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## Safe4RAIL-2: Advanced architectures and components for the Next-Generation Train Control and Monitoring System

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### Abstract

The Train Control and Monitoring System (TCMS) is responsible for the management of the different on-board train equipments, such as brakes, doors, or passenger information. The Next Generation TCMS (NG-TCMS) intends to increase communication reliability, incorporate wireless technologies and simplify the number of computing devices in the train. This paper describes the architecture and components that Safe4RAIL-2 project is developing for the NG-TCMS, including innovations in train communications and subsystem integration, which will be the basis for the future railway system. Synergies with previous and on-going research activities are also addressed.

*Keywords:* NG-TCMS; DbD; TSN; wireless; HVAC; FDF

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## 1. Introduction

The Train Control and Monitoring System (TCMS) is a distributed system which manages the different functionalities of a train, as described in Roll2Rail-D2.1 (2017). TCMS is made of several hardware and software components, such as Central Control Units (CCUs), network switching elements, and end devices. Its operation relies on the Train Communication Network (TCN), which is standardized by the IEC 61375 series, as detailed in IEC 61375-2-5 (2014) and IEC 61375-2-3 (2015). Shift2Rail's Multi-Annual Action Plan has identified several areas of improvement for the current TCMS, and has defined Technology Demonstrators (TDs) where these new advanced functionalities will be tested and validated. More specifically, TD1.2 includes novel features such as deterministic communications, wireless technologies, functional distribution architectures and train function virtualization. These building blocks will be the basis for future trains with enhanced interoperability, higher throughput and improved reliability.

Within this context, Safe4RAIL-2<sup>†</sup> is contributing directly to the technology blocks of TD1.2 by developing the hardware and software components for the Next Generation TCMS (NG-TCMS), and validating their functionalities in two railway demonstrators deployed in cooperation with CONNECTA-2 project. For this purpose, Safe4RAIL-2 builds on the results of previous projects such as SAFE4RAIL and Roll2Rail, and brings them to a higher Technology Readiness Level (TRL). This paper details the approach followed by Safe4RAIL-2 to achieve these goals.

The paper is organized as follows. In Section 2, the main objective and contribution of the presented work are described. Section 3 details the solutions that Safe4RAIL-2 provides for the deterministic wired TCN. Section 4 focuses on the wireless solutions proposed by Safe4RAIL-2 for the Train Backbone (TB) and Consist Networks (CN), and Sections 5 deals with train subsystem integration. Section 6 summarizes the paper.

## 2. Objective and Contribution

The activities of Safe4RAIL-2 project are focused on three technology blocks: devices for a deterministic wired TCN, wireless devices for WireLess Train Backbone (WLTB) and WireLess Consist Network (WLCN), and train subsystems integration on Functional Distribution Framework (FDF) and Simulation Framework (SF). The main objective of this paper is to describe how Safe4RAIL-2 project is bringing these technologies to a higher TRL, by developing devices and integrating them in laboratory demonstrators with CONNECTA-2 project. For this purpose, Safe4RAIL-2 has taken as a baseline the results of previous Shift2Rail projects, as detailed below:

- *Roll2Rail Project*: wireless train inauguration process, and laboratory tests of LTE technology for wireless train backbone.
- *Safe4RAIL Project*: Drive-by-Data concept, and the architecture of the Functional Distribution Framework and Simulation Framework.
- *CONNECTA Project*: requirements for Drive-by-Data, Wireless TCMS field tests, architecture of the Functional Distribution Framework and specifications of the Simulation Framework.

The higher-TRL results obtained by Safe4RAIL-2 and CONNECTA-2 will be used by future Shift2Rail projects, where they will be taken into field tests with trains.

## 3. Deterministic wired TCN

In CONNECTA and SAFE4RAIL projects, the Drive-by-Data (DbD) concept was developed, detailed in SAFE4RAIL-D1.3 (2017). A DbD network is based on strict temporal and spatial partitioning provided by deterministic Ethernet to achieve the necessary means for data communication for all subsystems in the train. In Safe4RAIL-2, DbD is brought into a higher TRL by implementing it on the different elements of the wired TCN and integrating these elements in demonstrators in order to obtain a deterministic behaviour in train communications. This implies modifying all the devices that currently deploy the wired communications inside

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<sup>†</sup> [www.safe4rail.eu](http://www.safe4rail.eu)

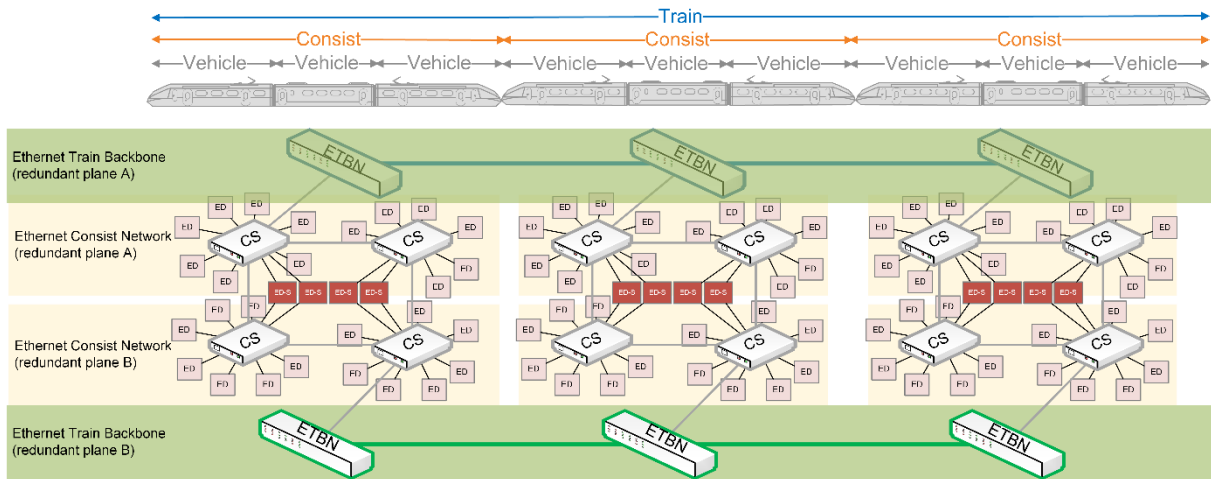


Fig. 1 Train Communication Network, from Safe4RAIL-2 Newsletter Issue 1 (2019)

the train, namely (see Fig. 1): Ethernet Train Backbone Nodes (ETBNs), Consist Switches (CSs), and End Devices (EDs).

For this purpose, the hardware and software of these devices is combined with Time-Sensitive Network (TSN) technology, which is a set of IEEE 802 Ethernet sub-standards that provides deterministic communication with real-time guarantees over Ethernet. TSN is able to partition the network robustly enough so that critical and non-critical traffic streams do not interfere with each other, and as a consequence critical/high-priority data can be sent correctly even under high load conditions. In Safe4RAIL-2 a special focus is put on the inauguration process of the train over the TSN network, in order to robustly handle the coupling and uncoupling of train units. Additionally, the interoperability among device implementations from different manufacturers is being carried out.

As depicted in Fig. 1, the new train network topology is based on a redundant line architecture for the backbone network. Within each consist, the local network is virtually split into the same redundant line architecture. Physically, the local network is connected in a ring. By introducing Drive-by-Data technology in these domains, the current TCN is superseded by the Next-Generation TCN (NG-TCN), which involves:

1. The development of a new train network topology and architecture
2. The introduction of Mixed-criticality Ethernet for converged real-time Ethernet
3. The robust coupling and uncoupling of trains (inauguration)
4. The achievement of the same level of safety as the current TCN

As a result of these activities on deterministic TCN, the public deliverable Safe4RAIL-2-D1.1 (2019) “Drive-by-Data Requirements Specification” has been produced. This deliverable defines the requirements for DbD ETBNs, consist switches and end devices, as well as the requirements for the safe train inauguration procedure. A top-down analysis has been followed in order to identify the technological requirements for the different devices, which have been discussed and analysed together with CONNECTA-2 project partners.

#### 4. Wireless Devices for WLTB and WLCN

The network domains inside a train have been depicted in Fig. 1, namely: the Train Backbone, which deploys the consist-to-consist communication via Ethernet Train Backbone Nodes (ETBNs) connected in the redundant planes A and B; and the Consist Network, which includes Consist Switches (CS) as well as the Safety and Non-Safety End Devices (ED-S and ED, respectively) connected in the virtual planes A and B. Nowadays, communications at both levels are wired. In Safe4RAIL-2, wireless technologies are introduced at backbone and consist levels, creating WireLess Train Backbone (WLTB) and WireLess Consist Network (WLCN) solutions, as depicted in Fig. 2. The inauguration of the train topology via these wireless technologies is also being explored.

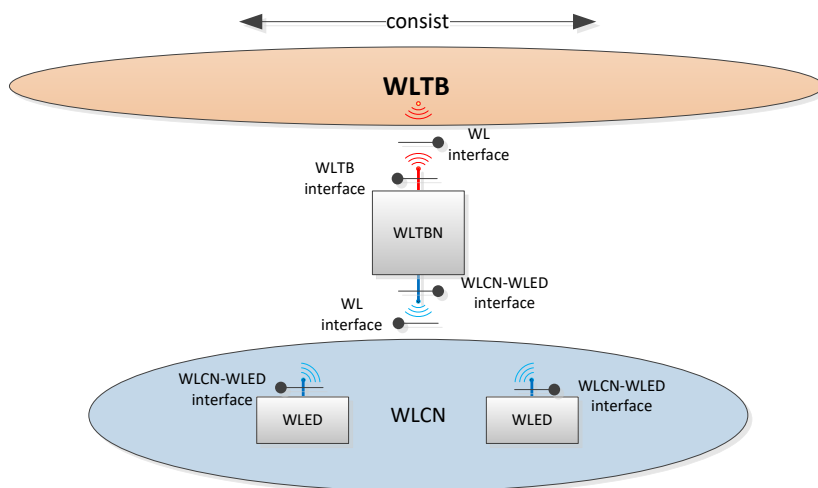


Fig. 2 WLTB and WLCN architecture, from Roll2Rail-D2.5 (2017)

#### 4.1. WireLess Train Backbone (WLTB)

For the WLTB, Roll2Rail project already defined the required network architectures and performed first tests with LTE technology, as detailed in Roll2Rail-D2.5 (2017) and Roll2Rail-D2.7 (2017). A wireless backbone is a suitable replacement for the current wired backbone, as it removes the issues caused by mechanical coupling and furthermore allows the deployment of novel applications, such as virtual coupling (i.e. consists running together without mechanical connection). In Safe4RAIL-2, WLTB nodes based on direct Device-to-Device (D2D) communications are being developed. For this purpose, OpenAirInterface (OAI) technology is being used. This technology supports direct User Equipment to User Equipment (UE-to-UE) communication and is fully compliant with 3GPP Proximity Services (ProSe) from LTE Release 14 V2X/D2D. Moreover, the train inauguration, considered a representative example of a train backbone functionality, will be validated using these LTE equipments. A new wireless inauguration procedure is currently under definition in CONNECTA-2 and Safe4RAIL-2 for this purpose.

The architecture of the Wireless Train Backbone (WLTB) is composed of one WLTB Node (WLTBN) for each ECN plane, whose role is to provide single hop and multi-hop wireless communication between WLTBNs of multiple consists of the same train (see Fig. 3). Each WLTBN is made of an LTE device and an ETBN. In addition, the WLTBN will be connected to a Consist Switch (CS) for WLTB-ECN interconnection. The requirements of the LTE equipment and ETBNs that make up the WLTBNs are detailed in the public deliverable Safe4RAIL-2-D2.1 (2019) “Requirements of LTE Equipment and ETBNs for wireless TCMS”.

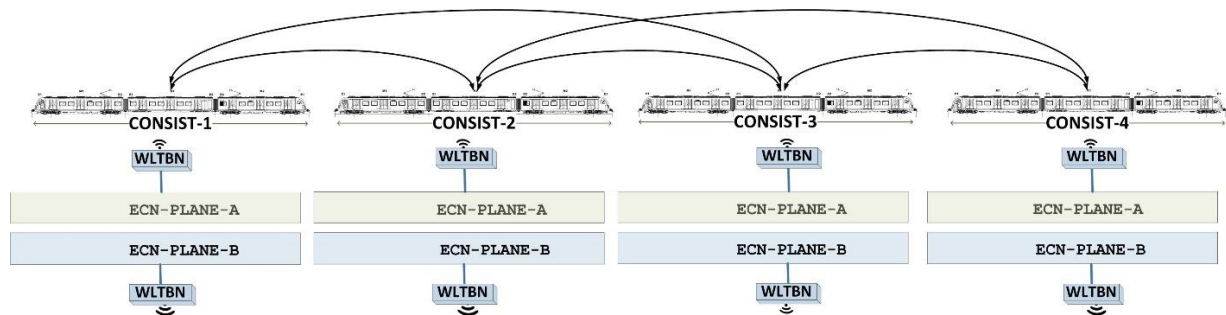


Fig. 3 Proposed Architecture for WLTB, Härril et al. (2019)

#### 4.2. WireLess Consist Network (WLCN)

For the WLCN, Roll2Rail-D2.5 (2017) defined its general architecture and requirements. The main difference between the WLCN and the WLTB lies in the fact that the WLCN requires a higher number of nodes and has to operate in a more complex propagation environment, as wireless communications inside a consist are highly influenced by the physical mechanism of the wave propagation (e.g. reflections on metallic structures and cabinets, influence of passengers, etc). Based on the inputs provided by CONNECTA-2, in Safe4RAIL-2 an state-of-the art of wireless technologies suitable for the WLCN has been done, and prototypes for Wireless End Devices (WEDs) and Wireless Access Points (WAPs) are being developed to be integrated in the project demonstrators.

Fig. 4 shows the architecture of the WLCN. This architecture is made of two redundant wireless networks, each of them having one Wireless Access Point (WAP) per vehicle. Wireless End Devices (WEDs) will be connected to a WAP, except the Safe Wireless End Devices (WED-S), which will be connected to two WAPs, each one from a different wireless network. Therefore, the WED-S will require two wireless interfaces. On the other hand, all WAPs will be connected to Consist Switches (CS), which will be interconnected via a wired Ethernet Consist Network (ECN). This is a suitable solution as it eases the integration of different wireless technologies. In the future, architectures with a complete wireless CN could be achieved (mesh technology); this would require deterministic and reliable communication for non-safe, safe, and time-critical devices.

Based on the requirements for the WLTB and the WLCN, a state-of-the-art review of wireless technologies has been done within Safe4RAIL-2 for these two domains, as reported in Härrä et al. (2019). This review has indicated that the future NR V2X (LTE rel.16) has been designed to support the required features in a highly mobile vehicular environment, and accordingly is expected to be a key enabler for Wireless TCMS, in particular the WLTB. For the WLCN, deterministic WiFi solutions also represent a promising solution, in addition to NR V2X.

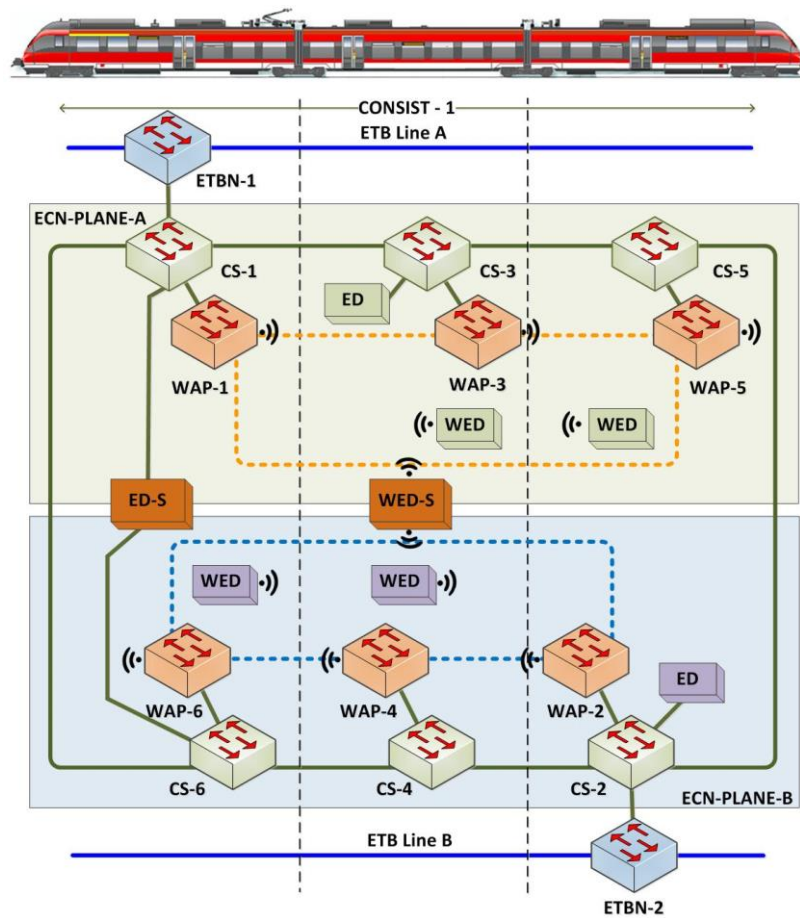


Fig. 4 Proposed Architecture for WLCN, Härrä et al. (2019)

## 5. Train subsystems integrated on Functional Distribution Framework and Simulation Framework for Virtual Certification

The previous sections have described those solutions proposed by Safe4RAIL-2 for NG-TCMS which are related to network performance and connectivity. In this Section, the advances for train subsystem integration are detailed, which are focused on two main aspects: operation over a Functional Distribution Framework (FDF), and early validation based on a Simulation Framework (SF).

### 5.1. HVAC Subsystem on Functional Distribution Framework (FDF)

Software complexity and electronics in railway for on-board train control functions are rapidly growing, and considering that nowadays every separate subsystem needs its own specific electronic equipment (CCU) including controllers, wires or connectors, this translates to high lifecycle, maintenance and recommissioning costs. The Functional Distribution Framework (see Fig. 5) offers an execution environment for distributed TCMS safe and secure applications up to Safety Integrity Level 4 (SIL4), which ensures strict temporal and spatial partitioning, location transparency and abstraction from the underlying network protocols and hardware. As a consequence, the FDF avoids having a dedicated equipment for each TCMS function, and allows integrating in the same CCU distributed hard real-time controls, safety signals and functions up to SIL4. The FDF also includes an Application Programming Interface (API) which supports reconfiguration and scheduling of partitions. On top of this API, the FDF can host different TCMS applications.

In Safe4RAIL-2, a Heating, Ventilation and Air Conditioning (HVAC) application is being integrated on top of two different FDF implementations: an AUTOSAR-based FDF, and a proprietary one provided by CONNECTA-2. The idea behind this approach is that the same HVAC application will be able to be hosted in different FDF implementations demonstrating portability and interoperability. Below the FDF, in order to operate correctly and act as an abstraction layer for the hosted applications, the FDF needs DbD technology that provides global synchronization and both real-time and best-effort communication capabilities.

### 5.2. HVAC Subsystem on Simulation Framework (SF)

Successful integration and commissioning of TCMS subsystems requires huge efforts and takes an extremely long time, not only due to the lack of standardised application interfaces and appropriate architectures, but also because of non-standardized simulation and testing frameworks. Therefore, the use of an standardized Simulation Framework (SF) that allows testing train subsystems in virtual implementation (Software-In-the-Loop, SIL), or even with real hardware in a remote location (Hardware-In-the-Loop, HIL) shortens drastically the duration of the validation stages. For this reason, Safe4RAIL-2 pursues to show the validity of the SF for performing SIL and HIL testing of an HVAC function. In the case of HIL, the TCMS is placed in one location, and the HVAC unit to be monitored and controlled is placed in a different one. Fig. 6 shows this concept, where the virtual/simulated HVAC software or a real HVAC controller are connected to a real train unit by means of a simulation bridge.

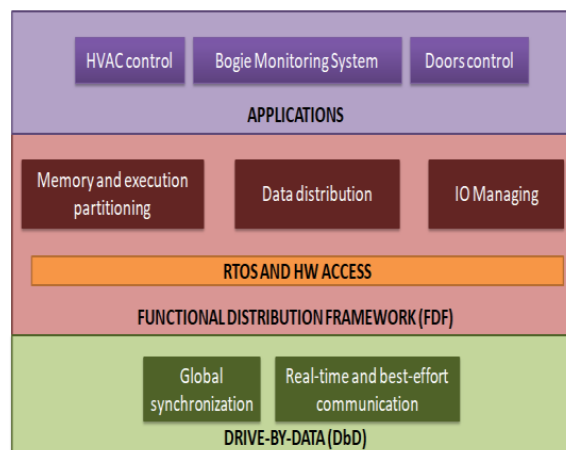


Fig. 5 Functional Distribution Framework, from SAFE4RAIL-D2.3 (2017)

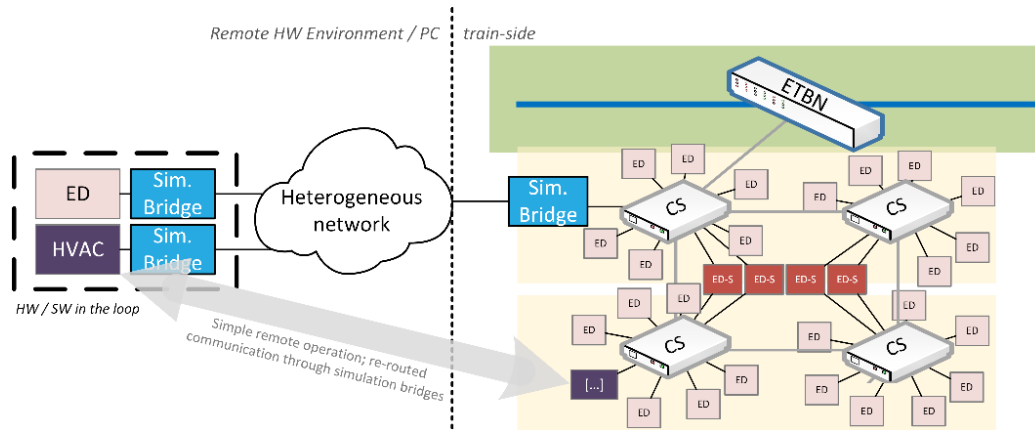


Fig. 6 Simulation Framework and HVAC subsystem

Following this approach, integration of TCMS subsystems will happen much earlier and in a highly modular and scalable way. For example, by cross-ECU functional integration before system integration, or single-ECU software integration into a defined simulated environment, or connecting a remote real subsystem to the train manufacturer’s simulation model for early mitigation of potential integration problems.

The requirements for the integration of the HVAC subsystem on the FDF and the SF have been detailed in the public deliverable Safe4RAIL-2-D3.1 (2019) “Report on requirements for integration of HVAC into the Functional Distribution Framework and Simulation Framework”.

## 6. Summary

In this paper, the solutions that are being developed in Safe4RAIL-2 project for the Next-Generation TCMS have been described. These solutions are focused on three main axes: obtaining reliable networks based on deterministic communications, increasing the flexibility of train operation using wireless communications, and reducing development and testing efforts for train subsystems through middleware integration and simulation. In addition, Safe4RAIL-2 aims at increasing the TRL of the proposed technical solutions by integrating them in demonstrators together with CONNECTA-2 project. As a result of all these activities, a NG-TCMS will be obtained which will be the basis for more robust and safer future trains.

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