Use of Artificial Intelligence as an Enabler for the Implementation of ETCS L3 and Other Innovative Rail Services

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Acronyms

ACS	Adaptable Communication System
AI	Artificial Intelligence
AMQP	Advanced Message Queuing Protocol
ATC	Automatic Train Control
ATO	Automatic Train Operation
ATP	Automatic Train Protection

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CCS	Command Control and Signalling
DGPS	Differential Geo-Positional System
ECC	Elliptic-Curve Cryptography
EKF	Extended Kalman Filter
ETCS	European Train Control System
FPGA	Field Programmable Gate Array
GLONASS	Global’naya Navigatsionnaya Sputnikovaya Sistema
GoA	Grade of Automation
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
I2V	Infrastructure to Vehicle
IMU	Inertial Measurement Unit
IoT	Internet of Things
ITS	Intelligence Transport System
KEM	Key Exchange Mechanism
KPI	Key Performance Indicator
MANET	Metropolitan Area Networks
ML	Machine Learning
MQTT	MQ Telemetry Transport
NIST	National Institute of Standards and Technology
OBU	On Board Unit
PQC	Post-Quantum Cryptography
RSSI	Received Signal Strength Indicator
S2R	Shift2Rail Initiative

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SME	Small and Medium-Sized Enterprises
TCMS	Train Control and Management System
TWR	Time Difference of Arrival
TEN-T	Trans-European Transport Network
UWB	Ultra-Wideband
V2I	Vehicle to Infrastructure
V2X	Vehicle to Everything
WSN	Wireless Sensor Network

1 Introduction (INDRA)

During the last decades, rail transport has been characterized for having a long haul and slow developments. However, in the past years the different European Initiatives as Shift2Rail [1][1] or ECSEL [2][2] have been able to include the last improvements and trend technologies to reach the current society needs for railways.

The irruption of new technologies (IoT, Cloud/Edge Computing and new V2X technologies) is increasing the number of devices connected due to the smartphones and vehicles connectivity developments. This involves:

- V2X Communication improvements such as the development of 5G and 802.11.bd for critical communications.
- The inclusion of IoT and Cloud/Edge Computing technology foreseen as one of the main technologies that will enhance all the rail management, development, operation infrastructure and resources in a short term.

All these connected elements bring us a big amount of available data, that together with the use of Artificial Intelligence allows to consolidate the enablers for ETCS L3 (Train Integrity, Absolute Safety Train Positioning and V2X communications) and to **develop new services** in order to improve safety and to increase the efficiency in railway operation.

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[1] Shift2Rail, as the first European rail initiative to seek focused research and innovation (R&I) and market-driven solutions by accelerating the integration of new and advanced technologies into innovative rail product solutions (2016–2023) that continues with ERJU (2023–2030) tries to address the new Rail Challenges by developing, integrating, demonstrating and validating innovative technologies and solutions following safety standards. To measure the value of these new solutions the S2R Multi-Annual Action Plan set the following key performance indicators [6]:

• 100% increase in rail capacity, leading to increased user demand;

• 50% increase in reliability, leading to improved quality of services;

• 50% reduction in life-cycle costs, leading to enhanced competitiveness;

• removal of remaining technical obstacles holding back the rail sector in terms of interoperability and efficiency.

• reduction of negative externalities linked to railway transport, in particular noise, vibrations, emissions and other environmental impacts.

[2] Addresed by the SCOTT Project use cases of railways [3].

SCOTT—Secure COnnected Trustable Things, Website: https://www.scottproject.eu.

In addition, the rail domain requires infrastructure and resources that are still expensive and require a long-time planning and execution. Therefore, the usage of the rail systems must be highly optimized, following strict security and safety regulations. **AI is the promising candidate**, identified as a trend technology in the following ten years by Gartner [4] to solve the limitations that were found in SCOTT, such as the lack of smoothing mechanisms in train coupling that provide comfort and safe conditions to the passengers and cargo, or the interconnection between rail traffic and road traffic in the smart city environment.

The SCOTT project following the ECSEL objectives, was focused on improving the rail systems capabilities in a safe and secure manner. However, the functionalities could be improved by moving the focus to the passenger's comfort and cargo security.

Using these key indicators and taking the Shift2Rail Innovative Programmes as a reference in the railway domain works, and based on SCOTT results, the project aims to continue the development of key technologies including AI to foster innovations in the railway domain and allocate the control resources in a more efficient way.

Moreover, in the project, the capacity of the railway systems to collaborate with other domains is one of the main strengths. Specifically, in a smart city environment, for the multi-modal traffic control it is essential to work in a cross-domain between rail and road, implementing AI mechanisms to allow a safe and secure management of the controlled area.

The scope of the project concerning the railway domain can be accomplished by improving safety and security, ensuring connectivity of all the railway systems, t by tackling the following objectives:

- Improve the Infrastructure management by increasing **the safety and security for both passengers and cargo**, providing clever, decentralized and flexible systems to enhance and substitute the Control Command and signalling (CCS) systems.
- Provide connectivity among maritime, road and rail domain through a full cargo manifest management, making use of a secure integration platform for the operators of different domains.
- Provide **safe and secure I2V/V2I communication** technology fully compatible with rail communication standards able to broadcast relevant information to different types of vehicles (train, cars) and the infrastructure in a trustable and smart way.
- Keep the **human user in the loop** during design, development, and evaluation to ensure safe, acceptable, and trustworthy overall performance of the system.
- Improve the flexibility on the rail and automotive domain, by increasing the efficiency in the decisions by making use of Edge-based Artificial Intelligence mechanisms to manage multimodal jam, providing interoperability in the smart city environment.
- **Increase the digitalization** in the railway domain to decrease costs and bureaucracy for EU citizens.
- Address social challenges through the **improvements over the electronic components and systems involved in the railway infrastructure**, increasing the globally competitive in the European Union by means of the Use Cases developed.

- **Inclusion of Small and Medium-Sized Enterprises** (SMEs) in the developments to reinforce solutions.

2 The Use Cases (INDRA)

2.1 T5.7 Intelligent Transportation for Smart Cities

The aim of this UC to use Artificial Intelligence (AI), making use of the system that priory among the rail and other different urban stakeholders, to enhance the control of the urban traffic. The integration of wireless technologies with AI is used to support V2X secure communications in the development of smart rail services based on Metropolitan Area Networks (MANET).

Current railway infrastructures coexist with other domains in urban environments where traffic events may occur. This UC aims to spread these developments to build, making use of AI, a smart management system for urban traffic control. This improvement on urban traffic management will reduce the number of injuries and human losses, by increasing safety and security in the railway lines due to the direct communication between the railway and other domains.

The urban traffic management system must make the decisions considering the information provided by all the different domains, (rail and road). Increasing the intelligence of the decision maker, the traffic jams in urban areas will be managed in a more effective way, making use of Artificial Intelligence mechanisms to develop the trustable decisor (Fig. 1).

Fig. 1 Smart city transport—UC overview

The innovation of this solution is based on:

- Increasing the communication between all involved actors in the specific critical area for considering as much data as possible before assigning priorities to a specific actor in an intelligent way.
- Enhancing the management of cross-domain areas making use of Edge-based AI mechanisms.
- Managing multimodal jams.
- Improving the efficiency on the rail and automotive domain, by increasing the efficiency in the decisions.

The aim of the UC5.7 is focused on the development of a decision-making system, which makes use of an AI mechanism to manage the traffic jams, improving road and rail traffic in the cities and maintaining the trustability of the system.

The developments carried out in this UC are based on previous works performed in SCOTT and DEWI projects.

Along the European railway lines, there are many critical scenarios where several accidents occur every year. Many of these are located on the level crossing, where different actors such as pedestrians or vehicles are involved. During 2017 in Spain, just the incidents in the level crossings, both with and without safety barrier, rise to 25 cases according to the annual report performed by the "*Agencia Estatal de Seguridad Ferroviaria*" [5].

The rail operators are interested in increasing safety in the critical points making use of the new technologies due to most of these scenarios not being able to eliminate the risk. In fact, a new system called Trustable Warning System (TWS) will be brought to the market in the coming years for managing critical scenarios such as level crossings or working areas through the use of wireless communications [6].

All these explained innovation works allow an efficient implementation of smart, trustable, safe, and secure systems for rail automation that:

- Increment the safety in critical scenarios such as level crossings.
  - by providing intelligence to the trustable decisor
  - by increasing the communication between actors in critical scenarios
- Enhance management of the cross-domains areas
  - by establishing priorities
  - by managing multimodal jams
- Minimize the CAPEX/ cost
  - by implementing wireless solution
- Improve the reliability, safety and security of the system:
  - by applying safety and security rules and directives for a reliable communication between the urban stakeholders involved.
  - by providing the specification for the safety and security requirements necessary for the use of distributed AI mechanisms.

2.2 T5.8 Intelligent Automation Services for Smart Transportation

This Use Case aims to improves automation for operation for different rail services making use of Artificial Intelligence. The use of wireless technologies with AI developments is used to support V2X secure communications and to enhance V2V communications for coupling compositions.

Specifically, this Use Case is focused on the use of Artificial Intelligence for automating the smoothing of coupling and uncoupling processes, the grade of automation by improving ATO and ATP mechanisms and the security at V2X communication level.

The works performed in SCOTT Virtual Coupling [7]—that provide a solution that implements a safe and secure wireless virtual coupling—do not resolve a specific issue related to the comfort of passengers and the cargo safe trip during the coupling mode. The mechanisms to couple the trains require a certain level of automation with a specific timing. This timing completely covers the technical requirements to successfully couple and uncouple the involved trains. However, once the coupling process is performed, the distance between trains can suffer abrupt changes due to the variation of the speed and the acceleration/deceleration. These events may affect passengers' comfort and certain types of cargo operation can be affected.

Following X2RAIL-3 Virtual Train Coupling System concept [8] and to avoid these consequences over the passenger trains or the cargo, the procedures that keep the trains coupled must be smoothed. Increasing the intelligence in the automation procedures involved through Artificial Intelligence methods, these consequences can be solved or at least reduced. These can make the travel experience more comfortable for the train passengers. In the case of freight trains, the smooth of the process of speed variation can reduce the damage over the cargo. Furthermore, the inclusion of AI in the works developed in SCOTT project may allow the increase of line capacity and optimize the track occupancy (Fig. 2).

In this way, this Use Case aims to make use of Artificial Intelligence to improve the Automatic Train Operation (ATO) which is mainly used on **automated guideway transits** and **rapid transit systems** where is easier to ensure safe rail operations improving the rail capacity lines.

The innovation of this solution is based on:

- Improve flexibility by connecting all involved stakeholders by means of an automated and distributed system.
- Provide mechanisms to improve network capacity with a safe, secure and trustable system.
- Decentralize the control of decisions making use of AI.
- Provide optimal control forecasting of all the devices of signaling systems along the railway track, by connecting all to all.
- Smooth the speed change processes to allow a more practical and safe coupling process.

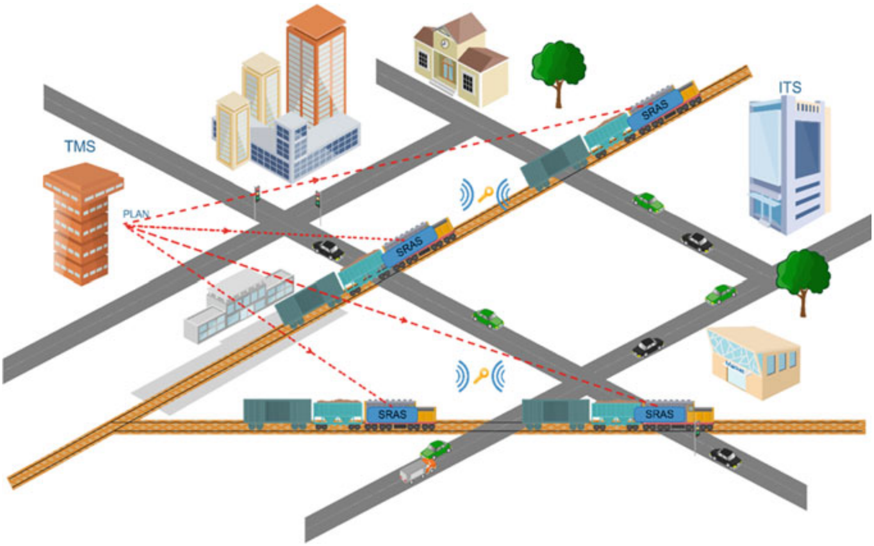

Fig. 2 Intelligent automation services for smart transportation—UC overview

- Implement AI technology to improve coupling, traveling and uncoupling phases.

This Use Case focuses on the automation of different train operation processes making use of Artificial Intelligence. The analysis of current technologies concerning the smoothing of virtual coupling and enhancing of ATO, ATC and ATP systems and the different grades of automation is needed to previously define the grade of automation that the system must reach.

The integration of existing technologies and new ones to enhance the automatic train operation to make the difference in the railway market. By improving functionalities such as speed control, timing control of the stops and decentralizing the decisions, it is possible to enhance the current state of the railway transportation, having an important impact in the railway market.

Moreover, the use of AI mechanisms to improve the deployment of smoother virtual coupling maneuvers during the trip will help to make the speed changes processes more comfortable for the passengers and safer for the cargo.

The development of this use case must accomplish the objective of solving or reducing the drawbacks and comfort for passengers and certain types of cargo operations in a safe and secure way. This will directly have an impact on the railway traffic, giving a new vision to the market concerning the possibility of reducing risks and improving the line capacity by making more efficient and comfortable coupling and uncoupling maneuvers.

Moreover, this development has to accomplish the objective of increasing the grade of automation of both the Rail operations and infrastructure, by implementing safe and secure capabilities. This will have an important impact in the market, allowing the implementation of a trustable system which enhances the features of current ATO and ATP systems by using AI, introducing IoT concepts in the railway market to make it more competitive.

All these explained innovation works will allow an efficient implementation of smart, trustable, safe and secure systems for rail automation that will provide:

- The increment of the efficiency of the rail infrastructure and the On-Board systems:
  - by the inclusion of automating the coupling and uncoupling maneuvers along the tracks, via Artificial Intelligence.
  - by smoothing these processes and making them comfortable for the rail users, both for passengers and freight lines.
- The progressive conversion of conventional lines into ATO lines:
  - by providing intelligence to the railway traffic processes connecting all to all
  - by increasing the grade of automation of rail operation and infrastructure
- Improvement of the system flexibility:
  - by introducing the automation of the CCS
  - by including distributed solutions to efficiently manage the exchange of information
  - helping to acquire major capacity and improving the timetable adherence due to a more efficient traffic management (i.e., minimizing unexpected train stops or reducing the safe distance between trains).
- Major capacity and improved timetable adherence for a more efficient traffic management:
  - by minimizing unexpected train stops
  - by safely reducing the distance between trains
- Improvements on the reliability, safety and security of the system:
  - by applying safety and security rules and directives for reliable communication between the infrastructure and the trains.
  - by providing the specification for the safety and security requirements necessary for the use of distributed AI mechanisms.

3 The Platform (INDRA, JIG)

To be able to perform and implement the different use cases Indra has make use of a common framework based on an IoT Platform developed in SCOTT, to deploy the different modules providing native communications through the different subsystems enabling to collect, fuse, enrich and exploit all the data on the edge or in the cloud following the safety, security and privacy levels required for the different systems.

The SCOTT project is built on the excellent basis of the predecessor project DEWI[3] and thereby, among others, reuse and extend the well-established DEWI Bubble concept and the related, ISO 29182 compliant multi-domain high-level architecture [9]. Within the DEWI project key solutions for wireless seamless connectivity and interoperability in smart cities and infrastructures were developed. DEWI was started in March 2014 as part of the ARTEMIS Joint Undertaking and ended in April 2017.

The DEWI bubble concept, the defined DEWI high-level architecture as well as the DEWI technology items, has been used as a starting point for systems development within SCOTT and can be seen as the continuation of DEWIs' technology solutions.

Complementary to DEWI the SCOTT project (2017–2020) puts additional focus on:

- extending and connecting Bubbles and integrating distributed Bubbles into the Cloud
- extending the high-level architecture concerning security, trustworthy and cloud integration
- the development of safe and secure solutions for wireless distributed systems: implementing a meta-bubble layer where multiple bubbles need to cooperate in deterministic (real-time) and secure way to establish systems in distributed locations
- elaboration of new approaches for secure distributed cloud integration—extending DEWI high-level architecture
- developing secure and trustable applications coming from new domains such as Health and Home (besides commercial/public buildings)

InSecTT goes a significant step further:

- **Bring Internet of Things and Artificial Intelligence together ("Artificial Intelligence of Things", AIoT)**
- **Move AI to the edge**, i.e., provide **intelligent processing** of data applications and communication characteristics **locally at the edge** to enable **real-time and safety–critical** industrial applications
- Develop **industrial-grade secure** and **reliable solutions** that can cope with cyberattacks and difficult network conditions
- Enable **AI-enhanced wireless transmission**
- Provide trust measures for user acceptance, **making AI/ML more explainable** and not just a black box that cannot be understood
- Provide **re-usable solutions across industrial domains** (Fig. 3)

The SCOTT IoT Platform—Fig. 4—results grant to InSecTT the necessary components to develop and deploy the different AI modules and to interconnect all the diferent subsystems (On-Board, On-Track deployments) on the different domains (Rail, Road) including the simulation and validations tools.

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[3] DEWI—Dependable Embedded Wireless Infrastructure, Website: http://www.dewiproject.eu/.

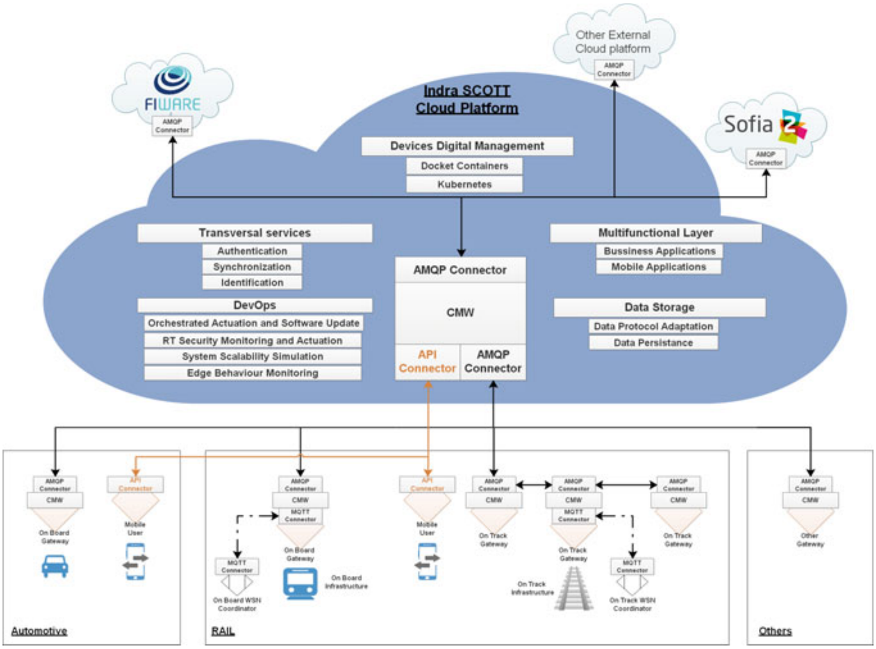


Fig. 3 The Indra IoT platform

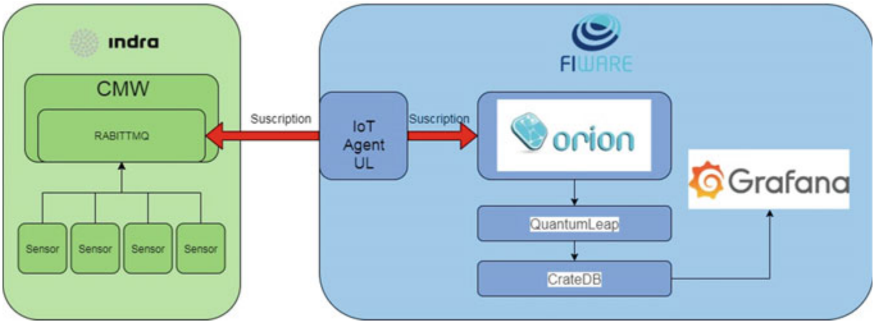


Fig. 4 Indra IoT platform–FIWARE integration

This platform has been essential to provide more than 30 millions of messages to the different AI modules (provided by different On-Board and On-Track subsystems) to be exploited for training and fine-tuning of the different AI modules.

To develop the applications and related services, an integration between the platform provided by Indra and a service structure based on Fiware has been carried out.

FIWARE [10] is an open-source initiative that aims to promote the creation of standards necessary to develop Smart applications in different domains: Smart Cities, Smart Ports, Smart Logistics, Smart Factories, among others. Any Smart application is characterized by collecting relevant information for the application from different sources about what is happening at any given time. This is known as “context information”. Current and historical context information is processed, visualized and analyzed on a large scale.

To integrate Indra and Fiware environments, the Fiware IoT Agent UL 2.0 has been used. This IoT Agent allows to convert AMQP communication protocol into MQTT, essential to use the CE Context Broker, and the communication between both environments:

To complete the environment, different Dashboards and a Mobile application have been developed.

The end-user application developed in the project has the following objectives:

- Control unassembled rolling stock: positioning, wagon details, tractor heads, etc.…
- Control of moving composite trains by mapping with points generated from GeoServer.
- Control and warnings on the sensor system installed on the train and connected through the WSN.

Figma framework has been used for the design of the application, on which the designs have been generated in a modular way. In this way, the components of the application can be reused to build new functionalities from these same components.

The design of the application contains the following functionalities:

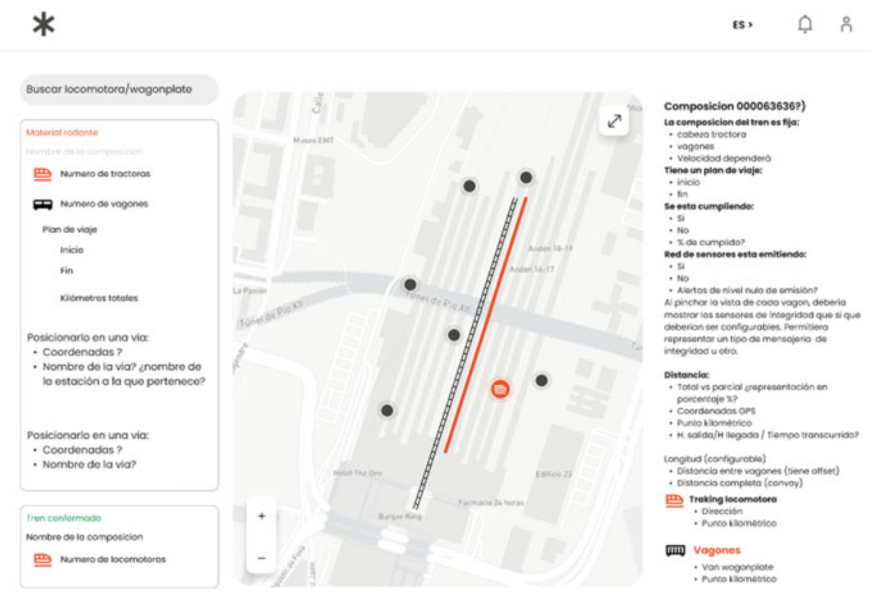
- Control of unassembled rolling stock: Here, wagons and tractor units are controlled before the composition of the train, as it is show on Fig. 5.
- Management and control of the trainsets and associated sensors: From this view the composed trainsets are monitored, as it is show on Fig. 6.

By selecting the desired train, the details of the start, destination and intermediate control points of the train are monitored, as well as the status and metrics of the different sensors installed, as it is show on Fig. 7.

In addition, different control panels have been designed for real-time monitoring of the different data captured both from the sensor networks deployed and from the different subsystems; as well as for their subsequent analysis to verify the different developments implemented, as it is showned on Fig. 8 where it is presented an example of train composition, train integrity and train length dashboard.

4 Relevant AI Enablers Developed (INDRA)

Artificial Intelligence and Machine Learning are in a strong growing phase, making significant advances in difficult pattern recognition tasks [11]. But these current successes have largely come from systems that run on central servers with abundant computational and memory resources. When deployed on IoT systems, application



Buscar locomotora/wagonplate

Material rodante

Nombre de la composicion

Numero de tractoras

Numero de vagones

Plan de viaje

Inicio

Fin

Kilómetros totales

Posicionario en una via:
- Coordenadas ?
- Nombre de la via? ¿nombre de la estación a la que pertenece?

Posicionario en una via:
- Coordenadas ?
- Nombre de la via?

Tren conformado

Nombre de la composicion

Numero de locomotoras

Composicion 000063636?)

La composicion del tren es fija:
- cabeza tractora
- vagones
- Velocidad dependerá

Tiene un plan de viaje:
- inicio
- fin

Se esta cumpliendo:
- Si
- No
- % de cumplido?

Red de sensores esta emitiendo:
- Si
- No
- Alertas de nivel nulo de emisión?

Al pinchar la vista de cada vagon, deberia mostrar los sensores de integridad que si que deberian ser configurables. Permitiera representar un tipo de mensajeria de integridad u otro.

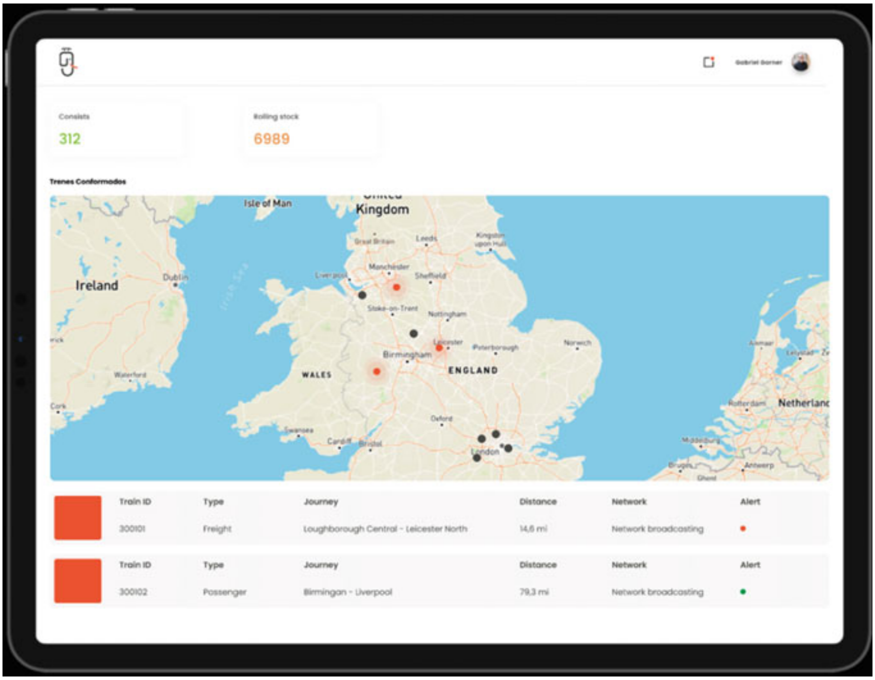
Distancia:
- Total vs parcial ¿representación en porcentaje %?
- Coordenadas GPS
- Punto kilométrico
- H. salida/H llegada / Tiempo transcurrido?

Longitud (configurable)
- Distancia entre vagones (tiene offset)
- Distancia completa (convoy)

Traking locomotora
- Dirección
- Punto kilométrico

Vagones
- Van wagonplate
- Punto kilométrico

Fig. 5 Rolling stock management



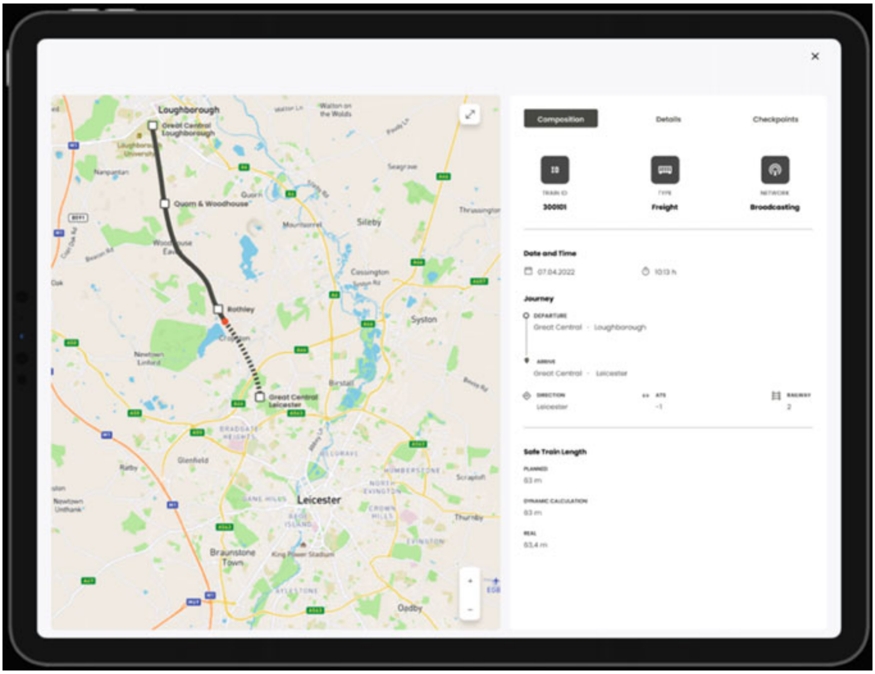
Consists
312

Rolling stock
6989

Trenes Conformados

Train ID	Type	Journey	Distance	Network	Alert
300101	Freight	Loughborough Central - Leicester North	14,6 mi	Network broadcasting	🔴
300102	Passenger	Birmingan - Liverpool	79,3 mi	Network broadcasting	🟢

Fig. 6 Train management



Composition Details Checkpoints

TRAIN ID
300101

TYPE
Freight

NETWORK
Broadcasting

Date and Time

07.04.2022 10:13 h

Journey

DEPARTURE
Great Central - Loughborough

ARRIVE
Great Central - Leicester

DIRECTION
Leicester

ATS
-1

RAILWAY
2

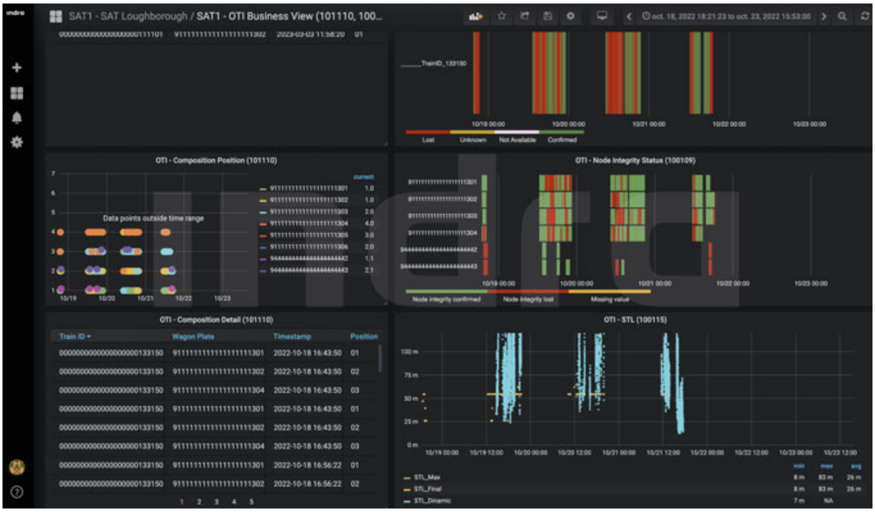
Safe Train Length

PLANNED
63 m

DYNAMIC CALCULATION
63 m

REAL
63,4 m

Fig. 7 Train detail



OTI - Composition Detail (101110)

Train ID	Wagon Plate	Timestamp	Position
0000000000000000000133150	911111111111111111111301	2022-10-18 16:43:50	01
0000000000000000000133150	911111111111111111111302	2022-10-18 16:43:50	02
0000000000000000000133150	911111111111111111111304	2022-10-18 16:43:50	03
0000000000000000000133150	911111111111111111111301	2022-10-18 16:43:50	01
0000000000000000000133150	911111111111111111111302	2022-10-18 16:43:50	02
0000000000000000000133150	911111111111111111111304	2022-10-18 16:43:50	03
0000000000000000000133150	911111111111111111111301	2022-10-18 16:56:22	01
0000000000000000000133150	911111111111111111111302	2022-10-18 16:56:22	02

1 2 3 4 5

Fig. 8 Train composition, train integrity and train length dashboard successes rely on high bandwidth connectivity, and very loose latency requirements for decisions. Industry, however, is now realizing the need for diverse applications that can run at very low latencies, and this will require new algorithms and models that can be deployed at the edge of the network, or on client devices. This has led to the rise of **fog computing** as a technology (e.g. [12]), and industry is now developing new architectures, capable of running on devices with limited CPUs and memory (e.g. [13, 14]). In addition, as **intelligence and autonomy** are being pushed out to the edge or to the device, there is a need for coordination of, and collaboration between, these intelligent systems, possibly in real time**. Distributed AI, or Multi-agent reasoning, is a well-established research discipline** (e.g. [15, 16]), but again relying on loose latency requirements and with few constraints on communication.

AI Managing and Monitoring IoT Systems and Simulations

Monitoring and managing the vastly increasing amount of IoT devices in operational and development phases is an ongoing challenge, which is yet to have harnessed the potential of AI/ML. Operational system status covers security, performance, device, and data integrity issues. In the development phase, comprehensive simulations for the interactions between different IoT devices and environment are necessary. AI solutions allow automatic realistic test case generations as well as automated evaluation of simulated performance under different conditions. Many solutions exist in providing management and monitoring of IoT systems and simulations, which are reliant on pre-defined rules input by humans. Deploying different machine learning methods and/or deep learning has great potential for increased efficiency and less reliance on human interaction.

Distributed AI on Edge Architecture

There is a clear need to develop reduced-order AI/ML models and algorithms which can be executed on resource-constrained devices. Further, there is a need for a general framework which can determine efficient placement of computational responsibilities over the end-to-end device-edge-cloud architecture. This may involve models trained in the cloud and then reduced and deployed on the edge, or it may require collaborative AI systems which execute what they can at the edge and communicate boundary cases along the chain for higher-powered processing.

Trust Framework for AI/IoT Development

InSecTT will provide a trustable framework for evaluating and developing trusted AI solutions. InSecTT will extend existing principles for trustworthy AI (such as transparency, controllability, and predictability) and generic Trust Framework created in the SCOTT project for providing models in addressing trust issues and trust requirements in AI operations used in IoT/Cyber physical systems.

4.1 AI Mechanisms for T2X Communications Systems (INDRA, EPS-MU, MTU)

The scenario is focused on the Adaptable Communication System (ACS), following X2RAIL-1 [17], X2RAIL-3 [18] works executed in Shift2Rail, to be used into a vehicle and the treatment of the communication system interfaces to reach a service specified accuracy. The figure shows, in a graphical perspective, the procedure to follow in the scenario. All the solutions, both in receiver and transmitter sides, exchange all the signalling information available for each of them to be able to select the channel in a coordinated manner. This data is provided to the AI modules to make the channel selection in a coordinated manner with the other side (Fig. 9).

Concerning the T5.7, sub-BB 3.4.1. "*Intelligent Routing Platform*", a decision maker has been developed to make dynamic decisions about the best channel for wireless communications. The selection is based on communication system metrics and rail KPIs using AI and ML methods. For this purpose, it is required to receive the output of the sub-BB 3.3.1 that provides precise information in real time from the different communication systems. The output of these modules is the communication system selected for each interface (V2I/I2V communications, Public Communication System, etc.).

During the project, INDRA has worked on studying the Multi-Access Management Services (MAMS) protocol as an Adaptable Communication System (ACS) selector when several networks are involved. In this type of scenario, a user can be simultaneously connected to multiple networks using different access technologies and network architectures that offer different QoS capabilities variable in time. The management of these scenarios nature is the motivation to use MAMS.

The smart selection of the network channel improves the QoS of the user. Focusing on the ACS scenario where it is deployed, it is not static since it is a transportation environment, so the characteristics of the available networks are constantly changing at each moment.

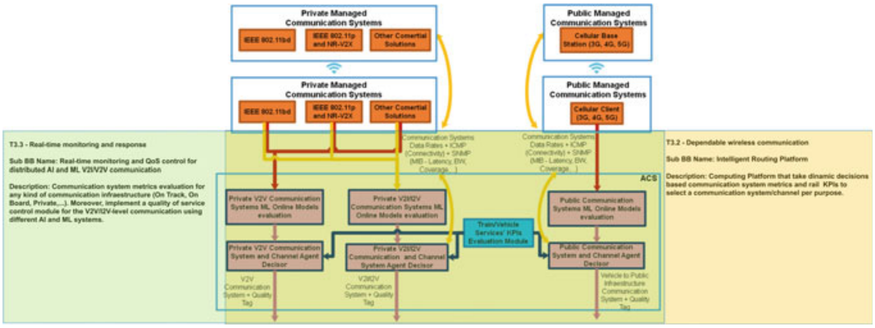


Fig. 9 T2X communication system architecture

The MAMS framework gives a solution for managing multi connectivity scenarios. The mechanisms used are not dependent on any protocol, since the idea of MAMS is to complement the existing ones giving a way to negotiate and configure them to enhance the use of the network. The fact that MAMS framework does not depend on the access technologies, allows the implementation to be change-proof regarding future new protocols and mechanisms. To know which network should be selected, the networks will be constantly monitored to ensure the best channel selection.

Has been concluded that the requirements of the MAMS framework to cover the ACS functionalities are as follows:

- Access-technology-agnostic interworking: the type of technology used by the network does not have to be relevant to the system.
- Independent access path selection for uplink and downlink: the communication should be able to be through different networks for uplink and downlink.
- Adaptive access network path selection: all the available networks must be monitored to select the best one considering delay and capacity.
- Multipath support and aggregation of access link capacities: it must be able to enable simultaneous paths. The aggregation must support existing protocols.
- Lossless path switching when changing from one connection to other, the framework should ensure mechanisms to receive messages in order.

The intelligent routing platform solution based on TBB3.4 and adopted in UC5.7 lead by INDRA in collaboration with the MTU and EPS- MU. INDRA has overseen designing and defining the high-level architecture based on the UC context and the development. Besides the identification of the requirements and definition of the KPIs, the developments has been also supervised as well as the different tests.

This development is a part of the intelligent routing platform module, which serves for both the scenarios of UC5.7 and UC5.8. However, in this case it has been focused on the Vehicle-to-Anything (V2X) communications. It is about the development of a hybrid vehicular communication platform, aka Multi-Radio Access Technology (multi-RAT) for vehicular communications. EPS-MU understands Dependability as a measure of availability and reliability, and in the field of wireless communications is governed by:

- Coverage probability of the network,
- Latency of data transmission, and
- Transmission error probability.

EPS-MU aims to address each of them by developing a vehicular communication platform which:

- Implementation of BS/RSU capabilities to enhance coverage (multi–Radio Access Technology in the 5.9 GHz band: 802.11p and C-V2X),
- Implementation of Edge node capabilities to decrease latency of data transmission, and

- Implementation of next generation Dedicated Short Range Communication protocol (specification under development in ETSI).

Because of the requirements of INDRA on the use of MAMS protocol, another bullet point has been added to the list, *implementation of the MAMS protocol on a virtual environment*, in close cooperation with MTU.

These actions have been reported within WP3 BB3.2 deliverables and a set of 21 requirements have been defined by EPS-MU. The results obtained from these methods have been important for the Adaptable Communication System (ACS).

This submodule will be used for testing AI algorithms also developed within InSecTT, with the aim of estimating the currently available data rates, and will make a near future prediction about how these data rates will develop. Additionally, to this AI functionality, EPS-MU initiated collaboration with ISEP, in relation to AI algorithm identification for channel prediction purposes. Yet this latter solution is in an early developing stage and thus has not been integrated into the ACS.

INDRA together with MTU and EPS-MU developed the smart router in the SCOTT project, whose objective was to select the best of the 3 protocols to carry the train-ground/ground-train/train-train communication.

In the context of this use case, sub-BB 3.3.1 "*Real-time monitoring and QoS control for distributed AI and ML V2X*" is about the development of AI and ML methods to monitor and control V2X communication links. The output of these methods is important for the Adaptable Communication System (ACS) to decide which communication links to use to fulfil the use case service KPIs. For each of the communication links that are available to the vehicle, AI algorithms estimate the current available data rates, and will make a near future prediction about how these data rates will develop. The AI algorithms used here will be online learning methods, for example based on Online Support Vector Regression (SVR), that take available link quality parameters as input. The link quality parameters to be used depend on the technology used on the link (e.g., 4G, 5G or other technologies).

4.1.1 Results

Within the scope of the ACS module development work, AI methods for uplink data rate estimation and interface selection have been developed with a focus on cellular networks, in particular 5G. Compared to earlier technologies such as 3G and 4G, data rate estimation based on link quality parameters is more challenging in current 5G deployments as these are usually 5G NSA (non-standalone), which means they rely on a 4G network for management and signaling and only use the 5G carrier for the actual data traffic. This challenge, as well as the proposed solutions and achieved results for data rate estimation and interface selection, are discussed in detail in the chapter "AI-enhanced Connection Management for Cellular Networks".

With the development of the MAMS protocol, the decision module of selecting an interface was moved from the onboard systems to the cloud. The onboard systems, running a MAMS CCM, report the outcome of data rate and latency estimation to a cloud server running a MAMS NCM, and the cloud server responds by matching them to required KPIs and decides which interface to use, based on the reported parameters and the KPIs. The decision is then sent back to the onboard system via MAMS, and the onboard system switches between interfaces accordingly. This setup was tested by deploying the onboard system in a car, deploying a stationary IEEE 802.11p device as a roadside unit, and then driving the car on a route which featured areas with and without connectivity to the roadside unit. Estimated data rates and latencies, as well as interface decisions, were stored on the cloud server during the tests.

The data that was stored during the test has then been analysed to verify whether the outcome of the interface decision fulfils the KPIs as required. Figure 10 shows the evolution of the latency over time. In the first graph, the latency of the selected interface is plotted, where it is always lower than the maximum level defined for the KPI. The graph below shows the latency for each interface. Comparing with the selection, it can be confirmed that the NCM is able to change CCM's configuration when the interface—in use—no longer fulfils the requirement (in this case, changing from 802.11p to 5G NR). In a similar way, Fig. 11: Data rate for the selected interface (top) and data rates of all available interfaces (bottom) shows the data rate, where the selected interface is always above or the same as the minimum level set in the KPI. Both figures also show that the selected interface KPI is not always optimal, as the routing criteria is giving different priorities for each interface, but these priorities are only applied when multiple interfaces meet the requirements. The priority list used in these tests is [802.11p, 5G NR, LTE, 3G], giving higher priority from left to right.

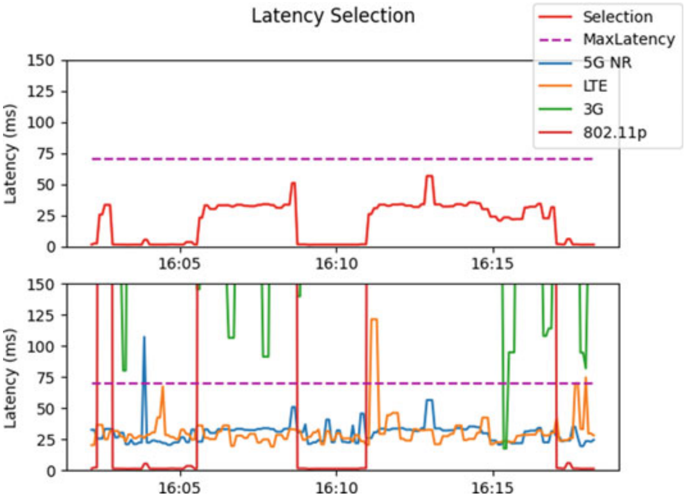


Fig. 10 Latency for the selected interface (top) and latency for all available interfaces (bottom)

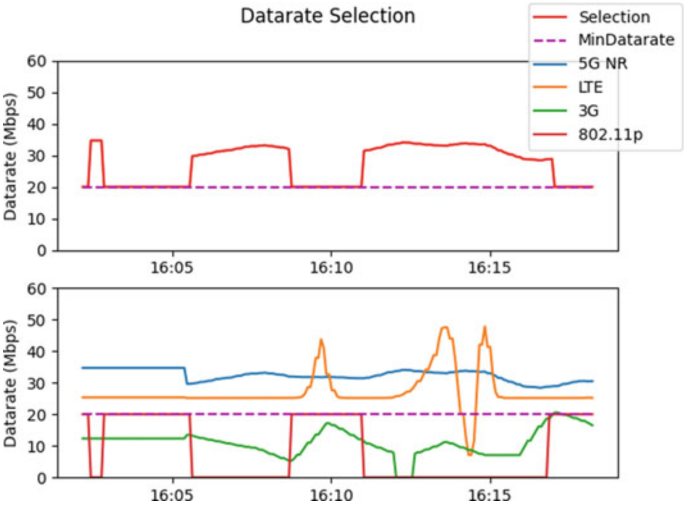
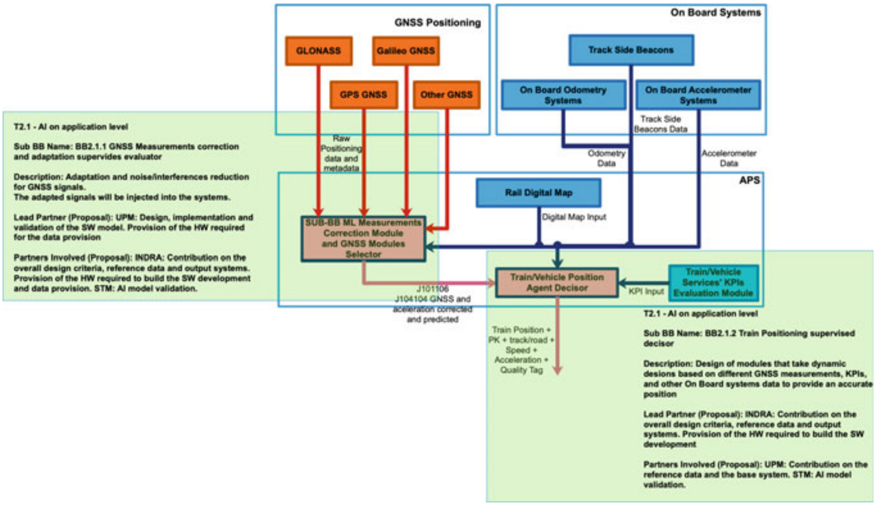


Fig. 11 Data rate for the selected interface (top) and data rates of all available interfaces (bottom)

4.2 AI Mechanisms for Train Positioning System (INDRA, UPM)

Two differents TBBs have been designed and implemented: GNSS Measurements correction and adaptation evaluator and Train Positioning supervised decisor as depicted on the following Fig. 12.



T2.1 - AI on application level

Sub BB Name: BB2.1.1 GNSS Measurements correction and adaptation supervides evaluator

Description: Adaptation and noise/interferences reduction for GNSS signals.
The adapted signals will be injected into the systems.

Lead Partner (Proposal): UPM: Design, implementation and validation of the SW model. Provision of the HW required for the data provision

Partners Involved (Proposal): INDRA: Contribution on the overall design criteria, reference data and output systems. Provision of the HW required to build the SW development and data provision. STM: AI model validation.

T2.1 - AI on application level

Sub BB Name: BB2.1.2 Train Positioning supervised decisor

Description: Design of modules that take dynamic desions based on different GNSS measurements, KPIs, and other On Board systems data to provide an accurate position

Lead Partner (Proposal): INDRA: Contribution on the overall design criteria, reference data and output systems. Provision of the HW required to build the SW development

Partners Involved (Proposal): UPM: Contribution on the reference data and the base system. STM: AI model validation.

Fig. 12 Train positioning system architecture

The current Autonomous Positioning System (APS), which was developed in SCOTT project, is only based on Global Position System (GPS). To fulfil the positioning requirements and provide a more accurate measurement, the need to develop a generic Global Navigation Satellite System (GNSS)[4] measurement evaluator has been identified.

This first TBB is focused on improving the GNSS signal quality of the positioning system by reducing interferences and noise generated. This is made making use of AI techniques to fuse the input GPS signal with measurements from odometers and inertial measurement units to obtain a corrected positioning signal.

Aid the selection of the GNSS source as well as to perform an initial noise and interference reduction stage.

The module will receive signals in real time from different GNSS systems such as Global Position System (GPS), Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS), and/or Galileo to analyze, evaluate and correct them. It also receives measurements from the odometry system and the On-Board accelerometers to be fused with the selected GNSS source.

The main objective of the second TBB (the decisor) is to dynamically decide the best GNSS source based on multiple KPIs. The best selected source will also be corrected and predicted, using on-board systems, as in the previous TBB, to properly locate the train. The GNSS sources that are considered in real time by the decisor are Global Position System (GPS), Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS), and/or Galileo.

The output will also be a digital map that allows the driver to know the real-time position in a graphical way including relevant data (legends) such as the kilometer point, the direction of the railroad track, the speed and/or the acceleration.

The positioning decisor solution based on TBB2.1 and adopted in UC5.7 has been developed by INDRA in collaboration with UPM. INDRA has overseen the requirement identification, high-level architecture design and specification as well as of providing the required datasets related with this module. UPM has developed and implemented the final module. Finally, INDRA has validated on real scenarios the different developments and implementations integrating the different submodules making use of X2RAIL-4 Demonstrator resources.

4.2.1 Results

A solution for edge prototyping based on the Cookie IoT hardware platform [19] developed at the Centro de Electrónica Industrial of the Universidad Politécnica de Madrid, which maximizes the concept of flexibility, reliability and modularity, is proposed in this work. To enable fast, robust, and energy-efficient integrity loss detection, two different networks are established depending on the type of module mounted in the Cookie: a low-power GNSS module and an UWB module. The GNSS cookie version also reports the IMU and RSSI values.

The GNSS module integrated within the IoT edge device a very low energy consumption, limiting its accuracy compared to other high end solutions. To enhance the accuracy of this approach, several solutions have been proposed.

GNSS Selector

The GNSS module can receive signals from GPS, DGPS, GLONASS and Galileo. By using range-based techniques to determine the position, the module can combine multiple signals to identify the satellites that offer optimal coverage in the current location.

To account for potential dynamic operation scenarios where not all system signals may be available, the operating mode of the GNSS edge device is selected, based on the quality of the signal, as determined by several parameters such as horizontal, vertical, and position dilution of precision. By monitoring these parameters in real-time, each node can determine and adjust its mode during operation. Furthermore, the coordinator also receives information about each node's active mode and quality of signal and can use configuration messages included in the routing protocol to set the thresholds of the algorithm or force a specific GNSS mode.

Extended Kalman Filter with Sensor Fusion

To overcome the disadvantages of fixed and irregular structures for track-side positioning, new approaches have been proposed, which fuse GNSS and IMU [20], resulting in what is known as sensor fusion. The reason they are used together is that the error provided by one system is reduced when integrated with the other, and vice versa. Traditional sensor fusion techniques come from the application of Bayesian filters such as the Extended Kalman Filter (EKF).

In this context, the Kalman filter is used to estimate the state of the measured element by processing a set of observations that contain both noise and uncertainty. The Kalman filter algorithm employs feedback to apply control and estimate the process. At any given time, the process state is predicted, and feedback is obtained through measurements, which incorporate noise and are weighted based on their certainty.

The system operates on the premise of correcting the measurements of the inertial system upon receipt of the GNSS signal, thereby preventing the accumulation of errors over time. In the absence of a GNSS signal, the EKF provides its solution integrating the IMU measurements. As a result, the fusion strategy provides a high update rate, a navigation solution in the event of GNSS absence and increased integrity, as faulty GNSS measurements will be detected and rejected.

Although the Kalman filter is a well-established technique for state estimation, especially when dealing with measurements incorporating noise, a major drawback is the requirement for prior knowledge of process and measurement noise statistics, since the variance of the Kalman filter is calculated as a function of the estimated variances. Therefore, the choice of the value of the fitting parameters makes a huge difference in the final state estimate.

For adjusting the filter and reducing the error of the output trajectory the STONEX S900 GNSS, a high precision GNSS receiver, has been used a reference ground truth, i.e. the “real trajectory”. The STONEX S900 is a GNSS receiver that is used for high-precision positioning applications. It works by receiving signals from multiple satellite constellations, including GPS, GLONASS, Galileo, and BeiDou, and using a differential positioning to improve the accuracy of the measurements. It compares the measurements from a reference station that provides the corrections for the accurate positioning.

In the first iteration, the filter is adjusted manually. To evaluate the effectiveness of the manual adjustment, the error in the trajectory is estimated with respect to the reference trajectory. This error metric is provided both as a mean value and over the entire path. This value is the module of the deviation at the time of the measurement, and the performance is based on its minimization. The aim of the manual adjustment is to reduce this error by varying the components of the R and Q matrices. First, the covariance matrix R, which measures variance in the GNSS position measurement, is modified. This modification consists of decreasing the value of the components of this matrix, with the aim of giving more weight to the correcting measurements, and thus making the output trajectory more similar to the one marked by the GNSS signals. Once the R matrix is estimated, the noise matrix, Q, is adjusted. It measures the variance of the acceleration and orientation variables. The effect of Q is related to the error of the process, i.e. how controllable it is and how well known it is. In other words, it informs about the noise of the model. If this deviation is taken to be zero, the estimates are assumed to be ideal.

The final stage of the tuning is focused on solving an optimization problem through the application of a genetic algorithm [21]. This process involves the use of a set of initial parameters that are the ones obtained from manual tuning. The proposed genetic algorithm, complying with Darwin’s theory of natural selection, obtains the vector of parameters that optimally adjusts the filter to the set of situations tested. The genetic algorithm is designed to generate offspring in each generation using an elitist strategy and mutation operators.

In the context of this problem, each individual would be a vector of component parameter values of the matrices R and Q. For the filter adjustment, the filter is run for each set of parameters and fitness is estimated according to the error between the estimated states and the actual values of the states. This error is measured with the same error function discussed previously. The type of genetic operator applied to solve the problem is the mutation operator. With an elitist strategy, we avoid losing the best individuals from each generation by copying them to the next generation. In our case, the top 10% of the population.

In the assessment of the integrated system’s positioning error, the evolutionary algorithm is utilized to optimize its performance in various scenarios. This is essential since the system can encounter multiple factors that may affect the accuracy of its results. Among these situations, the following cases have been tested:

- Periods of GNSS signal absence e.g. due to urban environments.
- Different vehicle operations on predominantly curved and predominantly straight sections.

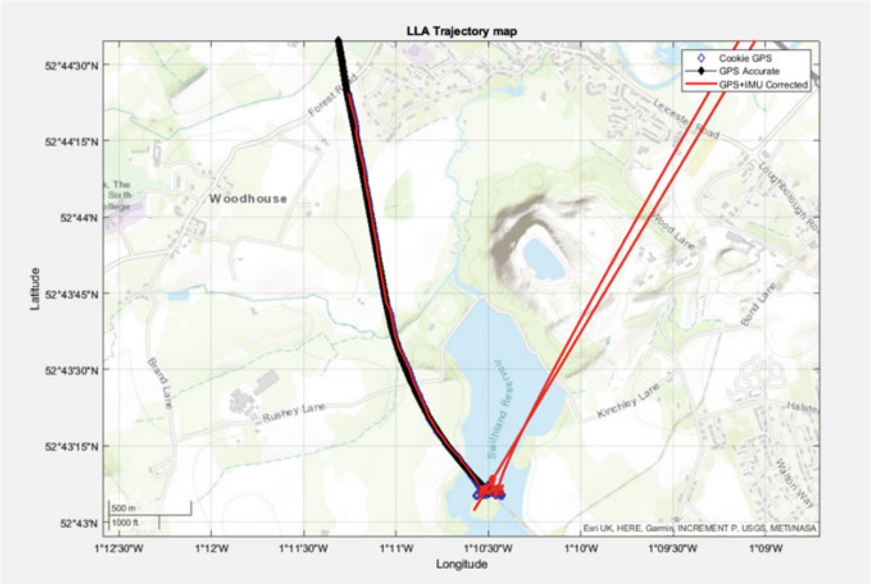


Fig. 13 Visualization of the IoT edge device and reference data collected in a railway

- Incorporation of ambient noise into the GNSS transmitted signal simulating the degradation of system accuracy caused by atmospheric changes, which affect the propagation of satellite signals.

The study evaluates several machine learning classification algorithms to identify the optimal Kalman parameter values for these different scenarios. In particular, a binary tree model is implemented to detect interruptions and noise in GNSS signals, achieving a success rate of 73%. Furthermore, the Naive Bayes method is utilized to detect vehicle maneuvers, with a success rate of 86% based on data obtained from the gyroscope and accelerometer. For all conditions, the obtained results show a reduction of the mean error of the trajectory with respect to the error without applying the Kalman filter (Fig. 13—Visualization of the IoT edge device and reference data collected in a railway).

With this filter and adjustment, a reduction in the mean error of 2.4117e-04 degrees has been obtained.

4.3 AI Mechanisms for Train Integrity System (INDRA, UPM)

The train integrity process has been developed in the SCOTT project based on a combination of all the outputs provided by the positioning sensors (UWB, GNSS, accelerometers) and the GNSS (Sect. 4.2) to generate a corrected estimation of the train integrity, following X2RAIL-2 [22–24] Shift2Rail project. However, this system does not consider the physical characteristics of the composition, which affects the calculation of the integrity. To improve the current system, this module processes the WSAN measurements (RSSI, Train Length, and Accelerometer) through an AI system to obtain a corrected and predicted measurement for the decisor.

The train integrity evaluator solution based on TBB2.1 and adopted in UC5.7 has been developed by INDRA and UPM.

The module requires the entry of different WSANs such as the RSSI, train length and accelerometer. Additionally, other WSAN as UWB could be integrated as is shown in the Fig. 14. The evaluator gathers information from the edge and as a result, we obtain the weighted measurement that will serve as input for the decisor.

The integrity process is essential for the system developed in the T5.7. Currently, the integrity is calculated through the collection of the edge nodes information that indicates the position of the wagons. This module enhances the present process by applying AI mechanisms that provide a precise measurement of the train length and train integrity based on the weights generated by the evaluator and the KPIs defined for each service.

The train integrity decisor solution based on TBB2.1 and adopted in UC5.7 lead by INDRA in collaboration with the UPM. INDRA has overseen the requirements

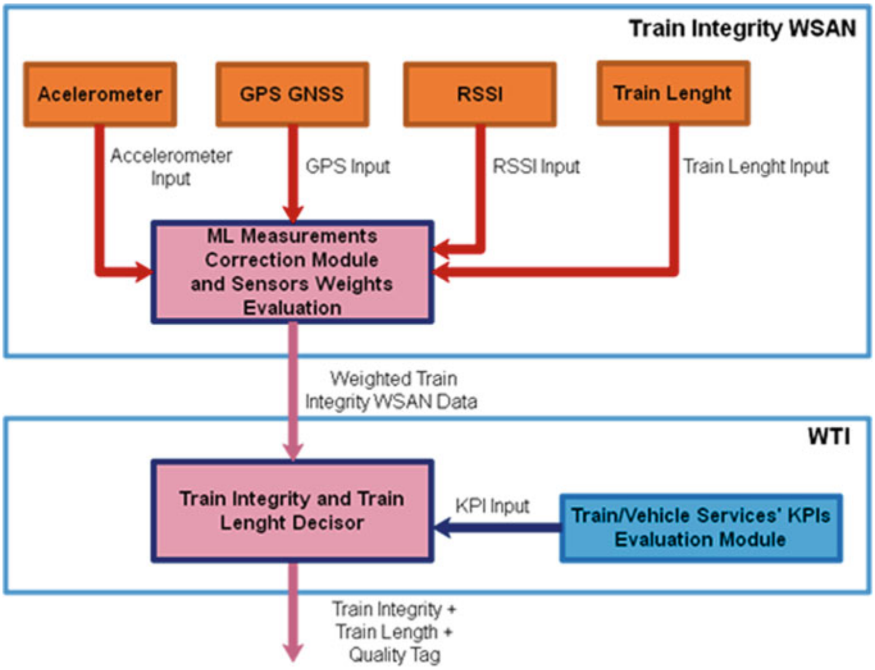


Fig. 14 Train integrity system architecture

definition and reference data provision, besides the execution tasks in a validation and verification layer. On the other hand, the UPM has contributed to the reference data and participated in the design and development tasks. Finally, INDRA has validated on real scenarios the different developments and implementation integrating the different submodules making use of X2RAIL-4 Demonstrator resources.

4.3.1 Results

To forward sensor reports, an optimized routing protocol over IEEE 802.15.4 for resource-constrained sensors is used, which enables the Wireless Sensor Network (WSN) to operate effectively even in unstable environments such as railway conditions. This protocol uses a multi-hop approach and adapts the network topology based on the RSSI value. This approach aims to reduce network overload by minimising the number of hops and ensures that the network can quickly reorganise in the event of node failure, thereby improving reliability.

All the data collected by the deployed WSNs is transmitted to the coordinators of the network, which serves as the anchor of the network and is located at the head of the train, which receives the packages and transmits the processed information to the central system of the train. The central system performs sensor fusion and provides the state of the composition. The proposed solution offers an effective and efficient approach to edge prototyping in the railway industry, but has been also identified as a potential solution for applications in other fields as well.

Communication between all the coordinators and the central system is established using IEEE 802.11 to enhance connectivity and robustness. Furthermore, to increase overall network robustness, two GNSS networks are deployed on both sides of the train, while two UWB WSNs are deployed between wagons. The nodes transmit at half the frequency of the coordinator to comply with the Nyquist-Shannon sampling theorem. This parameter can be configured in real time with configuration messages implemented in the custom protocol, along with other messages that enable power saving during non-operation windows and relative location message exchanges.

Prior to the integrity stage, it is necessary to determine the train composition, as each individual wagon may have distinct dynamic characteristics, such as weight, braking force or identification number. If the train composition remains constant, these parameters can be predetermined and fixed. Nevertheless, in cases of dynamic train compositions requiring wagon rearrangement, the use of WSNs can offer a flexible and economical solution to dynamically locate the composition's position. By implementing this approach, train compositions can be dynamically modified, leading to greater operational efficiency and adaptability.

This process takes place during the inauguration stage, which involves the identification of sensors that will transmit data during the integrity stage. At this stage, the position of the composition is determined based on the relative location of the nodes at that moment. Through the identification of transmitting sensors and their position, this process establishes the initial state of the composition, which is a prerequisite for the central system to accurately interpret the transmitted data.

To enable this relative positioning in environments where GNSS signals are not accessible and in static applications, a method that utilizes node sensor parameters that are intrinsically dependent only on the sensor node is proposed. To provide localization in outdoor environments without the need of dedicated hardware, this method utilizes RSSI and the topology of the network. For this use case involving trains, the linear topology of the train cars simplifies the localization problem by reducing its dimensions. Although RSSI is not typically a reliable parameter for accurate localization without dedicated hardware, in this particular case, the difference in length between train cars and the associated error in the position determined through the RSSI parameter provides enough accuracy for this relative localization problem.

The routing protocol utilized in this system is limited to only containing the parent MAC address and the number of hops for each node since it is designed for unstable environments. To obtain more information, custom messages are utilized, which include details such as the parent–child relationships between nodes, the number of hops along the route, and the RSSI value. By leveraging this additional information, the system's coordinator can determine the relative position of each node within the composition, enabling effective localization.

The systems were deployed in multiple tests carried out in the United Kingdom railway (Fig. 15—Deployment of Cookie node during tests conducted in the United Kingdom), verifying their functionality. Through the testing phase, any potential issues were identified and resolved. Consequently, the systems were successfully deployed and tested in a empirical setting, ensuring their reliability.

The UWB module, compliant with the Cookie architecture, implements the advantages of this technology. The wide frequency band used is ideal for unstable environments, since signals are spread and can resist interferences, increasing its reliability. Furthermore, low power consumption is a characteristic commonly found in this technology.

To determine integrity, the distance between UWB node and coordinator is determined with Two-Way Ranging (TWR), a range-based technique that uses the time

Fig. 15 Deployment of Cookie node during tests conducted in the United Kingdom

of flight of the signals. Since this is done in a wide band, a high precision is obtained with this technology. The value is received by the coordinator of this WSN and sent to the central system, where it is merged with the other sensor parameters.

The WSN utilizing UWB modules is deployed in the inter-wagon area, where a direct line of sight can be established. The system provides measurement reports with centimeter-level precision. To assess its performance, two mirror coordinator-node pairs are placed at the same joint.

4.4 AI Mechanisms for Object Detection System for Railways (INDRA, UPM)

The system developed in the T5.7 is mainly focused on enhancing the cross-domain areas as level crossings. Nowadays, a system known as "*Trustable Warning System*" (TWS) has been developed in SCOTT project to secure the critical areas in the tracks based on the object detection. However, this detection is only supported by the 3D-LIDAR sensor, which detects a set of objects previously defined and its speed.

This module integrates the data produced by RGB cameras and the 3D-LIDAR sensors to provide a set of relevant features from the objects visible in the scene. Among these features can be highlighted the mass and estimated weight of the object, its area and speed of movement, as well as the spatial composition of all the objects in the scene. The system is based on machine learning techniques.

The object selector solution based on TBB2.1 and adopted in UC5.7 has been developed by Indra and UPM (Fig. 16).

In surveillance systems, especially in high-risk areas like railway level crossings, object detection and object classification are crucial technologies. These systems need to accurately detect, track, and classify any object that enters into the monitored area in real-time to prevent collisions or accidents in the future. To address this need, the proposed solution is an edge IoT hardware platform that can detect, track, and classify objects in a railway level crossing scenario. The system calculates and transmits its response from the IoT platform to the train, triggering a warning action to avoid potential collisions.

The main objective has been to develop a reliable surveillance system for railway level crossings using a low-resolution LiDAR object detection and classification system that uses a single sensor and that is suitable for integration into a custom IoT edge node. The main innovation lies into the integrated implementation of LiDAR data management. To achieve this, a custom hardware platform including a Google Coral neural Accelerator and AM Cortex A5 processor has been used as the processing core element due to its trade-off between cost and performance.

To optimize computational resources and focus only on relevant areas, the object detection system first eliminates points outside the region of interest, which is the level crossing area. The frame is then projected onto a 2D plane in order to further optimize resource usage. As this is a static application, a golden background is stored

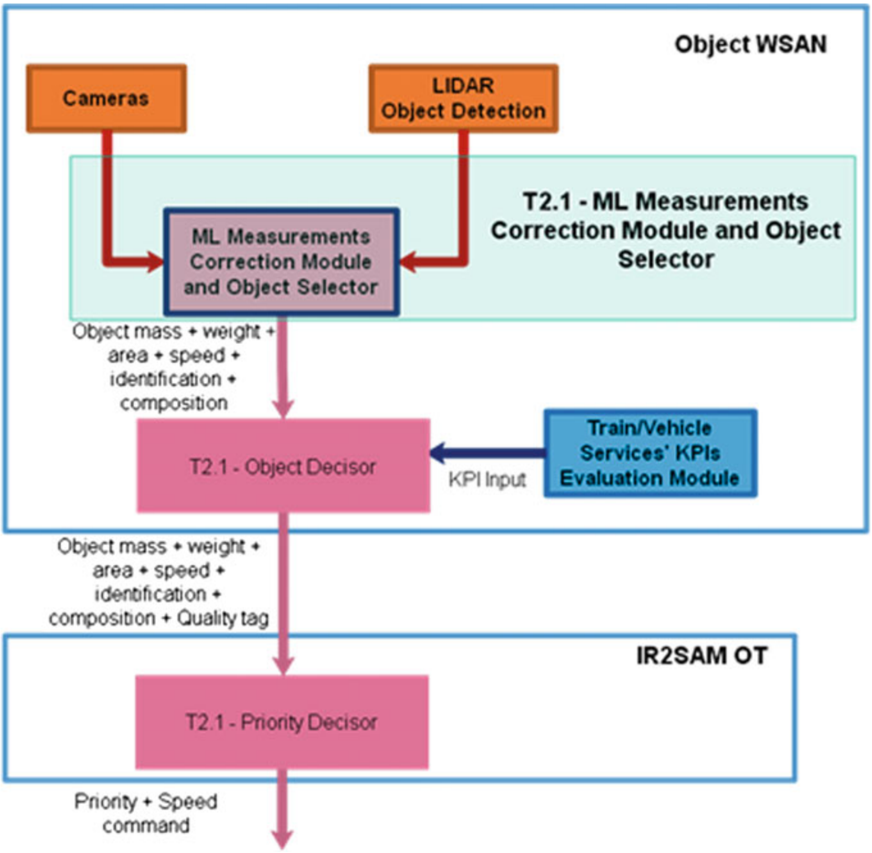


Fig. 16 Object detector system architecture

for frames with no moving objects, and this background is subsequently subtracted from the following frames. Object detection is then carried out on these areas to obtain bounding boxes of the objects that cluster the points that are used in the classification stage. Once any object is detected in the level crossing, it is tracked to estimate its location and speed. These parameters are required to decide whether the train must be stopped for safety reasons. By using this method, the system meets the requirements for both explainability and real-time performance.

During a second stage of the process, the detected objects are classified using the VoxNet DNN. This particular DNN provided the lowest processing time along with high accuracy, being the best solution to use in edge systems with point clouds. The points of each detected object are transformed into a voxel grid format before being fed into the DNN. The DNN has been trained with synthetic data captured in a simulation of the level crossing and fine-tuned with the real data. In this way, the DNN learns to recognize object features with a substantial volume of data that has been automatically generated and labeled in the custom simulated environment.

Subsequently, through the fine tuning process, it learns the specific details of the real data that were captured during deployment. The intensive processing involved in this stage is executed by the neural accelerator Coral EdgeTPU chip, which is incorporated into the custom IoT edge node.

4.4.1 Results

Table 2 illustrates the evaluation outcomes. The sensitivity value presented in the results is associated with the FN parameter, which is crucial for safety reasons in the proposed use case. A reduced rate of FN must be matched by a high value of F1, since it correlates the TP, FP, and FN performance metrics. Finally, the value of the specificity has also to be considered because it relates TN with FP rates.

4.5 AI Mechanisms for Adaptative Coupling Distance Control (INDRA, UPM)

To improve the virtual coupling system, two different modules has been developed: the real time monitoring and QoS control for platoon strategy and the real time monitoring and QoS control for vehicle.

The first one consists of the vehicle model fine-tuning that refines on real time the specific dynamic train characteristics model.

Figure 17 shows the connection between the monitoring module and components for the vehicle model characterization.

The second one consists of making use of the vehicle model fine-tuning described on the previous paragraph, to adapt on real time the movement directives to the specific dynamic train characteristics.

Figure 18 shows the connection between the monitoring module and components for the vehicle model characterization.

Both train dynamic characterization module and virtual coupling smoothing control have been defined and designed by INDRA in collaboration with UPM to

Table 2 Object detector results 1

	Object detection		Object detection and classification
	Fine exploration	Complete evaluation	
Evaluated frames	1800	23,417	3000
Sensitivity	98.65%	99.46%	96.43%
Specificity	98.68%	98.85%	96.65%
Precision	98.68%	98.70%	94.64%
F1	98.65%	98.93%	95.53%

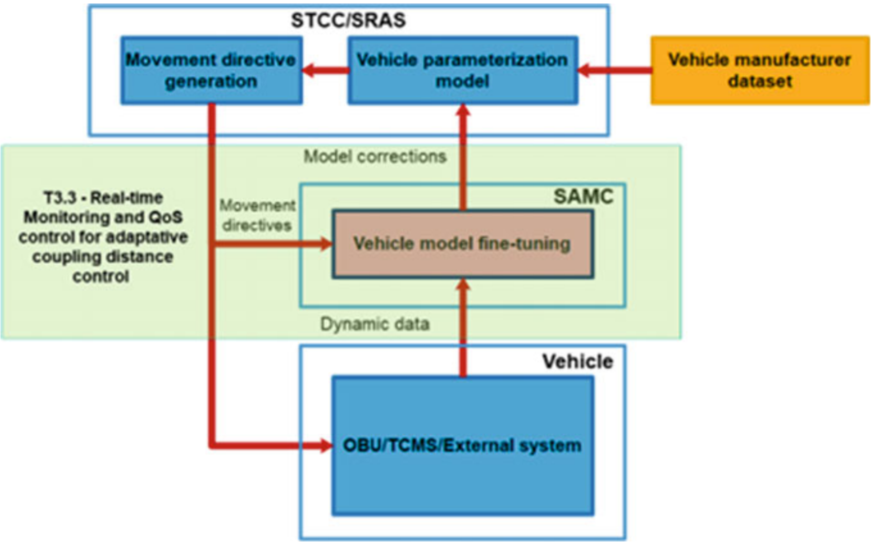


Fig. 17 Adaptative coupling distance control architecture 1

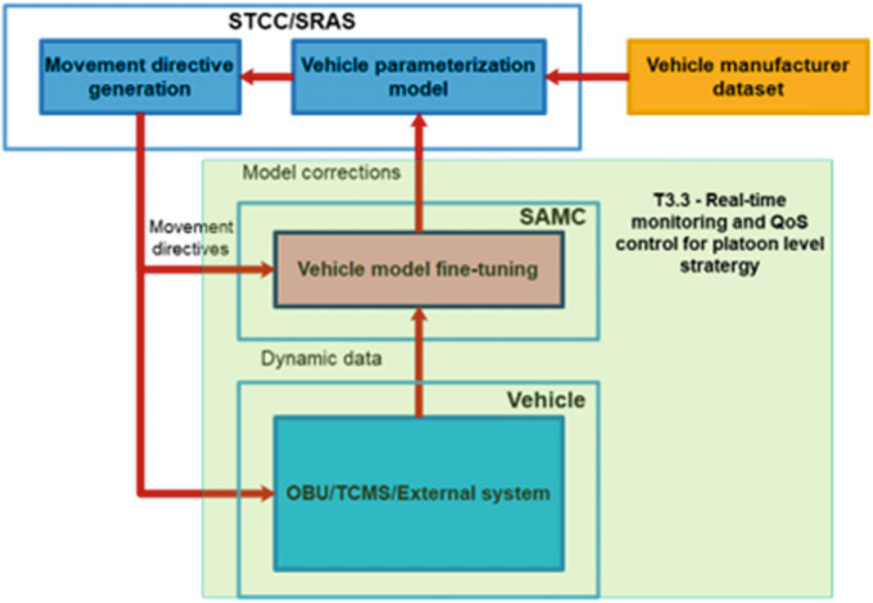


Fig. 18 Adaptative coupling distance control Architecture 2

integrate them on previous existing works developed and implemented by INDRA with the new modules to improve both tactical and operational virtual coupling layers.

4.5.1 Results

In the field of virtual coupling, UPM has worked in different areas. Firstly, the train dynamic characteristics establishing different categories have been parametrized. Up to date, three different categories have been considered: metro, intercity and high-speed. For each of them, the technical data that involves the dynamics of the train has been collected, with the objective of defining a "standard" train for each category. This train will be used in the different simulations to study and design the virtual coupling control between trains.

Secondly, UPM has parametrized three different lines, one for each category. A metro, an intercity and a high-speed line defining speed limitation, slope and curve radius have been modelled. These values correspond to real railway lines.

Thirdly, for each category, a nominal virtual coupling control to analyze several aspects has been implemented:

- Control strategies. The leader movement is defined by a standard tracking control of a predefined velocity profile. For the followers, several strategies have been studied: minimize the distance with the front train, minimize the relative velocity between trains, maximize the follower velocity, and combinations between them (for example, minimize the distance between trains and minimize the relative velocity between them). All these strategies have been studied with the objective of maximizing line capacity: maximum number of trains at the same time and minimum trip time.
- Security constraints. A security distance between the trains that must be respected all the times has been considered. This distance depends on the velocity of each train and on the braking deceleration of each train. Different situations from the most conservative to the most aggressive have been considered, analyzing the effect of the convoy behavior.
- Performance issues. The different parameters involved in the controller have been studied to reduce the computation time. UPM has studied the effect of increasing the prediction horizon and the discretization time to obtain the better controller performance with accurate results.
- Smoothness analysis. In the same way, the effect of different prediction horizons and different states predictions in order to have the smoothest behavior of the coupling have been studied.

After that, Indra has continued with the development of a robust control strategy for the coupling considering the uncertainties that can uncertainty appear in the train location, delays in communication and in the application of the traction/brake forces, line conditions: adherence and environment conditions as wind and tunnel factors, train characteristics: mass and aerodynamic drag. References [25] and [26] present the developed control system.

This model has been tested in a MatLab environment with three different categories: metro, intercity and high-speed. For each one of them, we have collected technical data that involves the dynamics of the train, with the objective of defining a "standard" train for each category. These trains have been used in the different simulations to study and design the robust controller for virtual coupling control between trains.

A comparative study has been also done between the nominal controller previously defined and the new robust controller, showing the differences between them.

Finally, the developed SW has been implemented to be used in the INDRA simulator where the virtual coupling module has been implemented through the SAMC module within the overall architecture of the simulator where the test cases have been tested and validated.

The control model was tested with a situation in which the convoy operationally behaves as a single train since, from the users' point of view, all the virtually coupled train set components arrive at the station at the same time and behave as if they were a single complete train. Although when the convoy is running, the distance between the components increases due to the safety conditions which have been set, we consider that the convoy preserves its integrity, operating as a single train, when the communication between trains is maintained and the above-mentioned condition of all the components arriving at the station at the same time is respected. The figures included in the following simulations illustrate this phenomenon.

Some examples of the simulations done in a metro line are included, in Fig. 19—Slope and radius considered in the simulation scenario. and in Fig. 20—Maximum driving speed in compliance with speed limits.

Figure 21 represent the behavior of the convoy when the follower experiences a 10% loss of adhesion during braking, comparing different controllers.

In this metro line, several simulations have been developed to test the controllers. As an example, the behavior of an uncertain variable that corresponds to a disturbance involving a loss of adhesion at the entrance of the third station. This situation is extremely unfavorable since the disturbance was applied only to the follower, and the train in front was considered to continue braking without any loss of adhesion.

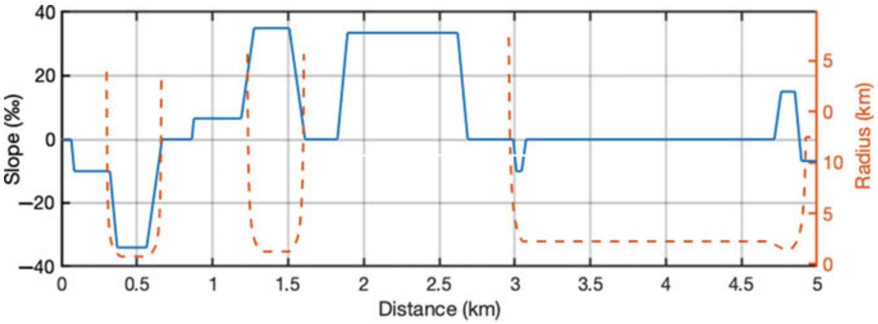


Fig. 19 Slope and radius considered in the simulation scenario

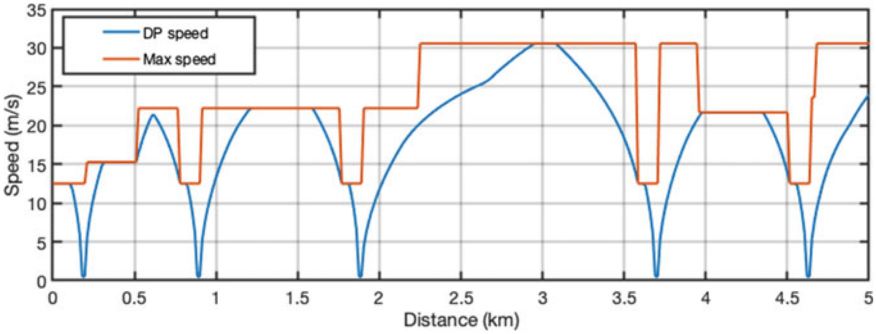


Fig. 20 Maximum driving speed in compliance with speed limits

Figure 21 represents the time–velocity curve and shows the speed of the leader, which is the same for both the nominal and robust controllers. Moreover, in acceleration (i.e., the increasing parts of the curves), the leader has a slightly higher velocity than the followers, thus increasing the distance between the trains. However, in braking (i.e., the decreasing part of the curve), when the velocity of the leader decreases, the follower becomes closer as it has a higher speed, always maintaining the safe distance imposed by the constraints. It is also possible to observe the stops at the stations.

In this figure, it can also be seen how the integrity of the convoy is maintained, as the two trains stop at the station at almost the same time. This effect can be seen in the time–velocity plot, where both trains in the convoy stop at the stations at almost the same time. The plot below shows the distance between the leader and the follower. Here, the most critical moment occurs at the entrance of the stations, where the leader stops, and the follower must also stop maintaining a safe distance.

The curves labelled "10% adhesion loss" include the distance between the leader and the follower for the NMPC and RMPC when there is no disturbance, i.e., no adhesion loss. These curves show a very similar behavior in both cases.

INDRA, based on previous works developed on SCOTT, has adapted the Virtual Coupling system to the system architecture defined on X2RAIL-3, including as a module the developments achieved by UPM on the Operational and strategic layer, validating the changes on the physical platforms making use of the simulator environment deployed at Indra premises covering the different use cases defined on X2RAIL-3.

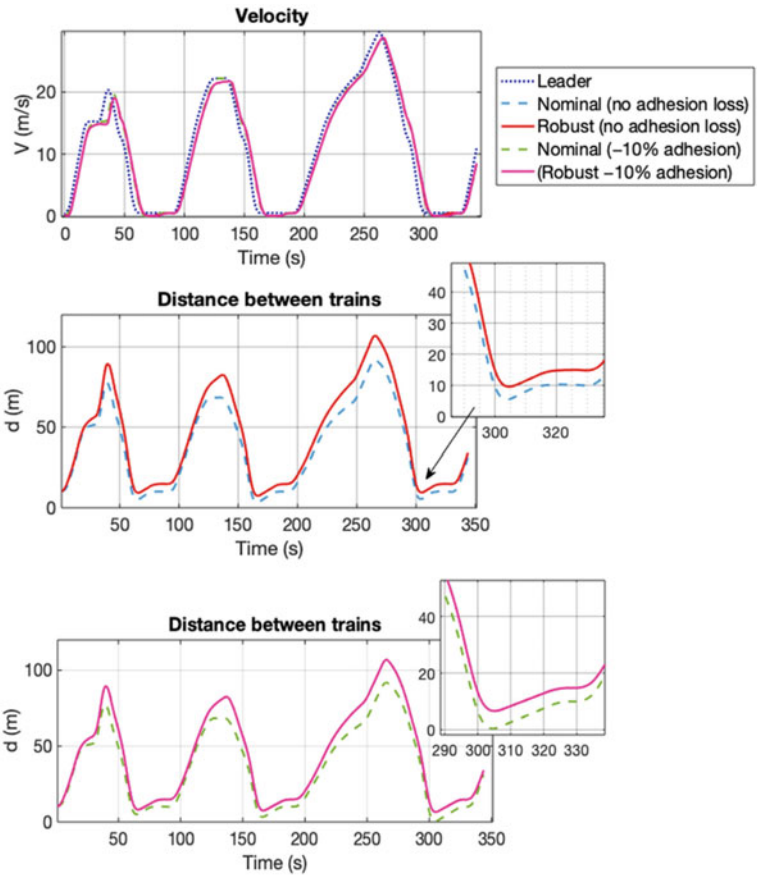


Fig. 21 Results of simulation 1: 10% adhesion loss. Variables versus time

4.6 Security Mechanisms in IoT Deployments in the Railway Domain (UPM)

The energy consumption constraints of the IoT edge devices are very restrictive when these ones are powered from batteries, which usually leads to using low-performance hardware with the aim of improving autonomy. These restrictions may be incompatible with the implementation of common cryptographic protocols that consume a non-negligible number of resources, making it easier for an attacker to gather data or get the control over the network.

To achieve a robust IoT application in terms of security, three main aspects must be considered:

- Confidentiality by means of encryption of sensitive data being transmitted along the network.

- Integrity, such as being able to check whether an attacker could have tried to modify any data.
- Authenticity of data, allowing to verify if the received data comes from who was supposed to have it.

With these points in mind, a common approach for securing communications in a network can be simplified in three steps:

1. Authenticate a user/node in the network prior to sending or requesting any sensitive data.
2. Establish a secure communication channel by exchanging some kind of shared secret, e.g., keys.
3. Use the previously shared secret to exchange sensitive data and verify its integrity.

Any of those steps can be made with symmetric or asymmetric schemes, depending on the requirements of the given application.

In addition, IoT deployments present an extra attack surface related to how easy it might be to access the nodes physically. Being this the case, a wide spectrum of side-channel attacks could be performed on the nodes, making it possible for an attacker to monitor leakage of information from power consumption or electromagnetic radiation.

This problem of securing IoT networks is a well-known one, and many solutions have been proposed [27]. A common approach is to speed up cryptographic tasks in hardware, thus reducing their impact on time and energy consumption. This idea is widely spread in the industry, where it is easy to find new microcontrollers targeting IoT designs that incorporate peripherals implementing commonly used ciphers or cryptographic operations. There are also commercial products that aim to solve the problem with side-channel attacks, such as the ATECC608B [28], which serves as a hardware accelerator but also as a trusted platform module storing data securely.

However, several new threats are being addressed due to the growth of technologies for quantum computing realization. There exist quantum algorithms that can solve efficiently the mathematical problems in which some classical cryptographic schemes are based on. Peter Shor's algorithm [29] can break not only schemes based on the large integer's factorization problem, such as RSA, but also the ones whose security relies on the discrete logarithm problem. This means that elliptic-curve cryptography (ECC) also becomes insecure, being this the preferred one on IoT networks because of the lower key sizes compared to RSA.

Regarding symmetric cryptography, Grover's quantum search algorithm [30] provides a quadratic speed up on brute force attacks on the key space. Nevertheless, this attack still presents an exponential complexity in execution time, thus, doubling the size of the keys would keep the same level of security.

Using symmetric schemes is, however, not recommended for all scenarios. The need for all the nodes in the network to share the same secret key becomes a problem when the communication channels cannot be trusted at all, and the distribution of this key material could be a point of attack. Therefore, new proposals have been made to keep using asymmetric schemes in the future presence of quantum computers.

In particular, post-quantum cryptography (PQC) aims to provide new asymmetric schemes whose security is based on mathematical problems that cannot be solved by known quantum algorithms but without the need of access to quantum resources (in contrast to quantum or semi-quantum alternatives). Thus, these schemes might be a possible solution to IoT security.

The interest in the study of PQC is such that the National Institute of Standards and Technology (NIST) proposed a call for standardization of some of these schemes. The final candidate for standardization in the key exchange mechanism (KEM) category was CRYSTALS-Kyber [31], which is a scheme based on the hardness of certain problems over lattices. The call for standardizing digital signature algorithms (DSA) is still running, being the three finalists CRYSTALS-Dilithium [32], FALCON [33] and SPHINCS + [34], being the first and the second also lattice-based cryptosystems, while the third one provides hash-based signatures.

The problem with PQC algorithms is that they tend to consume more resources than the ones used nowadays, since they present larger key and ciphertext sizes and/or execution times. Thus, the constraints imposed on IoT networks become even more restrictive if we want to keep acceptable security levels in the future. Works such as [35] and [36] show a comparison between NTRU (another lattice based PQC scheme proposed as finalist in the NIST's KEM standardization process), RSA and ECC. More focused on popular communication protocols, [37] presents an implementation of NTRU encryption along with the MQTT protocol.

The problem with the research related to PQC is that most works are focused on high-performance devices, such as processors commonly used in desktop-level applications or powerful FPGA architectures. The NIST defines the ARM Cortex-M4 processor as the reference for low-performance devices, but this is not the only architecture used on many IoT edge implementations, where it is easy to find simpler devices with ARM Cortex-M0 or AVR architectures. Thus, there is a need to study how these PQC schemes could be implemented within the heterogeneity of products available for IoT designs.

5 Conclusions (INDRA)

During this project, the decision-making system used in critical points along the railway lines has been enhanced using existing technologies and new ones. The integration of existing technologies and new ones for several services (i.e., decision-making system in shared areas, enhancing and smoothing virtual coupling management or improving functionalities such as speed control, timing control of the stops, positioning or Train integrity monitor), has to be the basis of the work to be performed during the project. For that purpose, the main focus has been on:

- Implement AI mechanisms for **improving Absolute and Relative Train Positioning** to increase rail lines capacity reinforcing safety conditions.

- Implement AI applications for **improving Train composition process and Train Integrity Monitoring** to automate the process of train inauguration and to improve Train Integrity calculus to be more reactive to a train integrity lost and consequently be able to increase the rail lines capacity.
- Implement **AI mechanisms to improve object detection systems** to increase the safety on critical areas (level crossing, crossing) but to obtain additional information for the different perception systems thinking about the future needs of the implementation of an ATO GoA 4 system
- Implement AI applications for **improving virtual coupling train** movements and distances adjustment in order to increase passenger comfort and cargo trust

This will significantly impact the European Union to achieve the full potential of the IoT and the Artificial Intelligence in the Railway domain. The wireless communications developed in SCOTT project set the basis for helping to reduce time and costs, making the development and management of rail infrastructures and train compositions smarter and more efficient.

Although SCOTT project scope tackled several issues of the railway domain in terms of Internet of Things and wireless technologies investigation, the functionalities developed in that project could be improved moving the focus to the passenger's comfort and cargo security, supplying to the SCOTT systems Artificial Intelligence and a better allocation of the control resources.

The development of innovative solutions for movement control, automatic operation, management of multimodal areas and distributed rail signalling systems will give the European Rail Supply Chain a competitive advantage in the worldwide market and will generate new business opportunities for the European Railway Industry.

The works performed in InSecTT project are fully aligned with the innovation and the transformation that have been carried out in the Shift2Rail Innovative Programmes. Several technologies investigated in S2R have been improved with the InSecTT innovation topics as IoT and AI setting the bases for ERJU new projects. It is important to remark that the use of AI technologies is just a first step in the integration of these technologies in the railway domain, deeply linked and aligned with S2R baselines and programmes. Several examples of the issues studied in S2R that InSecTT can improve to make railway domain more competitive are:

- The wireless technologies used to enhance the communication between the different objects and signalling systems
- Train determination techniques for the solution of a train coupling, making the manoeuvres more comfortable and safe for both passengers and cargo.
- Use of the freight rail innovative solutions to provide a real time management of the cargo in the railway domain, adding the connectivity with other domains thanks to the connection with port facilities.

In this way, the use of Artificial Intelligence on transportation for both Control and Management will improve the rail and road capacity, decreasing the delays and improving the plan, making the transportation experience more comfortable for passengers.

By connecting all-to-all, increasing the level of automation, decentralizing the decisions and enhancing the efficiency of the system, it is possible to enhance the current state of the railway transportation, having an important impact in the domain market.

As it stated in the Rail Use Cases description, the main objectives described above are covered.

Gathering all the topics explained above, the expected impacts of InSecTT project concerning the Railway domain are:

- Increase the safety of the current coupling processes, making the solution highly competitive and effective in secure and safe related environments.
- Adapt the speed change processes to improve passengers comfort and trust and cargo security by using Artificial Intelligence mechanisms to control the input parameters and smoothing the speed and acceleration/deceleration variations.
- Provide an improvement of Virtual Coupling manoeuvres via Artificial Intelligence by improving the smooth in the speed change processes in order to enhance passengers comfort as well as transport companies trust in this type of virtual composition.
- Improve the current state of the system to control coupling/uncoupling processes in a safe and secure way.
- Convert conventional lines into ATO lines in a safe and secure way, by means of all-to-all connection in a decentralized environment.
- Demonstrate new signalling systems based on wireless communications that make possible to connect On Board and On Track stakeholders in a distributed and decentralized environment
- Enhance the management of cross-domains areas, specifically rail and road areas and port facilities, focusing on the multimodal jams management.
- Achieve a more efficient multi-domain traffic management by allowing to share the vehicles and trains information and distributing it using decentralized systems. In addition, the system can integrate vessels to the network for cargo management.
- Solve the safety deficiencies in current systems with the purpose of reducing the number of injures and human losses as well as the damages on wagons, cargo and railways infrastructures.
- Improve the use of multipurpose WSN applying artificial intelligence for the safety and non-critical systems installed on vehicles, trains and multimodal infrastructures, such as railway connected ports.
- Include distributed solutions to efficiently manage the exchange of information and data distribution through a decentralized system, which controls specific areas and the wayside objects and signalling system, allocated within that area.
- Increase punctuality of operating lines reducing time and enhancing the timetable management in an automatic way. It improves passengers and end-users experience, making the services more trustable.

- Reduce costs and time concerning coupling services and control of coupled compositions, allowing an efficient management of the track capacity.
- Enhance energy efficiency of current railway systems, reducing the environmental impact.
- Connect devices and manage them in an intelligent way, increasing the level of automation and enhancing the efficiency of the system.
- Add flexibility to the routes and tracks management, by allowing several routes operating at the same time, controlled by an autonomous system, which makes use of Artificial Intelligent methods.

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