SUCCESS-6G: VERIFY

WP5 Deliverable E13

Project Title:	SUCCESS-6G: VERIFY
Title of Deliverable:	Initial testing and preliminary validation of service KPIs
Status-Version:	v1.0
Delivery Date:	18/02/2025
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Keywords:	MEC-based workload distribution; caching; traffic-aware optimization

Document revision history

Version	Date	Description of change
v0.1	30/09/24	Table of Contents (ToC)
v0.2	15/10/24	Content added
v0.3	30/11/24	Additional inputs
v0.4	31/01/25	Final inputs and revision
v1.0	18/02/25	Final version uploaded to the website

Disclaimer

Acknowledgment

The research conducted by SUCCESS-6G - TSI-063000-2021-39/40/41 receives funding from the Ministerio de Asuntos Económicos y Transformación Digital and the European Union-NextGenerationEU under the framework of the “Plan de Recuperación, Transformación y Resiliencia” and the “Mecanismo de Recuperación y Resiliencia”.

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Executive Summary

The computational overhead of over-the-air (OTA) software updates presents challenges in optimizing resource utilization and minimizing network congestion. SUCCESS-6G-VERIFY addresses these challenges by leveraging MEC-based workload distribution, AI-driven computation management, and predictive resource allocation. By intelligently offloading processing tasks to edge nodes and optimizing data caching strategies, the system significantly reduces update latency and improves overall network efficiency. Experimental validations highlight improvements in processing time, bandwidth allocation efficiency, and energy consumption, demonstrating that the SUCCESS-6G-VERIFY framework is well-equipped to support scalable and computationally optimized OTA software update mechanisms in connected vehicle ecosystems.

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1 Introduction

The increasing reliance on software-driven functionalities in modern vehicles necessitates a robust and efficient method for delivering over-the-air (OTA) software updates. As connected and autonomous vehicle ecosystems continue to evolve, manufacturers and service providers must ensure that software updates are timely, computationally optimized, and minimally disruptive to vehicular operations. Vehicle-to-Everything (V2X) communication is a key enabler of this transformation, facilitating seamless and reliable OTA updates while incorporating advanced computing mechanisms to enhance performance. However, reducing computational overhead, optimizing data transfer, and ensuring efficient network resource utilization remain critical challenges. SUCCESS-6G-VERIFY aims to address these challenges through the integration of Software-Defined Networking (SDN), Multi-access Edge Computing (MEC), and AI-driven computation management.

A fundamental requirement for efficient OTA software updates is leveraging distributed computing resources to offload processing from centralized cloud systems. Cellular V2X (C-V2X) technology, enabled by 5G and MEC, enhances the computational efficiency of OTA update delivery by optimizing data caching, bandwidth allocation, and real-time processing at edge nodes. The SUCCESS-6G-VERIFY framework integrates AI-driven workload distribution and dynamic resource allocation to manage the computational complexity of large-scale software updates. Additionally, containerized deployment models and microservices-based architectures ensure seamless update provisioning with minimal latency.

Beyond connectivity, computational efficiency is a primary concern for OTA software updates. The high frequency of updates, combined with varying network conditions, necessitates intelligent workload balancing and predictive resource allocation. SUCCESS-6G-VERIFY employs orchestration mechanisms that dynamically adjust computational resources based on real-time vehicular demand and network load. Through federated learning and distributed intelligence, the system reduces processing delays while maintaining service reliability and scalability.

Efficient computation management also plays a key role in reducing network congestion and improving overall vehicular performance. MEC-based resource scheduling minimizes data redundancy and accelerates update deployment by executing processing tasks closer to end-users. SUCCESS-6G-VERIFY integrates intelligent caching strategies and traffic-aware optimization to enhance update success rates while minimizing system downtime. These mechanisms ensure that vehicles receive software updates with optimal efficiency, reducing unnecessary data transfers and computational strain on network infrastructure.

This deliverable presents primary results on the implementation and validation of efficient OTA software updates within a V2X connectivity framework. Experimental evaluations conducted on the ADRENALINE Testbed demonstrate significant improvements in computational efficiency, network utilization, and latency reduction. The integration of SDN, MEC, and AI-driven workload management has resulted in a scalable and adaptive solution capable of addressing the evolving computational demands of connected vehicle ecosystems.

The preliminary findings from this research highlight the potential of SUCCESS-6G-VERIFY in revolutionizing vehicular software update methodologies. By leveraging cutting-edge computing and network optimization techniques, the proposed framework ensures that vehicles remain updated with minimal resource consumption and operational disruptions. As the automotive industry continues to transition towards fully connected and autonomous systems, the implementation of computationally efficient OTA update mechanisms will be instrumental in enhancing vehicle performance, service reliability, and regulatory compliance.

The subsequent sections present the specific methodologies employed, experimental setup, and detailed performance evaluations of the proposed efficient OTA update system, providing a comprehensive analysis of its benefits and potential industry applications.

2 Use case 2: Automated software updates for vehicles

2.1 General description and overall objectives

Over-the-air (OTA) software updates are delivered remotely from a cloud-based server, through a cellular connection, to the connected vehicle with the aim of providing new features and updates to the vehicle's software systems. Such software updates may include changes to any software that controls the vehicle's physical parts or electronic signal processing system. In practice, the updates often tend to apply more to user interfaces like infotainment screens and navigation (i.e., vehicle maps). The update procedure, when performed over-the-air, enables a vehicle's performance and features to be continuously up-to-date and improved. The integration of advanced data analytics, automated and remote service delivery eliminates the need for visiting repair/service centres, while technological advancements in these updates give vehicle manufacturers the freedom to constantly "freshen up" finished products remotely. C-V2X technology plays a crucial role in the update process, enabling efficient, scalable and seamless wireless communication between vehicles and software management platforms. Figure 1 illustrates the implementation phases for this use case.

Figure 1: Implementation phases for the automated software updates

The overall **objectives** of this use case can be summarized as follows:

- Safer and more entertaining driving experience.
- Hardware and software components maintained and updated regularly during a vehicle's lifespan, implying a slower rate of depreciation.
- Prevention of cyberattacks targeting outdated software.
- Compliance to new rules and standards.
- Lower repair costs and elimination of labour charges.
- Lower warranty costs for manufacturers and lower downtime for customers

The key **stakeholders** involved in the use case are:

- The ***Mobile Network Operator (MNO)***, providing wireless connectivity between the vehicle, the edge computing infrastructure, and the vehicular software management system. The MNO is interested in optimizing the network operation by enhancing its energy efficiency and coverage, while offering novel services to accommodate more users.
- The ***edge infrastructure provider***, offering and managing computational resources at the edge and supporting real-time services as well as virtualized network functions and AI-empowered algorithms for advanced computational tasks.
- The ***equipment provider,*** providing in-vehicle embedded devices, e.g., hardware components and sensor devices, that can be remotely reconfigured and updated.
- The ***vehicular software management system,*** operated by the equipment provider or vehicle manufacturer, is responsible for issuing periodically new software updates.
- The ***software developers***, devising and applying data-processing modules for automated update of vehicular components' software.

- The ***cloud providers*** can optionally be involved, offering additional computational resources to host the service.

Note that, without loss of generality, some stakeholders may assume multiple roles or, equally, some roles may be assumed by multiple stakeholders. For instance, the MNO could also be the owner of the edge infrastructure, or an equipment provider may also be responsible for the operation of the vehicular software management system or outsource it to a third party.

2.2 User story 2.3: Over-the-air vehicular software updates with efficient computation

Over-the-air software updates would substantially benefit from the realization of computationally efficient mechanisms to dramatically reduce data processing times. By leveraging edge-processing capabilities in conjunction with distributed learning techniques, the associated computational overhead is expected to be relieved. Additionally, zero-touch orchestration of container-based solutions will ensure the automatic reconfiguration of vehicular on-board units with an efficient usage of computational resources, while adapting to V2X network topology changes. This would require agile management of the edge-cloud continuum to guarantee seamless service delivery.

2.3 Overall UC2 architecture and network deployments

The elaboration of Figure 2 details a system architecture specifically designed for OTA software updates, integral to the SUCCESS-6G-VERIFY framework. This architecture addresses the complex requirements of the use case 2. In particular, Figure 2 Proposed overall UC2 system architectureprovides a high-level system architecture for OTA vehicular software updates within a robust V2X connectivity framework, leveraging ETSI TeraFlowSDN for network automation and control. The figure illustrates the key components enabling software update dissemination to connected vehicles via 5G mobile edge computing (MEC) nodes. At the core of this system is the ETSI TeraFlowSDN Controller, which manages the network infrastructure, including the gNBs (5G base stations) and Transport Network. The NFV Orchestrator (NFV-O) enables dynamic deployment and scaling of virtualized network functions, such as Distributed User Plane Functions (D-UPF) within MEC nodes.

Each edge node (Edge Node 1 & Edge Node 2) hosts a Software Update Server, responsible for caching and distributing updates to C-V2X On-Board Units (OBU) in connected vehicles. These updates are delivered via the 5G network, passing through the transport network, controlled by the TeraFlowSDN controller. To ensure security and integrity, the system integrates a Security-as-a-Service module, providing firewall protection and secure communications for software updates. The updates originate from local cloud infrastructure, which includes 5G Core Control Plane components such as SMF (Session Management Function), AMF (Access and Mobility Management Function), and UPF (User Plane Function). The software update client within the vehicle's C-V2X OBU interacts with the Software Update Servers over the network, ensuring efficient and timely delivery of critical updates for vehicle applications.

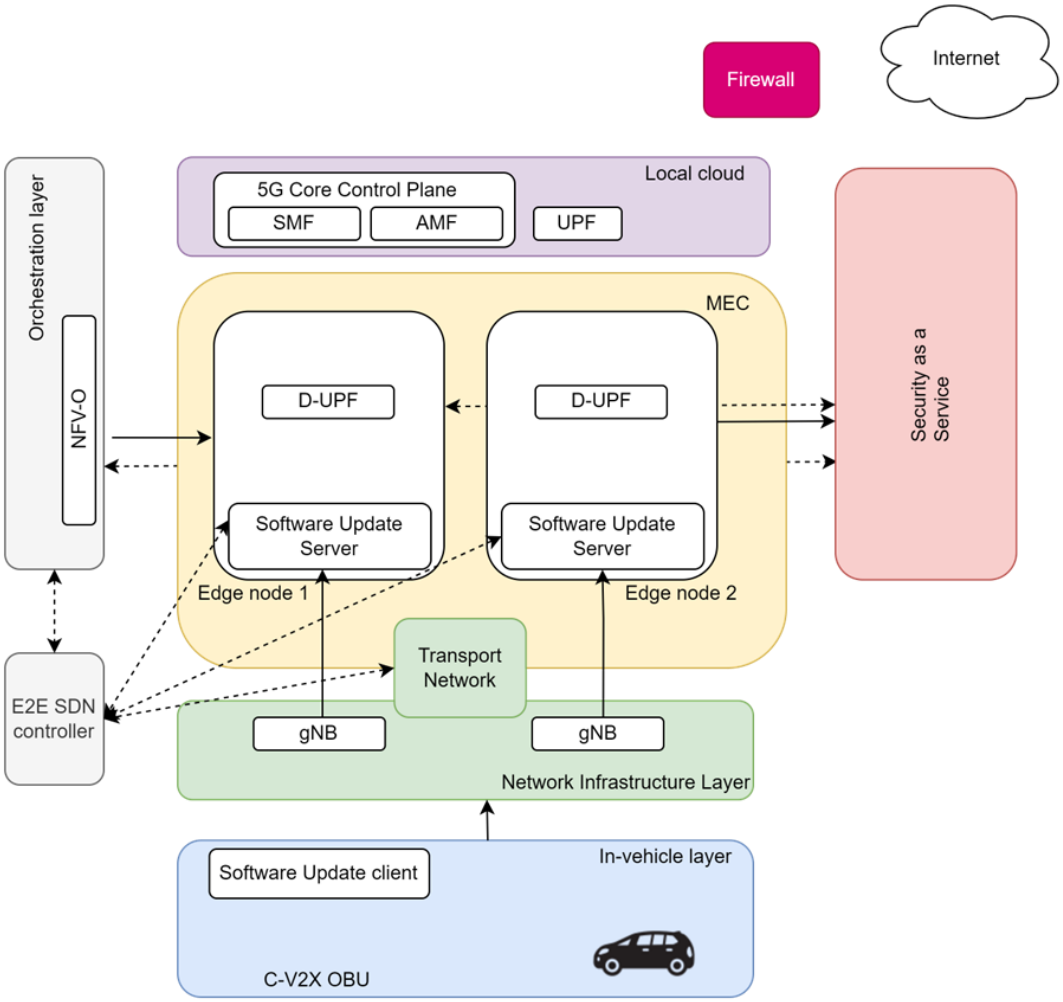


Figure 2 Proposed overall UC2 system architecture

This architecture highlights the interplay between 5G, MEC, SDN, and V2X technologies to facilitate secure and efficient OTA software updates, enabling reliable vehicle connectivity and automation.

2.4 Facilities for use case 2

2.4.1 ADRENALINE Testbed

The ADRENALINE testbed® is an open and disaggregated SDN/NFV-enabled packet/optical transport network and edge/core cloud infrastructure for 6G, IoT/V2X, and AI/ML services, constantly evolving since its creation in 2002, and reproducing operators' networks from an End to End (E2E) perspective and Data Centre Interconnect (DCI). The figure below summarizes the networking scenario of the ADRENALINE testbed, to be used for the execution of SUCCESS-6G-VERIFY.

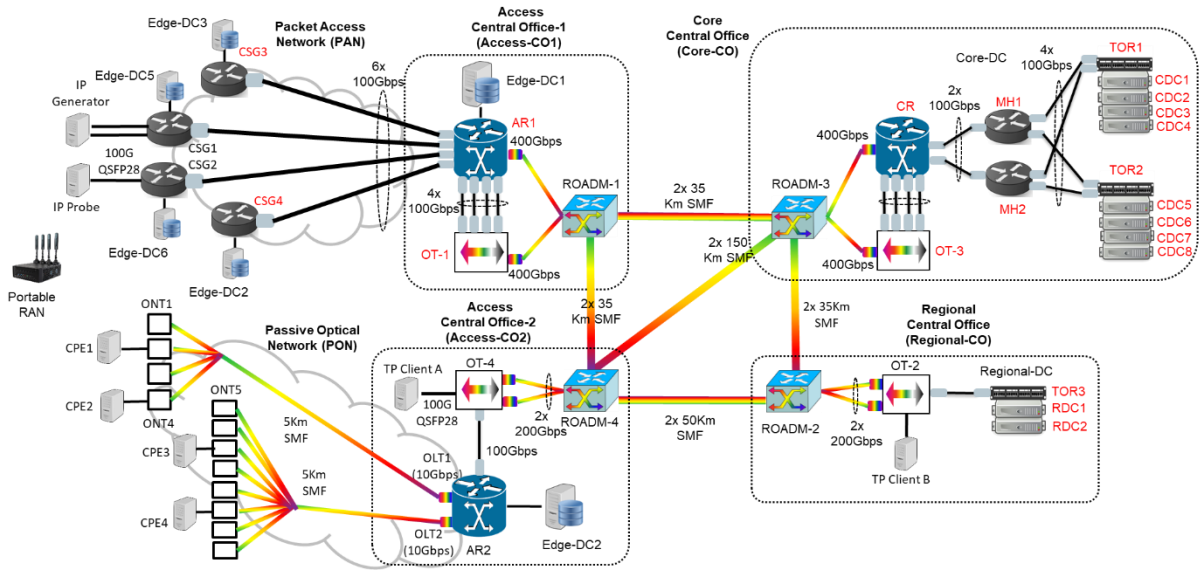


Figure 3 ADRENALINE Testbed to be used for Use Case 2

ADRENALINE spans the access, aggregation-metro, and core segments, and includes distributed Data Centres (DCs) geographically dispersed and located at the edge or in central locations. As depicted in Figure 3, the key elements are: (1) an SDN-controlled optical network (flexi-grid DWDM photonic mesh), with 4 ROADM nodes and over 600km of amplified DWDM links. Currently, all the links of the mesh are based on amplified C-band transmission, but one of them also supports amplified flexible L-band transmission; (2) packet-optical nodes with optical pluggable transceivers, providing aggregated 400G data rates (muxponders) for transporting traffic flows between the access networks and the core central offices or data centers; (3) programmable SDN-enabled S-BVTs able to transmit multiple flows at variable data rate/reach up to 1 Tb/s; (4) a Packet Access Network (PAN) connected to the metro infrastructure with IP Cell Site Gateways (CSGs); (5) a PON tree formed by disaggregated Optical Network Terminals (ONTs), offering connectivity to several Customer Premises Equipment (CPEs). ADRENALINE also includes a Portable 5G RAN platform for testing and validation of 5G and beyond use cases.

The different access networks (i.e., PON) and the photonic mesh are managed by dedicated orchestrators and controllers (e.g., CTTC FlexOpt Optical Controller) to automatically handle the connectivity services entailing the de-/allocation of heterogeneous network resources (i.e., packet and optical devices).

The *domain-specific* controllers and orchestrators are coordinated hierarchically by the ETSI TeraFlowSDN controller, which exposes a North Bound Interface to allow interaction of resources to request network connectivity services. This service platform orchestrates the transport (optical/packet) and computing:

i) Multi-VIM (virtualized infrastructure managers) combining OpenStack and K8s controllers for virtual machines and containers;

ii) TeraFlowSDN controller for E2E connectivity among virtual machines, containers, and endpoints. The service platform is also in charge of managing the life-cycle of network services and network slices: i) a network service is composed of chained NFs; ii) a network slice is composed of one or several concatenated network services that deploy a set of NFs.

2.4.2 Nextcloud platform

NextCloud is an open-source private cloud platform based on a dedicated server with extensive resources, orchestrated by a Debian-based distribution called Proxmox to manage virtualization

environments, offering a simple web interface to manage both virtual machines (VMs) and containers. These machines can be of various types, but we ideally use two of them:

- KVM (Kernel-based Virtual Machine): It is used for full virtualization, allowing to run complete operating systems as VMs.
- LXC (Linux Containers): It also supports LXC containers, which are lighter and more efficient environments to run applications or services.

These virtual machines can be scaled on demand, whether in storage, memory, or network resources. NextCloud bundles core technologies such as PHP, JavaScript, HTML, CSS, MySQL, SQLite, Redis and Nginx, and provides full control over the data and privacy, offering self-host option to deploy custom applications. The following capabilities ensure that NextCloud is ideal for delivering SUCCESS-6G-VERIFY catalogue services such as vehicle data storage and Firmware Over-The-Air (FOTA). NextCloud will be fully customized to fit the needs of the project.

3 Over-the-air vehicular software updates with efficient computation: Implementation at the ADRENALINE testbed

3.1 MEC Bandwidth Management

In the field of vehicular technology, the integration of Multi-Access Edge Computing (MEC) with advanced network control and management, such as TeraFlowSDN (TFS), presents a formidable solution for OTA software updates. MEC offers ultra-low latency and high bandwidth, along with real-time access to data and radio network information, which are crucial in swiftly and efficiently managing OTA updates.

The MEC BandWidth Management (BWM) service plays a pivotal role in allocating and adjusting bandwidth resources, including bandwidth size and priority, specifically tailored for MEC applications. This feature enables MEC applications to specify bandwidth requirements, essential for the smooth transmission of OTA updates.

This demonstration examines the synergistic relationship between the BWM service and TeraFlowSDN (TFS) in optimizing resource allocation for OTA software updates in vehicular networks. The BWM service empowers applications to designate specific bandwidth allocations and other quality of service constraints, such as latency, crucial for the timely and effective delivery of OTA updates. Concurrently, TFS provides sophisticated orchestration of traffic flow management and control, ensuring that OTA update traffic is given priority.

Exploring the benefits of MEC BWM and TFS within the context of OTA updates reveals several advantages. Improved update efficiency, reduced network congestion, and enhanced scalability are prominent among these. The prioritization of OTA update traffic, facilitated by BWM and TFS, is instrumental in reducing latency, thereby streamlining the update process. Allocating dedicated bandwidth to OTA updates also alleviates network congestion, ensuring a more efficient update process for all connected vehicles.

Moreover, the scalability offered by MEC BWM and TFS is critical in adapting to the rapidly evolving field of vehicular technology and the increasing volume of OTA updates. As vehicles become more connected and reliant on software, the need for robust solutions that can adapt to growing demands becomes paramount.

In summary, the integration of MEC BWM and TFS emerges as a significant enabler for network operators aiming to deliver seamless and efficient OTA software updates to vehicles. This demonstration unveils the dynamics and potential of this integration, highlighting its capacity to transform the landscape of vehicular network management.

3.2 Requirements and KPIs

As the automotive industry progresses toward increasingly connected and software-driven vehicles, robust mechanisms for efficient bandwidth management and traffic orchestration become paramount. OTA updates must be delivered swiftly, reliably, and securely to ensure that vehicles remain functional and protected against emerging threats. This section establishes a series of requirements designed to optimize bandwidth usage, integrate advanced networking technologies, and ensure the scalability needed to accommodate growing demands. From leveraging Multi-Access Edge Computing (MEC) for ultra-low latency to integrating TeraFlowSDN (TFS) for intelligent traffic control, each requirement addresses a critical facet of managing and distributing OTA updates effectively. By fulfilling these requirements, automotive networks can maintain high performance even under increased load, ensuring seamless, real-time updates for a rapidly expanding fleet of connected vehicles.

3.2.1 Requirements

3.2.1.1 MEC Bandwidth Management

The system should integrate MEC for efficient bandwidth management. This involves allocating and adjusting bandwidth resources dynamically to ensure that OTA software updates are transmitted smoothly and efficiently. MEC provides ultra-low latency and high-bandwidth access to vehicles, optimizing resource utilization in vehicular networks.

The rationale for MEC Bandwidth Management is to ensure seamless and timely software updates in connected vehicles. As vehicles increasingly rely on software for performance and security features, the ability to provide updates efficiently with minimal network congestion becomes critical. MEC reduces latency and enhances update reliability by processing data closer to end-users, reducing the load on centralized data centers.

3.2.1.2 TeraFlowSDN (TFS) Integration

The system should leverage TFS to orchestrate traffic flow and prioritize OTA updates. TFS enables dynamic resource allocation and traffic engineering, ensuring that software updates receive preferential treatment within the network while maintaining overall network stability.

The rationale for integrating TFS is to provide a sophisticated network control and management layer that optimizes network performance. By prioritizing OTA traffic and dynamically adjusting bandwidth allocations, TFS prevents network congestion and guarantees high-speed, reliable software distribution to connected vehicles.

3.2.1.3 Bandwidth Reservation for OTA Updates

The system must enable OTA update applications to request specific bandwidth allocations and quality of service constraints. This ensures that update transmissions are not interrupted due to competing network traffic, particularly in high-load scenarios.

The rationale for bandwidth reservation is to ensure the availability of dedicated network resources for critical OTA updates. Without bandwidth allocation, software updates might experience delays, affecting vehicle security and performance. By implementing reservation mechanisms, the system enhances reliability and predictability of updates.

3.2.1.4 Scalability of OTA Update Distribution

The system must support the growing number of connected vehicles by dynamically adapting to increasing demands. This includes optimizing network and computational resources at MEC nodes to handle simultaneous OTA update requests efficiently.

The rationale for scalability is to accommodate the rapid expansion of vehicular networks. As more vehicles require frequent software updates, network operators must ensure that OTA systems can scale to meet the rising demand while maintaining service quality and minimizing latency.

3.2.1.5 Network Congestion Control

The system should implement congestion management mechanisms to prevent excessive network load, which could disrupt update delivery. MEC and TFS should dynamically adjust traffic flow to prevent bottlenecks.

The rationale for congestion control is to maintain overall network stability. Without proper traffic engineering, excessive OTA update traffic can degrade network performance for other critical applications. Intelligent congestion management ensures that all services operate efficiently.

3.2.2 Key Performance Indicators (KPIs)

3.2.2.1 Bandwidth Allocation Efficiency (%)

This KPI measures the efficiency of bandwidth usage in delivering OTA updates, ensuring optimal resource utilization within MEC networks.

Efficient bandwidth allocation ensures that network resources are optimally utilized while preventing excessive congestion. Higher efficiency translates to smoother OTA updates and better network performance.

Target Value: The system should maintain at least 90% bandwidth allocation efficiency for OTA updates.

3.2.2.2 End-to-End Update Latency (ms)

This KPI measures the total time taken for an OTA update to reach its destination from the MEC server to the vehicle.

Minimizing latency is crucial to ensuring timely updates, particularly for security patches. Delayed updates can leave vehicles vulnerable to cybersecurity threats or outdated functionalities.

Target Value: The system should deliver OTA updates within 300 ms in optimal network conditions.

3.2.2.3 Network Congestion Avoidance Rate (%)

This KPI evaluates the effectiveness of congestion control mechanisms in preventing excessive traffic buildup during OTA update distribution.

Avoiding network congestion ensures that critical vehicular communication is not disrupted. A higher avoidance rate indicates an efficient traffic management system that prioritizes essential updates while maintaining network stability.

Target Value: The system should achieve at least a 95% congestion avoidance rate.

3.2.2.4 Update Success Rate (%)

This KPI measures the percentage of successfully delivered and installed OTA updates without failures or retransmissions.

A high success rate ensures that vehicles receive updates without disruptions. Failures in OTA updates can compromise vehicle performance and require costly manual interventions.

Target Value: The system should maintain an OTA update success rate of at least 99%.

3.3 UC2 Architecture and network deployment

Figure 4 illustrates a multi-layered architecture for enabling secure and efficient software updates in a 5G-enabled Connected Vehicle-to-Everything (C-V2X) environment. The system integrates Multi-access Edge Computing (MEC), Software-Defined Networking (SDN), and Network Function Virtualization (NFV) to optimize software updates and network resource management. Various components interact across different network layers to facilitate low-latency, secure, and efficient software updates for in-vehicle systems.

The E2E SDN Controller, located in the orchestration layer, is responsible for managing the end-to-end transport network and traffic routing. This component ensures dynamic and programmable network management, allowing efficient routing of software updates from Software Update Servers to the in-vehicle system. Through SDN principles, this controller provides centralized visibility and control, optimizing network paths and prioritizing update traffic based on real-time network conditions and Quality of Service (QoS) policies. By interacting with the NFV Orchestrator (NFV-O), it ensures network resources are allocated dynamically, improving network efficiency and scalability.

Two Software Update Servers, represented in dark blue, are deployed at edge nodes within the MEC infrastructure. These servers play a critical role in reducing software update latency by caching and distributing updates closer to vehicles, rather than relying on centralized cloud servers. The use of Distributed User Plane Functions (D-UPFs) in each edge node enables localized data processing, minimizing backhaul traffic to the 5G Core Network. These servers handle OTA software updates for vehicles, ensuring real-time updates for safety-critical systems such as autonomous driving algorithms, infotainment software, and cybersecurity patches. The interaction between D-UPFs and Software Update Servers optimizes traffic flow, ensuring fast and secure update delivery without overloading the core network.

The Transport Network, centrally placed in the figure and highlighted in dark blue, serves as the data transmission backbone for distributing software updates. It connects the edge nodes, 5G base stations (gNBs), and in-vehicle systems, ensuring seamless data transfer. The E2E SDN Controller dynamically manages this network, optimizing bandwidth allocation and ensuring updates are delivered efficiently. This transport layer is crucial for maintaining low-latency connectivity between software update servers and C-V2X onboard units (OBUs). The Software Update Client, highlighted in dark blue, resides in the In-Vehicle Layer and represents the onboard unit (OBU) in the connected vehicle. This client is responsible for receiving, validating, and installing software updates sent through the transport network from the Software Update Servers. The client ensures updates are properly authenticated and installed without disrupting the vehicle's real-time operations. By leveraging secure communication protocols and MEC-based caching, the update process is optimized to be fast, reliable, and resilient to network disruptions.

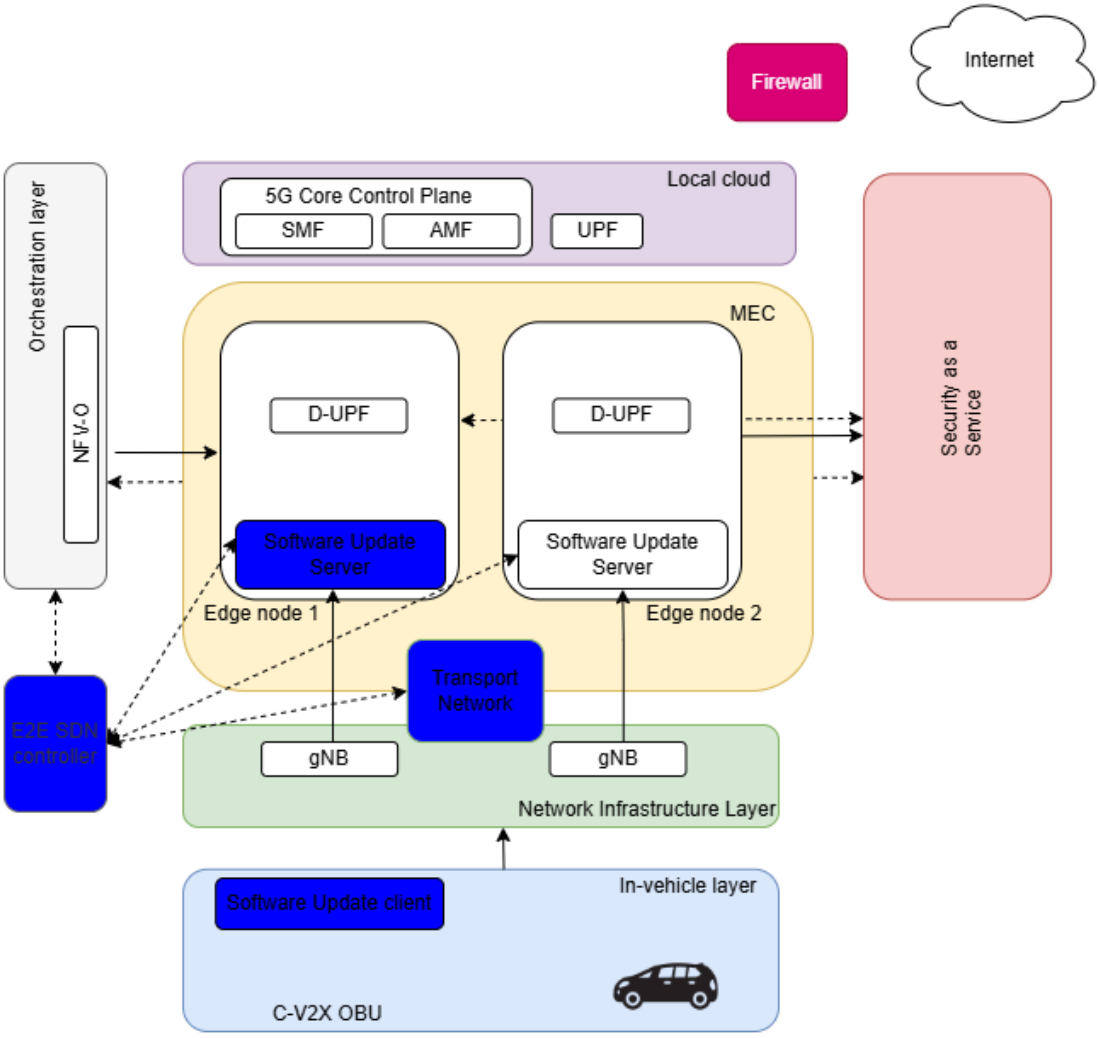


Figure 4 Instantiation of SUCCESS-6G-VERIFY architecture for OTA vehicular software updates with efficient computation

3.4 Exposed interfaces

The ETSI GS MEC 015 Bandwidth Management API[2] is a standardized API specification designed for Multi-access Edge Computing (MEC) environments. It defines a structured mechanism for managing bandwidth allocations, ensuring efficient data traffic handling across MEC applications. The API is built using OpenAPI 3.1.0, providing a well-documented, machine-readable format for service interoperability. The latest version of the API is 2.2.1, and it follows the BSD-3-Clause license, making it accessible for open-source and commercial implementations.

The API supports interactions over the server endpoint https://localhost/bwm/v1, allowing applications to allocate, retrieve, update, and remove bandwidth resources dynamically. It provides a RESTful interface for MEC applications to request bandwidth for specific sessions or application instances, ensuring optimized network resource utilization. The API documentation is complemented by ETSI GS MEC 015 V2.2.1 Traffic Management APIs, which provide additional details on its operational framework.

The API exposes two key resource endpoints for bandwidth allocation management:

- /bw_allocations (Collection Resource)
    - GET: Retrieves a list of bandwidth allocation resources, allowing applications to fetch configured bandwidth reservations.
    - POST: Creates a new bandwidth allocation resource, enabling MEC applications to request dedicated bandwidth.
- /bw_allocations/{allocationId} (Instance Resource)
    - GET: Fetches details of a specific bandwidth allocation instance.
    - PUT: Updates the entire resource, replacing the previous configuration.
    - PATCH: Partially modifies an existing allocation by applying deltas (incremental updates).
    - DELETE: Removes an existing bandwidth allocation, unregistering it from the MEC system.

Each request method follows the RESTful principles, ensuring standardized request-response interactions with HTTP status codes for error handling and success confirmation.

The core data model revolves around the BwInfo schema, which defines how bandwidth allocation requests and responses are structured. The schema includes fields such as:

- allocationId: Unique identifier for the bandwidth allocation instance.
- appName: Name of the application making the request.
- allocationDirection: Defines whether the bandwidth is downlink, uplink, or symmetrical.
- appInsId: Identifies the specific application instance requesting bandwidth.
- fixedAllocation: Specifies the bandwidth allocation in bits per second (bps).
- fixedBWPriority: Sets allocation priority when multiple applications or sessions compete for bandwidth.
- requestType: Distinguishes between application-specific and session-specific bandwidth allocations.

Additionally, the API provides filtering options through query parameters like:

- app_instance_id: Filters allocations for a specific application instance.
- app_name: Retrieves allocations based on application name.
- session_id: Fetches allocations related to a given session.

[2] https://forge.etsi.org/rep/mec/gs015-bandwith-mgmt-api/-/raw/master/BwManagementApi.yaml?ref_type=heads

For updates via PATCH, the BwInfoDeltas schema is used, containing only the fields that need modification, ensuring minimal impact on existing configurations.

3.5 Workflow

Figure 5 offers a sophisticated and scholarly representation of the orchestrated network operations within an End-to-End (E2E) Software-Defined Network (SDN) environment. This diagram serves not merely as a visual aid but as an academic illustration of the intricate interplay among various controllers, infrastructure components, and end-user interactions. The processes depicted in this figure are emblematic of the advanced capabilities and integrations within modern network architectures.

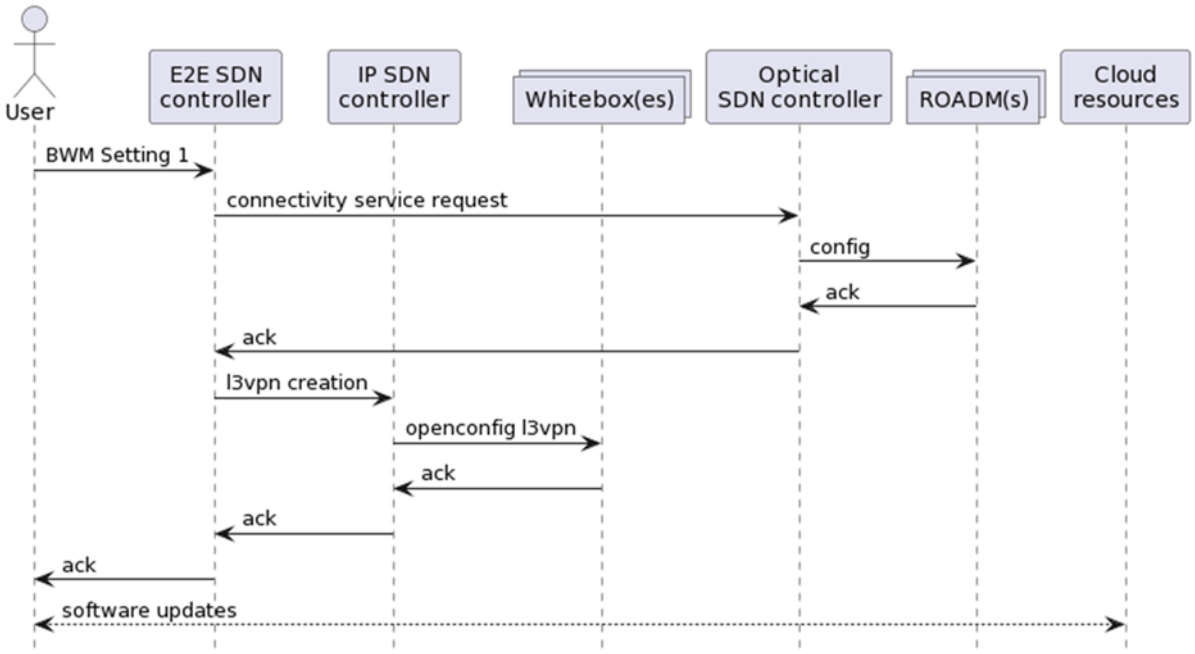


Figure 5 Sequence diagram for OTA vehicular software updates with efficient computation

The diagram's narrative commences with the user, denoted as "edge1", initiating a bandwidth setting, referred to as BWM Setting 1. This action triggers a critical communication sequence with the E2E SDN controller, a pivotal entity within the network framework. The E2E SDN controller, embodying advanced computational capabilities, processes this request, engaging in a nuanced dialogue with the Optical SDN controller. This interaction is vital for the fulfillment of a connectivity service request, an operation that is foundational to network performance and efficiency.

The request encompasses the configuration of pivotal optical network infrastructure components, namely Whiteboxes and Reconfigurable Optical Add-Drop Multiplexers (ROADMs). These components play an instrumental role in the optical networking realm, facilitating efficient data transmission and network flexibility. The sequence diagram meticulously illustrates the exchange of acknowledgments between the Optical SDN controller and the ROADMs, a process that guarantees the successful configuration and establishment of connectivity. Subsequently, the Optical SDN controller communicates the acknowledgment back to the E2E SDN controller, completing this segment of the orchestration.

In parallel, a sophisticated integration process unfolds involving the E2E SDN controller and the IP SDN controller. The E2E SDN controller, in this context, initiates the creation of a Layer 3 Virtual Private Network (L3VPN). This is achieved through a communicative interface with the IP SDN controller. The IP SDN controller, operating under the OpenConfig standard, interacts with Whiteboxes to configure

the L3VPN. This interaction highlights the seamless integration of different network layers and the versatility of the controllers in managing diverse network functions.

The diagram further delineates the exchange of acknowledgments between the Whiteboxes and the IP SDN controller, an essential step in confirming the successful execution of the L3VPN creation. This successful interaction is communicated back to the E2E SDN controller, which, in an emblematic demonstration of the integrated network architecture, acknowledges the User's initial request.

The concluding segment of the sequence diagram emphasizes the dynamic interaction between the User and Cloud resources. This interaction is particularly significant in the context of software maintenance and updates. The User engages in a bidirectional dialogue with the Cloud, reflecting the ongoing need for software updates and the dynamic nature of cloud-based resource management. This interaction underscores the importance of cloud resources in contemporary network environments, particularly in the realm of software deployment and updates.

3.6 Preliminary experimental validation of the functionalities

The integration of the ETSI GS MEC 015 Bandwidth Management API and ETSI TeraFlowSDN (TFS) Controller presents a promising approach to enhancing network resource allocation and optimizing software-defined traffic orchestration in vehicular networks. These technologies aim to ensure efficient OTA software update delivery by dynamically managing bandwidth and intelligently directing network traffic, thereby improving reliability, reducing latency, and preventing congestion.

The ETSI GS MEC 015 Bandwidth Management API, as depicted in Figure 6, provides a RESTful interface that allows for dynamic bandwidth allocation and resource management. The API supports essential operations such as retrieving existing bandwidth allocations (GET), creating new allocation requests (POST), updating bandwidth configurations (PUT/PATCH), and removing outdated allocations (DELETE). By leveraging Multi-Access Edge Computing (MEC), the system can allocate network resources close to end-users, optimizing the transmission of OTA updates and reducing the strain on centralized data centers. This dynamic bandwidth provisioning ensures that software updates are delivered smoothly and efficiently, preventing potential delays caused by competing network traffic.

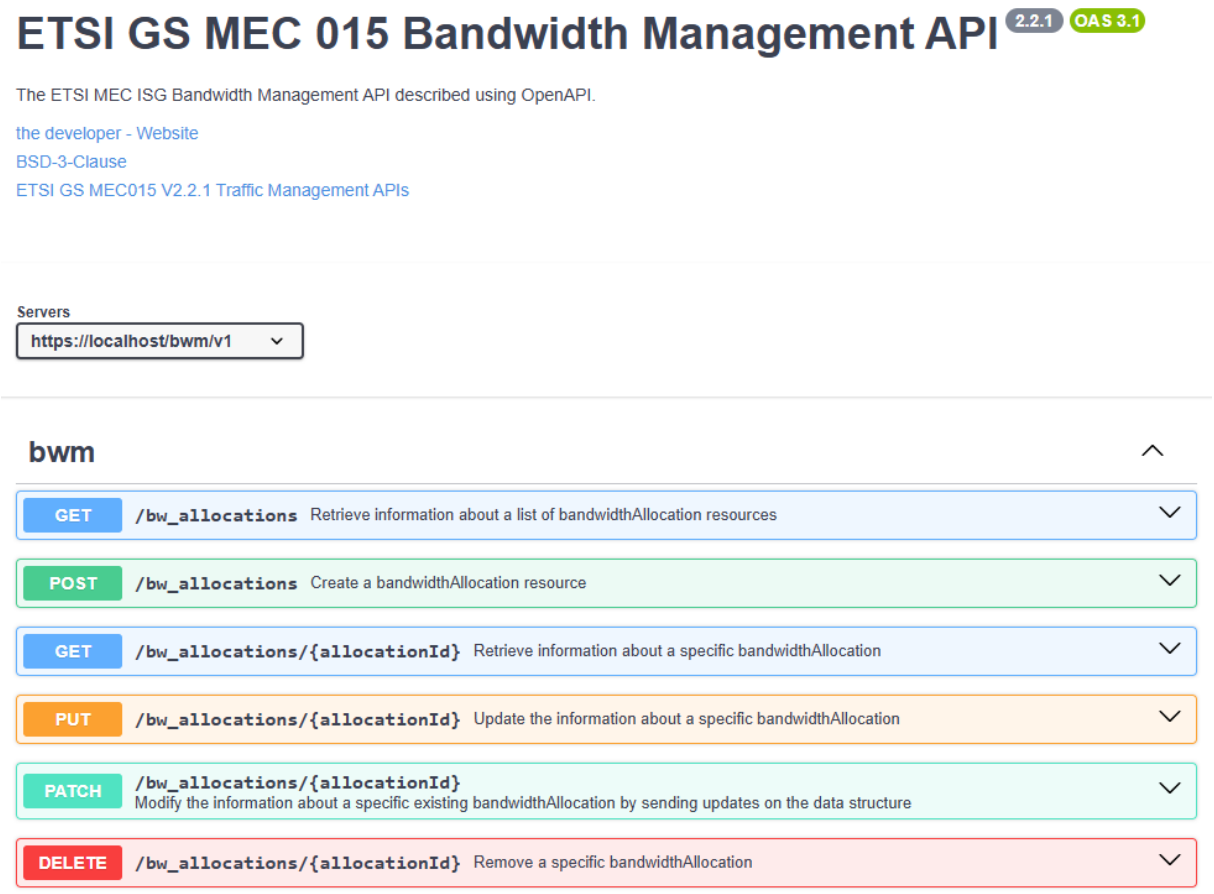


Figure 6 MEC 015 Bandwidth Management API

The ETSI TeraFlowSDN Controller, as shown in Figure 7, facilitates software-defined networking (SDN)-based traffic control and network orchestration. The interface allows users to select network topologies, upload JSON-based network configuration descriptors, and visualize managed network resources. By implementing SDN principles, TeraFlowSDN enables dynamic path selection, congestion avoidance, and real-time traffic engineering. This capability is particularly valuable for vehicular networks, where OTA updates must be transmitted over complex, heterogeneous infrastructures. The ability to reconfigure network paths dynamically ensures minimal disruptions and enhances the reliability of the update distribution process.

The preliminary findings from these two technologies indicate a strong potential for seamless network automation in vehicular ecosystems. The MEC Bandwidth Management API provides a scalable solution for prioritizing OTA updates while preventing excessive congestion. Simultaneously, TeraFlowSDN introduces intelligent traffic control mechanisms that dynamically optimize network routes based on real-time conditions. The combination of these technologies demonstrates the feasibility of a more adaptive, efficient, and secure approach to software updates in connected vehicles.

Overall, integrating MEC-based bandwidth management with SDN-powered network orchestration has the potential to significantly enhance the performance of vehicular networks. This approach ensures that software updates are delivered reliably while maintaining network stability and scalability. Future evaluations will focus on measuring key performance indicators (KPIs) such as end-to-end update latency, bandwidth allocation efficiency, and congestion avoidance rates to validate the effectiveness of this integrated solution.

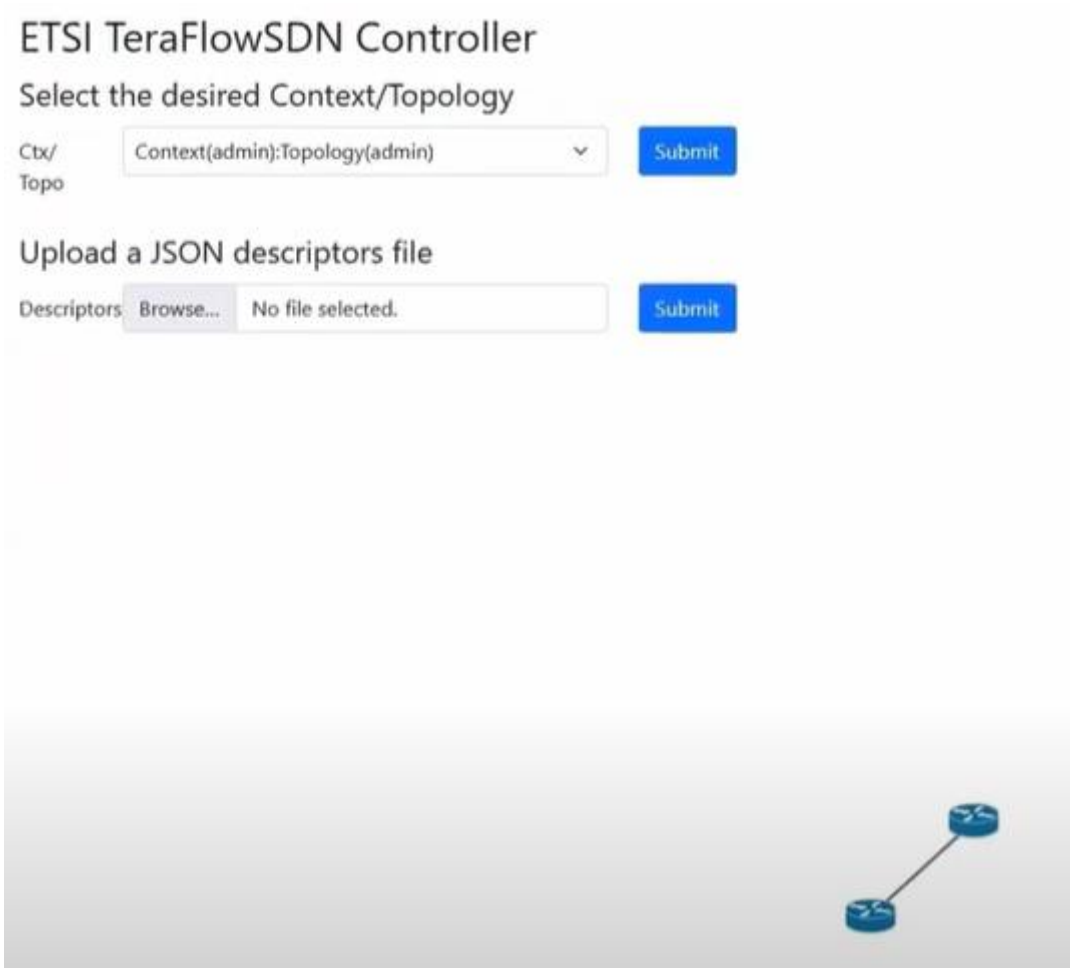


Figure 7 Integration with TeraFlowSDN

4 Use case 2 proof-of-concept (PoC)

4.1 Phase 1: PoC at Nextcloud

To carry out phase 1 testing, a test setup has been provided where the entire team can work on the same devices. This has the following advantages.

The acquisition of vehicular data requires tools to facilitate development work. For this, logs were created from the data provided by the sensors, which we called Datasets. These corresponded to the acquired analog values along with their respective timestamps. Figure 8 shows the distinction between the actual implemented architecture and the development architecture.

Remote Collaboration: Developers can access hardware from anywhere in the world, allowing them to work on the project regardless of their physical location.

Reduced operational costs: Only one set of hardware is needed, which can be shared by all developers. This reduces the costs of purchasing multiple devices for each team member.

More efficient testing: Hardware can be accessed 24/7, allowing for continuous testing and debugging, even when developers are in different time zones.

Ease of maintenance and updating: Updates to the operating system or applications built for the project can be performed centrally and instantly available to all developers.

Scalability: If more developers need to work on a project, access to hardware can be easily scaled without the need to purchase more physical equipment.

Security and Access Control: Security controls can be implemented to restrict access to hardware to only those who need it, ensuring that sensitive or confidential data is protected.

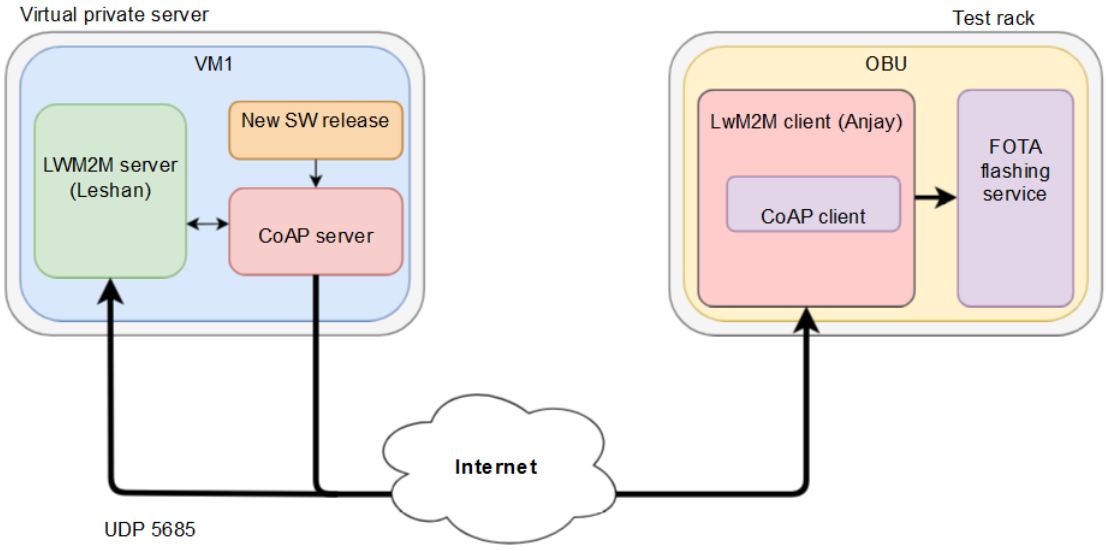


Figure 8: UC2 phase 1: development architecture

4.1.1 On-board unit test setup

The on-board unit (OBU) developed, called VMAX, is based on an aarch64 architecture, as opposed to the PCs used for development, which is based on the X86-64 architecture.

```
vmaxsetup@vmax:~ $ ssh -oHostKeyAlgorithms=+ssh-rsa root@192.168.2.4
root@192.168.2.4's password:
~ # uname -a
Linux ag215scnaa 4.14.206-perf #1 SMP PREEMPT Tue Dec 12 09:58:25 UTC 2023 aarch64 GNU/Linux
```

This means our code must undergo a process known as cross-compilation, which involves compiling a software project on a machine with one architecture, in this case, X86-64, so that it can run on a machine with a different architecture. For this reason, a test setup is necessary for the cross-compiled code. This setup consists of a Raspberry Pi connected to two device units equipped with a C-V2X PC5 interface for radio communications, linked via an Ethernet switch (see Figure 9). The Raspberry Pi is accessible over the Internet through a TLS reverse tunnel to a dedicated server managed by IDNEO, and from there, access to the VMAX units is provided via serial and/or local network interfaces.

Alternatively, the setup also allows access to the VMAX units through a Uu cellular connection, either via access permissions granted to the public IP of the IDNEO dedicated server or through other permanent TLS reverse tunnels.

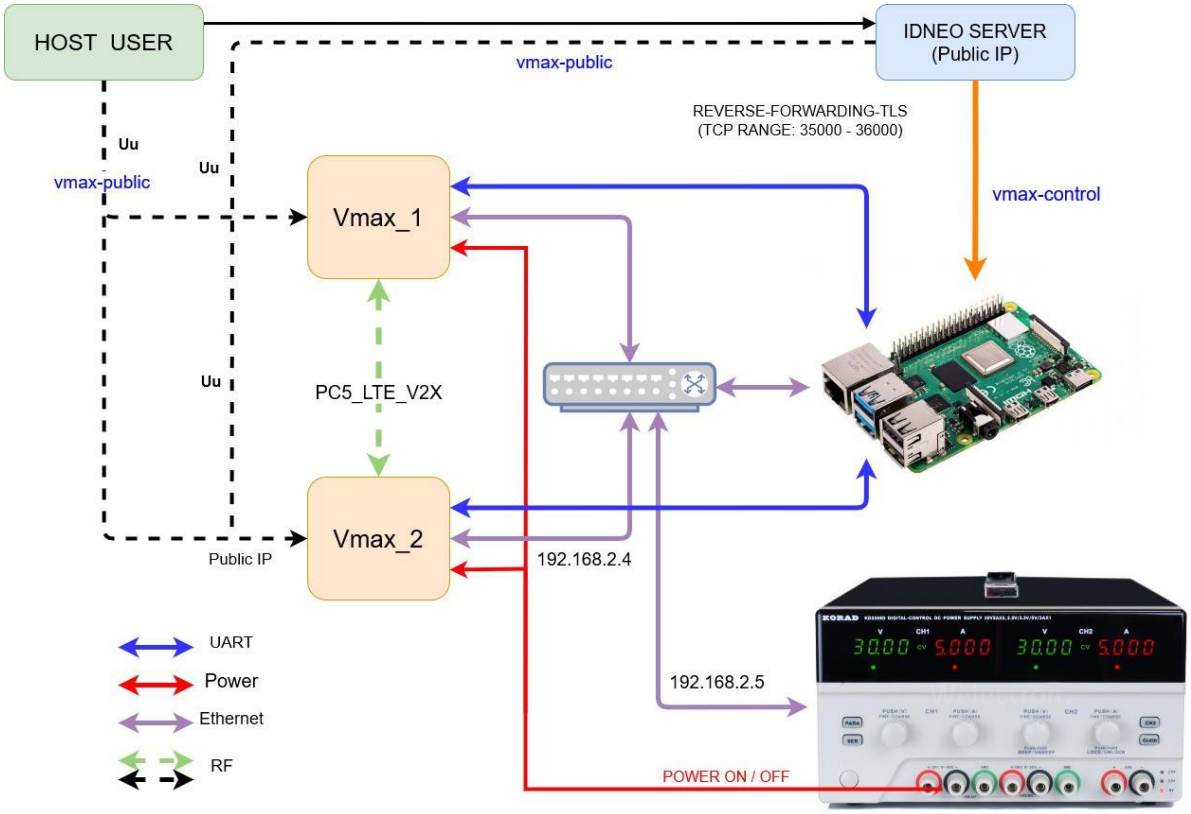


Figure 9: Test setup

In Figure 9, it is possible to identify the access interfaces that allow remote control of the Vmax. The control that this setup allows with respect to each Vmax, goes from turning it on or off, through a network-managed power source or serial interfaces that allow debugging from the Vmax boot start-up from the Raspberry PI.

4.1.2 TLS Reverse Tunnel

This tunnel allows to create a permanent connection between the Raspberry Pi, which is located behind a local network, and the IDNEO server. To run this tunnel, the openssl TLS client is used in reverse forwarding mode, which establishes a port on the remote host and redirects it locally to the Raspberry Pi TLS server. To do this, a systemd service is created that executes the corresponding command and manages the recovering process.

```
* backdoor.service - Backdoor Service
     Loaded: loaded (/etc/systemd/system/backdoor.service; enabled; preset: enabled)
     Active: active (running) since Thu 2024-10-10 15:34:38 CEST; 6min ago
      Until: Thu 2024-10-10 18:34:38 CEST; 2h 53min left
   Main PID: 28106 (bash)
      Tasks: 2 (limit: 8734)
        CPU: 136ms
     CGroup: /system.slice/backdoor.service
             |-28106 /bin/bash /usr/bin/backdoor.sh
             `-28108 /usr/bin/ssh -N -R 35990:localhost:22 ficosa-root@193.70.33.60 -p 27022

oct 10 15:34:38 vmax systemd[1]: Started backdoor.service - Backdoor Service.
oct 10 15:34:38 vmax bash[28106]: New port:  35990
```

On the IDNEO server side, this TLS client has automatic access because the public key of the client host, Raspberry Pi, is in the list of authorized keys on the TLS server, so no user and password authentication is needed.

4.1.3 Firewall on the on-board unit

The iptables architecture relies on these three components working together:

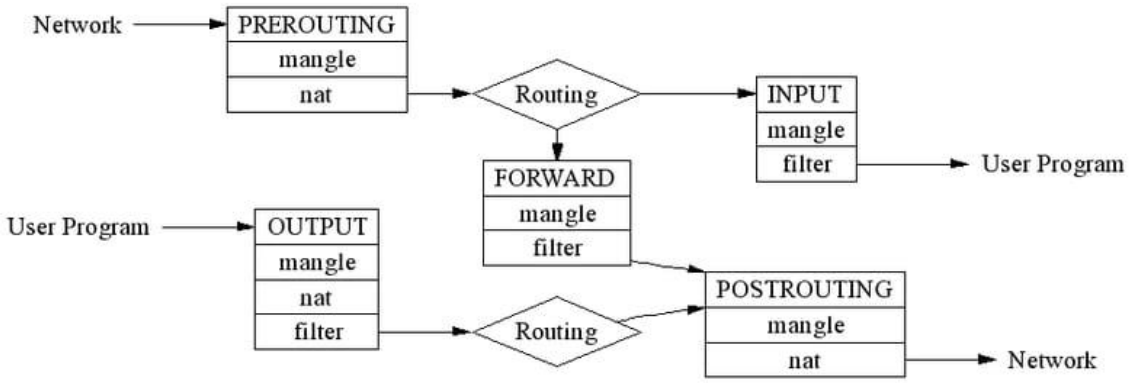
- **Tables:** Organize rules by function (e.g., filtering, mangling).
- **Chains:** Define the path packets take and the order in which rules are applied.
- **Rules:** Specify the criteria for matching packets and the actions to take (e.g., ACCEPT, DROP, REJECT).

The filter table is the default table used to filter packets. Its rules determine whether a packet should be accepted or rejected. This table contains the core chains used for traffic management: INPUT, OUTPUT, and FORWARD.

INPUT: This chain handles incoming traffic destined for the local system itself. When a packet arrives at a network interface and is intended for the device, it is processed by the rules within the INPUT chain.

OUTPUT: This chain handles outgoing traffic originating from the local system. Any packets generated by the device and sent out through a network interface are processed by the rules in the OUTPUT chain.

FORWARD: This chain handles traffic that is neither destined for nor originating from the local system. It is used for packets that are being routed or forwarded to other networks or machines. This chain is essential for devices acting as routers or gateways.



In the OBU, restrictive input rules have been configured, which are automatically configured at system startup. OBUs have access to the public network through the Quectel AG550 modem. In this modem, incoming and outgoing traffic rules are configured for network management. By configuring the INPUT and OUTPUT chains to discard unauthorized traffic and the FORWARDING chain to only allow access to port 22 (TLS server of the AG215 AP) to certain configured public IP addresses, a filter is achieved for all traffic that is not allowed access.

```
/ # iptables -L -t filter
Chain INPUT (policy DROP)
target     prot opt source               destination
ACCEPT     icmp --  anywhere             anywhere
ACCEPT     all  --  anywhere             anywhere
ACCEPT     all  --  192.168.225.0/30     192.168.225.0/30

Chain FORWARD (policy ACCEPT)
target     prot opt source               destination
ACCEPT     tcp  --  193.70.33.60         anywhere             tcp dpt:ssh
ACCEPT     tcp  --  88.98.97.234         anywhere             tcp dpt:ssh
ACCEPT     tcp  --  46.136.172.101       anywhere             tcp dpt:ssh
DROP       tcp  --  anywhere             anywhere             tcp dpt:ssh

Chain OUTPUT (policy DROP)
target     prot opt source               destination
ACCEPT     icmp --  anywhere             anywhere
ACCEPT     all  --  anywhere             anywhere
ACCEPT     all  --  192.168.225.0/30     192.168.225.0/30
```

This configuration allows to avoid brute force attacks since the TLS server will only serve the clients that the iptables rules allow.

4.2 Phase 2: PoC at Castellolí

To deploy phase 2 of the tests, all software, both server-side and OBU software, has been migrated to their final locations: the Castellolí server and the IDNEO-developed OBU installed in the test vehicle. Figure 10 details the phase 2 architecture.

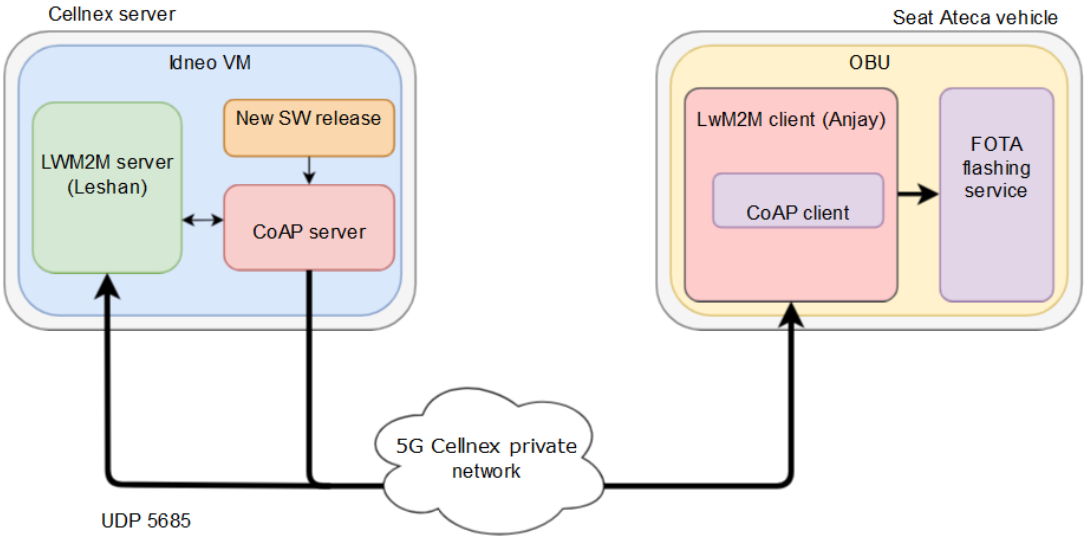


Figure 10: UC2 phase 2: real architecture (Castelloli)

This tool simplifies development to the extent that accessing the vehicle for algorithm testing was no longer necessary, as real values were used for testing, albeit with different timestamps.

5 Conclusions

Efficient computation management for OTA vehicular software updates is crucial in reducing latency, optimizing network resources, and ensuring seamless service delivery. SUCCESS-6G-VERIFY demonstrates how MEC-based workload distribution and AI-driven predictive resource allocation can improve the efficiency of update deployment while minimizing network congestion. The experimental results validate the advantages of intelligent caching and traffic-aware optimization in enhancing computational performance. Future research should focus on refining AI-driven orchestration techniques and expanding edge computing capabilities to support the growing complexity of vehicular software updates in increasingly connected and autonomous transportation systems.

A significant challenge in computation-efficient OTA updates is balancing the workload distribution between cloud and edge computing resources. The use of federated learning models and distributed processing architectures ensures that updates are processed closer to vehicles, minimizing reliance on centralized servers and reducing latency. This approach not only accelerates update dissemination but also enhances overall system resilience.

Furthermore, the integration of AI-enhanced resource scheduling optimizes bandwidth utilization and computational efficiency. By dynamically prioritizing critical updates and allocating processing resources based on real-time demand, the system prevents network congestion and improves update success rates. Continued advancements in edge AI and MEC infrastructure will be instrumental in achieving even greater levels of efficiency and reliability in vehicular software update ecosystems.

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