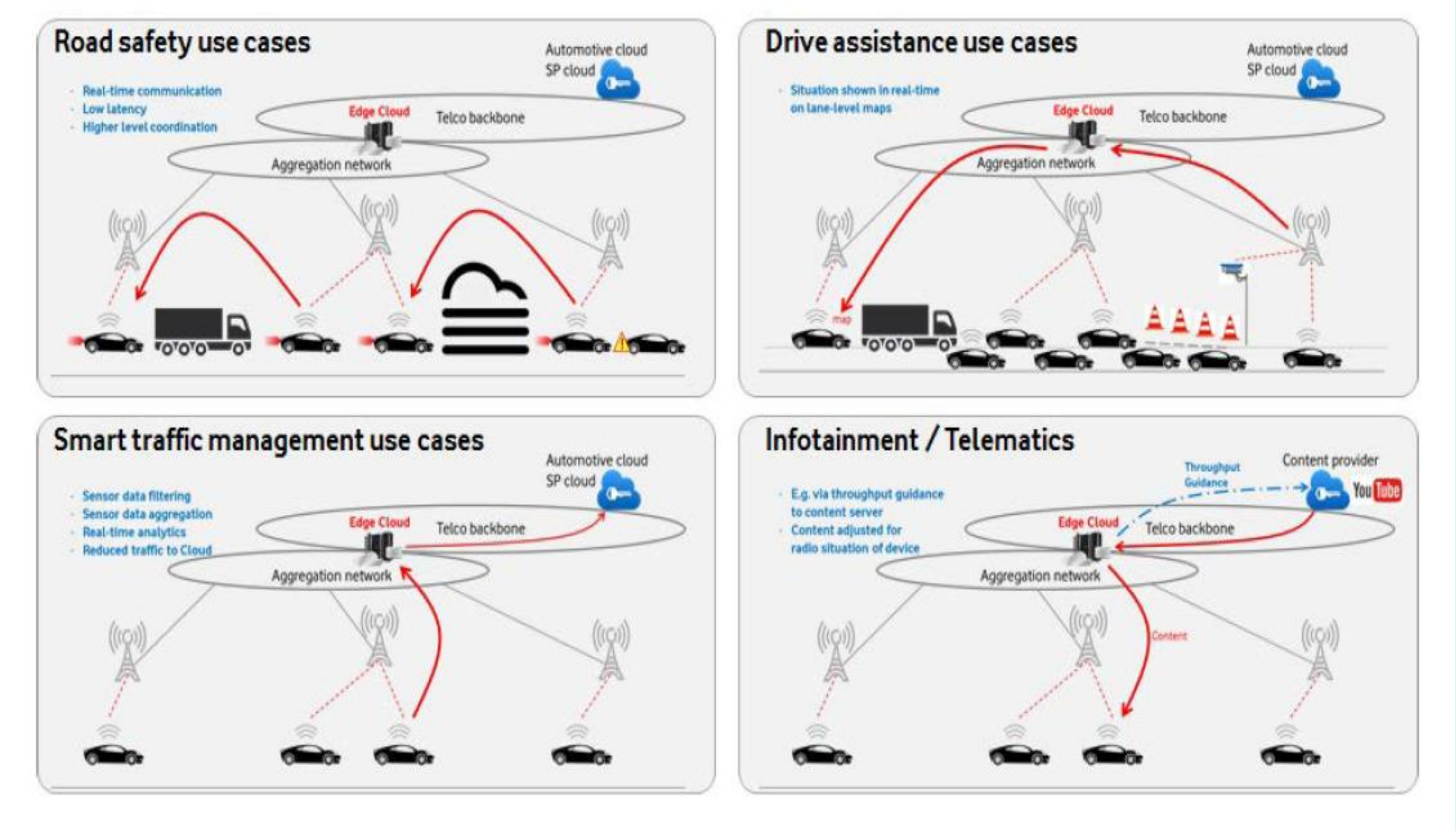
4. MEC support for V2X 5G systems

4.4 Examples of MEC support for V2X Use Cases

- **V2X use case group "advanced driving assistance“**
  - distribution of a large amount of data with high reliability and low latency
  - predictive reliability (vehicles moving along could receive a prediction of the network availability to plan ahead
    - **Real Time Situational Awareness & High Definition (Local) Maps**
    - **See-Through (or High Definition Sensor Sharing)**
- **V2X use case group "vulnerable road user" (VRU)**
  - the (VRU) use case covers pedestrians and cyclists
  - requirement: accuracy of the positioning information provided by these traffic participants
  - additional means for better and reliable accuracy is important, to allow a real-world usage of information shared from VRUs
  - cooperation between vehicles and VRUs through their mobile devices
  - **MEC system can provide services such as:**
    - support for **timely accurate positioning**
    - **interoperability** by supporting V2X information exchange among road users
    - **multi-operator operation** for V2X mobiles/users

4. MEC support for V2X 5G systems

4.4 Examples of MEC support for V2X Use Cases



Source: ETSI, "Multi-access Edge Computing (MEC); Study on MEC Support for V2X Use Cases," Tech. Rep., March 2018 https://portal.etsi.org/webapp/workProgram/Report_WorkItem.asp?wki_id=52949.

4. MEC support for V2X 5G systems

4.5 MEC based solutions for V2X support

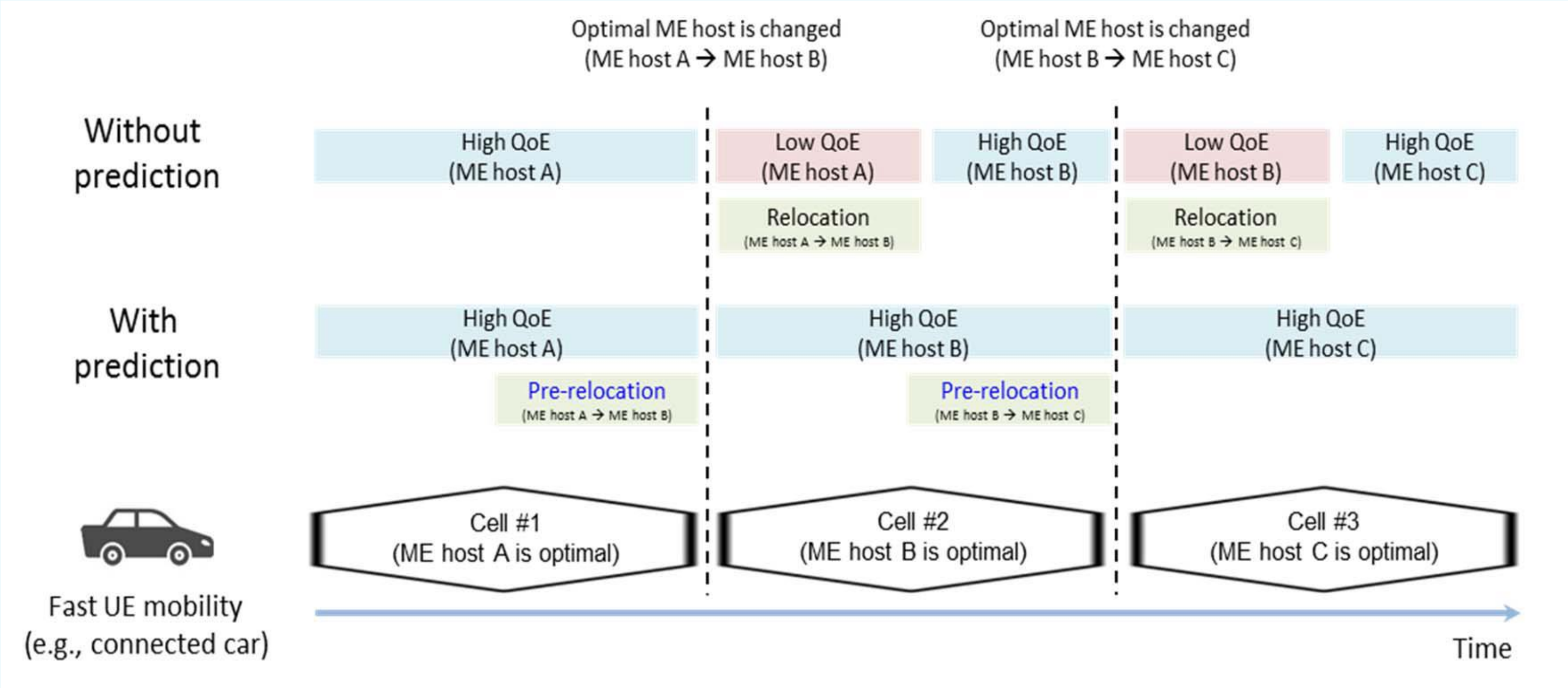
- **V2X Mobility and QoS/QoE support**
  - **Predictive QoS support**
    - ***Handover (HO)*** (between cells) ***prediction*** with the estimated QoS performance can help the vehicle UEs to select BS or MEC host
    - The transit time in each cell can be estimated by the assistance of the UE application (e.g. the in-car navigation system) or by a MEC based solution
    - The ***location service*** (LS) (e.g. based on the LS defined in ETSI GS MEC 013) may also support prediction of the HO timing by retrieving the location information of vehicle UEs and BSs
    - the estimated QoS performance of the available cells (e.g. based on the RNI service defined in ETSI GS MEC 012 can help with optimal BS and MEC host selection from QoE point of view
  - **Predictive reliability for advanced automatic driving - use cases**
    - **Moving vehicles can receive a prediction of the network availability to plan ahead**
      - **Example 1:** *High Definition Sensor Sharing* or *see-Through*
      - **Example 2:** vehicles entering a tunnel, or approaching a jammed part of the city

Adapted from source: ETSI GR MEC 022 V2.1.1 (2018-09), Multi-access Edge Computing (MEC);Study on MEC Support for V2X Use Cases

4. MEC support for V2X 5G systems

4.5 MEC based solutions for V2X support

- **V2X Mobility and QoS/QoE support** (cont'd)
  - **Pre-relocation of application state information**
  - App. state information to the target MEC host is completed before connecting to the MEC host
  - The MEC system enables the prediction of the HO timing and informs the MEC app. which then initiates state relocation to the optimal MEC host in advance

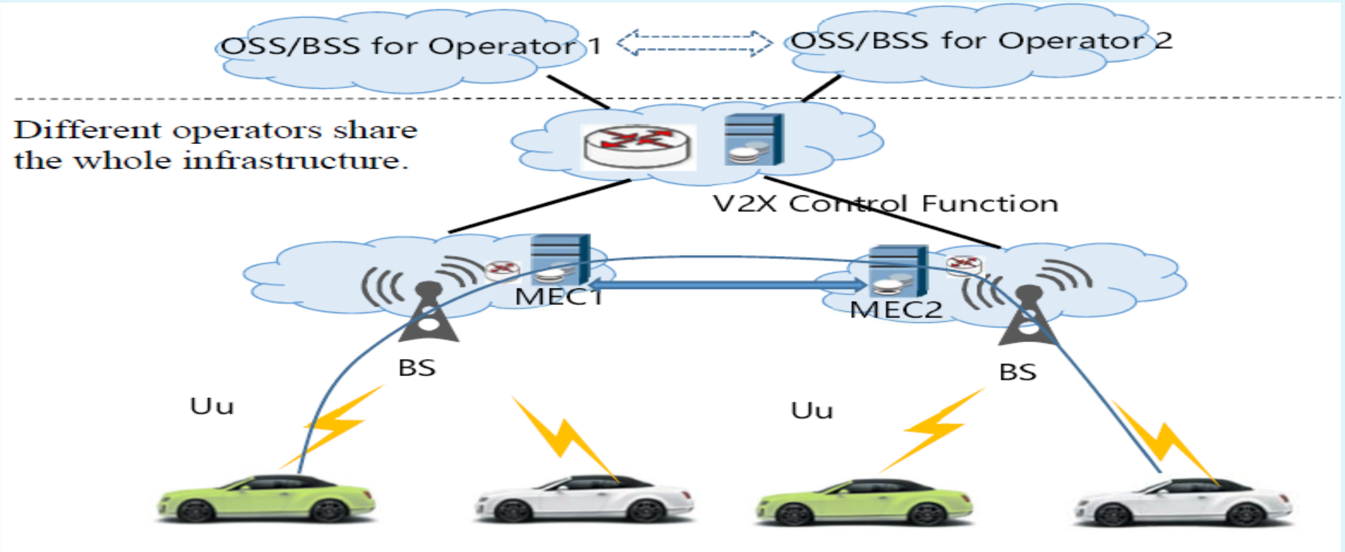


Source: ETSI GR MEC 022 V2.1.1 (2018-09), MEC;Study on MEC Support for V2X Use Cases

4. MEC support for V2X 5G systems

4.5 MEC based solutions for V2X support

- **Low latency communication support with multi-operator operation**
  - Cross-operator interoperability is critical for V2X apps. enabled in the edge cloud
  - **Solution 1: shared underlying network**
    - The underlying network can be shared between operators (e.g. RAN sharing)
    - The MEC system should also be shared as a part of the unified infrastructure
    - The horizontal (H) communication path between local peering points can lower the latency transmission (due to direct links between the two MEC hosts)
    - Business problem: coordination between operators (e.g., multiple OSSs coordination to the shared orchestrator, etc.)
    -



Source: ETSI GR MEC 022 V2.1.1 (2018-09), MEC;Study on MEC Support for V2X Use Cases

4. MEC support for V2X 5G systems

4.5 MEC based solutions for V2X support

- **Low latency communication support with multi-operator operation** (cont'd)
- **Solution 2: independent underlying network**
  - The underlying networks are independently operated by different operators
  - The MEC system can be: shared by the involved operators, or offered by a 3rd party, or the MEC systems are run independently by each operator

  - **Key requirement: a coordinated V2X service,** while it could still be run in different operators' MEC systems
  - A direct comm. between the peering points is needed →low latency for V2X services,
    - This is different with the traditional transport network layer arrangements between different PLMNs

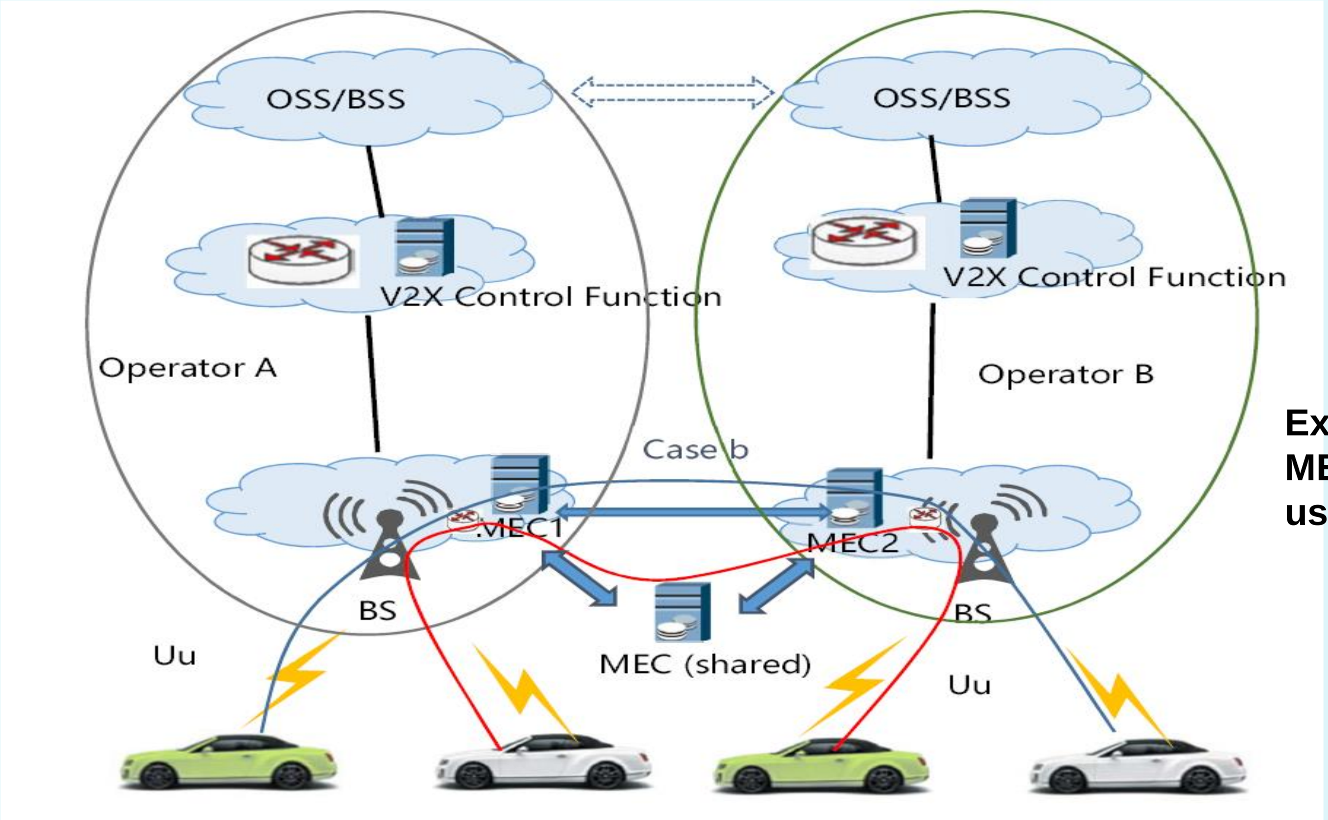
  - **Two subcases:**
    - the MEC system is shared by the operators, requiring low latency communication with both underlying networks;
    - the adjacent MEC hosts belong to different operators, requiring the low latency communication path between the peer points.
  - The cases require the coordination between the involved operators in both network planning and especially transport network planning.

Adapted from source: ETSI GR MEC 022 V2.1.1 (2018-09), Multi-access Edge Computing (MEC);Study on MEC Support for V2X Use Cases

4. MEC support for V2X 5G systems

4.5 MEC based solutions for V2X support

- **Low latency communication support with multi-operator operation** (cont'd)
- **Solution 2: independent underlying network**



Example shared MEC system use case

Source: ETSI GR MEC 022 V2.1.1 (2018-09), Multi-access Edge Computing (MEC);Study on MEC Support for V2X Use Cases

4. MEC support for V2X 5G systems

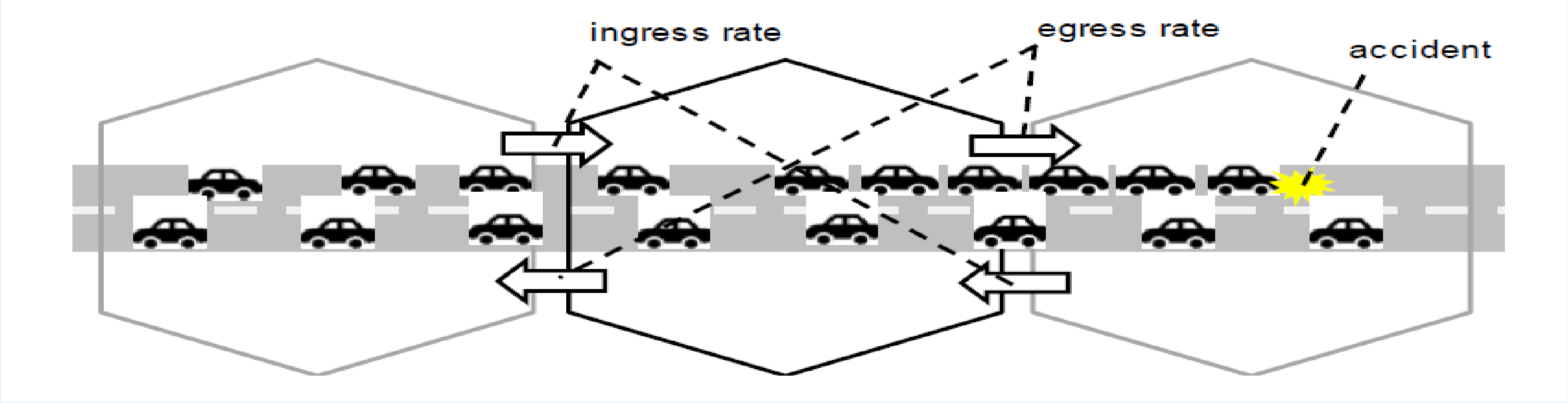
4.5 MEC based solutions for V2X support

- **Communication traffic coordination with vehicles**
  - Connected vehicles generate various data (w. different requirements) and upload them through the radio network in order to provide V2X services
  - Some communications are rt and need high reliability
  - The vehicle transportation traffic congestion may give rise to radio network (RN) congestion (e.g., LTE uplinks)
  - Need to harmonise vehicles with MEC system for controlling RN congestion especially in uplink
  - **Solution: provide to vehicles information on communication traffic congestion**
-
    - The MEC system can predictively recognize the RN congestion based on vehicle transitions and then notify it to the vehicle (the transmission of non-real time information can pause)
    - RN congestion is in proportion to the number of vehicles, which is correlated by MEC Radio Network Information (RNI) services
    - The estimation of the number of vehicles connecting to a BS helps to predict RN congestion (see figure on next slide)

4. MEC support for V2X 5G systems

4.5 MEC based solutions for V2X support

- **Communication traffic coordination with vehicles** (cont'd)
- **Example of the estimation of transportation mapping to radio cell**
  - The ingress/egress rate of vehicle transitions from/to the adjacent radio cell may be calculated by the MEC services (ETSI GS MEC 012 "MEC Radio Network Information API" and ETSI GS MEC 013: "MEC Location API")
  - It also depends on the road structure, so, the estimation accuracy is improved if MEC system can associate road structure with radio cell area
  - The rates are used for predicting the number of vehicles in the next time slot, (e.g., by Markov chain model)
  - Note: a vehicle accident may cause transportation traffic congestion, increasing the number of vehicles in radio cell where the accident occurs, and in turn propagates to the linked cells

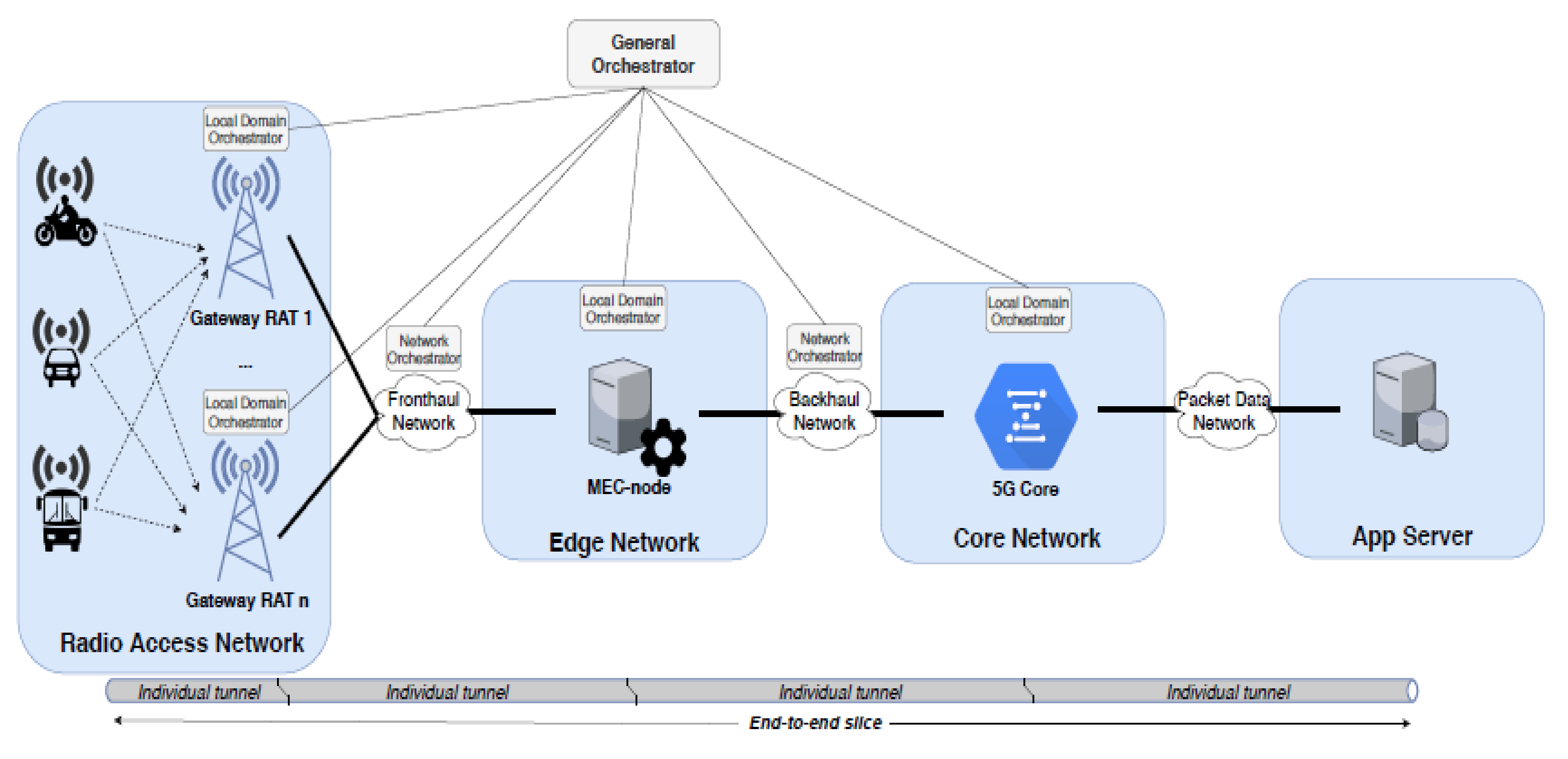


Adapted from source: ETSI GR MEC 022 V2.1.1 (2018-09), Study on MEC Support for V2X Use Cases

4. MEC support for V2X 5G systems

4.5 MEC based solutions for V2X support

- **Example of a multi-RAT end- to end slice with embedded MEC services**

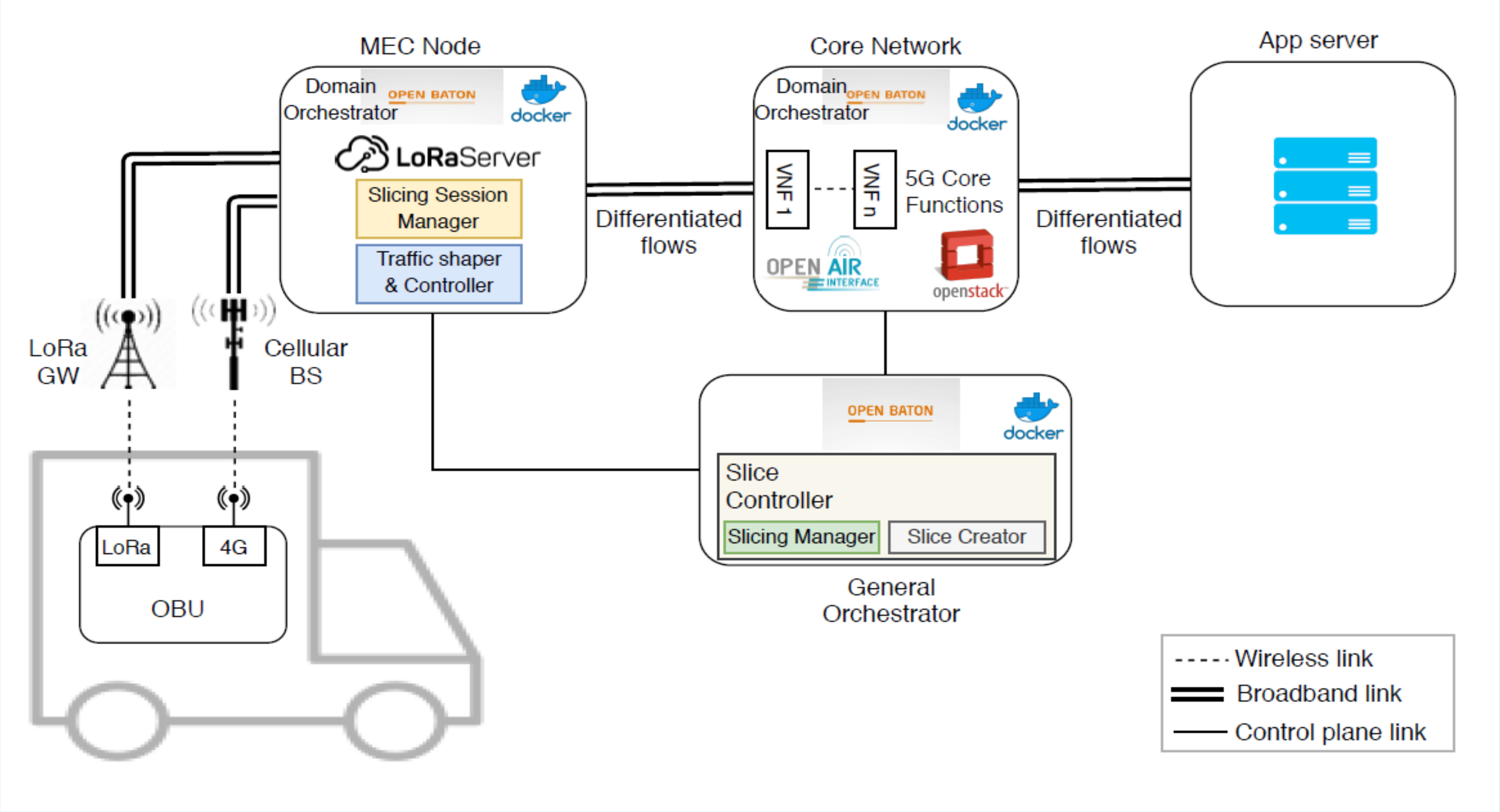


Source: Ramon Sanchez-Iborra et.al., "Empowering the Internet of Vehicles with Multi-RAT 5G Network Slicing", https://www.ncbi.nlm.nih.gov/pubmed/31337087

4. MEC support for V2X 5G systems

4.5 MEC based solutions for V2X support

- **Example of a multi-RAT end- to end slice with embedded MEC services** (cont'd)



Source: Ramon Sanchez-Iborra et.al., "Empowering the Internet of Vehicles with Multi-RAT 5G Network Slicing", https://www.ncbi.nlm.nih.gov/pubmed/31337087

CONTENTS

5. Task offloading in MEC V2X

5.1 Vehicular task offloading problem

- **Task Offloading (TOff):** data transfer from one processing device to another
  - The offloading concept covers data/traffic and task/computation

- V2X/IoV applications needs –can be higher than vehicles‘ limited computing resources
  - Example: apps. for **Connected Autonomous Vehicles (CAV)**: delay-sensitive and computation intensive
  - Traditional solution: intensive computing tasks - offloaded to a **cloud data center;** drawback: delays could result
- Recent solution : **Toff** over **Vehicular Communication Networks (VCN)-** using edge network elements capabilities

- **Vehicular Edge Computing (VEC):** allows proactive TOff to edge servers, thus solving intensive computing burdens
- VEC can be performed on top of **Vehicular Edge Computing Networks (VECN)**
  - Example of VECN: 5G+MEC
  - **MEC – main VEC technology providing support for TOff** (offer computing capabilities in the proximity of vehicles)
    - The vehicles can offload computation-intensive applications to a nearby MEC server (e.g., installed in an RSU) for processing

5. Task offloading in MEC V2X

5.1 Vehicular task offloading problem

- **Task Offloading (TOff)**
- Questions to be answered to prepare task offloading, e.g. :
  1. **Can the task be offloaded**?
     - The task manager/scheduler must determine if the task can be offloaded, i.e., what to offload, partial or total offload?
  2. **When to offload** the task?
     - The task scheduler must determine the time slot for offloading while considering the application constraints
  3. **To what server to offload?**
     - Which server/location is the best for offloaded workload execution ?
     - Available resources distribution must be evaluated
  4. **Which offload policy?**
     - What are the main objective of the TOff?
       - maximization of a single performance metric
       - joint optimization and trade-offing among multiple objectives?
     - Different offloading policies lead to different delays, power consumption, resource allocation balance, etc.
     - A good offloading policy must find the optimal balance between the overall computation delay, data transmission, and other performance metrics

5. Task offloading in MEC V2X

5.1 Vehicular task offloading problem

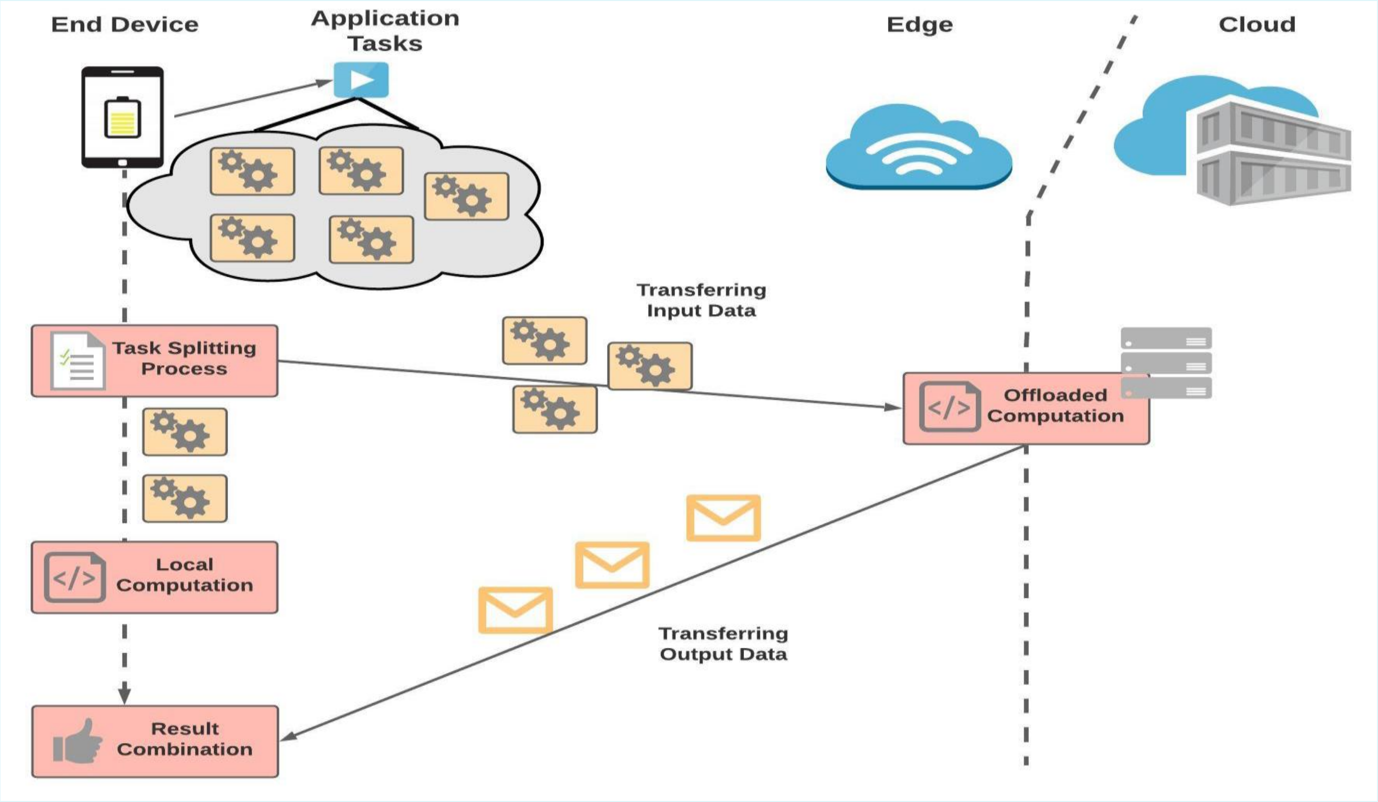
- The **main Toff challenges in VEC** are coming from: dynamic context, high mobility and distributed system characteristics
- A **Vehicular Terminal (VT)** in VEC can be:
  - **Task Vehicle (TaV)** who generates tasks and requests computing service
  - **Service Vehicle (SeV)** who helps to execute tasks

- **Offloading phases**
  - VTs transmit the computing tasks to VEC service nodes for processing (one can save energy or reduce the time consumption)
  - Service provider name is used for the entity performing computation during TOff time
  - **General phases:**
    - **a. Service discovery:** TaVs discover neighboring entities (e.g. possible SeVs, RSUs or base stations,) within their communication range
    - **b. Upload task:** TaVs send computing tasks to the service providers via V2X communication
    - **c. Processing task:** The service providers run a resource allocation policy to determine where the task should be offloaded
    - **d. Return result:** Service providers send results back to the TaVs

5. Task offloading in MEC V2X

5.1 Vehicular task offloading problem

- Task Offloading phases- high level view



Source: F.Saeik, M.Avgeris, D.Spatharakis, N.Santi, D.Dechouniotis,et al., Task Offloading in Edge and Cloud Computing:A Survey on Mathematical, Artificial Intelligence and Control Theory Solutions, 2018
https://www.chistera.eu/projects/druid-net, https://www.sciencedirect.com/science/article/abs/pii/S1389128621002322

5. Task offloading in MEC V2X

5.1 Vehicular task offloading problem

- **Offloading benefits:** relieving the network overload and reducing delay (due to proximity between VTs and servers)
  - Avoid long distance transmission for large amount of data
  - Offloading can be made mobility-aware – important for moving vehicles
- **Task Offloading Policies**
  - **Binary offloading:** a whole task is executed either locally on a vehicle or remotely on a VEC server
    - simpler to implement; appropriate for tasks that cannot be divided
    - **Local process**: the vehicular terminal (TaV) generates a computing task and processes the entire task locally (no offloading is executed)
    - **Full offloading: t**he whole computing task is offloaded to one or some service providers (SP) for processing and is executed on a particular entity of the SP
  - **Partial offloading:** a task is partitioned; a part is executed locally and the other is offloaded to an edge server for execution (this approach is suitable for complex tasks, consisting of multiple parallel segments)
    - It is necessary that TaVs understand the type of applications, in order to determine if sub-tasks can be handled separately
    - The management of the offloading process is complex

5. Task offloading in MEC V2X

5.1 Vehicular task offloading problem

- **Task Offloading Modes**
  - **Roles of vehicles:** TaVs, or relay nodes, or SeVs
  - **Direct Vehicle to Vehicle Offloading** : Vehicles directly offload (in a distributed manner via **V2V communication**) their tasks to neighboring SeVs which have some available computing resources
  - **Direct Vehicle to Infrastructure Offloading**: Computing tasks are directly offloaded to the infrastructure **(**via **V2I communication)**
  - **Multi-hop Vehicle-Infrastructure Offloading:** The multi-hop V2V helps TaVs to transfer tasks to the target infrastructure, through other VTs **(V2V, V2I,** i.e., **V2X communication)**
  - **Multi-hop Vehicle-Vehicle Offloading**: The multi-hop V2V helps TaVs to transfer tasks to the target SeVs (**V2X communication**)
- **Examples of Offloading modes:**
  - Vi <--> Vj <--> Vk using V2V links
  - Vi <--> RS or eNB (4G) or gNB(5G) using V2I links
  - Vi <--> eNB (4G) or gNB(5G) <--> Internet using V2X links
  - Combinations of the above on V2X links; e.g.: Vehicle- edge server- cloud data center

5. Task offloading in MEC V2X

- **5.1 Vehicular task offloading problem**
- The **delay** (in computation, communication) is a challenging QoS constraint in some offloading applications, including CAV
  - A key performance indicator/metric is the delay with three components
    - uploading delay (i.e., associated with the task's data size);
    - computing delay at the serving vehicle/edge node (depending on the data size and computational complexity)
    - downloading delay (i.e., associated to the output data size)
- Each client vehicle can perform **offloading decisions**
  - **independently** in a distributed manner, or under decision of a **centralized entity**
- **Factors to be considered in offloading** (by the client vehicles)
  - Set of neighbor vehicles located in their communication range, moving direction, relative velocities and longer contact time
- **Application needs - examples**
  - Autonomous vehicle (AV) need high data rates (e.g. 1Gbps) in road environments
  - Safety applications can use video streaming, augmented and virtual reality and multi-player online gaming applications
  - Data are generated at a fast rate by a variety of data sources
  - The delays in collecting/ processing/ transporting the data may have high negative impact
  - **General requirement:** VEC should ensure **low latency** and **high bandwidth**

See source: M.Ahmed , S.Raza, M.A. Mirza, A.Aziz, M.A.Khan, W.U. Khan, J.Li, Z.Han, "A survey on vehicular task offloading: Classification, issues, and challenges", Journal of King Saud University –Computer and Information Sciences, February 2022.

5. Task offloading in MEC V2X

- **5.2 Vehicular task offloading modes- general view**
- **V2V based Computation/Task Offloading**
  - **Vehicle roles**: task generators (TaV) or servers (SeV), or relays
  - Vehicles can offload their tasks fully/ partially to other Vs single or groups placed in proximity (cloudlets; name: vehicular cloudlet computing)
  - **Main optimization objectives : latency minimization and resource allocation**
  - The V2V -based TOff can exploit the underutilized vehicles' resources, thus avoiding workload on the infrastructure-based network (RSUs and BSs)
- **Issues to be solved:**
  - Uncertainty in the completion time of the task due to the vehicular mobility
  - Need of **mobility aware TOff**
  - The vehicular density may impact the offloading processes
  - Possible lack of resources; so, one must consider realistic scenarios such as multi-lane roads in urban and highways, variable size tasks, varying vehicular computing resources and speeds and mobility models
  - **How many wireless hops?**
    - **One-hop** is a conventional technique: less likely to fail, but not full exploitation of network's computing resources
    - **Multi-hop** offloading can exploit this potential, but can result in more failures and delays
  - Incentive means are needed for Vs, to cooperate in the computation process

5. Task offloading in MEC V2X

- **5.2 Vehicular task offloading modes- general view**

- **V2I based Computation/Task Offloading**
  - The Vs may have not enough local computing resources, to perform computation-intensive and complex tasks individually
  - The Vs can access **VEC servers** through V2I links
  - A V can connect to the roadside infrastructure (e.g., RSUs or BS), to offload its task entirely or partially to a MEC server
  - **Main optimization objectives: latency, resource allocation, server selection, load balancing, energy, computation and communication costs**

- **Issues to be solved**
  - In case of dense traffic, the overall quality can be low on roads
  - It is necessary to overcome the latency issues
  - Complexity is high : **multi- criterial optimization with several criteria**
  - The vehicles might have individual preferences for selecting edge servers
    - It is difficult to develop a unified TOff decision that can meet each vehicle's interests

5. Task offloading in MEC V2X

- **5.2 Vehicular task offloading modes- general view**

- **V2I based Computation/Task Offloading (cont'd)**

- **Issues to be solved** (cont'd)
  - An application type-specific framework needs should achieve a certain QoS level, while considering realistic and practical mobility models
    - Mobility-aware TOff is highly useful in mobile environments
  - There are not yet enough comprehensive evaluations under real-world traffic data to model the dynamic environment and show actual vehicle performance
  - The selection procedures of the testing platform for networks and mobility should be based on experiments in real-world settings
    - However, this may necessitate significant financial resources and thorough verification and configuration of the environment

  - **Mobility prediction based on AI/ML** can be employed to improve the offloading delay by providing resources proactively or pre-fetching computation tasks

5. Task offloading in MEC V2X

- **5.2 Vehicular task offloading modes- general view**

- **V2X based Computation/Task Offloading**

  - V2X communication is the most general mode including V2V, V2I, V2P and V2N
  - A vehicle can communicate to neighbor vehicles, roadside infrastructures, internet, or pedestrian via V2V, V2I, V2N and V2P, to offload tasks completely or partially

  - Possible schemes utilizing multiple modes in parallel: e.g., V2I to access the MEC server and V2V to access nearby vehicles (NV) for computation offloading in the V2X category
  - The modes V2V, V2I, V2N and V2P **can be utilized in parallel**
  - Some solutions use different RAT technologies, including DSRC and cellular, to avoid interference caused by spectrum reuse
  - Some schemes consider **multiple levels of offloading servers** such as:
    - near vehicle, MEC server, or Vehicular cloudlet computing (VCC)
    - Data centers for the case of cooperation with traditional vehicular cloud computing (TVCC)
  - **Main optimization objectives: latency, resource allocation, server selection, load balancing, computation and communication costs, energy**

5. Task offloading in MEC V2X

- **5.2 Vehicular task offloading modes- general view**

- **V2X based Computation/Task Offloading** (cont'd)
- **Issues to be solved**
  - The algorithms that deal with QoS in VEC scenarios should be extended to consider different QoS metrics
    - packet success/transmission rate, mean packet delivery delay, E2E multi-hop data communication path availability, packet loss percentage

  - More realistic and large - scale evaluation scenarios must be developed to accurately
  - evaluate proposed algorithms
  - The assumptions on stationary vehicles, or vehicles moving along predefined paths, are not fully realistic for traffic management in smart cities

  - The vehicular cloudlet computing paradigm can be of benefit for MEC servers by relieving the pressure of load, enhancing the use of computing resources, and lowering deployment costs
    - The VCC's self-organizing nature will also cause resource management and security provisioning challenges

  - Partitioning of computation tasks – need more studies

5. Task offloading in MEC V2X

- **5.2 Vehicular task offloading modes- general view**

- **V2X based Computation/Task Offloading** (cont'd)

- **Issues to be solved** (cont'd)
  - To ensure security and privacy while offloading tasks for delay-critical applications, existing encryption and authentication methods may be too slow in mobility scenarios

  - Lightweight encryption techniques are necessary

  - AI algorithms are powerful but need a high amount of computational resources
    - (e.g., DRL may take much time and computing resources to achieve the optimal outcome)

  - Lightweight learning algorithms take less time and consume less computing resources but may not produce optimal offloading decisions

  - It is essential to investigate the mixture of learned features like statically and dynamically, transfer learning, and domain adaptation

5. Task offloading in MEC V2X

- **5.3 Granularity levels of task offloading**

- **Entities involved in TOff**
  - **HW**: end user devices and Edge/Cloud devices
  - **multiple computing processes**, including task splitting and computational processing either locally or remotely
  - **networking components**
- **Operational phases**
  - The end device, through a task splitting process, decides which of the tasks should be executed locally and which ones should be offloaded
    - This decision is based on several factors (e.g., QoS reqs., battery lifetime, etc.)
  - The tasks to be offloaded are transferred to the GW and from there to a remote physical machine (either at the MEC/Edge or Cloud)
    - the tasks are executed there (e.g., creating a VM or container)
  - At the same time, the tasks remained on the device are executed locally
  - The last step is to combine the results of both local and remote executed tasks to provide the final output of the application
- **Partial Offloading at the Edge**
  - It is typically the most effective, since it benefits from both local and remote resources
  - level of complexity is high (decision on what to be executed locally and what – remote)

5. Task offloading in MEC V2X

- **5.3 Granularity levels of task offloading**

- **Full Offloading at the Edge**
  - The problem is translated into a resource allocation problem, where tasks can be executed on VMs or containers at the Edge
  - Total energy consumption should be evaluated (end devices, networking, remote server device)
  - A network path needed (TAV—SeV), while meeting possible QoE/QoS constraints

- **Partial/Full Offloading at the Edge and Cloud**
  - A collaboration between the Edge and Cloud infrastructures is established
  - The main challenge is the two-level TOff decision
    - *First level of decision is on V* (which tasks can be executed locally in the device and which ones should be offloaded)
    - *Second-level of decision is at the Edge:* a second task partitioning, no matter the type of offloading (i.e., partial or full) to determine the subset of tasks to be executed at the Edge level and which executed at the Central Cloud
    - Attention should be paid on the transport network interconnecting the Edge and the Central Cloud

5. Task offloading in MEC V2X

5.4 Mobility aspects

- **End device mobility is a critical components of the TOff decision**
- Mobility adds another level of splitting decision, as it needs to be decided at which Edge site should the tasks be offloaded while the user (V) is static or moving
- Note: More general Edger Server notation will be used (e.g., MEC Server)
- **Mobility is a challenge**, but also an **opportunity** for the **TOff**
  - One can initiate a **load balancing** to allow the system to provide the necessary services in distributed Edge site scenarios
  - Appropriate **prediction solutions** can enhance the system's capacity, by finding the potential next associated BS/AP of the user
    - This is more beneficial in a dense scenario: the system can analyze the active users and their mobility patterns and online allocate resources, while considering existing and newly requested services
  - Mobility can benefit from **handover (HO) mechanisms** that can enable service migrations between BSs and their Edge servers.
- **Issues**
  - Requirements of ~ zero mS HO in 5G mobility prediction
  - The mechanisms should be fast in order to predict beforehand where the tasks should be offloaded
  - The TOff decisions in mobility context impacts the overall performance in dense Edge deployments with multiple mobile users

5. Task offloading in MEC V2X

5.4 Mobility aspects

- **Static (Low-Mobility)**
  - The Vs are static or relatively static (low levels of mobility) during the TOff procedure
  - This context is simpler (no dynamicity)
  - No HO delays are involved

- **Mobile (High-Mobility)**
  - Many studies are focused on **TOff in mobile context; the problem is complex**
  - The Vs movement has a direct effect on the network conditions considered for TOff task and the resource allocation
  - In some solutions the user can offload the task, based on the **mobility pattern** and an opportunistic computing decision
    - It is taking advantage of the contact patterns regulated by the devices' mobility (e.g., which Edge site the V is visiting and what type of interactions occur on daily basis), in order to determine the amount of computation to be offloaded to other devices

  - Users may make TOff to remote servers or peer devices, possibly through the gateways or even via the Edge servers

  - Mobility can influence the decision: which BS and Edge server to select; when to perform HO

5. Task offloading in MEC V2X

5.4 Mobility aspects

- **Mobile (High-Mobility)** (cont'd)
- To minimize the execution delay, the **V mobility information** needs to be combined with the task characteristics and information about **resource availability**
  - This mobility information can be captured by trajectory prediction models to actually uncover motion patterns of the users in real-time scenarios

- Usually the TOff is made to BSs closer to the V's position and have sufficient resources

- **Examples:**
  - Case 1: a lightweight task can be fast executed; no migration to a neighbor Edge site is needed and the results are immediately returned to the mobile user

  - Case 2: the task requires longer time; it is split into sub-tasks and transferred to neighboring BSs along the user's trajectory

- Most solutions integrate mechanisms to obtain the device's current and future positions and tune the offloading infrastructure accordingly

5. Task offloading in MEC V2X

5.4 Mobility aspects

- **Mobility solutions classes**
  - **Proactive style - related to user behavior**
    - **Mobility information can be estimated** and leveraged towards predicting the users' position at any given moment based on:
      - services (e.g., Google Location Services), which tracks and logs the user's historic mobility behavior; they made trajectory pattern crowdsourcing a reality
      - distributing intelligence at the Edge has allowed for logging the times an end user device connects and disconnects to an AP extracting users' periodic movement patterns
      - - (normally, an agreement of the user would be needed for such tracking..)
  - **Specific details**
    - mobility information can be extracted in a probabilistic way, by utilizing **Mobility Markov Chains (MMC)** to model the historic behavior of a user as a discrete stochastic process
    - the prediction of a user moving to a specific location depends on their previous visited locations and the probability distribution of the transitions between them

See source: F.Saeik, M.Avgeris, D.Spatharakis, N.Santi, D.Dechouniotis,et al., Task Offloading in Edge and Cloud Computing:A Survey on Mathematical, Artificial Intelligence and Control Theory Solutions, 2018
https://www.chistera.eu/projects/druid-net, https://www.sciencedirect.com/science/article/abs/pii/S1389128621002322

5.4 Mobility aspects

- **Mobility solutions classes** (cont'd)
  - **Proactive style - related to user behavior** (cont'd)
  - **Specific details**
    - A **Markov model can be trained** to estimate the expected network quality and the expected staying time under the coverage of each Edge server
    - **Proactive installation** of the services frequently consumed in the Edge servers near to the positions that will be most probably visited by users
    - The **sojourn time PDF** of a V (the time a V is expected to spend within the coverage area of an Edge site), can also be used to predict the V next location and seamlessly migrate the service to be used for the task offloading appropriately
    - Examples: Mobility-aware mechanisms for partial TOff

- **Proactive style related to trajectory**
  - It exploits the V ongoing movement characteristics, i.e., trajectory, duration and speed
    - So, one can predict the location and the time of the next Edge server HO

  - Additionally, time-stamped geolocation updates periodically received from a moving V produces rt travel information for route segments, usable for trajectory estimation

5. Task offloading in MEC V2X

5.4 Mobility aspects

- **Mobility solutions classes** (cont'd)

- **Proactive style related to trajectory** (cont'd)
  - The mobility information can guide Edge servers to route the collected offloaded tasks to adjacent servers at the next location on the user's moving direction
  - When a V arrives at the coverage area of the next Edge site, it receives the product of its completed offloaded task, with the minimum additional delay

  - **Example: a two-step offloading mechanism**
    - Firstly: every V takes the initial TOff decision based on a dead reckoning technique and measurements of its signal strength.
    - Secondly, at the Edge side, a Kalman filter predicts the number of users and a controller is responsible for the final offloading decision and the allocation of resources to VMs

See source: F.Saeik, M.Avgeris, D.Spatharakis, N.Santi, D.Dechouniotis,et al., Task Offloading in Edge and Cloud Computing:A Survey on Mathematical, Artificial Intelligence and Control Theory Solutions, 2018
https://www.chistera.eu/projects/druid-net, https://www.sciencedirect.com/science/article/abs/pii/S1389128621002322

5. Task offloading in MEC V2X

5.4 Mobility aspects

- **Mobility solutions classes** (cont'd)
- **Reactive style**
  - The current 5G network infrastructures can efficiently adapt to the changing user environment, in real time.

  - The Edge servers **can utilize a central agent**, located at the Cloud, to form a mobility aware TOff infrastructure that tracks the V position and optimally routes the task and its response throughthe closest server to the users' locations

  - A whole virtual server can migrate to the topologically closest Edge server to the user, reactively, every time a relocation is detected
    - utilizing IP tracking, remote caching and SDN one can realize an efficient and timely task offloading as well
    - an SDN controller can track the user's network location, i.e., the Edge server in proximity and quickly react to changes in it by rerouting the offloaded task's response

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **General view of approaches**
  - Three main classes of solutions have been proposed for offloading solutions
    - **Traditional optimization algorithms**
    - **Artificial Intelligence and its subclass Machine learning**
    - **Control Theory based approaches.**

  - **Traditional optimization algorithms**
    - **Most common solution**, already used in resource allocation and scheduling networking problems
    - The main goal is to find the optimal solution among a set of possible solutions
    - The input data are Edge/Cloud infrastructure, end users, available resources, task distribution size and duration, etc.
    - **Exhaustive search** can lead to the optimal solution but with high complexity and execution time
    - One can reduce the complexity and time if relaxing some constraints of the input and accepting sub-optimal but fast and rt solution
    - **Issues:** many algorithms have a static nature (no adaptation feature)→ they should be re-executed and re-customized every time changes happen

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **General view of approaches** (cont'd)
  - **AI/ML task offloading mechanisms**
    - Use **data driven models**, learning from batch or online data
    - They provide real-time task offloading decisions and elastic resource allocation
    - Decisions are made by generalizing historical data, recognizing in an automatic way the prevailing data patterns and evaluating the possible destination states of the main actors in the Edge/Cloud environment
    - The state of Edge infrastructures includes
      - the status of computing nodes in terms of resource utilization
      - the number of application requests and
      - the user requirements contracted as SLAs
    - **ML advantages**
      - not explicitly designed by human but self-trained based on the available data
      - can handle multi-dimensional and multi-variety data in a unified way
      - capable of identifying hidden patterns
    - **Issues**
      - Some cases of significant inconsistency between training and testing data properties, may lead to performance degradation
      - Special care is required for data preparation tasks, synchronization, transformation, and normalization
      - A large amount and high frequency of data can make the training model a computational heavy and resource-intensive process

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **General view of approaches** (cont'd)
  - **System and Control Theories**
    - provides many formal methodologies to analyze and control the performance of the process
    - have been used for industrial processes and computer networks
  - **System theory - based task offloading**
    - provides black- or gray-box training algorithms, namely system identification, to compute MIMO models to capture the system dynamics of continuous or discrete systems
    - problem: system identification is performed offline and the computed mode may have low accuracy
  - **Control-based task offloading**
    - enable rt decisions against the dynamic network and workload conditions
    - can get an optimal operating point and guarantee various system properties, such as stability and reachability
      - **stability** :the system will reach specific operating conditions and will remain on them against any disturbance.
      - **reachability**: given the current system state, one can compute all possible destination states
    - **Issue:** the complexity of a controller increases with the complexity of the system model (linear or not) and the properties to be guaranteed

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods**
  - **1.Traditional optimization algorithms**
    - Problem formulation: defining the **objective function** and the **optimization strategy**
    - Strategies : Mixed Integer Programming (MIP), heuristics, game theory
    - **Mixed integer programming (MIP)**
      - IP/MIP- frequently used for resource allocation and scheduling in networks
      - Problem types: network synthesis and resource assignment
      - It can treat multi-objective function (several goals and offloading constraints
      - Usual: linear objective function (MILP), where at least one of the variables takes integer/binary values.
      - Issue: complexity in some cases e.g., in large scale scenarios
      - Example of objectives: minimize the mobile energy consumption in a multi-user system; under latency constraints minimize the tx and processing delay
    - **Mixed Integer non-linear programming (MINLP) or quadratic (MIQP)**
      - The objectives formulation are of non-linear
      - Multi-objective optimization can be a target
    - **Examples:** non-linear objective- weighted delay cost and energy consumption among all users; energy -objective and latency as a constraint plus other conditions (e.g., power consumption, channel states and resource heterogeneity)

Source: Z. Ning, P. Dong, X. Kong, F. Xia, A cooperative partial computation offloading scheme for mobile edge computing enabled Internet of Things, IEEE Internet Things J. (2018).

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods (cont.d)**
  - **1.Traditional optimization algorithms** (cont'd)
    - **Heuristics approaches**
      - Advantages: simple algorithms, low execution time, fast (but sub-optimal) solutions
      - No need of a specialized optimization tools; they can be expressed as pseudo-code, easily implementable
      - **Toff problems solved:**
        - minimizing the overall cost of energy, computation and delay, by applying appropriate relaxation and randomization techniques, to optimize the resource allocation at the edge
        - optimize parameters, such as QoE in a Cloud–Edge collaboration with various computational and bandwidth restrictions
      - They are efficient

        when the TOff problem is modeled as a non-linear constrained optimization problem

        in large-scale TOff offloading scenarios

Source: Y. Zhao, S. Zhou, T. Zhao, Z. Niu, Energy-efficient task offloading for multiuser mobile cloud computing, in: 2015 IEEE/CIC Int'l Conference on Communications in China, ICCC, IEEE, 2015, pp. 1–5.

Source: C. You, K. Huang, H. Chae, B.-H. Kim, Energy-efficient resource allocation for mobile-edge computation offloading, IEEE Trans. Wireless Commun. 16 (3) (2016) 1397–1411.

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
  - **1.Traditional optimization algorithms** (cont'd)
  - **Game theory - based**
    - The TOff problem can be modeled as a resource allocation game
    - Partial TOff in a multi-user,Edge Computing infrastructure and a multi-channel wireless interference environment, can be modeled as an offloading game
      - Example -Goal: to maximize the spectrum efficiency during offloading by allocating the proper channel to each user/player.
      - The approach can be complemented with a second matching game that will maximize the efficiency of resource allocation at the Edge, by appropriately selecting the right edge servers
  - A multi-step/slot game theoretic approach can be applied, to find the optimal state, expressed as the Nash Equilibrium
    - *[Nash Equilibrium –defines the solution of a non-cooperative game (≥2 players); each player knows the equilibrium strategies of the other players, and no one has anything to gain by changing only one's own strategy]*
    - In each step, the end users can make decisions on whether to offload their tasks, trying to get a potentially optimal offloading
    - A similar slotted approach can be followed by treating each user as a player with the goal to optimize the CPU-cycle frequency, to maximize the energy efficiency

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
  - **1.Traditional optimization algorithms** (cont'd)

  - **Game theory – based** (cont'd)
    - Edge–Cloud interplay-example: the set of players can be considered as the corresponding infrastructure
      - Using a Stackelberg game, a leader player tries to maximize a utility function expressed in order to obtain the optimal revenue for the Edge and Cloud providers, while satisfying the delay requirements
    - Another example: the objective is to minimize the overall energy consumption under delay constraints in an Edge–Cloud collaboration, where the two infrastructures comprise the players

- *Sources*
  - *X. Chen, L. Jiao, W. Li, X. Fu, Efficient multi-user computation offloading for mobile-edge cloud computing, IEEE/ACM Trans. Netw. 24 (5) (2015) 2795–2808.*
  - *Q.-V. Pham, T. Leanh, N.H. Tran, B.J. Park, C.S. Hong, Decentralized computation offloading and resource allocation for mobile-edge computing: A matching game approach, IEEE Access 6 (2018) 75868–75885.*
  - *Y. Liu, C. Xu, Y. Zhan, Z. Liu, J. Guan, H. Zhang, Incentive mechanism for computation offloading using edge computing: A Stackelberg game approach, Comput. Netw. 129 (2017) 399–409.*

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods**
  - **1.Traditional optimization algorithms** (cont'd)
    - **Local search**
    - The algorithms **explore neighbor solutions in the search space**, that allow to gradually converge to local optimum solutions
    - Such algorithms can be used as components of heuristics and meta-heuristics in order to provide solutions very close to optimality
      - Example: a one-dimensional local search algorithm can be used for a partial task offloading solution, minimizing the average execution delay, expressed as a Markov chain process, under the energy constraints imposed by the device
    - To minimize energy and latency of the partial TOff, a univariate search technique can be used. This type of search can transform a nonconvex problem into a convex one, by finding a local optimum solution
    - Multiple iterations of the local search can provide a better resource allocation of computing and channel resources in a partial offloading scenario

Sources: J. Liu, Y. Mao, J. Zhang, K.B. Letaief, Delay-optimal computation task scheduling for mobile-edge computing systems, in: 2016 IEEE International Symposium on Information Theory, ISIT, IEEE, 2016, pp. 1451–1455.
Y. Wang, M. Sheng, X. Wang, L. Wang, J. Li, Mobile-edge computing: Partial computation offloading using dynamic voltage scaling, IEEE Trans. Commun. 64 (10) (2016) 4268–4282.
J. Zhang, X. Hu, Z. Ning, E.C.-H. Ngai, L. Zhou, J. Wei, J. Cheng, B. Hu, Energy-latency tradeoff for energy-aware offloading in mobile edge computing networks, IEEE Internet Things J. 5 (4) (2017) 2633–2645.

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
  - **1.Traditional optimization algorithms** (cont'd)
    - **Contract theory- based**
    - The **TOff can introduce conflicts between the actors** (e.g., maximize energy and spectrum efficiency vs. minimizing consumption of some resources)
      - In the wireless networks (e.g., 5G) the agents can be BS, service provider, spectrum owner, small cells, smart devices and users
    - **Contract can achieve cooperation between the conflicting actors/agents**
    - In TOff, combining contract theory with game theory and a monetary rewards system, can eliminate the influence of information asymmetry in a user–Edge server relationship
    - **Incentives** can be utilized when dealing with small-cell base stations (SBSs) and heterogeneous ultra-dense networks (HetUDNs)
    - Dynamic programming concepts can be integrated with contract approach, e.g., to optimize bandwidth allocation in TOff

Sources:

M. Zeng, Y. Li, K. Zhang, M. Waqas, D. Jin, Incentive mechanism design for computation offloading in heterogeneous fog computing: A contract-based approach, in: 2018 IEEE International Conference on Communications, ICC, 2018, pp. 1–6.

J. Du, E. Gelenbe, C. Jiang, H. Zhang, Y. Ren, Contract design for traffic offloading and resource allocation in heterogeneous ultra-dense networks, IEEE J. Sel. Areas Commun. 35 (11) (2017) 2457–2467.

Z. Hu, Z. Zheng, L. Song, T. Wang, X. Li, UAV offloading: Spectrum trading contract design for UAV-assisted cellular networks, IEEE Trans. Wireless Commun. 17 (9) (2018) 6093–6107.

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)
  - Traditional algorithms - TOff limitations
    - static approach for many of them
    - opportunistic working style - addressing the objectives of the task offloading in a short-term scale
  - **AI**
  - includes multi-disciplinary techniques : **machine learning (ML),** consensus-based and constraint- based algorithms
  - can solve optimization problems including ones with math formulation of uncertain, stochastic and dynamic information; **AI-strong candidates for the TOff problem**
  - can potentially reduce the complexity by enabling recursive feedback-based learning, local interactions and faster speed
  - for TOff problems, AI learns from data and tasks distributed across the Edge infrastructure, and can provide a smart, real-time, and dynamic resource management framework
  - can avoid costly data offloading, by enabling data estimation or prediction
  - **AI problem formulation: defining the objective function and the algorithmic strategy to be followed**

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)
  - **Machine learning (ML)**
    - **ML-enabled -devices/systems learn** useful patterns and behaviors from historic data and make decisions about new ones
    - The models are **built without explicit programming**
    - **ML parameterized models** (Linear Discriminant Analysis, Logistic Regression, Naive Bayes) the models are built by tuning a fixed number of parameters of a predefined mapping function
    - **ML non-parametric models** (RBF-kernel Support Vector Machines, Decision Trees, K-Nearest Neighbor), use a flexible number of parameters with no prior knowledge about the data distribution and mapping function
      - In both cases, a **mapping function maps the independent data variables to the dependent variables**, i.e., the variables the model predicts
    - **Basic ML models :** ***supervised (SL), unsupervised (UL) and reinforcement learning (RL) ;*** **SL and DL are based on the available training data**
    - **Deep Learning (DL)** involves **Artificial Neural Networks (ANN)** with multiple layers of representation
    - **Deep Reinforcement Learning –cooperation of RL and DL**

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)
  - **Machine learning (ML): Supervised ML Models (SL)**
    - **Main** models : **classification and regression**; in classification, the model predicts classes while in regression the model estimates continuous values
    - The TOff decision can be modeled with a **multiclass classification method** and the **resource allocation with a regression model**
    - **Methods already used**
      - **Classification and Regression Trees** to select the fittest Edge device for TOff , minimizing time and energy
        - parameters considered: authentication, confidentiality, integrity, availability, capacity, speed and cost
      - **Classifiers such as JRIP and J48** -for **context sensitive offloading** in a Mobile Cloud Computing environment using a robust profiling system
        J48 is one of the classification-decision tree algorithm
      - J-Rip classifier is one of the decision tree pruning models based on association rules
    - **Logistic regression** to calculate the load of each Edge node and enhance a dynamic resource allocation strategy

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)
  - **Machine learning (ML): Supervised ML Models (SL)** (cont'd)
    - The **Apriori algorithm** has been used to generate TOff rules for every task, allowing section of the Edge node that offers the minimum completion time
    - **Linear Regression** can be used to predict
      - the total processing duration of each task on each candidate Edge node, in order to offload entire tasks to one Edge node instead of a local execution
      - the over-loaded and underloaded nodes, in order to facilitate a live migration process of tasks
    - **Gaussian Process Regression** can predict the future workload of the tasks, allowing the deployment of new, delay sensitive applications and reducing energy consumption, blocking of requests and latency

Sources: B. Yang, X. Cao, J. Bassey, X. Li, T. Kroecker, L. Qian, Computation offloading in multi-access edge computing networks: A multi-task learning approach, in:ICC 2019 - 2019 IEEE International Conference on Communications, ICC, 2019, pp. 1–6 (ISSN: 1938-1883).

D. Rahbari, M. Nickray, Task offloading in mobile fog computing by classification and regression tree, Peer-to-Peer Netw. Appl. 13 (1) (2020)104–122.

W. Junior, E. Oliveira, A. Santos, K. Dias, A context-sensitive offloading system using machine-learning classification algorithms for mobile cloud environment, Future Gener. Comput. Syst. 90 (2019) 503–520.

H. Bashir, S. Lee, K.H. Kim, Resource allocation through logistic regression and multicriteria decision making method in IoT fog computing, Trans. Emerg.Telecommun. Technol. n/a (n/a) (2019) e3824, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/ett.3824, https://onlinelibrary.wiley.com/doi/abs/10.1002/ett.3824.

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)
  - **Machine learning (ML): Unsupervised ML Models (UL)** (cont'd)
    - **Clustering models**
      - **do not require annotated data for training**
      - **discover groups of objects that are similar**, close and dense or share some common properties
        - have been used in TOff to group resources based on the distance between Edge nodes, wireless and computational resources in order to minimize the response delay
          - Edge sites can be grouped for different task resource demands
          - Edge servers can be grouped using an analysis of the allocated computing resources
    - The inter-task dependencies can be modeled by a graph and, by following a fuzzy clustering makespan (i.e., the time difference between the start and finish of tasks), monetary and energy costs can be minimized
    - The **K-means clustering** method can provide efficient task scheduling, based on the type of resource requirements in terms of CPU, I/O and communication
    - A **policy-based clustering** can provide energy-efficient TOff solutions, by organizing the interactions among the Edge nodes

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods**(cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)

  - **Machine learning (ML): Unsupervised ML Models (UL)** (cont'd)
    - **Source references for UL**

    - *M. Bouet, V. Conan, Mobile edge computing resources optimization: A geo-clustering approach, IEEE Trans. Netw. Serv. Manag. 15 (2) (2018) 787–796.*
    - *G. Li, Q. Lin, J. Wu, Y. Zhang, J. Yan, Dynamic computation offloading based on graph partitioning in mobile edge computing, IEEE Access 7 (2019) 185131–185139.*
    - *A.A.A. Gad-Elrab, A.Y. Noaman, Fuzzy clustering-based task allocation approach using bipartite graph in cloud-fog environment, in: Proc. of the 16th EAI Int'l Conf. on Mobile and Ubiquitous Systems: Computing, Networking and Services, MobiQuitous '19, ACM, https://doi.org/10.1145/3360774.3360833.*
    - *I. Ullah, H.Y. Youn, Task classification and scheduling based on K-means clustering for edge computing, Wirel. Pers. Commun. 113 (4) (2020) 2611–2624, https://doi.org/10.1007/s11277-020-07343-w.*

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)
  - **Machine learning (ML): Deep Learning** (DL)
    - **DL**
      - **useful in multiple decision and scheduling problems**
      - has been studied in the context of the IoV
      - can provide accurate results
      - can leverage large amounts of data
        data are collected by resource monitoring tools, logging mechanisms and network sniffers
    - A modular DL model can
      - integrate different sources of data
      - manipulate the data observations with hierarchical layers of representations
      - extract generalized knowledge beyond the historical observations
    - DL – used in TOff can provide timely and accurate decisions, based on the resource usage of processing Edge nodes, the load and the constraints defined in SLA
    - A DL model works as a **function approximator** which has
      - **inputs:** the current infrastructure and workload status
      - **outputs:** the appropriate processing nodes where each tasks will be offloaded

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)
  - **Machine learning (ML): Deep Learning** (DL) (cont'd)
    - DL models can
      - provide decisions for V/H scaling and VM migration in a dynamic computing environment
      - minimize the computation and TOff overhead in different network conditions and limited computation resources
      - take close to the optimal joint TOff decisions
      - decide bandwidth allocation with a distributed DL TOff offloading algorithm for Edge networks

Sources:

S. Yu, X. Wang, R. Langar, Computation offloading for MEC: A deep learning approach, in: 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications, PIMRC, 2017, pp. 1–6 (ISSN: 2166-9589).

L. Huang, X. Feng, A. Feng, Y. Huang, L.P. Qian, Distributed deep learning based offloading for mobile edge computing networks, Mob. Netw. Appl. (2018) https://doi.org/10.1007/s11036-018-1177-x.

X. Wang, X. Wei, L. Wang, A deep learning based energy-efficient computational offloading method in internet of vehicles, China Commun. 16 (3) (2019) 81–91.

Z. Ali, L. Jiao, T. Baker, G. Abbas, Z.H. Abbas, S. Khaf, A deep learning approach for energy efficient computational offloading in mobile edge computing, IEEE Access 7 (2019) 149623–149633.

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)
  - **Machine learning (ML): Deep Reinforcement Learning (DRL)**
    - **Reinforcement Learning (RL)** models take actions in an environment in order to maximize a cumulative reward or minimize expected loss
    - DRL generalizes with previously unseen data in terms of environment, states and actions
    - The DRL model been implemented in the Edge Computing context, can make the binary TOff decisions (partial or full)
    - Deep Q-Networks can
      - automatically infer the TOff decisions
      - be enhanced to capture the sequence of data with long short-term memory (LSTM) layers, for mobile tasks in a large-scale heterogeneous Edge environment in multi-Edge networks

Sources

L. Huang, S. Bi, Y.J. Zhang, Deep reinforcement learning for online computation offloading in wireless powered mobile-edge computing networks, IEEE Trans. Mob. Comput. (2019)

R. Zhao, X. Wang, J. Xia, L. Fan, Deep reinforcement learning based mobile edge computing for intelligent Internet of Things, Phys. Commun. (2020) 101184.

K. Zhang, Y. Zhu, S. Leng, Y. He, S. Maharjan, Y. Zhang, Deep learning empowered task offloading for mobile edge computing in urban informatics, IEEE Internet Things J. 6 (5) (2019) 7635–7647.

H. Lu, C. Gu, F. Luo, W. Ding, X. Liu, Optimization of lightweight task offloading strategy for MEC based onDRL , Future Gener. Comput. Syst. 102 (2020) 847–861, http://www, sciencedirect.com/science/article/pii/S0167739X19308209.

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)
  - **Bio-inspired and evolutionary algorithms**
    - Nature-inspired algorithms can provide close to optimal solutions in combinatorial problems, following a metaheuristic approach
    - Relevant algorithms: **Swarm Intelligence(SI)** and the **Evolutionary Algorithms(EA)**
    - They can provide efficient solutions in TOff challenges.
    - **Swarm Intelligence (Consensus-based)**
      - SI algorithms tries to allow the entire system to converge into a global consensus state, while keeping the ability to perform assigned individual tasks in the swarm.
      - Most common: **Ant Colony Optimization (ACO)** and **Particle Swarm Optimization (PSO)**
      - ACO- performs efficient task scheduling (it has search abilities) and low response time of IoT applications by distributing the tasks over the Edge nodes
      - PSO can
        - minimize both the tx and the processing delay, (result: minimize the total E2E delay) during a partial TOff at the Edge
        - include TOff mechanisms: VM migration and tx power management, to minimize service delay
        - jointly minimize energy consumption and completion time

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)
  - **Bio-inspired and evolutionary algorithms** (cont'd)
  - *References for ACO and PSO*
    - M.K. Hussein, M.H. Mousa, Efficient task offloading for IoT-based applications in fog computing using ant colony optimization, IEEE Access 8 (2020) 37191–37201.
    - T.G. Rodrigues, K. Suto, H. Nishiyama, N. Kato, A PSO model with VM migration and transmission power control for low service delay in the multiple cloudlets ECC scenario, in: IEEE, 2017, pp. 1–6.
    - L.N.T. Huynh, Q.-V. Pham, X.-Q. Pham, T.D.T. Nguyen, M.D. Hossain, E.-N.Huh, Efficient computation offloading in multi-tier multi-access edge computing systems: A particle swarm optimization approach, Appl. Sci. 10 (1) (2020) 203, https://www.mdpi.com/2076-3417/10/1/203.

  - **Evolutionary Algorithms (EA)**
    - **EA**
      - are based on natural selection principles, such as reproduction, mutation, recombination and selection
      - generate populations of candidate solutions and perform iterations, discarding the unfit solutions, aiming to get closer to optimal solutions
      - can be used in Edge nodes deployment and the TOff strategies

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)
  - **Bio-inspired and evolutionary algorithms** (cont'd)
    - **Evolutionary Algorithms (EA)** (cont'd)
      - **Genetic Algorithms (GA)** – subclass of EA

        use crossover operations in the reproduction of candidate solutions

        can be applied for sequential TOff and proactive fault tolerance

        can be combined with PSO to achieve close to optimal task offloading of IoT applications, while minimizing the total make-span and energy consumption

- *References for EA*
  - *F.Saeik, M.Avgeris, D.Spatharakis, N.Santi, D.Dechouniotis,et al., Task Offloading in Edge and Cloud Computing:A Survey on Mathematical, Artificial Intelligence and Control Theory Solutions, 2018* *https://www.chistera.eu/projects/druid-net, https://www.sciencedirect.com/science/article/abs/pii/S1389128621002322*
  - *D. Zhang, F. Haider, M. St-Hilaire, C. Makaya, Model and algorithms for the planning of fog computing networks, IEEE Internet Things J. 6 (2) (2019) 3873–3884.*
  - *A.A. Al-habob, O.A. Dobre, A. Garcia Armada, Sequential task scheduling for mobile edge computing using genetic algorithm, in: 2019 IEEE Globecom Workshops, GC Wkshps, 2019, pp. 1–6.*
  - *V. Yadav, B.V. Natesha, R.M.R. Guddeti, GA-PSO: Service allocation in fog computing environment using hybrid bio-inspired algorithm, in: IEEE Conf. TENCON, 2019, pp. 1280–1285 (ISSN: 2159-3450).*

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)
  - **Constraint satisfaction methods**
    - The TOff problem has also been modeled as a **Constraint Satisfaction Problem (CSP)** related to the AI
    - Constraint types examples: SLA, QoS, QoE, heterogeneity of devices, VMs characteristics, dynamicity of the task generation process
    - CSP finds solutions by using constraint propagation, local search, backtracking and various heuristics
    - Task properties, user mobility and network constraints have been jointly formulated as a CSP to reduce the task execution delay in MEC infrastructures
    - A CSP model can be used combined with Min-conflicts scheduling algorithm, to achieve load balancing of the Edge resources and minimizing energy consumption
    - TOff for distributed processing of data streams: aim to minimize E2E latency through the appropriate placement of the stream operators, either on Cloud nodes or Edge devices

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **2. Artificial intelligence (AI) based algorithms** (cont'd)
  - **Constraint satisfaction methods** (cont'd)
    - **Constraint Programming (CP)**
      - programming paradigm for solving complex proble
      - instead of defining a sequence of execution steps for the program one defines the relationships between variables in the form of constraints to be met
      - by following the steps of branching and exploration, CP finds feasible solutions to the problem.
      - it has been proposed for a generic placement service for Fog Computing with short resolution times and quality solutions
      - It has been combined with an event-based finite state model, in order to optimize mobile battery life and guarantee QoS and cost minimization simultaneously
    - *References for CSP*

      - *Z. Wang, Z. Zhao, G. Min, X. Huang, Q. Ni, R. Wang, User mobility aware task assignment for mobile edge computing, Future Gener. Comput. Syst. 85 (2018) 1–8, http://www.sciencedirect.com/science/article/pii/S0167739X17318587.*
      - *S. Vakilinia, D. Qiu, M.M. Ali, Optimal multi-dimensional dynamic resource allocation in mobile cloud computing, EURASIP J. Wireless Commun. Networking 2014 (1) (2014) 201, https://doi.org/10.1186/1687-1499-2014-201.*
      - *C. Lecoutre, Constraint Networks: Targeting Simplicity for Techniques and Algorithms, John Wiley & Sons, 2013.*
      - *F. Rossi, P. Van Beek, T. Walsh, Handbook of Constraint Programming, Elsevier, 2006.*

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **Algorithms based on control theory**
  - **Control Theory**
    - designed to regulate dynamic systems behavior and keep the system output(s) following the desired (reference) control signal
    - feedback mechanisms is essential in control systems; one measures the difference between the actual output and the desired reference
  - Control theory has been applied in Edge Computing for : decision-making control, network design selection, time-critical systems, admission control network management, network switching, etc.
  - Control theory - based algorithms can be used also in task offloading

  - **Optimal control** (examples)
  - Linear optimal control theory (i.e., Linear Quadratic Regulator (LQR),
    - designs a selection strategy in a heterogeneous wireless network, aiming to maximize the network resource utilization, while meeting the services constraints
    - LQR can be used in UAVs-related TOff to achieve robust adaptive attitude control

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **Algorithms based on control theory** (cont'd)
  - **State feedback control**
    - TOff can benefit from control theory methods for system modeling, analysis and evaluation
    - Example: an adaptive TOff resource allocation problem has been proposed
      - two-level admission and resource allocation management system for an Edge application cluster
      - mobile users have alternative options for performing their tasks
      - mobile users can offload application-specific tasks within the coverage area
  - **Lyapunov Optimization approaches**
    - Such algorithms
      - Can find the sufficient conditions for stability in dynamical systems.
      - due to the stability theory of dynamical systems, they can be used in TOff
      - can be used for minimizing the energy consumption of mobile devices, where a number of dynamic variables need to be fine-tuned and converged to optimal values. Lyapunov optimization will find the necessary stability in the CPU-cycle frequency of the device, transmission power, spectrum utilization and latency
    - An online TOff algorithm, using the current system information, can predict the user's resource availability

5. Task offloading in MEC V2X

5.5 Task offloading approaches

- **Specific methods** (cont'd)
- **Algorithms based on control theory** (cont'd)
  - ***References***
  - *F.Saeik, M.Avgeris, D.Spatharakis, N.Santi, D.Dechouniotis,et al., Task Offloading in Edge and Cloud Computing:A Survey on Mathematical, Artificial Intelligence and Control Theory Solutions, 2018 https://www.chistera.eu/projects/druid-net, https://www.sciencedirect.com/science/article/abs/pii/S1389128621002322*
  - *M. Avgeris, D. Dechouniotis, N. Athanasopoulos, S. Papavassiliou, Adaptive resource allocation for computation offloading: A control-theoretic approach, ACM Trans. Internet Technol. (TOIT) 19 (2) (2019) 1–20.*
  - *P. Skarin, J. Eker, M. Kihl, K. Årzén, Cloud-assisted model predictive control, in: 2019 IEEE International Conference on Edge Computing, EDGE, 2019, pp. 110–112.*
  - *N. Kalatzis, M. Avgeris, D. Dechouniotis, K. Papadakis-Vlachopapadopoulos, I. Roussaki, S. Papavassiliou, Edge computing in IoT ecosystems for UAV enabled early fire detection, in: 2018 IEEE International Conference on Smart Computing, SMARTCOMP, IEEE, 2018, pp. 106–114.*
  - *S. Li, N. Zhang, S. Lin, L. Kong, A. Katangur, M.K. Khan, M. Ni, G. Zhu, Joint admission control and resource allocation in edge computing for Internet of Things, IEEE Netw. 32 (1) (2018) 72–79.*
  - *Y. Mao, J. Zhang, S. Song, K.B. Letaief, Power-delay tradeoff in multiuser mobile-edge computing systems, in: 2016 IEEE Global Communications Conference, GLOBECOM, IEEE, 2016, pp. 1–6.*
  - *Y. Mao, J. Zhang, K.B. Letaief, Dynamic computation offloading for mobile-edge computing with energy harvesting devices, IEEE J. Sel. Areas Commun. 34 (12)(2016) 3590–3605.*

CONTENTS

6. Conclusions

- **Task offloading in vehicular networks is a major method to relieve the edge devices (subsystems of vehicles) from intensive computing and contributes to increasing in the overall system efficiency**

- Many methods have been developed and still are in study

- Edge infrastructures servers, and in **particular MEC servers constitute a strong support** nodes for task offloading

- **Cooperation between edge and central cloud processing** is possible

- **Balance** between local processing and task offloading is necessary

- **Decisions between partial or full offloading** need a complex evaluation of tasks and also the current availability of edge computing resources

- **Dynamicity of vehicular networks** has impact on task offloading decisions and creates real time problems

6. Conclusions

- **Challenges and still open research issues in task offloading to Edge (such as MEC) servers**
- **Dynamic vehicular network conditions and topology – determined by vehicle mobility**
  - A particular mobility context of a vehicle may impact the TOff related decisions
  - More algorithms to learn in parallel the user's behavior and network dynamics needed to reduce communication and computational costs, are of utmost importance for new and emerging
  - Development of 3D vehicles (e.g., UAV) – driving factor to such needs
  - Novel higher requirements are challenging in case of high speed mobility- real time responses needed to preserve service continuity
  - Vehicular mobility management for the applications to ensure the service continuity while vehicle is moving between cells
- **System components heterogeneity**
  - Real life systems – high heterogeneity (HW, SW, network, resource capabilities, applications)
  - Such factors can strongly influence the TOff overall efficiency; so, careful solution selection is necessary
  - TOff in such conditions need further studies and experiments

6. Conclusions

- **Challenges and still open research issues in task offloading to Edge (such as MEC) servers** (cont'd)
- **System components heterogeneity** (cont'd)

  - **Network heterogeneity**
  - TOff scenarios In 5G cellular systems: single-cell, contiguous cluster-cell scenario, not-adjacent cluster-cell; these scenarios are no yet sufficiently elaborated
    - **single-cell** scenario- new variables can influence the TOff cell decision: interference amount and congestion percentage
    - **clustered-cells** - the devices in the cell edge can extend the comm. capacity and some management capabilities through nearby devices, to neighboring cell
      - new problem: involving inter-cell communication and management aspects.
    - **not adjacent, cluster-cells** – open issues on resource allocation, delays, management problems etc.
    - edge-cloud cooperation problems

- Cases of multiple end-user devices(vehicles) reusing the spectrum to connect to multiple Edge and Cloud servers: signaling overhead, handover and dynamic resource allocation on the offloading, are important

6. Conclusions

- **Challenges and still open research issues in task offloading to Edge (such as MEC) servers** (cont'd)

- **Management and Control-related challenges**

  - Optimizing the decision making for computation offloading when nearby MEC resources are limited and local networks are congested
  - Management, distribution, and deployment of MEC resources allocating MEC computing and storage resources with special aspects in sliced networks
  - Balance MEC and network load and respecting the QoS requirements
  - Assuring the stability of the system in dynamic conditions
  - Management of virtualization techniques, including migration of virtual machines
  - Enhancing the modeling of the offloading-based applications

6. Conclusions

- **Challenges and still open research issues in task offloading to Edge (such as MEC) servers** (cont'd)
- **Management and Control-related challenges** (cont'd)
  - **Resource allocation in distributed mode**
    - In 5G networks , usually the traffic goes through a BS
    - A TOff directed to a distributed Edge infrastructure will need a backhaul network (increasing energy and cost); optimization is required, especially in a heterogeneous context
    - The dynamic behavior of vehicles adds complexity
      - one should select appropriate Edge servers
      - while maintaining as much as possible the user association vehicle-BS
    - Important challenge: developing a real-time TOff algorithms that considers the vehicle interactions and a distributed Edge infrastructure
    - More studies are needed for real-time real time allocation adaptive schemes that learn from system history

6. Conclusions

- **Challenges and still open research issues in task offloading to Edge (such as MEC) servers** (cont'd)
- **Mobile edge servers**
  - Novel solution applicable in special context of (user)vehicle distribution
  - If end devices have not convenient paths to Edge servers then Edge (MEC) mobile servers can be moved closer to the set of users
  - Issue: mobile Edge resources might be limited in capabilities w.r.t static servers
  - TOff challenges and open research issues: moving strategy of mobile Edge servers, selection of tasks to be offloaded, selection of end devices-servers peers

- **Fault management in a mobile environment**
  - Not fully solved problem of seamless connectivity and uninterrupted access to an Edge server during moving. Communication bandwidth /throughput are variable
    - TOff should be fault tolerant, while assuring a low response time an energy optimization

6. Conclusions

- **Challenges and still open research issues in task offloading to Edge (such as MEC) servers** (cont'd)
- **Security and privacy**
  - The TOff transfers a lot of data to third party Edge infrastructures, thus security and privacy are important
  - Entities involved : end user device, Edge server, transport through the network
  - Threats are frequently directed on the data transfer through the network
  - Possible solutions: steganography, homomorphic encryption, hardware-based security
  - ssues: encryption may involve high volume of data transferred, computation on encrypted data
  - More flexible monolithic distributed solutions are necessary to be developed
  - Enhanced TOff is needed regarding security and privacy constraints treatment

- Thank you !
- Questions?

References

1. ETSI EN 302 665 V1.1.1 (2010-09, European Standard (Telecommunications series) Intelligent Transport Systems (ITS); Communications Architecture
2. G.Karagiannis,et.al.,"Vehicular Networking:A Survey and Tutorial on Requirements,Architectures, Challenges, Standards and Solutions“, IEEE Comm. Surveys and Tutorials, 2011
3. 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
4. “Mobile edge computing (MEC); Framework and reference architecture,” ETSI, Sophia Antipolis, France, Mar. 2016. [Online].Available: http://www.etsi.org/deliver/etsi_gs/MEC/001_099/003/01.01.01_60/gs_MEC003v010101p.pdf
5. Cloudlets: all about cloudlet-enabled mobile computing. http://elijah.cs.cmu.edu/
6. M.Satyanarayanan, 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
7. OpenFog Reference Architecture for Fog Computing, February 2017, OpenFog Consortium Architecture Working Group, www.OpenFogConsortium.org
8. M.Iorga et. al., NIST Special Publication 800-191 (Draft) 1, “The NIST Definition of Fog Computing”, 2017
9. “Innovations in Edge Computing and MEC (Latest in Multi-access Edge Computing, Fog Computing, Distributed Clouds)”, 2017, http://www.linkedin.com/in/kmsabidurrahman/
10. 5G-PPP Architecture Working Group, “View on 5G Architecture”, Version 3.0, June, 2019, https://5g-ppp.eu/wp-content/uploads/2019/07/5G-PPP-5G-Architecture-White-Paper_v3.0_PublicConsultation.pdf, [retrieved June, 2019].
11. 3GPP TR 28.801 V15.1.0 (2018-01), Study on management and orchestration of network slicing for next generation network, (Release 15)
11. 3GPP TR 23.799 V14.0.0 (2016-12), TSG Services and System Aspects, “Study on Architecture for Next Generation System, (Release 14)
12. 3GPP TR 23.785 V14.0.0 (2016-09), TSG Services and System Aspects; "Study on architecture enhancements for LTE support of V2X services“, (Release 14)

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

References

13. 3GPP TR 22.886 V16.2.0 (2018-12), TSG Services and System Aspects; "Study on enhancement of 3GPP Support for 5G V2X Services“ (Release 16)
14. 3GPP TS 28.530 V1.2.1 (2018-07), Management and orchestration of 5G networks; Concepts, use cases and requirements
15. 3GPP TS 23.501 V16.3.0 (2019-12) TSG and SA, System Architecture for the 5G System; Stage 2 (Release 16)
16. ETSI EN 302 665 V1.1.1 (2010-09, European Standard (Telecommunications series) Intelligent Transport Systems (ITS); Communications Architecture
17. ETSI GS NFV 002 v1.2.1 (2014-12), NFV Architectural Framework
18. ETSI GR NFV-EVE 012 V3.1.1 (2017-12), Release 3; NFV Evolution and Ecosystem; Report on Network Slicing Support with ETSI NFV Architecture Framework
19. ETSI GS NFV-EVE 005, "Network Functions Virtualisation (NFV); Ecosystem; Report on SDN Usage in NFV Architectural Framework," v. 1.1.1, Dec. 2015.
20. ETSI GS NFV 003 V1.3.1 (2018-01) Network Functions Virtualisation (NFV); Terminology for Main Concepts in NFV
21. ETSI EN 302 665 V1.1.1 (2010-09, European Standard (Telecommunications series) Intelligent Transport Systems (ITS); Communications Architecture
22. ETSI GS NFV 002 v1.2.1 (2014-12), NFV Architectural Framework
23. ETSI GR NFV-EVE 012 V3.1.1 (2017-12), Release 3; NFV Evolution and Ecosystem; Report on Network Slicing Support with ETSI NFV Architecture Framework
24. ETSI GS NFV-EVE 005, "Network Functions Virtualisation (NFV); Ecosystem; Report on SDN Usage in NFV Architectural Framework," v. 1.1.1, Dec. 2015.
25. ETSI GS NFV 003 V1.3.1 (2018-01) Network Functions Virtualisation (NFV); Terminology for Main Concepts in NFV
26. ETSI GR NFV-IFA 022 V3.1.1 (2018-04) Network Functions Virtualisation (NFV) Release 3; Management and Orchestration; Report on Management and connectivity for Multi-Site Services
27. ETSI, "Multi-access Edge Computing (MEC); Study on MEC Support for V2X Use Cases," Tech. Rep., March 2018 https://portal.etsi.org/webapp/workProgram/Report_WorkItem.asp?wki_id=52949.

References

28. 3GPP TR 21.915 V15.0.0 (2019-09), TSG Services and System Aspects; Release 15
29. 3GPP TR 23.786 V16.1.0 (2019-06), TSG Services and System Aspects; "Study on architecture enhancements for the Evolved Packet System (EPS) and the 5G System (5GS) to support advanced V2X services", (Rel.16)
30. 3GPP TS 23.285 V16.2.0 (2019-12) 3GPP TSG SSA Architecture enhancements for V2X services(Release 16)
31. J. Ordonez-Lucena, P. Ameigeiras, D. Lopez, J.J. Ramos-Munoz, J. Lorca, J. Folgueira, Network "Slicing for 5G with SDN/NFV: Concepts, Architectures and Challenges" , IEEE Communications Magazine, 2017, Citation information: DOI 10.1109/MCOM.2017.1600935
32. ONF TR-526, "Applying SDN Architecture to 5G Slicing", Apr. 2016
33. M.K. Priyan and G. Usha Devi, "A survey on internet of vehicles: applications, technologies, challenges and opportunities", Int. J. Advanced Intelligence Paradigms, Vol. 12, Nos. 1/2, 2019
34. C.Campolo, A.Molinaro, A.Iera, F.Menichella, "5G Network Slicing for Vehicle-to-Everything Services", IEEE Wireless Communications, Volume: 24 Issue: 6, DOI: 10.1109/MWC.2017.160040
35. A.Molinaro and C.Campolo, "5G for V2X Communications", https://www.5gitaly.eu/2018/wp-content/uploads/2019/01/5G-Italy-White-eBook-5G-for-V2X-Communications.pdf
36. S.A.Ali Shah, E.Ahmed, M.Imran, and S.Zeadally, "5G for Vehicular Communications", IEEE Communications Magazine, January 2018, pp.111-117
37. K.Katsaros and M.Dianati, "A Conceptual 5G Vehicular Networking Architecture", October 2017, https://www.researchgate.net/publication/309149571, DOI: 10.1007/978-3-319-34208-5_22
38. J.Mei, X.Wang, and K.Zheng, "Intelligent Network Slicing for V2X Services Towards 5G", arXiv:1910.01516v1 [cs.NI] 3 Oct 2019
39. C.Renato Storck and F. Duarte-Figueiredo, "A 5G V2X Ecosystem Providing Internet of Vehicles" , Sensors 2019, 19, 550; doi:10.3390/s19030550 www.mdpi.com/journal/sensors
40. M.Ahmed , S.Raza, M.A. Mirza, A.Aziz, M.A.Khan, W.U. Khan, J.Li, Z.Han, "A survey on vehicular task offloading: Classification, issues, and challenges", Journal of King Saud University –Computer and Information Sciences, February 2022.

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

References

41. Friedhelm Ramme, ITS, Transport & Automotive, Ericsson 5G: "From Concepts to Reality“ Technology Roadmaps https://5gaa.org/wp-content/uploads/2019/02/Final-Presentation-MWC19-Friedhelm-Ramme-ERICSSON.pdf
42. 5G-PPP Automotive Working Group A study on 5G V2X Deployment, V1.0, February 2018 https://5g-ppp.eu/wp-content/uploads/2018/02/5G-PPP-Automotive-WG-White-Paper_Feb.2018.pdf
43. U.S. Department of Transportation: “IEEE 1609 – Family of Standards for Wireless Access in Vehicular Environments (WAVE)”. https://www.standards.its.dot.gov/Factsheets/Factsheet/80
44. R.Soua, et al., “Multi-Access Edge Computing for Vehicular Networks: a Position Paper”,2018, https://www.researchgate.net/publication/331854387_MultiAccess_Edge_Computing_for_Vehicular_Networks_A_Position_Paper
45. Ramon Sanchez-Iborra et.al., "Empowering the Internet of Vehicles with Multi-RAT 5G Network Slicing", https://www.ncbi.nlm.nih.gov/pubmed/31337087
46. NGMN Alliance, V2X White Paper, V1.0, 17-06-2018, https://5gaa.org/wp-content/uploads/2018/08/V2X_white_paper_v1_0.pdf
47. Mao, Y., You, C., Zhang, J., Huang, K., Letaief, K.B., 2017. A survey on mobile edge computing: The communication perspective. IEEE Commun. Surveys Tutorials 19, 2322–2358.
48. F.Saeik, M.Avgeris, D.Spatharakis, N.Santi, D.Dechouniotis,et al., Task Offloading in Edge and Cloud Computing:A Survey on Mathematical, Artificial Intelligence and Control Theory Solutions, 2018 https://www.chistera.eu/projects/druid-net, https://www.sciencedirect.com/science/article/abs/pii/S1389128621002322
49. K.Katsaros and M.Dianati, "A Conceptual 5G Vehicular Networking Architecture“, October 2017, https://www.researchgate.net/publication/309149571, DOI: 10.1007/978-3-319-34208-5_22
50. Friedhelm Ramme, ITS, Transport & Automotive, Ericsson 5G: "From Concepts to Reality“ Technology Roadmaps https://5gaa.org/wp-content/uploads/2019/02/Final-Presentation-MWC19-Friedhelm-Ramme-ERICSSON.pdf
51. U.S. Department of Transportation: “IEEE 1609 – Family of Standards for Wireless Access in Vehicular Environments (WAVE)”. https://www.standards.its.dot.gov/Factsheets/Factsheet/80

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

References

52. S. Sultan, M. Moath Al-Doori, A.H. Al-Bayatti, and H.Zedan “A comprehensive survey on vehicular Ad Hoc Network”, J.of Network and Computer Applications, Jan. 2014
53. K.Zheng, et.al., “Architecture of Heterogeneous Vehicular Networks”, Springer 2016, www.springer.com/cda/.../9783319256207-c1.pdf
54. M.J.Khan, M.A.Khan, S.Malik, P.Kulkarni, N.Alkaabi , O.Ullah , H.El-Sayed, A.Ahmed and S.Turaev Advancing C-V2X for Level 5 Autonomous Driving from the Perspective of 3GPP Standards Sensors 2023, 23, 2261. https://doi.org/10.3390/s23042261. https://www.mdpi.com/journal/sensors Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).
55. 3GPP TR 21.915 V15.0.0 (2019-09), TSG Services and System Aspects; Release 15
56. X. Foukas, G. Patounas, A.Elmokashfi, and M.K. Marina, Network Slicing in 5G: Survey and Challenges, IEEE Communications Magazine, May 2017, pp.94-100.
57. A.Galis and K.Makhijani, Network Slicing Landscape: A holistic architectural approach, orchestration and management with applicability in mobile and fixed networks and clouds, v1.0, Network Slicing Tutorial – IEEE NetSoft 2018.
58. End to End Network Slicing – White paper 3 Outlook 21, Wireless World , Nov 2017.
59. 5GPPP Technology Board Working Group, 5G-IA’s Trials Working Group Edge Computing for 5G Networks, 2021.
60. Wazir Zada Khan, et al., “Edge computing: A survey”, in Future Generation Computer Systems, Feb. 2019, https://www.researchgate.net/publication/331362529
61. ETSI GS MEC 003 V2.2.1 (2020-12), Multi-access Edge Computing (MEC); Framework and Reference Arch
62. https://portal.etsi.org/Portals/0/TBpages/MEC/Docs/Mobile-edge_Computing_ _Introductory_Technical_White_Paper_V1%2018-09-14.pdfMobile-Edge Computing – Introductory Technical White Paper
63. T.Taleb,et al., "On Multi-Access Edge Computing: A Survey of the Emerging 5G Network Edge Cloud Architecture and Orchestration", IEEE COMMUNICATIONS SURVEYS & TUTORIALS, VOL. 19, NO. 3, THIRD QUARTER 2017 1657

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

References

64. J.Mei, X.Wang, and K.Zheng, "Intelligent Network Slicing for V2X Services Towards 5G“, arXiv:1910.01516v1 [cs.NI] 3 Oct 2019.
65. S.A.Ali Shah, E.Ahmed, M.Imran, and S.Zeadally, "5G for Vehicular Communications", IEEE Communications Magazine, January 2018, pp.111-117.
66. ETSI GR MEC 022 V2.1.1 (2018-09), Multi-access Edge Computing (MEC);Study on MEC Support for V2X Use Cases.
67. Z. Ning, P. Dong, X. Kong, F. Xia, A cooperative partial computation offloading scheme for mobile edge computing enabled Internet of Things, IEEE Internet Things J. (2018).
68. Y. Zhao, S. Zhou, T. Zhao, Z. Niu, Energy-efficient task offloading for multiuser mobile cloud computing, in: 2015 IEEE/CIC Int'l Conference on Communications in China, ICCC, IEEE, 2015, pp. 1–5.
69. C. You, K. Huang, H. Chae, B.-H. Kim, Energy-efficient resource allocation for mobile-edge computation offloading, IEEE Trans. Wireless Commun. 16 (3) (2016) 1397–1411.
70. X. Chen, L. Jiao, W. Li, X. Fu, Efficient multi-user computation offloading for mobile-edge cloud computing, IEEE/ACM Trans. Netw. 24 (5) (2015) 2795–2808
71. Q.-V. Pham, T. Leanh, N.H. Tran, B.J. Park, C.S. Hong, Decentralized computation offloading and resource allocation for mobile-edge computing: A matching game approach, IEEE Access 6 (2018) 75868–75885.
72. Y. Liu, C. Xu, Y. Zhan, Z. Liu, J. Guan, H. Zhang, Incentive mechanism for computation offloading using edge computing: A Stackelberg game approach, Comput. Netw. 129 (2017) 399–409.
73. J. Liu, Y. Mao, J. Zhang, K.B. Letaief, Delay-optimal computation task scheduling for mobile-edge computing systems, in: 2016 IEEE International Symposium on Information Theory, ISIT, IEEE, 2016, pp. 1451–1455.
74. Y. Wang, M. Sheng, X. Wang, L. Wang, J. Li, Mobile-edge computing: Partial computation offloading using dynamic voltage scaling, IEEE Trans. Commun. 64 (10) (2016) 4268–4282.
75. J. Zhang, X. Hu, Z. Ning, E.C.-H. Ngai, L. Zhou, J. Wei, J. Cheng, B. Hu, Energy-latency tradeoff for energy-aware offloading in mobile edge computing networks, IEEE Internet Things J. 5 (4) (2017) 2633–2645.

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

References

76. M. Zeng, Y. Li, K. Zhang, M. Waqas, D. Jin, Incentive mechanism design for computation offloading in heterogeneous fog computing: A contract-based approach, in: 2018 IEEE International Conference on Communications, ICC, 2018, pp. 1–6
77. J. Du, E. Gelenbe, C. Jiang, H. Zhang, Y. Ren, Contract design for traffic offloading and resource allocation in heterogeneous ultra-dense networks, IEEE J. Sel. Areas Commun. 35 (11) (2017) 2457–2467.
78. Z. Hu, Z. Zheng, L. Song, T. Wang, X. Li, UAV offloading: Spectrum trading contract design for UAV-assisted cellular networks, IEEE Trans. Wireless Commun. 17 (9) (2018) 6093–6107.
79. B. Yang, X. Cao, J. Bassey, X. Li, T. Kroecker, L. Qian, Computation offloading in multi-access edge computing networks: A multi-task learning approach, in:ICC 2019 - 2019 IEEE International Conference on Communications, ICC, 2019, pp. 1–6 (ISSN: 1938-1883).
80. D. Rahbari, M. Nickray, Task offloading in mobile fog computing by classification and regression tree, Peer-to-Peer Netw. Appl. 13 (1) (2020)104–122
81. W. Junior, E. Oliveira, A. Santos, K. Dias, A context-sensitive offloading system using machine-learning classification algorithms for mobile cloud environment, Future Gener. Comput. Syst. 90 (2019) 503–520.
82. H. Bashir, S. Lee, K.H. Kim, Resource allocation through logistic regression and multicriteria decision making method in IoT fog computing, Trans. Emerg.Telecommun. Technol. n/a (n/a) (2019) e3824, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/ett.3824, https://onlinelibrary.wiley.com/doi/abs/10.1002/ett.3824
83. M. Bouet, V. Conan, Mobile edge computing resources optimization: A geo-clustering approach, IEEE Trans. Netw. Serv. Manag. 15 (2) (2018) 787–796.
84. G. Li, Q. Lin, J. Wu, Y. Zhang, J. Yan, Dynamic computation offloading based on graph partitioning in mobile edge computing, IEEE Access 7 (2019) 185131–185139.
85. A.A.A. Gad-Elrab, A.Y. Noaman, Fuzzy clustering-based task allocation approach using bipartite graph in cloud-fog environment, in: Proc. of the 16th EAI Int'l Conf. on Mobile and Ubiquitous Systems: Computing, Networking and Services, MobiQuitous '19, ACM, https://doi.org/10.1145/3360774.3360833.
86. I. Ullah, H.Y. Youn, Task classification and scheduling based on K-means clustering for edge computing, Wirel. Pers. Commun. 113 (4) (2020) 2611–2624, https://doi.org/10.1007/s11277-020-07343-w.

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

References

87. S. Yu, X. Wang, R. Langar, Computation offloading for MEC: A deep learning approach, in: 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications, PIMRC, 2017, pp. 1–6 (ISSN: 2166-9589).
88. L. Huang, X. Feng, A. Feng, Y. Huang, L.P. Qian, Distributed deep learning based offloading for mobile edge computing networks, Mob. Netw. Appl. (2018) https://doi.org/10.1007/s11036-018-1177-x.
89. X. Wang, X. Wei, L. Wang, A deep learning based energy-efficient computational offloading method in internet of vehicles, China Commun. 16 (3) (2019) 81–91.
90. Z. Ali, L. Jiao, T. Baker, G. Abbas, Z.H. Abbas, S. Khaf, A deep learning approach for energy efficient computational offloading in mobile edge computing, IEEE Access 7 (2019) 149623–149633
91. L. Huang, S. Bi, Y.J. Zhang, Deep reinforcement learning for online computation offloading in wireless powered mobile-edge computing networks, IEEE Trans. Mob. Comput. (2019)
92. R. Zhao, X. Wang, J. Xia, L. Fan, Deep reinforcement learning based mobile edge computing for intelligent Internet of Things, Phys. Commun. (2020) 101184.
93. K. Zhang, Y. Zhu, S. Leng, Y. He, S. Maharjan, Y. Zhang, Deep learning empowered task offloading for mobile edge computing in urban informatics, IEEE Internet Things J. 6 (5) (2019) 7635–7647.
94. H. Lu, C. Gu, F. Luo, W. Ding, X. Liu, Optimization of lightweight task offloading strategy for MEC based onDRL , Future Gener. Comput. Syst. 102 (2020) 847–861, http://www, sciencedirect.com/science/article/pii/S0167739X19308209
95. M.K. Hussein, M.H. Mousa, Efficient task offloading for IoT-based applications in fog computing using ant colony optimization, IEEE Access 8 (2020) 37191–37201.
96. T.G. Rodrigues, K. Suto, H. Nishiyama, N. Kato, A PSO model with VM migration and transmission power control for low service delay in the multiple cloudlets ECC scenario, in: IEEE, 2017, pp. 1–6.
97. L.N.T. Huynh, Q.-V. Pham, X.-Q. Pham, T.D.T. Nguyen, M.D. Hossain, E.-N.Huh, Efficient computation offloading in multi-tier multi-access edge computing systems: A particle swarm optimization approach, Appl. Sci. 10 (1) (2020) 203, https://www.mdpi.com/2076-3417/10/1/203.

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

References

98. D. Zhang, F. Haider, M. St-Hilaire, C. Makaya, Model and algorithms for the planning of fog computing networks, IEEE Internet Things J. 6 (2) (2019) 3873–3884.
99. A.A. Al-habob, O.A. Dobre, A. Garcia Armada, Sequential task scheduling for mobile edge computing using genetic algorithm, in: 2019 IEEE Globecom Workshops, GC Wkshps, 2019, pp. 1–6.
100. V. Yadav, B.V. Natesha, R.M.R. Guddeti, GA-PSO: Service allocation in fog computing environment using hybrid bio-inspired algorithm, in: IEEE Conf. TENCON, 2019, pp. 1280–1285 (ISSN: 2159-3450).
101. Z. Wang, Z. Zhao, G. Min, X. Huang, Q. Ni, R. Wang, User mobility aware task assignment for mobile edge computing, Future Gener. Comput. Syst. 85 (2018) 1–8, http://www.sciencedirect.com/science/article/pii/S0167739X17318587.
102. S. Vakilinia, D. Qiu, M.M. Ali, Optimal multi-dimensional dynamic resource allocation in mobile cloud computing, EURASIP J. Wireless Commun. Networking 2014 (1) (2014) 201, https://doi.org/10.1186/1687-1499-2014-201.
103. C. Lecoutre, Constraint Networks: Targeting Simplicity for Techniques and Algorithms, John Wiley & Sons, 2013.
104. F. Rossi, P. Van Beek, T. Walsh, Handbook of Constraint Programming, Elsevier, 2006.
105. M. Avgeris, D. Dechouniotis, N. Athanasopoulos, S. Papavassiliou, Adaptive resource allocation for computation offloading: A control-theoretic approach, ACM Trans. Internet Technol. (TOIT) 19 (2) (2019) 1–20.
106. P. Skarin, J. Eker, M. Kihl, K. Årzén, Cloud-assisted model predictive control, in: 2019 IEEE International Conference on Edge Computing, EDGE, 2019, pp. 110–112.
107. N. Kalatzis, M. Avgeris, D. Dechouniotis, K. Papadakis-Vlachopapadopoulos, I. Roussaki, S. Papavassiliou, Edge computing in IoT ecosystems for UAV enabled early fire detection, in: 2018 IEEE International Conference on Smart Computing, SMARTCOMP, IEEE, 2018, pp. 106–114.
108. S. Li, N. Zhang, S. Lin, L. Kong, A. Katangur, M.K. Khan, M. Ni, G. Zhu, Joint admission control and resource allocation in edge computing for Internet of Things, IEEE Netw. 32 (1) (2018) 72–79.
109. Y. Mao, J. Zhang, S. Song, K.B. Letaief, Power-delay tradeoff in multiuser mobile-edge computing systems, in: 2016 IEEE Global Communications Conference, GLOBECOM, IEEE, 2016, pp. 1–6.
110. Y. Mao, J. Zhang, K.B. Letaief, Dynamic computation offloading for mobile-edge computing with energy harvesting devices, IEEE J. Sel. Areas Commun. 34 (12)(2016) 3590–3605.

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- **List of Acronyms**

1G	First Generation of Mobile Networks
2G	Second Generation of Mobile Networks
3G	Third Generation of Mobile Networks
4G	Fourth Generation of Mobile Networks
5G	Fifth Generation of Mobile Networks
3GPP	3rd Generation Partnership Project
5G CN	Core Network
5G-AN	5G Access Network
5GS	5G System
5QI	5G QoS Identifier
ACO	Ant Colony Optimization
AF	Application Function
AI	Artificial Intelligence
AMF	Access and Mobility Management Function
AN	Access Network
API	Application Programming Interface
AR	Augmented Reality
AS	Access Stratum
AU	Application Unit
AUSF	Authentication Server Function
BBU	Baseband Unit
BS	Base Station
CA	Certificate Authority
CAV	Connected Autonomous Vehicles
CDMA	Code Division Multiple Access

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

- **List of Acronyms**

CC	Cloud Computing
CN	Core Network
CP	Control Plane
CRAN	Cloud based Radio Access Network
CSP	Constraint Satisfaction Problem
C-V2X	Cellular V2X Communication
D2D	Device to Device
DC	Data Center
DLK	Downlink
DL	Deep Learning
DRL	Deep Reinforcement Learning
DN	Data Network
DNN	Data Network Name
DoS	Denial of Services
DP	Data Plane (User Plane UP)
DSRC	Dedicated Short Range Communication
E2E	End to End
EA	Evolutionary Algorithms
EC	Edge Computing
eNB	Evolved Node B
ePDG	evolved Packet Data Gateway
ETSI	European Telecommunications Standards Institute

- **List of Acronyms**

FC	Fog Computing
FDMA	Frequency Division Multiple Access
GA	Genetic Algorithms
GPS	Global Positioning System
HD	High Definition
HetNets	Heterogeneous Networks
HR	Home Routed (roaming)
Het-MEC	Heterogeneous MEC
HO	Handover
HSS	Home Subscriber System
IaaS	Infrastructure as a Service
ICI	Inter-Cell Interference
INaaS	Information as a Service
INS	Insurance
InP	Infrastructure Provider
IoV	Internet of Vehicles
ISLP	Infrastructure Slice Provider
IST	Infrastructure Slice Tenant
IoT	Internet of Things
IT&C	Information Technology and Communications
ITS	Intelligent Transportation Systems
LADN	Local Area Data Network
LLC	Logical Link Control

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

- **List of Acronyms**

LMF	Location Management Function
LRF	Location Retrieval Function
LTE	Long-Term Evolution
M2M	Machine to Machine
MANET	Mobile Ad hoc Network
MANO	Management and Orchestration
MBB	Mobile Broadband
MCC	Mobile Cloud Computing
MDP	Markov Decision Process
MEC	Multi-access (Mobile) Edge Computing
ML	Machine Learning
MIMO	Multiple-Input and Multiple-Output
MINLP	Mixed Integer non-linear programming
MME	Mobility Management Entity
mmWave	millimeter Wave
mMTC	Massive Machine Type Communication
MNO	Mobile Network Operator
N3IWF	Non-3GPP InterWorking Function
NaaS	Network as a Service
NAI	Network Access Identifier
NEF	Network Exposure Function
NF	Network Function
NFV	Network Function Virtualisation
NFVI	Network Function Virtualisation Infrastructure
NOMA	Non-Orthogonal Multiple Access

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

- **List of Acronyms**

NR	New Radio
NRF	Network Repository Function
NSI ID	Network Slice Instance Identifier
NSSAI	Network Slice Selection Assistance Information
NSSF	Network Slice Selection Function
NSSP	Network Slice Selection Policy
NWDAF	Network Data Analytics Function
OBU	On Board Unit
OFDM	Orthogonal Frequency-Division Multiplexing
OMA	Orthogonal Multiple Access
ONF	Open Networking Foundation
PaaS	Platform as a Service
PCF	Policy Control Function
PKI	Public Key Infrastructure
PLMN	Public Land Mobile Network
PNF	Physical Network Function
PSO	Particle Swarm Optimization
QFI	QoS Flow Identifier
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RL	Reinforcement Learning
RP	Reference Point
RRH	Remote Radio Head

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

- **List of Acronyms**

RSU	Road Side Unit
SA NR	Standalone New Radio
SaaS	Software as a Service
SBA	Service Based Architecture
SBI	Service Based Interface
SD	Slice Differentiator
SDN	Software Defined Networking
SEAF	Security Anchor Functionality
SEPP	Security Edge Protection Proxy
SeV	Service Vehicle
SM	Service Management
SMF	Session Management Function
S-MIB	Security Management Information Base
SMSF	Short Message Service Function
SL	Supervised Learning
S-NSSAI	Single Network Slice Selection Assistance Information
SSC	Session and Service Continuity
SST	Slice/Service Type
TaV	Task Vehicle
TNL	Transport Network Layer
TNLA	Transport Network Layer Association
TOff	Task Offloading
TSP	Traffic Steering Policy
TVCC	Traditional Vehicular Cloud Computing

- **List of Acronyms**

UDM	Unified Data Management
UDR	Unified Data Repository
TDMA	Time Devision Multiple Access
TNL	Transport Network Layer
TNLA	Transport Network Layer Association
TSP	Traffic Steering Policy
UAV	Unmanned Air Vehicle
UDM	Unified Data Management
UDR	Unified Data Repository
UDSF	Unstructured Data Storage Function
UL	Unsupervised Learning
UPF	User Plane Function
URSP	UE Route Selection Policy
URLLC	Ultra Reliable Low Latency Communication
V2I	Vehicle to Infrastructure
V2N	Vehicle to Network
V2P	Vehicle to Pedestrian
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VANET	Vehicular ad-hoc Networks
VCC	Vehicular Cloud Computing
VCN	Vehicular Communication Network
VEC	Vehicular Edge Computing
VECN	Vehicular Edge Computing Networks

Task Offloading in 5G Multi-access Edge Computing for Vehicular Networks

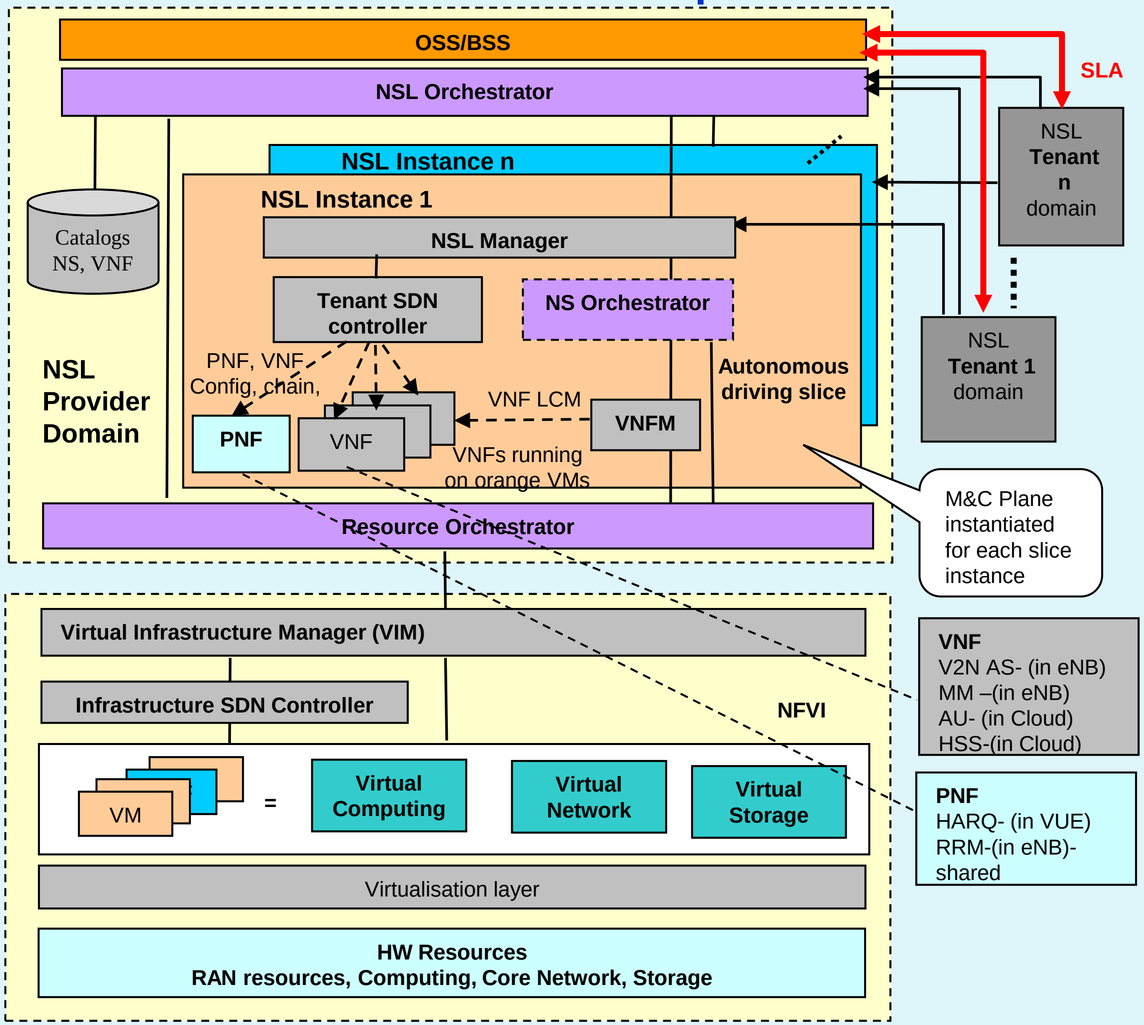
- **List of Acronyms**

VF	Virtualized Function
VIM	Virtualised Infrastructure Manager
VNF	Virtualized Network Function
VR	Virtual Reality
VRU	Vulnerable Road User
VT	Vehicular Terminal
WAVE	Wireless Access in Vehicular Environment
WiFi	Wireless Fidelity
WPT	Wireless Power Transfer
WSMP	Wave Short Message Protocol

- **Backup slides**

4.7 V2X slicing functional architecture

- **Functional architecture example – for autonomous driving slice**



Adapted from sources:

ETSI GR NFV-EVE 012 V3.1.1 (2017-12), Release 3; NFV Evolution and Ecosystem; Report on Network Slicing Support with ETSI NFV Architecture Framework

C.Campolo, et al., "5G Network Slicing for Vehicle-to-Everything Services", IEEE Wireless Communications, Volume: 24 Issue: 6, DOI: 10.1109/MWC.2017.160040

J.Ordonez-Lucena, et.al., "The Creation Phase in Network Slicing: From a Service Order to an Operative Network Slice", European Conference on Networks and Communications (EuCNC), 2018, https://arxiv.org/abs/1804.09642

4. MEC support for V2X 5G systems

4.7 V2X slicing functional architecture

- **Functional architecture example**
  - **Management and control: NFV + SDN+ slicing**
  - Main slicing architecture concepts applied + **V2X specialization functions**
  - Functional entities/layers
    - **OSS/BSS** – Operation/Business Support System
    - **NSLP** - Network slice provider
    - **NFVI**- Network Function Virtualization Infrastructure including HW resources
    - **NSL Tenants + End users**

- **Slicing management and orchestration** - include
  - **Slice description**
    - includes the SLA requirements as agreed by vertical segments
    - OSS/BSS monitors the SLA assurance
    - the description is translated to network elements
  - **Slice instantiation**:
    - identification of: CP/UP architecture, interfaces, sets of slice-specific and common VNFs/PNFs in the CN and RAN
    - a tenant SDN controller will control their interconnection and parameter settings
  - **Slice lifecycle management (LCM) -** configuration, adaptation and monitoring to fulfill isolation constraints and agreed SLAs.

4. MEC support for V2X 5G systems

4.7 V2X slicing functional architecture

- **Functional architecture example – for autonomous driving slice** (cont'd)
- **Notations** (previous slide)
- **General (5G slicing, NFV)**
  - SDN Software Defined Networking
  - SLA – Service Level Agreement
  - MANO- Management and Orchestration
  - NS – Network Service
  - NSO- Network Service Orchestrator
  - NSL - Network Slice
  - NSLO - Network Slice Orchestrator
  - RO- Resource Orchestrator
  - VNF – Virtualized Network Function
  - PNF- Physical Network Function
  - VNFM – VNF Manager
  - LCM – Life Cycle Management
  - VIM – Virtual Infrastructure Manager
  - IC- Infrastructure SDN Controller
- **V2X –dedicated entities**
  - AS- Application Server
  - AU- Authentication and Authorization Management
  - MM Mobility Management
  - V2N – Vehicle to Network
  - RRM – Radio Resource Management
  - HARQ- Hybrid Automatic Repeat Request

4. MEC support for V2X 5G systems

4.6 V2X Information Services (VIS)

- **Reference scenarios for the VIS service**
- **ETSI: Multi-X** (X=access, network ,operator) scenarios are the reference assumptions motivating the need for MEC normative work on this area
- **Case 1.** V2X services can be
  - managed by **OEMs ("Vehicle OEMs scenario")-** in single or multi-operator provided by different Network Operators (same/different country)
- **Case 2. "ITS Operator scenario"** may also provide services for different vehicle OEMs
  - country-wide V2X service, by exploiting different operators' networks (deploying different MEC systems) and offering this service to Vehicles belonging to different OEMs.
  - V2X services can be provided by different NOs in the same country and/or in different countries.
- MEC VIS should support C-V2X systems implemented in the most general scenarios
  - one may have multiple MEC vendors and the need to enable interoperable data exchange between them

Vehicle OEM scenario, single MNO
Vehicle OEM scenario, multiple MNO

ITS operator, single MNO	ITS operator, single OEM, single MNO
ITS operator, multiple MNO	ITS operator, multiple OEM, multiple MNO

Source: ETSI GS MEC 030 V2.1.1 (2020-04), (MEC), V2X Information Service API

4. MEC support for V2X 5G systems

4.6 V2X Information Services (VIS)

- **MEC VIS functionalities**
  - **Gathering of PC5 V2X** relevant information from the 3GPP network (e.g. the list of authorized UEs, the information about the authorization based on the UE subscription and the relevant PC5 configuration parameters)
  - **Exposure of this information to MEC apps** (also potentially belonging to different MEC systems)
  - **Enable the MEC apps to communicate securely** with the V2X-related 3GPP core network logical functions (e.g. V2X control function)
  - **Enable the MEC apps in different MEC systems to inter-communicate securely**

  - Possibly **gathering and processing information available in other MEC APIs** (e.g. RNI API (see ETSI GS MEC 012) Location API (see ETSI GS MEC 013), WLAN API (see ETSI GS MEC 028), etc. in order to predict radio network congestion and provide suitable notifications to the UE

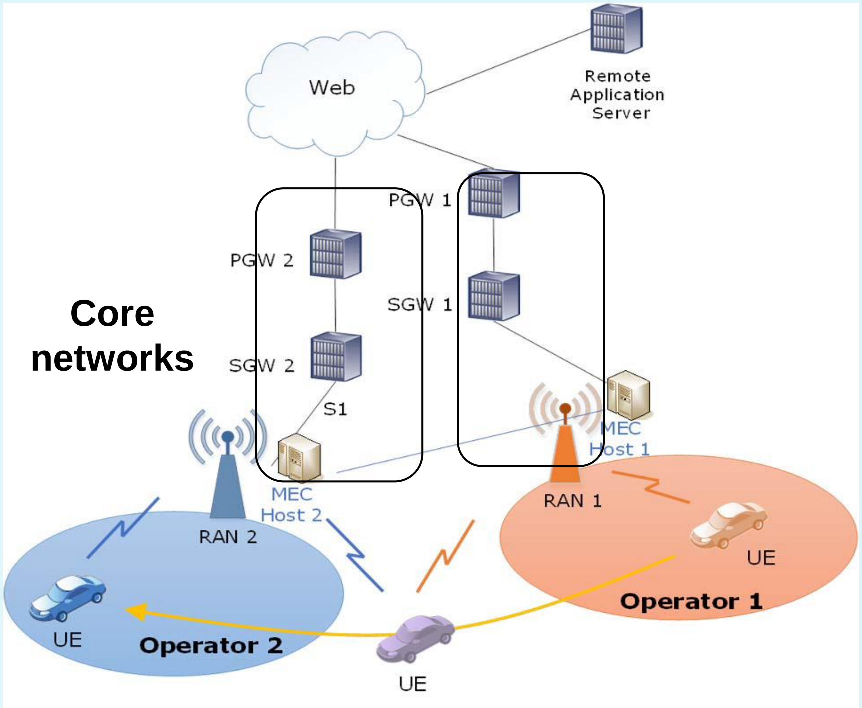
  - **The VIS API provides information to MEC applications in a standardized way**
    - this is essential for interoperability in multi-vendor scenarios
    - however, MEC applications may communicate in a direct way (i.e. without the use of MEC platform)

Source: ETSI GS MEC 030 V2.1.1 (2020-04), (MEC), V2X Information Service API

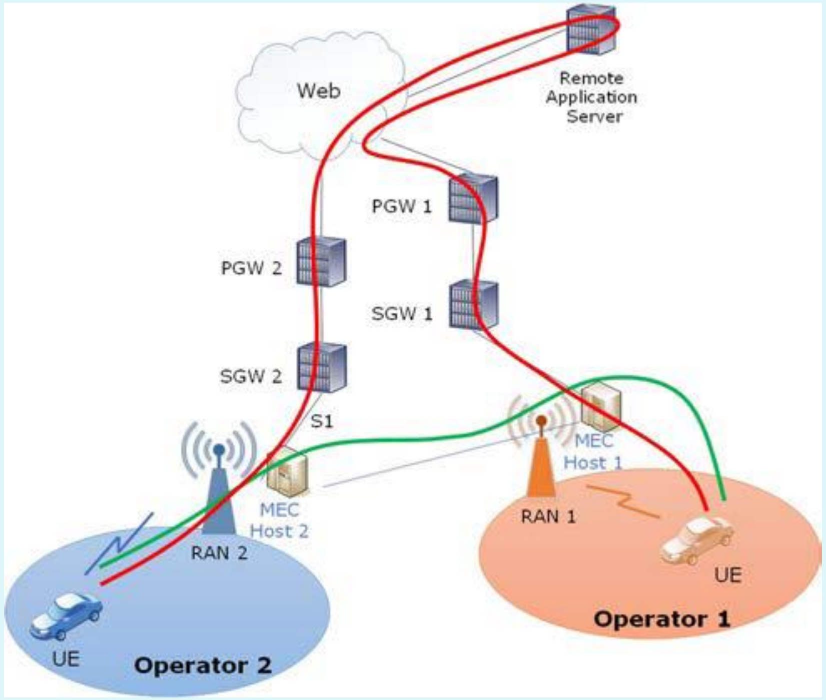
4. MEC support for V2X 5G systems

4.6 V2X Information Services (VIS)

Example of a multi-operator scenario for V2X services



Path for data exchange w/o the VIS service (in red) and with the VIS service (in green)



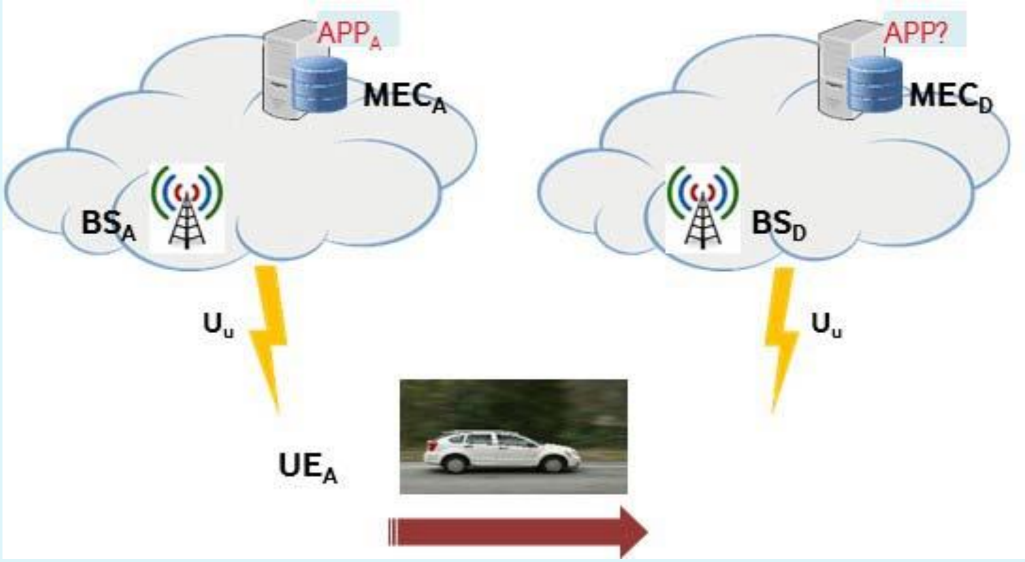
- In a V2X system with no VIS the interconnection between MNOs is terminated at the remote side; high E2E latency (red line)
- VIS service achieves lower E2E latency (due to a “H communication“)
- VIS exposes information on PC5 configuration parameters and manages the multi-operator environment, especially when a UE is out of coverage

Adapted from Source: ETSI GS MEC 030 V2.1.1 (2020-04), (MEC), V2X Information Service API

4. MEC support for V2X 5G systems

4.6 V2X Information Services (VIS)

- **V2X service continuity in multi-operator operation scenarios**
  - To maintain the V2X service continuity (with low latency requirement) is a challenge when the road users (e.g. vehicular UEs) are roaming among PLMNs
  - inter-MEC system coordination is required to prepare in advance the UEs in transit and thus reduce the interruption time
    - based on the agreements among operators, roam or HO to a new PLMN
  - **Task offloading can be applied in such cases**

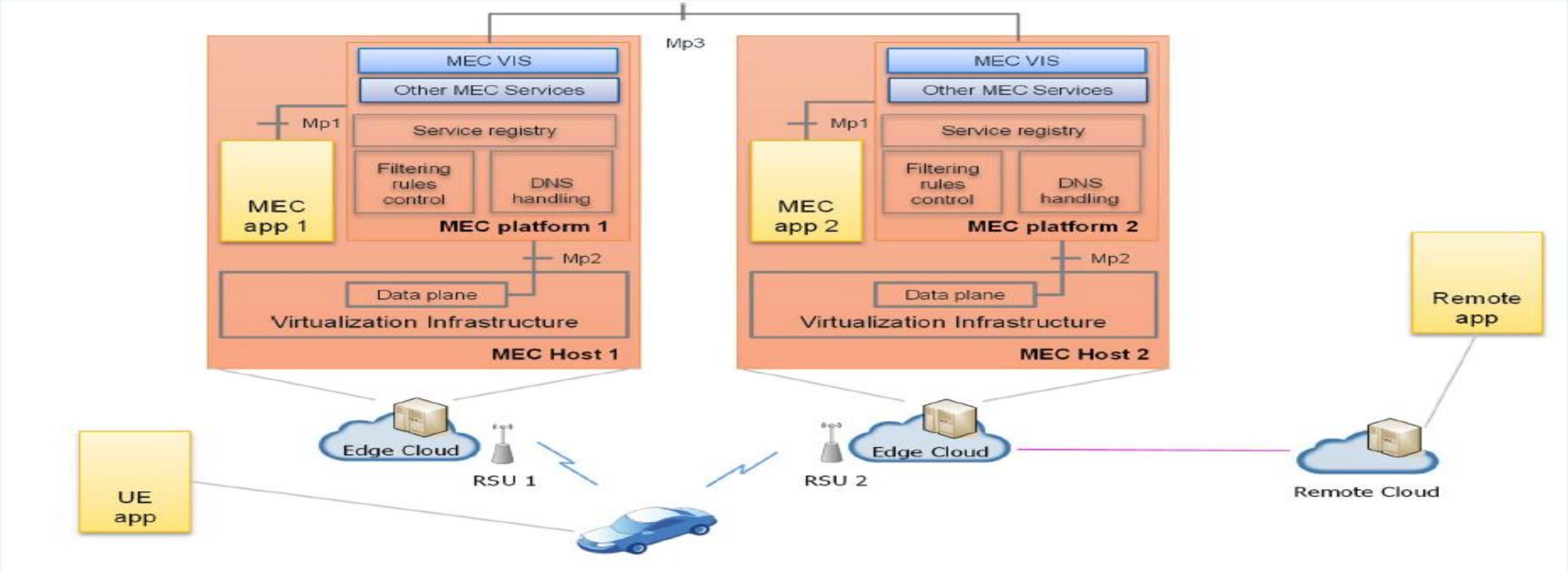


Source: ETSI GS MEC 030 V2.1.1 (2020-04), (MEC), V2X Information Service API

4. MEC support for V2X 5G systems

4.6 V2X Information Services (VIS)

- **Example of application instances in a V2X service with VIS API**
  - Typical V2X system involving multiple MEC hosts and the use of the VIS service.
  - A car is hosting a client app. and is connected to a certain MEC host
  - In multiple MEC hosts context, the VIS permits to expose information between MEC apps. running on different MEC hosts
  - Other remote app. server instances can be located somewhere else (e.g. private clouds owned by the operator or by the OEM)
  - The VIS service may be produced by the MEC platform or by the MEC application



Source: ETSI GS MEC 030 V2.1.1 (2020-04), (MEC), V2X Information Service API

4. MEC support for V2X 5G systems

4.6 V2X Information Services (VIS)

- **Example of architecture enabling the communication between the VIS and the V2X Control Function**

  - In a 3GPP network, **V2X applications can be deployed on V2X Application Server**
  - The **V2X Control Function** is the NF in core network part, used for V2X network-related actions
  - The **HSS provides the list of the PLMNs,** where the UE is authorized to perform V2X communication over PC5 reference point (RP_ to the V2X Control Function, (ETSI TS 123 285)

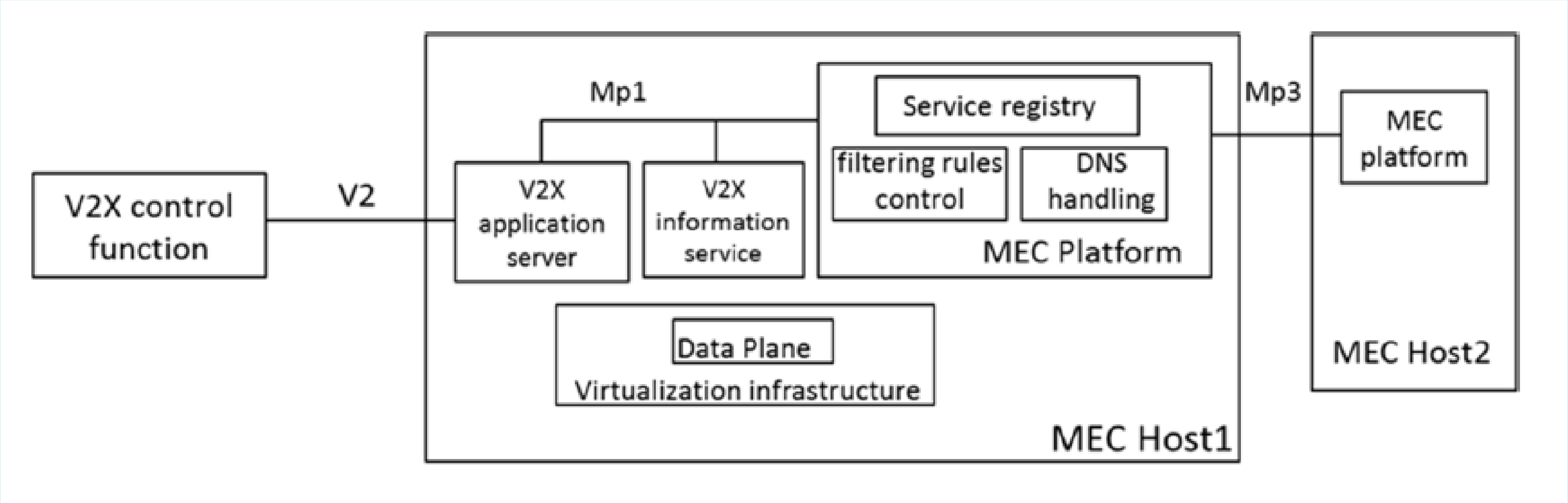
  - **V2 is the RP between the V2X Application Server and the V2X Control Function** in the operator's network

  - The **MEC VIS supports V2X interoperability** in a multi-vendor, multi-network and multi-access environment
    - Therefore, the VIS should obtain the UE's subscription data (e.g. PC5 based V2X communication allowed PLMN), from the V2X Control Function

4. MEC support for V2X 5G systems

4.6 V2X Information Services (VIS)

- **Example of architecture enabling the communication between the VIS and the V2X Control Function** (cont'd)
  - The V2X Application Server bears multiple V2X apps; it can, therefore, be deployed in MEC platform as an app.
  - The VIS can communicate with the V2X Application Server through Mp1, and it can obtain the UE's V2X subscription data from the V2X Control Function through the V2X Application Server



Source: ETSI GS MEC 030 V2.1.1 (2020-04), (MEC), V2X Information Service API