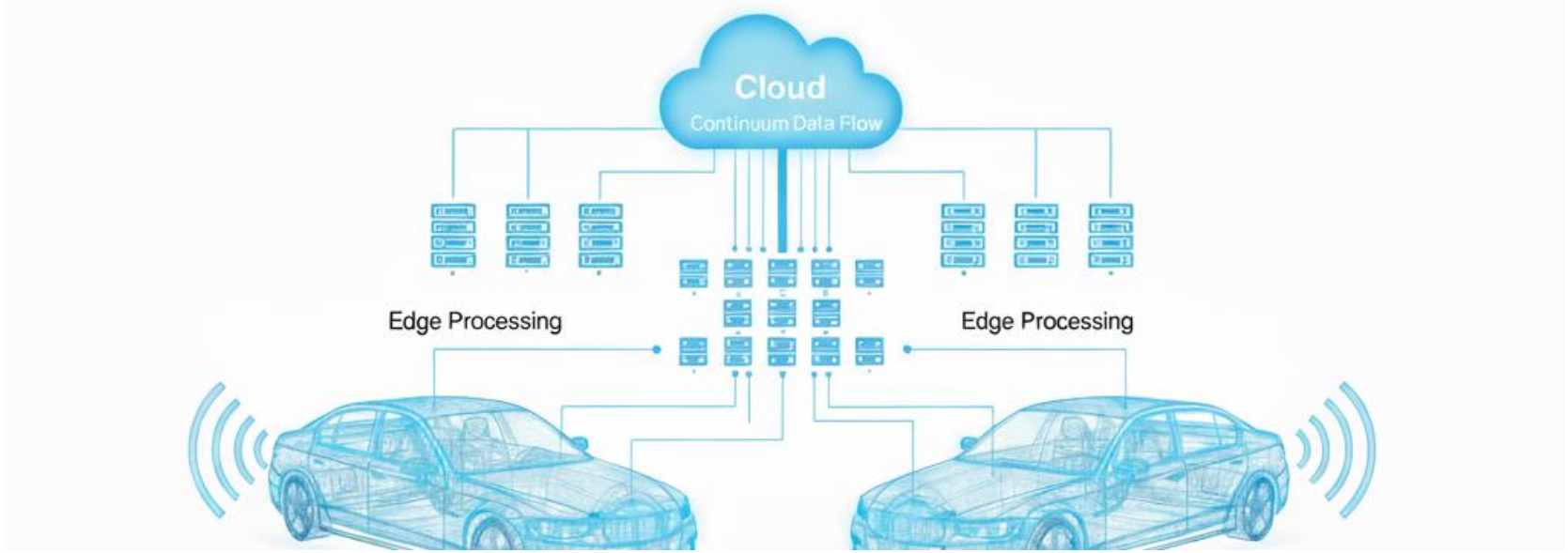

V2X Connectivity and the Continuum: Building the SDV Digital Backbone

Prof. Javier Gozalvez
Universidad Miguel Hernández de Elche, Spain

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Technology Trends in Automotive

- Connected vehicles (CV)
- Autonomous driving (AD)
- Software Defined Vehicle (SDV)

- V2X connectivity: key technological enabler for all

V2X Ecosystem

- Vehicle to Everything (V2X): a multi-modal proposition
  - Direct (or sidelink) and network-based communications
  - C-V2X (LTE-V2X, 5G NR V2X), ITS-G5, cellular, WiFi, satellite
- Direct or sidelink V2X communications: V2V and V2I comms
  - Local communications that do not require network coverage

"I got so fed up with dropped calls and no service, I bought my own cell tower and take it where ever I go."

  - Mostly for safety, cooperative driving and traffic management
  - SDV (e.g. with WiFi): upload driving data (Tesla, Nexar & Spectrum)

V2X Ecosystem

- Vehicle to Everything (V2X): a multi-modal proposition
  - Direct (or sidelink) and network-based communications
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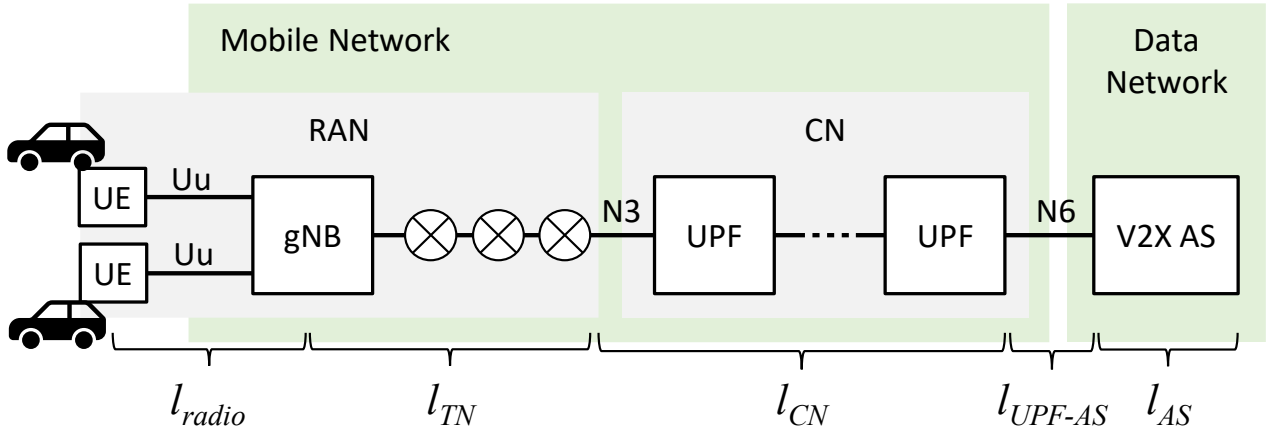
- Direct or sidelink V2X communications: V2V and V2I comms
  - Local communications that do not require network coverage
  - Deployment status:
    - Europe: focused ITS-G5 initial deployment (one group, infrastructure operators), technology neutrality, more focus on 5G NR V2X within C-V2X family
    - Adoption (cautious) of C-V2X in USA and a strong priority for China

V2X Ecosystem

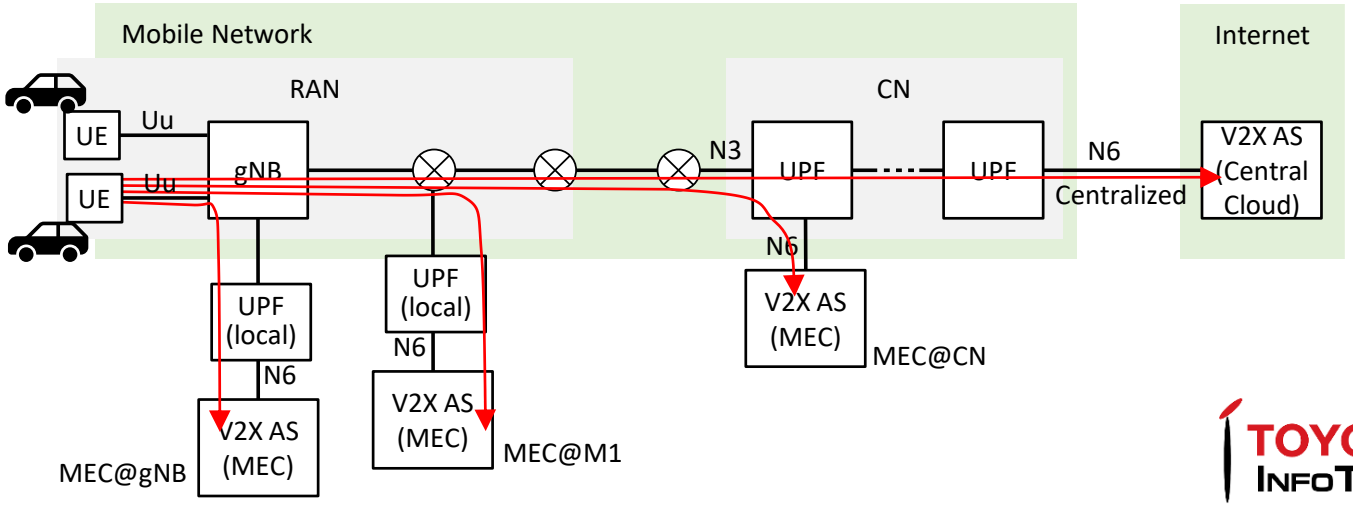
- Networked-based V2X communications
  - Traditionally focused on V2N (network) or V2C (cloud) comms
    - Non-terrestrial networks (NTN) to complement terrestrial cellular networks for ubiquitous automotive connectivity
  - Less time-critical services:
    - Navigation & mapping, telematics, diagnosis, road alerts/events, …
    - SDV: critical for software Over-the-Air (OTA) Updates
  - Growing interest in supporting time-critical & safety services with networked-based comms: V2N2V (Vehicle to Network to Vehicle)
    - Slow roll-out of direct V2X, technology roadmap and incompatibilities, increasing expectations/capabilities of 5G/B5G

V2X Ecosystem

- Networked-based V2X communications
  - 5G network deployments impact 5G End-to-End (E2E) latency



Centralized deployment



Edge-based deployment

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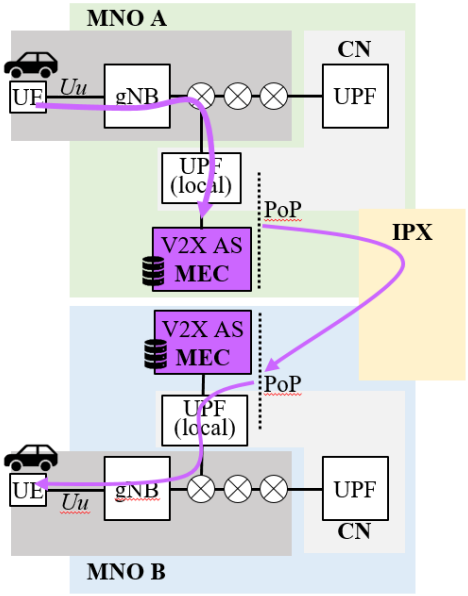
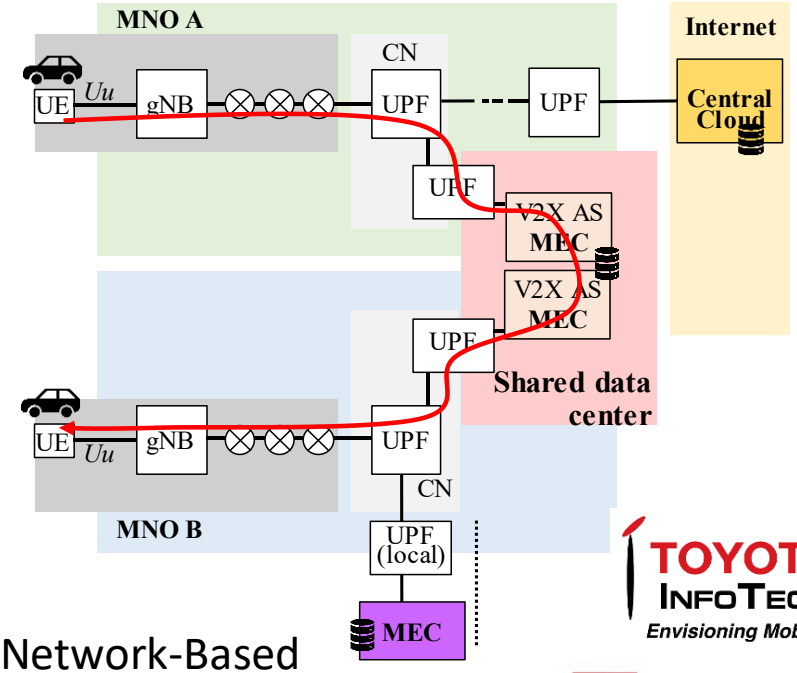
V2X Ecosystem

- Networked-based V2X communications
  - Challenge when vehicles are supported by different MNOs



- Peering points or connections between MNOs add significant latency or cost



- Solution: shared datacenters where MNOs deploy their V2X AS

M.C. Lucas-Estañ, et al., "Direct-V2X Support with 5G Network-Based Communications: Performance, Challenges and Solutions", IEEE Network, 2023

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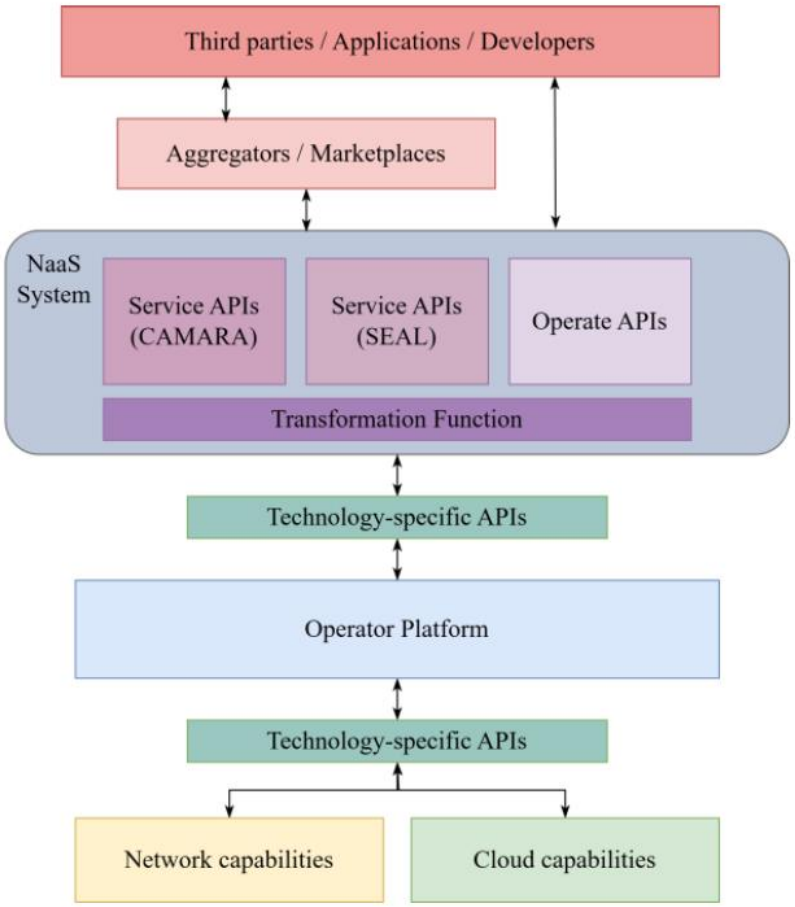
Network-as-a-Service (NaaS)

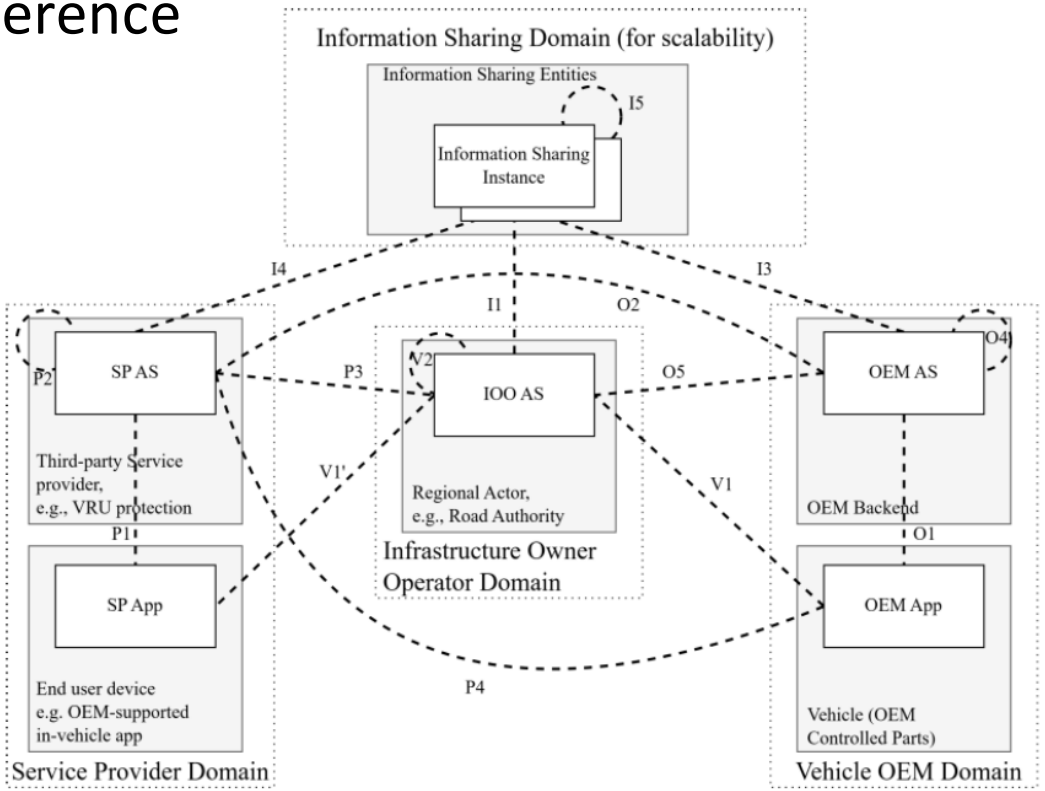
- Telco-driven efforts to better support verticals through standardized and open Network-as-a-Service (NaaS) APIs
  - Abstract underlying infrastructure & expose network capabilities to facilitate integration & deployment of network-based CV services



  - 3GPP's Service Enabler Architecture Layer for Verticals (SEAL): APIs targeted at verticals
  - GSMA Open Gateway Framework & open-source CAMARA: a higher level of abstraction for developers to easily consume network services

Cross-Stakeholder Networked Ecosystem

- A cross-stakeholder networked ecosystem needed to support real-time exchange of data between CVs and all stakeholders
- Centralized CV data sharing approaches
  - National access points (NAP), e.g. DGT3.0 in Spain
- 5GAA V2N2X service-level reference blueprint architecture
  - Federated architecture with Information sharing domain connecting stakeholders
  - Road traffic operation

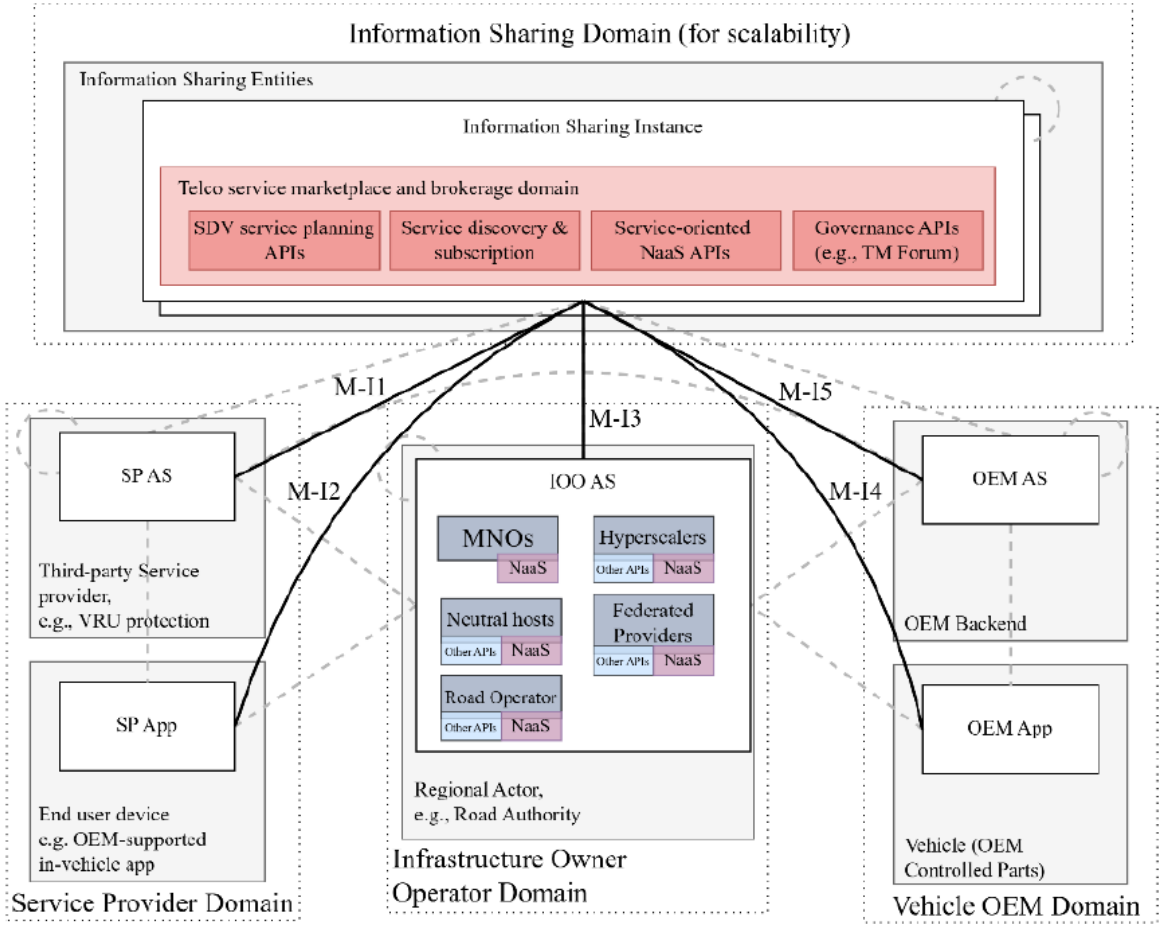


Source: 5GAA

Building an interoperable SDV Ecosystem

- SDV-oriented NaaS-based V2N2X architecture
  - IOO domain extended with MNO and cloud/edge resources
  - Telco service marketplace and brokerage domain with service-oriented NaaS functionalities based on Open Gateway & CAMARA

Information sharing domain: data exchange



Service-oriented NaaS: consumption & adaptation of network & computational resources by SPs and OEMs

Novel Open APIs for SDVs

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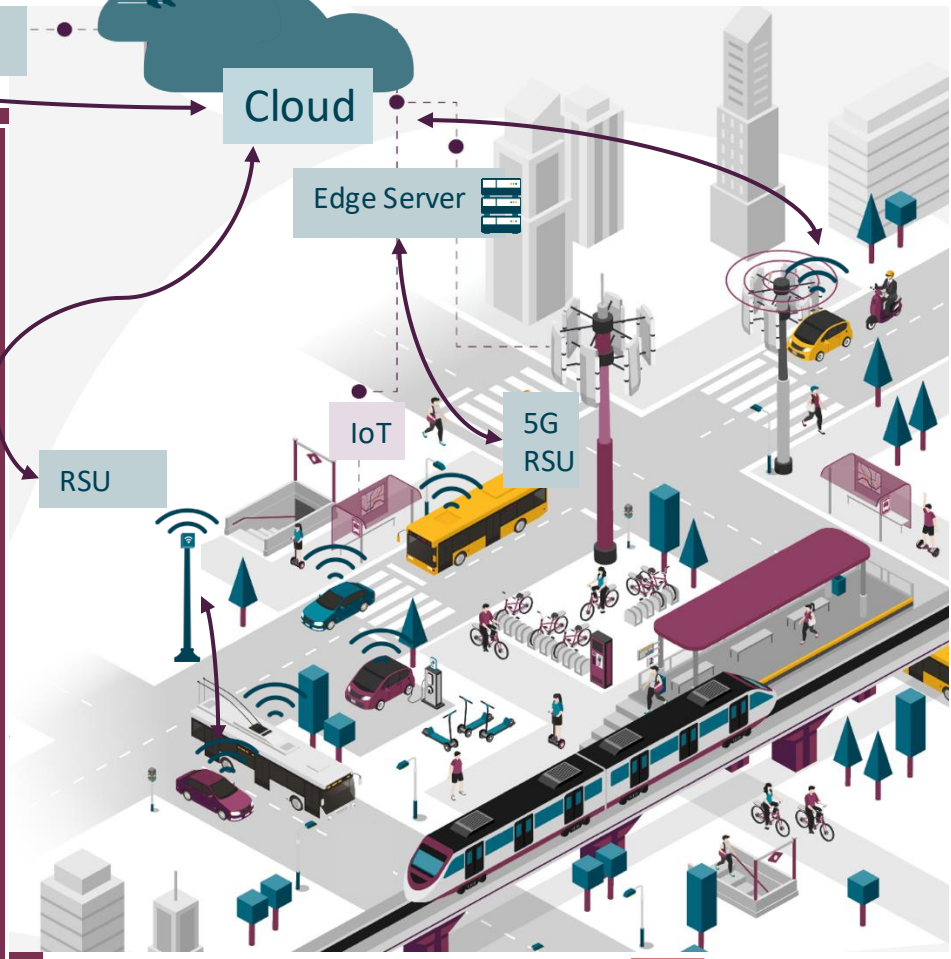
End-to-End Connected Vehicle Continuum



Flexible deployment approach

V2X platform deployed in two configurations

- Cloud
- On-Premise

Modular platform

V2X platform included as:

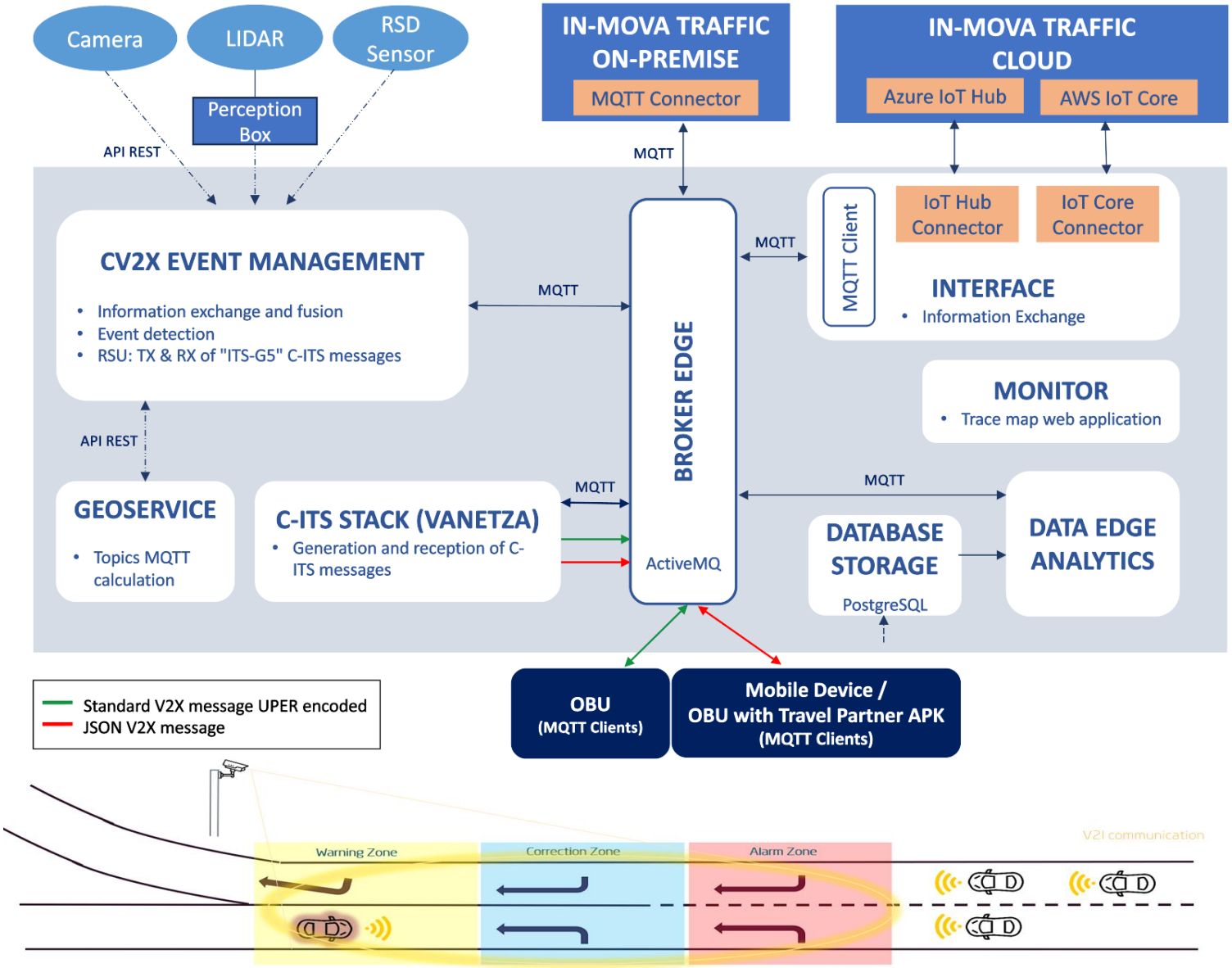
- Module on the ATMS
- Independent system

Road Side Equipm.

Indra integrates different options for V2X equipment on road infrastructure:

- C-V2X RSU: Supported different multi-vendor field equipment
- 5G 'RSU' deploying V2X services on an Edge node

End-to-End Connected Vehicle Continuum



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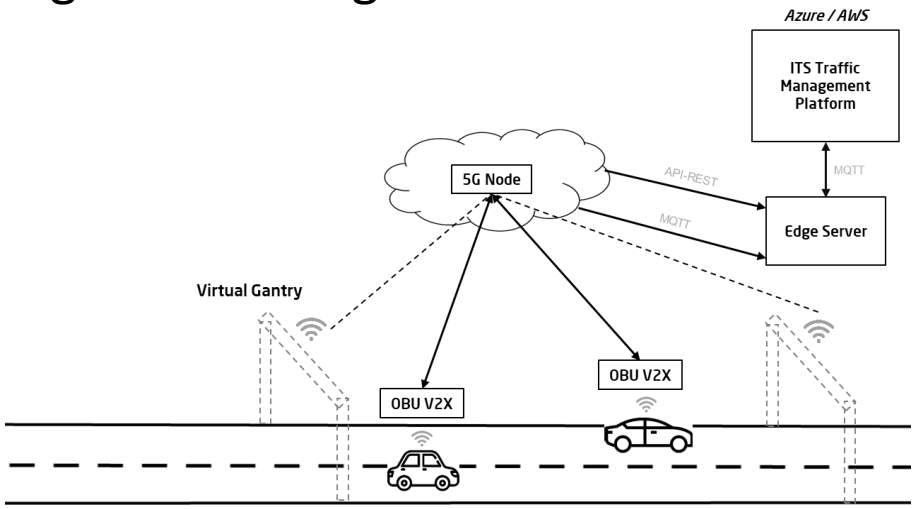
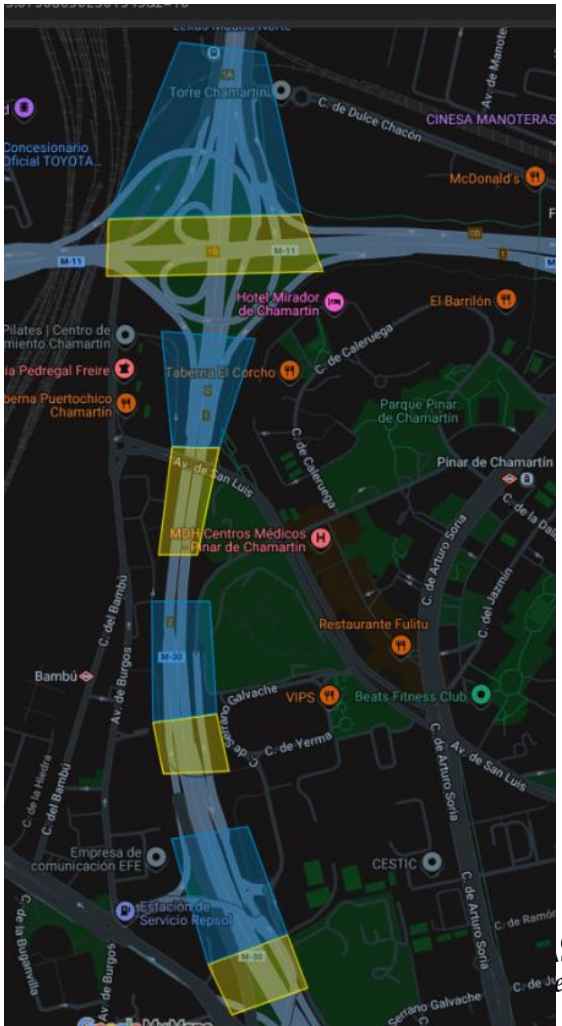
End-to-End Connected Vehicle Continuum

- Multi-service CV platform
  - 5G V2X-based toll collection with adaptive tolling
  - Real-time event notification over 5G
- 5G V2X-based toll collection with adaptive tolling
  - Growing moment in US to deploy tolling services using C-V2X
    - Use same V2X infrastructure for multiple services (safety, traffic, tolling)
    - Indra first in US to deploy it in North Carolina
  - C-V2X toll-based collection following SAE J3217 standard:
    - Physical gantry (RSU) transmits TAM messages to provide toll payment information to incoming CVs
    - CVs transmit TUM messages when exiting the toll zone for charging and RSU acks reception

End-to-End Connected Vehicle Continuum

- 5G V2X-based toll collection with adaptive tolling
  - C-V2X toll-based collection limited by local coverage around gantry
  - UMH and INDRA 1st worldwide to demonstrate dynamic tolling through virtual gantries using 5G continuum

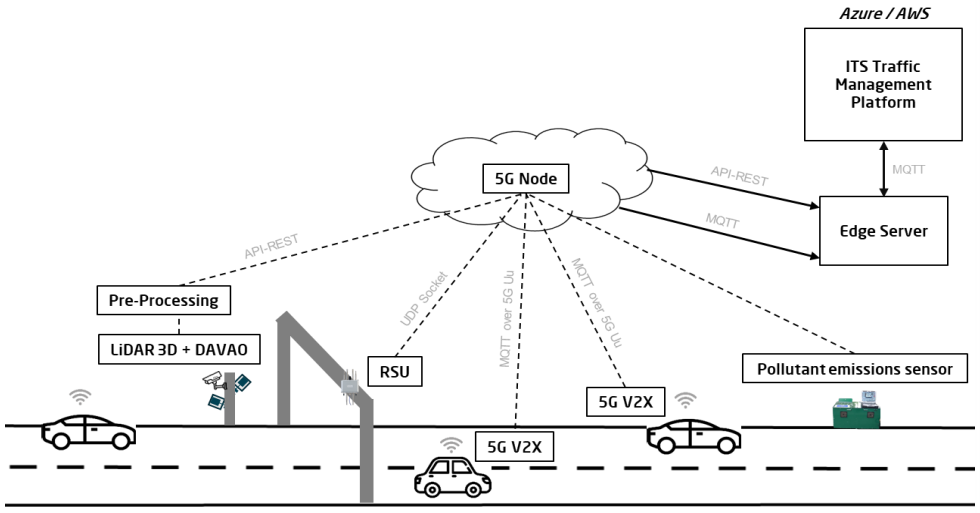


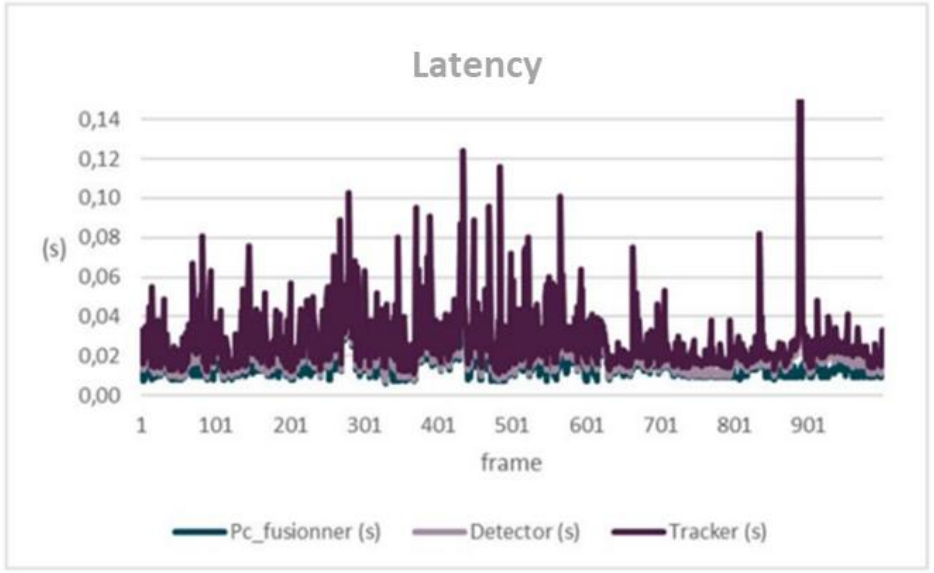


  - Virtual gantries and tolling areas can be dynamically defined anywhere within the 5G coverage (adapting SAE J3217)
  - More flexible and adapted tolling to each CV managed by continuum

End-to-End Connected Vehicle Continuum

- Real-time event notification using DENM messages over 5G
  - Ability to localize events using Quadtrees & Geoservice minimizes unnecessary alerts: focus on informing only relevant users





  - Low-latency communication enabled by edge-based 5G deployments ensures prompt event notifications (latency<110ms)

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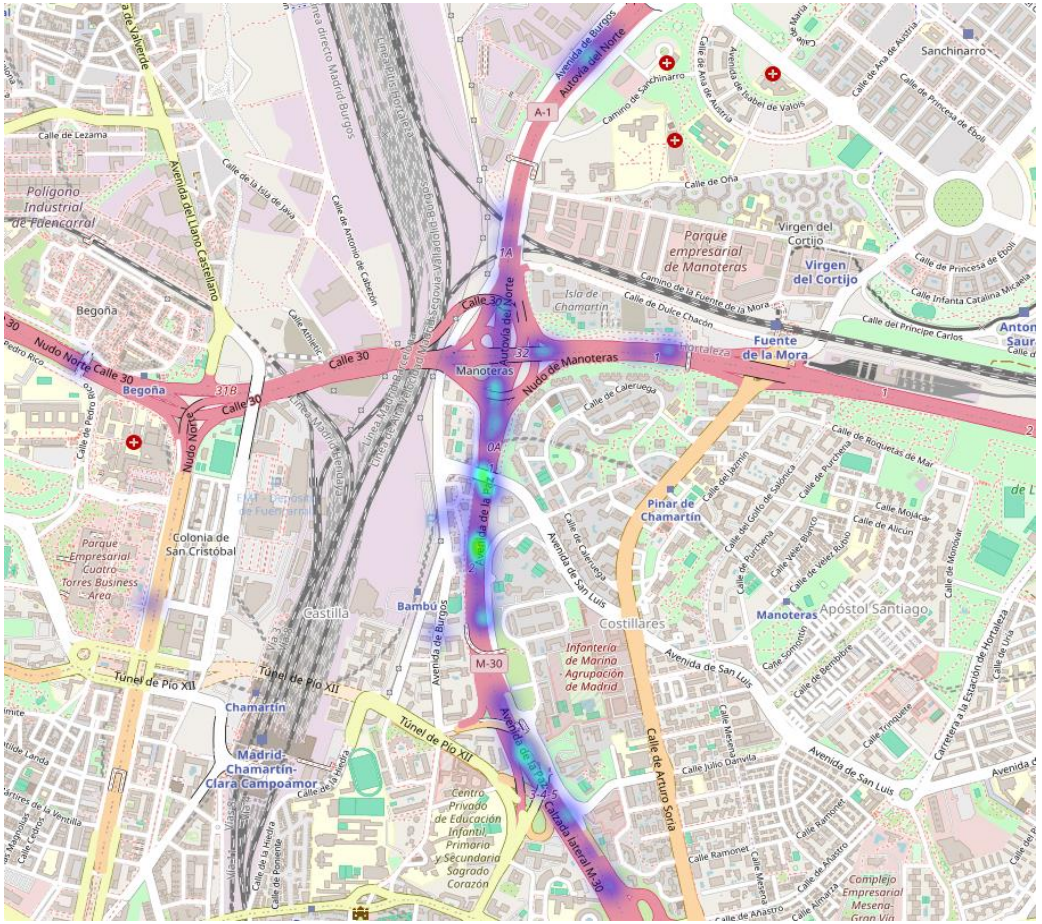
End-to-End Connected Vehicle Continuum

- Real-time event notification using DENM messages over 5G
  - Traffic events can also be generated by vehicles
  - “Traffic jam ahead“ notifications in M30 deployment in Madrid

Vehicles/stationIDs reporting DENM	101
Total number of DENMs (7 days)	3099



- 1 emergency braking & 1 stopped vehicle notification

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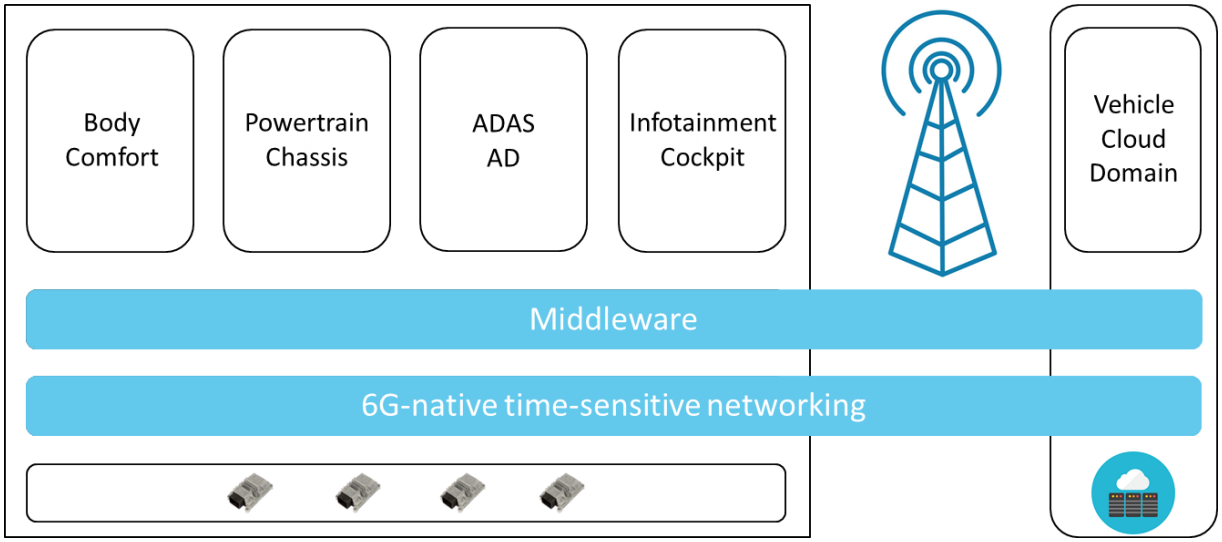
The Continuum: Digital Backbone for SDV

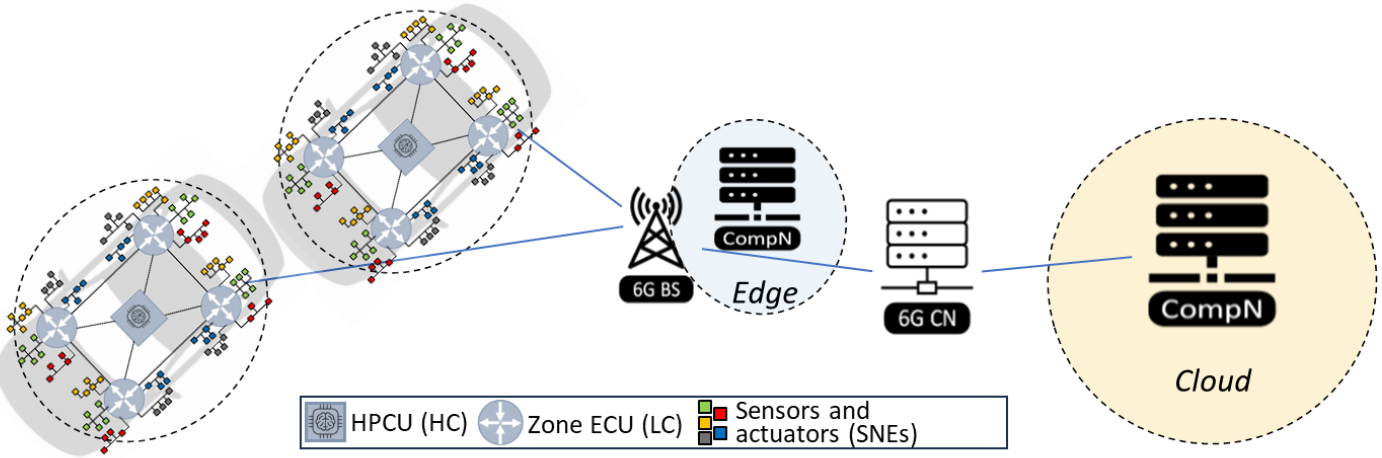
- SDV ecosystem strongly benefits from an edge-cloud continuum:
  - Software OTA updates, remote diagnostics and predictive maintenance, network-supported ADAS, teleoperated driving, Digital Twins



- Seamless connection of physical and digital worlds (CPS continuum)
  - Critical functions: E2E deterministic service levels & high availability
    - Continuous loop: sensing, computing, control and actuation
  - Deterministic continuum: 6G-native time-sensitive networking

The Continuum: Digital Backbone for SDV

- Deterministic task scheduling policies for SDVs In-Vehicle Networks (IVNs) ⇨ Deterministic task offloading policies for 6G continuum



  - Increased capacity to satisfy more tasks, handle higher workloads and better balance workload across the continuum (scalability)

"Deterministic Task Scheduling in In-Vehicle Networks for Software-Defined Vehicles", *IEEE/CIC 2025*
"Deterministic Task Offloading and Resource Allocation in the IoT-Edge-Cloud Continuum", *IEEE VTC2025-Spring*

6G Short range extreme communication IN Entities, https://6gshine.eu/

Co-funded by the European Union

Concluding Remarks

- (Multi-modal) connectivity is critical for CV, AD and SDV
  - It is time for large-scale deployments!
- Continuum: an opportunity & need for verticals (including SDV)
  - Convergence between physical and digital worlds: E2E deterministic service levels
    - Comms, computing, control & reasoning: co-design & planning
    - Capacity to scale beyond controllable environments
  - No continuum industrial champion!

Thank you for your attention!

j.gozalvez@umh.es

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