TRACE: a Reference Architecture for Intelligent Logistics Operations in B5G Networks

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Abstract. As supply chains grow increasingly complex and demand for autonomous delivery solutions rises, traditional logistics systems struggle with real-time coordination requirements across multiple transportation modes. The TRACE Reference Architecture (RA) addresses these challenges through a telecommunications-aware design that integrates multimodal transportation systems with advanced network capabilities. Following a layered structure, the proposed RA incorporates user interfaces, application services, data management modules, and physical infra-structure components, fostering real-time decision-making and coordination across logistics stakeholders. The architecture also leverages edge computing, distributed intelligence, and blockchain technologies to ensure secure data exchange while supporting autonomous vehicles (e.g., ground vehicles, drones) as part of multi-modal logistics operations. We demonstrate the architecture's versatility through three distinct implementation scenarios in Italy, Slovenia, and Greece, showcasing different network configurations including 5G Stand-Alone, Non-Stand-Alone, and Vehicle-to-Vehicle communications that sup-port autonomous delivery, platooning, and multimodal transport coordination. This paper illustrates how the TRACE RA provides a scalable foundation for next-generation logistics that balances operational efficiency with security and privacy requirements in the emerging B5G ecosystem.

Keywords: multimodal logistics, edge computing, B5G Networks.

1 Introduction

1.1 B5G evolution in logistics

The logistics industry is currently undergoing a transformation driven by the growing complexity of supply chains requiring real-time coordination [1]. We observe an increasing demand for autonomous and unmanned delivery solutions to be integrated with traditional truck-based delivery systems to enhance last-mile delivery efficiency [2-4] which highlights the rising expectations for end-to-end visibility and traceability, coupled with an emerging need for multi-modal transportation optimisation [5,6]. The integration of 5G/B5G technologies with industrial Internet of Things (IoT) revolutionises logistics through various enabling technologies. These include Ultra-reliable Low-Latency Communication (URLLC) for reliability, massive Machine-Type Communications (mMTC) for scalability, enhanced mobile broadband (eMBB) for high-bandwidth applications. All of them supported by network slicing for service-specific optimisations [7-9]. Thus, B5G/6G technology seems to be suitably placed as a key enabler, addressing challenges in logistics, e.g., the need for real-time decision making at the edge in the last mile, and complex data integration, taking also into consideration security and privacy [10, 11]. Market drivers such as the demand for last-mile delivery through the integration of unmanned vehicles, adhering also to greener logistics operations, dictate the evolution towards intelligent logistics, transitioning from centralised to distributed intelligence, integrating Artificial Intelligence (AI)/ Machine Learning (ML) at the network edge and providing enhanced situational awareness through sensing capabilities [12,13].

1.2 TRACE project overview and objectives

TRACE is a research initiative funded under the Horizon Europe Research and Innovation program which introduces an innovative platform designed to integrate services from diverse multimodal logistics operations [14]. The TRACE RA enables the seamless integration of logistics services across multiple stakeholders and transportation modes. Structured in interconnected layers, the architecture includes an intuitive user interface, applications for scheduling, routing, and event management, real-time data processing and a cloud-based persistent storage. At the foundation, the infrastructure layer supports various communication technologies including 4G/5G and WiFi, alongside diverse transport systems. A semantic framework supports the platform’s interoperability with different logistic operators, while harmonises the data from different logistics sources, through standardised integration points between components and a common TRACE data model enabling consistent data exchange. Through a hybrid cloud-edge deployment architecture, TRACE leverages advanced B5G telecommunications capabilities, enabling low-latency Vehicle-to-Vehicle (V2V) communications and supporting diverse network technologies from 4G/5G to WiFi. The platform's distributed architecture integrates real-time event processing at the edge with blockchain-based security. Next-generation mobility solutions including unmanned vehicles are supported as parts of multi-modal logistics. The use of standardised and strong security mechanisms ensures end-to-end security and privacy, thus optimising operational efficiency and enabling new business models. The TRACE platform follows a telecommunications-aware design which provides a scalable foundation for modern logistics operations. The design allows for seamless integration of diverse communication technologies and edge computing capabilities, thus addressing complex supply chain requirements.

1.3 Paper organisation

The paper is organised as follows: Section 2 presents the TRACE Reference Architecture, its methodology and approach, the key layers, as well as the intelligent data management frameworks. Section 3 describes the transport communication infrastructure integration and implementation. Finally, Section 4 concludes the paper with insights on the TRACE platform's contribution to modern synchromodal logistics operations.

2 TRACE Platform Reference Architecture

2.1 Architectural methodology and approach

We followed a structured and iterative methodology for the architecture design in order to address the complex and modular TRACE platform, taking into consideration the requirements of various stakeholder. Our methodological approach aligns closely with the principles of The Open Group Architecture Framework (TOGAF) Architecture Development Method (ADM), combined with distributed systems design guidelines, that recent research [15] has shown that can be proven effective in logistics settings. This approach provided us with a clear framework for creating a robust, flexible, and future-ready platform, spanning from the collection of initial requirements to the definition of the high-level concepts, detailing components, and planning deployment. Starting from the requirements analysis, the platform workflows were defined, which led to the conceptual architecture design. Following, the detailed architecture design was conducted, resulting in the implementation and deployment plan of the TRACE platform. This plan was then validated against the set requirements, adopting a continuous iteration approach. These fundamental steps ensure that stakeholders needs are translated into a fully deployable system architecture. As such, the methodology was largely based on modern design principles, alongside best practices for implementation and validation, thus ensuring that the TRACE platform is optimised for real-world operations and seamless integration with external systems.

Requirements analysis. The first step of the TRACE platform design was to collect the goals and operational challenges of the stakeholders, as well as their expectations and then translate them into functional and non-functional requirements. This has been achieved through workshops, questionnaires, and interviews, within the TRACE consortium and through engagement with external stakeholders. As a result, key functional requirements, such as real-time data collection, route optimisation, and scheduling, as well as non-functional requirements, such as scalability, performance thresholds, and security compliance (e.g., GDPR) have been identified. After categorising by importance using prioritisation techniques, each requirement was then mapped to user stories that illustrate how stakeholders will interact with the platform, leading to the next phase of the methodology.

Platform workflows. In this phase, the stakeholder needs were translated into actionable workflows that define how the TRACE platform will operate in real-world scenarios. Each workflow determines how users and services interact with the platform and the expected outcomes. The approach was to specify the sequence of interactions between the end users, platform components, and external systems, based on user stories. This resulted in the production of sequence diagrams that visualise the platform workflows, in a way that the user requirements and needs are aligned with the system's capabilities and functionalities.

Conceptual architecture design. A high-level structure of the TRACE platform that includes all the functional sections of the system has been developed in this next step. The architectural blocks are organised into horizontal layers, such as User Interface, Application, Data Management, and Infrastructure. Each layer is assigned specific responsibilities, while depicts the technological domains that the platform covers. The high-level architecture diagram visualises also the platform components, and their position in each layer and domain, as presented in **Fig. 1**.

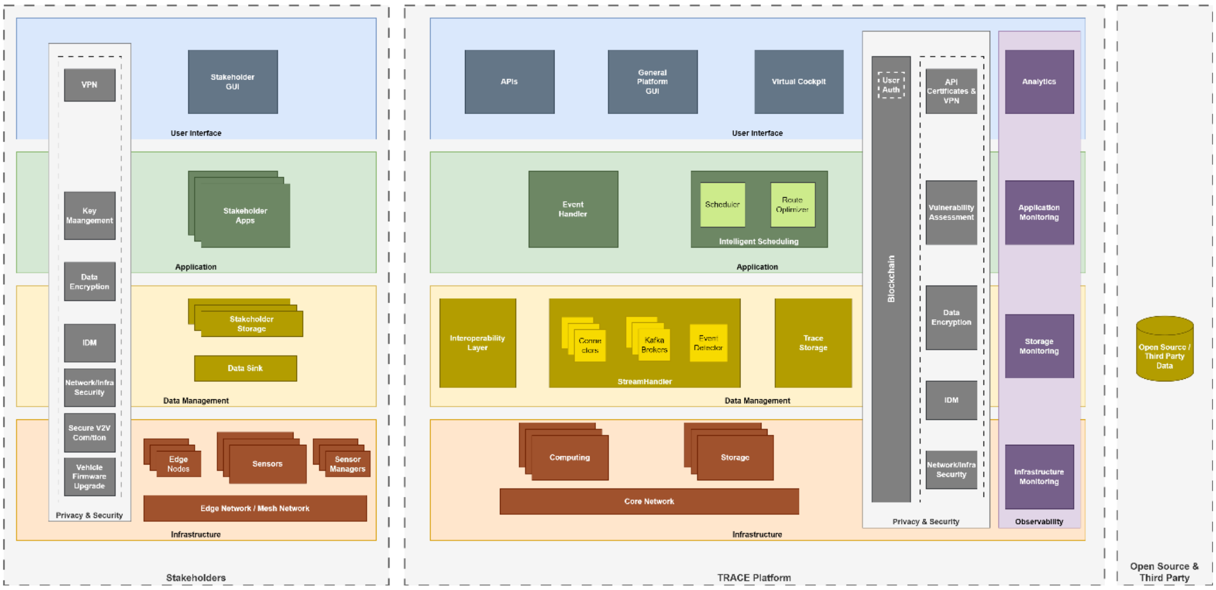

Fig. 1. TRACE Platform Conceptual Architecture

2.2 Key architectural layers

Fig. 1 depicts the highly modular approach of the TRACE architecture, where multiple components work together as microservices to optimise its functionalities related to transportation, logistics, data management, and communication infrastructure. Each component, contained within a horizontal layer, utilises components from the same layer or the layers beneath that. Starting from the left/top layer where we find the user interface, we move down/right to the application layer, the data management and finally the infrastructure layer. TRACE platform operations, namely the Stakeholders' domain, includes all hardware and software components of the logistics companies and the platform. The TRACE Cloud Platform that comprises the backbone for integrating data from stakeholders, handles processing and analytics, and optimises operations through intelligent scheduling and route optimisation. Last, the Open-Source Domain, which offers integration of open-source and third-party data sources, runs vertically on the architectural layers. Certain components are clustered as to formulate logical cross-layer groups on top of the horizontal layers, which are used to define the security, observability, and blockchain groups of the reference architecture.

User Interface Layer. The first component of this layer is the Application Programming Interface (API) gateway, a collection of backend services, acting as a reverse proxy to streamline API calls, aggregate data, and implement common functionalities, enabling data exchange and integration with third-party services. The lightweight Dashboard is a user-friendly interface designed to provide real-time insights and control over various aspects of the TRACE platform. Finally, the Virtual Cockpit is a virtual reality application that offers functionalities related to 3D map route visualisation and current coordinates, event visualisation through real-time stream connection and emergency functionality (outbound).

Application Layer. The core functional components are stored in the Application layer, which acts as an enabler for the essential services and applications for transportation and logistics optimisation. These components are the Scheduler for shipment requests coordination and optimisation of delivery operations; the Route Optimiser for the calculation of optimal paths with respect to travel time and distance; and the Resource and Event Manager, which continuously receives sensory and other relevant data through the StreamHandler platform and monitors the transfer of shipments after the definition of the initial route. Upon detection of deviations from the transfer plans delivered by the Scheduler and Route Optimiser, the Resource and Event Manager triggers the appropriate mitigation actions (e.g., re-route) for updates in the transfer plan affected by any type of events (e.g., a disruptive event).

Data Management Layer. The flow, storage, and processing of data within the TRACE platform is processed through this architectural layer in a way to ensure the efficient data exchange, integration, and management, operating through the Cloud-based Data Management System, the StreamHandler platform and the Interoperability layer. The Cloud-based Data Management System is a centralised and highly available data lake that supports data storage, querying, and retrieval functionalities which stores data of the platform and information from external sources. The StreamHandler platform, developed by Netcompany-Intrasoft S.A., supports the interconnection of the various data sources, deployed as a distributed event-driven streaming platform that manages a large amount of heterogeneous data, messages and events, based on Apache Kafka [16]. It is a sophisticated low-latency high-performance middleware that supports real-time or near real-time streaming of events from multiple producers to multiple consumers [17]. Finally, the Interoperability Layer facilitates seamless data exchange between TRACE components and external systems of the logistics companies, satisfying the requirement for compatibility, data translation, and communication between diverse systems. The system's design emphasises data sovereignty while ensuring semantic consistency. By this, logistics companies are allowed to maintain their existing database structures while participating in a broader collaborative ecosystem, presenting great benefits for multi-modal transportation scenarios. This is achieved through a sophisticated semantic framework operating in two distinct phases: i) The Preparatory Phase, for the semantic alignment of heterogeneous data sources with the TRACE Data Model through a unified data representation framework for logistics operations, and ii) The Query Phase, which builds upon this semantic foundation, enabling both technical and non-technical users to access harmonised logistics data through a centralised query endpoint.

Infrastructure Layer. This is the backbone infrastructure for the deployment, management and scaling of the TRACE components. This layer ensures high availability and performance through the Edge Network/Mesh Network, and the Edge Nodes, Sensors, and Sensor Managers, offered as a Platform-as-a-Service (PaaS) that provides centralised computing and storage capabilities, supporting high-performance data processing and analytics, coupled with elements that ensure adequate computational power and storage capacity for the platform's operations. The Edge Network / Mesh Network incorporates the network elements that enable decentralised data processing and communication at the edge, reducing latency and bandwidth usage. The data collection from physical devices such as vehicles, drones and infrastructure sensors, is achieved by the Edge Nodes, Sensors, and Sensor Managers.

2.3 Cross-layer components

Privacy & Security Group. The integrity, confidentiality and available of TRACE data and services is protected by this cross-layer cluster of components. Secure communication channels between external systems and internal components, in terms of data encryption and authentication, are ensured by a Virtual Private Network (VPN) and API certificates. In addition, the user data in TRACE distributed or centralised storage are encrypted and thus accessible only to authorised participants. There is also an Intrusion Detection Module (IDM) placed on top of sensors/ communications streams that spots potential intrusions and proposed mitigations, integrated with other TRACE components to facilitate the management of any required recovery activity. Finally, there is an additional security tier incorporated in the Vehicle-to-Vehicle (V2V) communication protocol, coupled with a secure protocol for keys' exchange in an ad-hoc set of nodes belonging to the same platform (e.g., all vehicles of the same logistics company).

Blockchain Group. Secure, immutable and transparent data exchange between stakeholders is achieved by a cluster of blockchain components and services. The Distributed Ledger Structure allows the TRACE platform to securely connect with the Algorand Blockchain [18]. The Digital Wallet secures the storage digital identity credentials. TRACE Platform is integrated with a Public Key Infrastructure (PKI) system, while a component for Smart Contracts handles all transactions related to authentication and storage of references on the Blockchain, serving as the system's backbone for executing the PKI ecosystem and ensuring the unshakable integrity of collaboration agreements.

Observability Group. This group involves dedicated services for advanced analytics and monitoring of the TRACE platform's health. Analytics services provide insights into system performance, user behaviour, and operational efficiency. Continuous monitoring of applications and storage enables performance tracking and supports the identification and resolution of any issues in a proactive manner. Finally, there is a dedicated service that interacts with the infrastructure layer elements to ensure that the underlying hardware and network infrastructure are functioning optimally, continuously supervising all infrastructure components.

3 Communication Infrastructure Layer

Considering the layered TRACE architecture, the lower layer is defined as the infrastructure layer. This layer comprises the communication- and transportation-related infrastructure equipment/ vehicles/ devices, etc., that are needed to provide the logistic services as well as to support the communication between the TRACE platform and the underlying logistics equipment. Considering the transportation infrastructure, this includes the infrastructural elements that are needed for the actual delivery of goods i.e., vehicles, type of roads, roadside equipment etc. as well as the communication devices and functions for the V2V communication. Considering the TRACE Conceptual Architecture schema, depicted in **Fig. 1**, this corresponds to the "Vehicles" architectural components. Given that the transportation infrastructure building blocks depend highly on the stakeholders involved in each logistics use case, and also given that the transportation infrastructure can be extremely versatile, the blocks need to be defined in the deployment phase of TRACE solution.

3.1 Communication Infrastructure Layer Architecture

Considering the telecommunication layer, the identified architectural blocks at the stakeholders' side include the end-user devices (sensors along with their controlling equipment), edge compute nodes hosting any near-to-end-user functions, and edge/mesh network equipment; while at the TRACE platform side the communication infrastructure architectural blocks include the core network functions and the underlying compute infrastructure along with any storage infrastructure. The sub-architecture of this layer depends on the selected communication technologies/ deployments/ solutions ranging from cellular 3GPP to WiFi IEEE based. The selection of the underlying network layer will depend highly on the network performance characteristics (achievable data-rate, latency, availability – area coverage, mobility etc.). Three main network solutions will be explored for the TRACE deployment and Use Cases, namely: 3GPP 4G/LTE/5G NSA (non-Stand Alone), 3GPP 5G SA (Stand Alone) and IEEE WiFi, each adhering to the relevant standards' architectures.

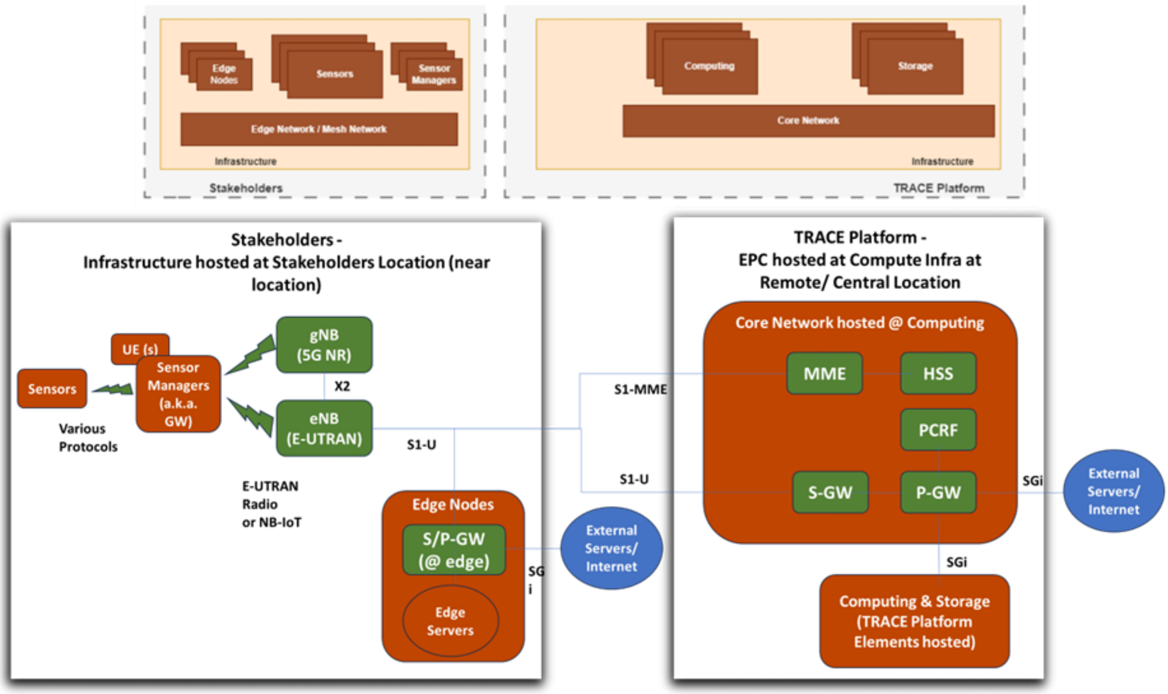

Fig. 2. 5G NSA Network Architecture – mapped on TRACE Architecture

In particular, **Fig. 2** illustrates the adoption of Long Term Evolution (LTE) network architectures [19] comprising a set of segments namely: the 4G/LTE Radio Access Node (RAN), the LTE Core Network, known as EPC (Evolved Packet Core including the Serving Gateway (SGW), Packet Data Network Gateway (PGW), the Mobility Management Entity (MME), the HSS (Home Subscriber Server) and the PCRF (Policy and Charging Rules Function)), the underlying transport network segments and the underlying compute infrastructure where the EPC components are hosted. Edge resources can be exploitable for TRACE application components hosting by deploying multiple S/P-GWs near the stakeholders’ locations (e.g. at edge compute resources). As depicted, the 4G/LTE network RAN can be further extended with 5G NP (New Radio) nodes comprising the 5G Non-Stand-Alone flavour of 3GPP networks; essentially providing the data-rate enhancements over the 4G EPC. Adopting 5G SA architectures with far-edge and edge segments (based on [20] in the context of TRACE solution is presented in **Fig. 3**). The 5G network architecture comprises a set of segments namely: the 5G RAN (residing at the stakeholder’s infrastructure block), the 5G Edge (residing at the stakeholder’s infrastructure block but hosting TRACE Platform capabilities) and the 5G Core Network (5GCN) (residing at the TRACE platform block), the underlying transport network segments and the underlying compute infrastructure where the 5G RAN and 5G Edge and 5GCN components are hosted. According to 3GPP standardization, the 5G core network provides the logical - session layer that is necessary for the transfer of communication services with specific QoS and mobility characteristics between the user device and the Radio Network part and any internal or external the Data Network (DN). The basic 3GPP network elements/ functions are the following: Access and Mobility Management Function (AMF), Session Management Function (SMF), User Plane Function (UPF), Unified Data Management (UDM), the Authentication Server Function (AUSF), the Network Repository Function (NRF), the Policy Control function (PCF) and the Network Slice Selection Function (NSSF).

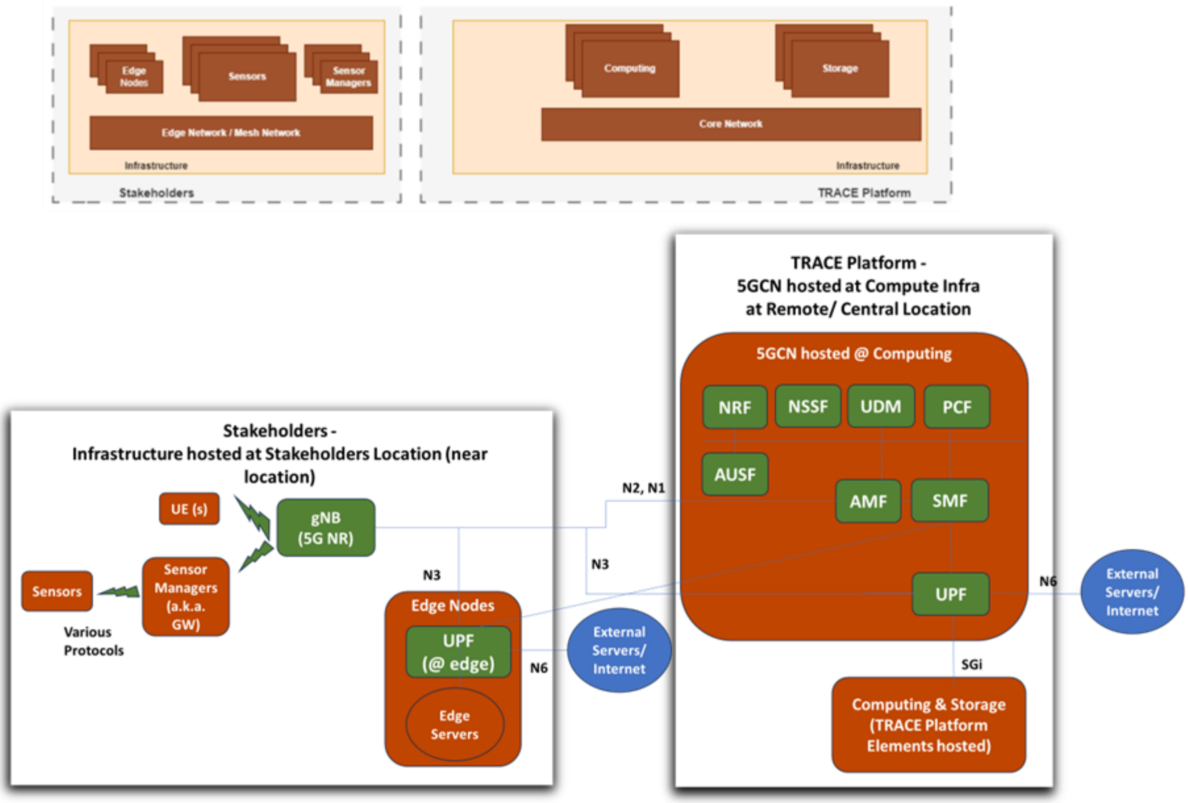

Fig. 3. 3GPP 5G Network Architecture – mapped on TRACE Architecture

3.2 Vehicle-to-Vehicle Network Architecture

For some services incorporated in the TRACE functionalities, like platooning, other network architectures are considered for V2V communication as presented in **Fig. 4**, which are based on direct communication between vehicles of the same group without the mediation of the Infrastructure Network elements. Such network deployments are especially useful considering latency and cost aspects, as well as network traffic aspects. Such configurations are also useful considering areas with infrastructure network coverage holes. For instance, in case of temporary lack of coverage, the group of vehicles will be able to perform the planned delivery, and vehicles will be able to coordinate with each other. In cases where the leader of the platoon detaches from the group temporarily (e.g. in order to make a delivery), the V2V module will be critical to communicate the updated configuration of the platoon, such as identifying the new leader and determining which bike to follow when multiple bikes are present. In this case, V2V communication – or potentially a combination of V2V and V2I (Vehicle to Infrastructure) communication – will ensure all actions are tracked and synchronized effectively. In the context of TRACE, V2V communications are considered in the network infrastructure architecture, at the access network segment as shown in the following figure, while the protocols used can be versatile depending on the vehicle vendor, the vehicle/ logistics operator licensing (radio-frequency licensing schemes), etc.

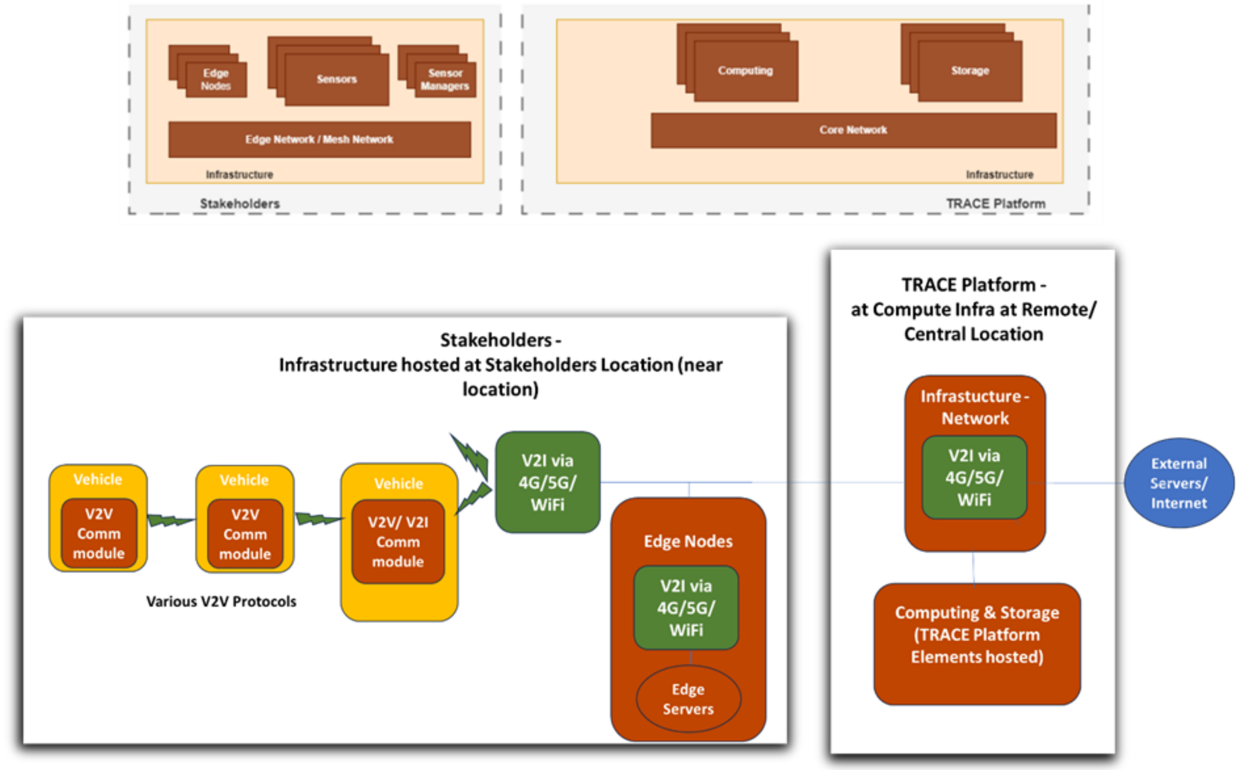

Fig. 4. 5G V2V Communication – mapped on TRACE Architecture

3.3 Indicative Implementations of TRACE Communication Infrastructure Layer

Based on the aforementioned architectural options we can foresee versatile implementation of the TRACE system. Three of these options will be deployed in the corresponding three TRACE demonstrations in Italy, Slovenia and Greece.

Smart and connected vehicles for last-mile deliveries optimisation – the Italian case. The network infrastructure layer that will support the Italian Use Case, will be based on 4G/5G network architecture/ deployment. The infrastructure that will be used for the communication system, involving different transportation entities, including drones, cargo bikes, and platooning systems. In the context of this use case connectivity between the end-devices and vehicles and the Modena Automotive Smart Area (MASA) Server will be established over 4G/5G network infrastructure. The MASA server processes data, relaying it through a a Message Queue Telemetry Transport (MQTT) Broker that interface with the TRACE platform for further processing and applications. Additionally, roadside equipment or smart devices, represented as "Other Type", can feed data into this system, ensuring integration between vehicles and the platform for real-time logistics tracking. Platooning based on V2V (Time-Division-Multiple-Access – TDMA based solution) communication will be also deployed.

Optimising First and Last-Mile logistics with heterogeneous vehicle types – The Slovenian case. The network infrastructure layer that will support the Slovenian use case, will be based on 4G/5G and WiFi network architecture/ deployment. The infrastructure that will be used for the communication system, involves different transportation entities, including the autonomous delivery robots, the cargo bikes, and the electric delivery vehicles.

Efficient and secure shared logistics services with reduced environmental effects – the Greek case. Last but not least, the network infrastructure layer that will support the Greek Use Cases, will be based on 5G network architecture/ deployment, while WiFi connectivity can be also an option depending on the devices network interfaces. The infrastructure that will be used for the communication system, involves different transportation entities, including cargo trains, trucks and last mile vehicles (drones, autonomous vehicles), roller cages, etc. The vehicles and end devices of this Use Case communicate via a 4G/5G network that is deployed at the local logistics company and selected train station sites in Thessaloniki, Chalkis and Athens areas. This connectivity enables communication from the end devices to the central cloud Infrastructure where the TRACE Platform will reside for data processing and application provisioning. Connectivity between the devices or/and the TRACE Platform with external / other applications will be performed over the 4G/5G network and any interconnected ISP networks (DNs).

4 Conclusions and Future Work

This paper presents a Reference Architecture incorporating intelligence at network edges to support intelligent logistics operations in B5G networks (based on the EU funded project TRACE). The proposed platform enables real-time coordination across multimodal transportation systems, ensuring scalability, interoperability and security using cutting-edge technologies like edge computing, blockchain-based security and real time decision-making incorporating AI/ML. Additionally, three deployment options of the TRACE platform are indicated in scenarios focusing on optimising autonomous delivery, platooning and multimodal transport coordination. These pilots showcase how TRACE addresses challenges in last-mile delivery, route optimisation, and autonomous logistics orchestration. While TRACE architecture provides an efficient solution deployable over the existing latest generation networks (5G), a number of topics are open for further research, considering the evolution of the edge segment in 6G networks, and the ever increasing interest on energy efficiency in the logistics sector. In conclusion, TRACE bridges the gap between advanced network technologies and real-world logistics challenges, creating the way for next-generation logistics ecosystems in the B5G era.

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