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3rd SmartRaCon Scientific Seminar - Proceedings

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Acting Institute Director:
Prof. Dr.-Ing. Michael Ortgiese

Preface

Dear reader,

you are holding the newest volume of the series „Reports of the DLR-Institute of Transportation Systems" in your hands. In this series we publish fascinating scientific research results from our Institute of Transportation Systems at the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt e.V. - DLR) and its collaborating partners.

With this series we communicate results of our scientific work in the fields of automotive, railway systems and traffic management. We hope to enable a broad access to scientific work and results for the national and international scientific community and practitioners in the field of transportation. Beyond that, researchers in the early phase of their academic career of our staff and external doctoral candidates are offered the opportunity to publish their dissertation. In addition, the publication includes outstanding scientific contributions and project reports as well as proceedings of conferences in our house with different contributors from science, economy and politics.

The current volume contains the proceedings of the third SmartRaCon Scientific Seminar, which has been held on September 2nd, 2021 virtually from Braunschweig, Germany. This SmartRaCon Scientific Seminar aimed to bring together researchers from different railway research areas with focus on adaptable communications, virtual coupling and zero on-site testing. The seminar was a vivid and fruitful forum for the presentation and discussion of new and on-going research.

We wish you an interesting and inspiring reading!

Prof. Dr.-Ing. Michael Ortgiese

All contributions have been double refereed as abstract and full paper by the International Scientific Committee

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The 3rd SmartRaCon Scientific Seminar has been hosted by DLR, Institute of Transportation Systems, Braunschweig, Germany

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1 Introduction by SmartRaCon: The way forward

Marion Berbineau; COSYS, Université Gustave Eiffel, IFSTTAR, Villeneuve d'Ascq, France; Michael Hutchinson; GMV NSL, Nottingham, United Kingdom; Emilie Masson; IRT RAILENIUM, Famars, France; Jaizki Mendizabal; CEIT, San Sebastián, Guipúzcoa, Spain; Michael Meyer zu Hörste; German Aerospace Center (DLR), Institute of Transportation Systems, Braunschweig, Germany

1.1 Smart Rail Control Systems - SmartRaCon

Innovative technologies enable new approaches for train control, command and signaling systems. E.g. digitalization and automation lead to completely new concepts. The partner RAILENIUM, GMV NSL, CEIT and DLR have founded the consortium Smart Rail Control (SmartRaCon) to develop new concepts, approachs and technologies for the train control, command and signaling systems of the future. In this contribution the developments in the areas of communication, localization and train integrity will be discussed.

Figure 1-1: SmartRaCon Logo and Partners Logos

Digitalization and Automation will prepare the ground for a completely new generation of train control and railway management systems. In the frame of X2RAIL-3 [3] SmartRaCon aims to design and develop a technology-independent system for an adaptable train-to-ground communication system resilient to radio technology evolution considering threats such as interferences or cyber-attacks, reducing the field tests required including novel tools and additional prameters such as human factors, and evolve to the virtual coupling concept ensuring its safe operation leading to move efficient management of the network. Some of the concepts to be explored are:

- Communication concepts
    - Antenna Integration in Railway Environment
    - SDN-based slicing and network resource distribution in train-to-ground railway communication

  - Adaptable Communication System in regional and freight demonstrator including Channel Emulator Tool

- Zero on-site testing & Moving Block
  - ETCS radio communication link laboratory testing saboteur
  - Integrate operational data related to the temporality of the driver's actions in the test architecture

- Virtual Coupling & TD 2.3 Moving Block
  - Simulating the Impact of ETCS L2 and Improved Coupling Mechanisms on Station Capacity
  - Safety and Performance analysis of virtually coupled train sets
  - Concept and Performance Analysis of Virtual Coupling for Railway Vehicles

The overall concept is based on the idea to reuse COTS and to integrate them into a railway network in a modular way, which allows on the one hand a flexible scaling of the rail control system in a cost-efficient way and on the other hand a building block approach for certification and modulewise change of technology.

1.2 The methodology

Smart Railway Control (SmartRaCon) will be the core to enable high capacity and cost-efficient rail systems for the next century. The proposed approach of SmartRaCon is to control smartly intelligent, autonomous trains on a scalable and more flexible infrastructure. Main challenges for the rail system are the enhancement of capacity, the reduction of investment and operations cost. The reductions of energy consumption as well as the reduction of cost for test and certification are two aspects for the cost reduction. These are the conceptual objectives of SmartRaCon [1] and are coherent with the Master Plan topics of Shift2Rail [2]. The SmartRaCon idea for a credible, coherent and long-term approach to achieve the Master Plan Objectives is to meet those challenges by:

- intelligent trains, which communicate safely & securely, localize & supervise integrity autonomously and operate as virtual coupled train-sets;
- infrastructure which is flexible, easy & fast to configure, less fixed (e.g. wired) & scalable, communicating safely & securely with trains and operating them in moving block;
- traffic management system operating both with optimization algorithms;
- supported by cost-efficient process for design, test and certification which uses highly automated test labs to avoid on-site tests based on formal test specifications.

For the capacity increase, an integrated moving block (MB) system has to be implemented. Hence technologies work together: train positions need to be reported safely & securely in real-time to the trackside train control and traffic management system (TMS). Positioning and communication are ensured by combining different technologies. To implement the MB logic on-board train integrity (TI) supervision is required, applying similar technologies. An evolution of the TMS is needed to adopt the MB logic besides increasing the efficiency of dispatching. Virtual coupled train-sets can help to improve capacity by reducing the number of train routes required. The approach is fully in line with the standardized European Rail Traffic Management System (ERTMS) and the European Train Control System (ETCS) and enhances interoperability. New functionalities & technological solutions require being formally specified and tested. Hence testing needs to be automated & moved from on-site to lab. This achieves the objectives of reliability, improved standardization, lower costs & simplified processes. This prioritization is justified since traffic management, positioning and communication are enabling technologies that need to be tested and certified. The complementary work in areas as e.g. moving block and decentralized interlocking technologies extends the concept to reach a significant and sustainable effect on capacity & cost.

1.3 Technological research areas

The overall SmartRaCon concept is based on technology-independent adaptable train-to-ground communications resilient to radio technology evolution, ensuring safety levels of GNSS based on-board positioning and train integrity supervision. Some of the most relevant areas of SmartRaCon technological research are shown in Fig. 1-2 and the conceptual groups "Adaptable communications", "Zer On-site Testing" and "Virtual Coupled Trani Sets" related to X2RAIL-3 [3] and Impact-2 [4] projects are discussed below.

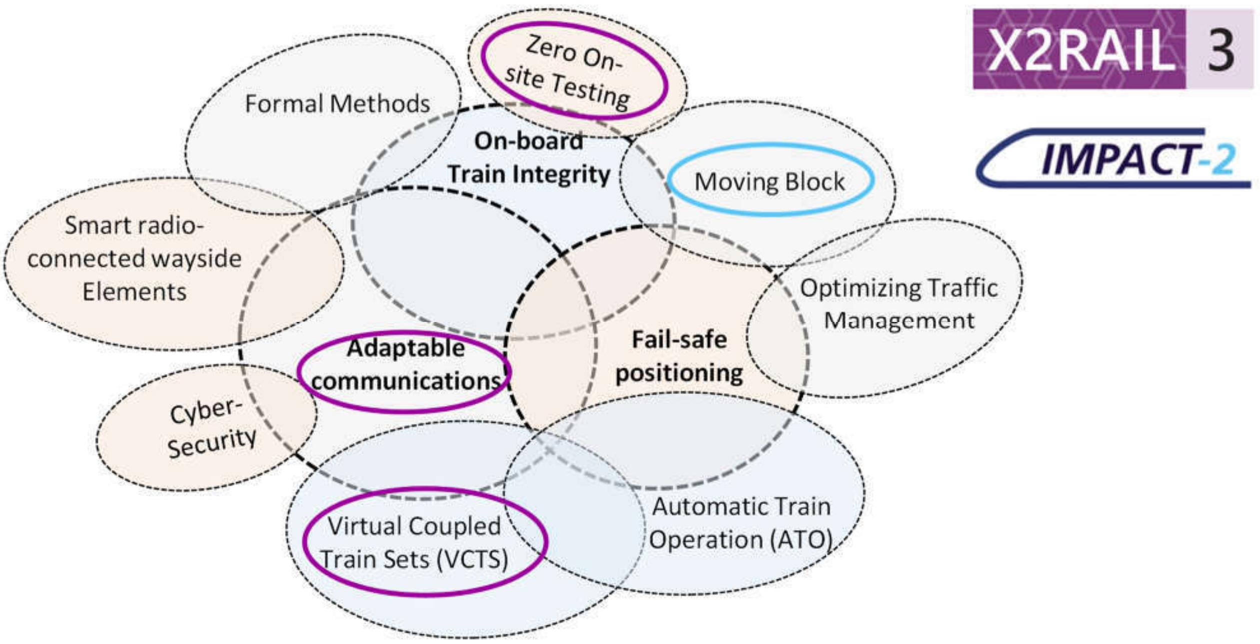

Figure 1-2: Core Areas of Research in SmartRaCon

1.3.1 Conceptual group "Adaptable communications"

The contribution from communication is based on the idea to reuse COTS and to integrate them into a railway network. For that, SmartRaCon will design and develop a technology-independent system for an adaptable train-to-ground communications system resilient to radio technology evolution considering threats such as interferences or cyber-attacks. Some of the concepts to be explored are a) the anticipation of the 5G standardization; b) Software Defined Networks (SDN) and Network Function Virtualization (NFV); c) radio system KPI evaluation; d) hardware development using Software Defined Radio (SDR) platforms, e) IP-based communication gateway with bandwidth aggregation, dynamic spectrum allocation and mobility support; f) traffic pattern recognition tool to ensure minimum conditions; g) innovative use of satellite communications technologies.

The impact for future communication infrastructure relying on standardized technologies and COTS products is high for the European railway, telecom and space industry as well. The use of satellite communications is especially relevant for railway lines, where the availability of a reliable communication infrastructure is critical. By using cognitive radio systems maximum use of surrounding infrastructures will be achieved. Through the use of cognitive radio, 5G, satellite and adaptable, resilient architecture CAPEX will be reduced and moreover IP communication technology supporting a fast radio technology evolution will reduce OPEX.

Current radio technology, i.e. GSM-R, will become obsolete by 2030 and therefore 4G is being analyzed. 5G is already planned to be commercialized by 2020, which will limit the life-cycle of a 4G-only solution. The main advance relies in the ability to successfully integrate a number of heterogeneous technologies and communication protocols into one network in order to take advantage of various deployments (3G, 4G, 5G, Satellites) provided by external network operators (Network as a service) and/or dedicated infrastructures (Network as an asset). Thus, CAPEX and OPEX of communication systems can be minimized. Smooth migration will be enabled by designing middleware platforms for transparent switching radio components.

Impacts on the infrastructure, line capacity and definition of certification processes will be made thanks to the future communications and on-board positioning.

Among SmartRaCon activities there are wireless comumnication antenna Integration, SDN-based slicing and network resource distribution and channel emulator tool communication system testing.

1.3.2 Conceptual Group "Zero On-site testing"

Zero On-site testing aims to improve standardization and integration of laboratory testing methodologies reducing time to market and improving effectiveness in the introduction of new signalling and supervision systems. Due to the complexity of signalling systems and the differences between specific deployments, a large amount of tests are required to be carried out on-site. It is considered that on-site tests take about 5 to 10 times the effort compared to similar tests done in the laboratory. Reduction of on-site tests for signalling and telecom systems is hence the way forward to reduce testing costs. Moreover, and adding more complexity to the process, procedures of verification & validation testing might differ in differnet countries around Europe. Overcoming these differences by standardizing the procedures and test scopes will improve the interoperability and reduce the time to market.

Activities related to Zero On-site testing include new functionalities to complete the general test architecture, generic communication model between the different components of the test environment(s) defined, standardized interfaces between the products from the test environments of different suppliers and operators and between the test environments and the subsystems under test, simulators to support automated testing in the laboratory. Among SmartRaCon activities there are tools for safety testing of ETCS radio communication link at laboratory and test architecture to integrate operational data related to the driver's actions.

1.3.3 Conceptual Group “Virtual Coupled Train-Sets”

New signalling concepts such as Virtual Coupled Train Sets would be able to improve line capacity, reduce LCC and enhance system reliability. Virtual Coupling concept is an innovative concept capable of operating trains much closer to one another (inside their absolute or relative braking distance) and dynamically modifying their own composition on the move. Virtual Coupled Train Sets are based on very precise and highly safe absolute and relative localization as well as adaptable train-to-train and train-to-trackside communication. By replacing current mechanical coupling by wireless communications, virtual coupled train sets aims at virtually coupling the trains by exchanging information, such as location, speed, acceleration, etc. among the coupled trains. This will allow to increase the capacity thourg reducing headway and time to couple. Among SmartRaCon activities there are simulation analysis to check the impact in ETCSL2, safety and performance analysis and concept and performance analysis.

1.3.4 Further conceptual Groups

The three above mentioned conceptual groups are related to many others in the context of future systems. Some examples are given below and visualization is given in Fig. 1-3:

- Automatic train operation requires a high performance adaptable communication as well as safe and precise localization.
- Future traffic management systems, which can optimize capacity, punctuality or energy-consumption require real-time precise localization.
- Smart radio-connected wayside elements require a highly safe and secure communication
- Freight telematics needs an adaptable communication and localization.
- Moving block operation requires safe localization and train integrity as well as reliable as well as adaptable communication.
- On-board train integrity determination for the implementation of more efficient signalling systems based on concepts like moving block. Systems based on these concepts will deliver very significant advantages in terms of capacity (shorter

headways will be allowed), capital and maintenance cost resiliency, and others such as compatibility among lines, etc.

- Localization is based on the need to ensure that the safety levels provided by existing signaling systems are not compromised when a train-borne positioning system is employed. SmartRaCon covers activities and concepts related to test campaigns, improve specifications, safety case, simulation based KPI evaluation, multi-constellation, sensor integration, developing and certifying dedicated hardware, algorithms.

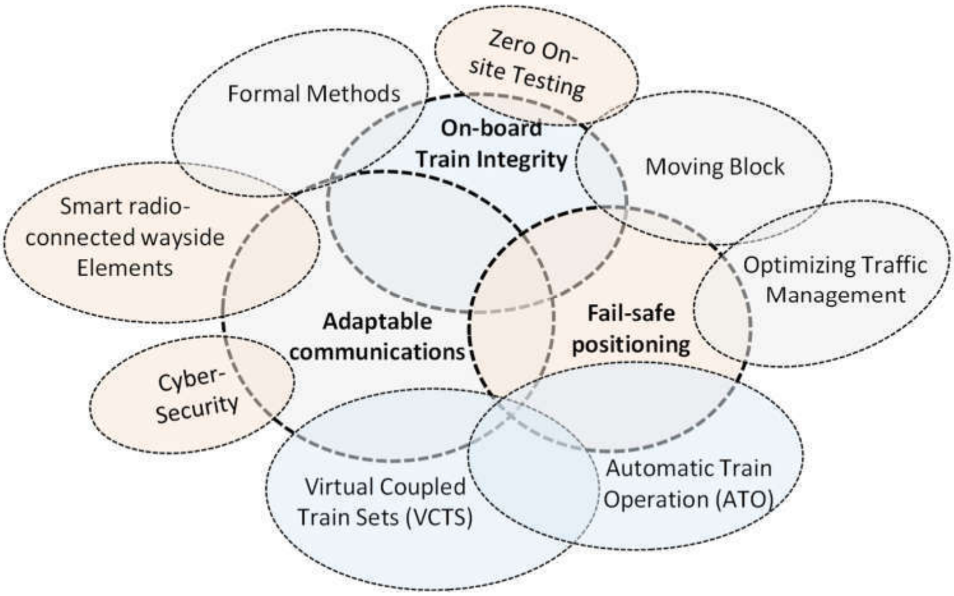

Figure 1-3: Core and further Areas of Research in SmartRaCon

1.4 Outlook for the ERJU

The research work for advance traffic management and control systems (IP2) in the frame of Shift2Rail is facing the last projects X2RAIL-4 [5] and X2RAIL-5 [6], once X2RAIL-1 [7], X2RAIL-2 [8] and X2RAIL-3 [3] come to the end. The results of all the work are paving the way for. Shift2Rail successor Europe's Rail Joint Undertaking (ERJU). This Rail European Partnership will focus on accelerating, with an integrated system approach, research, development and demonstrations of innovative technologies and operational solutions (enabled by digitalization and automation) for future deployment to deliver on European Union policies towards "European Green Deal" objectives "a Europe fit for the digital age", "an economy that works for people" and "a stronger Europe in the world"[9].

ERJU will implement an ambitious research and innovation programme, designed in line with the Sustainable and Smart Mobility Strategy, and delivered by the System and Innovation Pillars, bringing the most advanced technological and operational solutions to rail. Steered by an integrated system approach, implemented with a multi-annual programme enabled by the JU's Members, the new Programme will start delivering major flagship solutions as from 2025-26 to be demonstrated at large scale in the following years, and to bridge the future activities in the post-2028 era [10]. Among the innovation topics that would be covered there are the evolution of operational and business aspects such as [11]:

- Configuration of the new European reference operations framework and architecture for Control, Command and Signalling (CMS).
- Future evolution of the ERTMS system
- Advances in telecommunications (5G developments with specific railway service and business use cases)
- Traffic management platforms
- Automation of logistics chain, terminals and freight operations
- Intelligent rail asset management and maintenance
- BIM development for use in digital rail twins

1.5 Conclusions

The SmartRaCon Partners are performing research work on innovative technologies for Digitalization and Automation to prepare the ground for new generations of train control and railway management systems. Some of the core elements are technologies covered in the 3rd SmatRaCon Workshop 2021 topics, namely adaptable communications, Zero on-site testing, Moving Block and Virtual Coupling, linked to X2RAIL-3 [3]. In parallel to the technological research, SmartRaCon Partner are developing and operating simulators and research infrastructures for the validation of the technologies.

To disseminate the results of the scientific work, SmartRaCon organizes the yearly Scientific Seminars to present and discuss their results on a high scientific level. The first SmartRaCon Scientific Seminar took place on the 25th of June 2019 in Villeneuve d'Ascq in France [12] and the second seminar the 24th of November 2020 in a digital format from San Sebastian in Spain [13], due to the due to the pandemic situation in Europe. The third seminar takes place now, in the #EUYearOfRail, on the 2nd of September 2021 from Braunschweig in Germany, again in a complete digital format due to the pandemic situation in Europe. The fourth SmartRaCon Scientific Seminar is expected to take place in 2022.

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[5] X2RAIL-4 Advanced signalling and automation system - Completion of activities for enhanced automation systems, train integrity, traffic management evolution and smart object controllers https://projects.shift2rail.org/s2r_ip2_n.aspx?p=X2RAIL-4

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1.7 Authors

Dr. **Marion Berbineau** received the Engineer degree from Polytech'Lille (France) and the Ph.D. degree from the University of Lille, both in electrical engineering, respectively in 1986 and 1989. She is a full time Research Director at Université Gustave Eiffel in the Component and SYStem department and in charge of coordination of Railway R&I activities of the University. She is associated researcher at LEOST laboratory. She is expert in the fields of radio wave propagation in transport environments (particularly in railway tunnels and high speed lines), electromagnetic modeling, channel characterization and modeling, MIMO, wireless systems for telecommunications, cognitive radio for railways and GNSS localization-based system for ITS particularly for the rail and public transport domains. She is responsible for Railway research coordination for the Institute. She is active as an expert for the GSM-R and future systems like LTE-A or 5G NR and beyond 5G. She is involved in several National and European research projects. She is author and co-author of several publications and patents. She is expert at the French national council for the railway system. She is on the reserve list of the Scientific Council of Shift2Rail.

marion.berbineau@univ-eiffel.fr

Michael Hutchinson has over 14 years of experience in the GNSS industry. Michael has developed solutions for and provided consultancy on a wide range of GNSS applications involving robust and reliable positioning and navigation. This includes aviation approach operations, liability critical automotive programmes, future train control systems and Unmanned Aerial Vehicles (UAVs). Michael also provides consultancy on GNSS system level topics. Michael currently works as Business Manager and Principal Navigation Engineer at GMV NSL, coordinating business development activities and leading the company's work in the railway domain.

michael.hutchinson@gmvnsl.com

Dr. **Émilie Masson** is a Project coordinator at Railenium, France. She received the Engineer degree from the Institut Supérieur de l'Électronique et du Numérique, Lille, in 2005 and the PhD degree in electronics from the University of Poitiers, in 2010. She joined Railenium in 2014 as a researcher. She conducted research activities related to telecoms on various European and national projects. She then moved on to become a project manager. Since 2017, she has been coordinating the TC-Rail project, which aims to test the feasibility of railway remote driving. She also coordinates all Railenium activities on Shift2Rail IP2 since 2016.

emilie.masson@railenium.eu

Dr. **Jaizki Mendizabal** received his M.Sc. and Ph.D. degrees in Electrical Engineering from TECNUN (University of Navarra, San Sebastián, Spain) in 2000 and 2006 respectively. He joined Fraunhofer Institut (Nuremberg, Germany) and SANYO Electric Ltd, Japan as RF-IC designer. Nowadays, he is at CEIT, in San Sebastián (Spain) where his research interests include communications and electronic systems. He is lecturing "Communications Electronics" and "Communications via Radio" at TECNUN (University of Navarra).

jmendizabal@ceit.es

Dr.-Ing. **Michael Meyer zu Hörste** holds a PHD in mechanical engineering from the Technical University of Braunschweig. He has joined DLR Institute of Transportation Systems in 2001 bringing already 6 years of railway research experience with him. He is expert in railway operations, command, control and signalling systems, especially ERTMS/ETCS as well as train localisation. Currently he is working the business development of the DLR Institute of Transportation Systems. He was a major contributor in building the DLRs ETCS test laboratory RailSiTe®. He is chairman of the ERTMS Reference Labs Association since 2012. He is fellow of the Institution of Railway Signalling Engineers (FIRSE) since 2012. He is member of the Shift2Rail governing board and coordinator in the DLR for Shift2Rail.

Michael.MeyerzuHoerste@dlr.de

2 Flexibility, Performance and Efficiency: The X2Rail-3 Contribution for CCS-Systems of Future

Bettina Dötsch, Thales, Stuttgart, Germany
Michael Meyer zu Hörste, Christian Rahmig, DLR, Braunschweig, Germany

2.1 Introduction

In the European Joint Undertaking Shift2Rail are five Innovation Programs from which the IP2 is focussed on "Advanced Traffic Management & Control Systems". The work is organised in the series of the X2Rail-Projects, X2Rail-3 being the third project. The focus is on research and development of innovations in the areas of Adaptable Communications, Moving Block, Zero On-site Testing, Virtually Coupled Train Sets, Cybersecurity and ATO over ETCS for Freight. X2Rail-3 is based on the results already achieved in X2Rail-1 as well as the activities in IP5 supporting specifically the ATO for Freight demonstrator. A specific area of work which is unique in X2Rail-3 is the study about Virtually Coupled Train Sets which has the target that trains will be able to run much closer to one another and to dynamically modify their own composition while running. As most – if not all – of the above-mentioned innovations are using communication technologies the Cyber Security is of major importance. Finally, a large integrated demonstrator is planned for ATO over ETCS for freight applications with the primary aim to get an early feedback for improvements.

2.2 Objectives

2.2.1 Overall Objectives

The second pillar of the European Joint Undertaking Shift2Rail is the innovation program IP2 "Advanced Traffic Management & Control Systems" which is focussed on control, command and communication systems (CCS). The target is to develop new innovative technologies which provide new functionalities for railway operation. Besides the specification and demonstration activities there is the need for European Harmonisation to ensure a smooth deployment. The main challenge is to extend the functionalities of the existing signalling and automation systems as well as develop the related design and validation processes providing a more competitive, flexible, real-time, intelligent traffic control management and decision support system. Nevertheless, the backward compatibility to the existing European Rail Traffic Management System (ERTMS) and especially its European Train Control System component (ETCS) shall be maintained.

The project X2Rail-3 continues the research and development of key technologies to foster innovations in the field of railway control, command & signalling, adaptable telecommunication, testing automation methodologies and Cyber Security, as part of a longer term Shift2Rail IP2 strategy towards a flexible, real-time, intelligent traffic control management and decision support system. X2Rail-3 will also explore the innovative concept of Virtual Coupling capable of operating physical traction units much closer to one another inside their absolute or relative braking distance as well as dynamically modifying their own composition on the move. The demonstration of ATO over ETCS for the specifically challenging use case Freight is another major task of the project.

Figure 2-1: X2Rail-3 Logo

The actions to be undertaken in the scope of X2Rail-3 are related to the following specific objectives given in the project description [1]:

- "To improve line capacity and to achieve a significant reduction of the use of traditional train detection systems by means of the introduction of the Moving Block together with train positioning;
- To overcome the limitations of the existing communication system by adapting radio communication systems which establish the backbone for the next generation advanced rail automation systems;
- To ensure security among all connected signalling and control systems by developing new cyber security systems dedicated to railways;
- To analyse new signalling systems (Virtual Coupling) that potentially would be able to improve line capacity, reduce LCC and enhance system reliability.
- To improve standardization and integration of the testing methodologies reducing time to market and improving effectiveness in the introduction of new signalling and supervision systems;
- To ensure the evolution and backward compatibility of ERMTS/ETCS technologies, notwithstanding of the required functional enrichment of the future signalling and control systems.

Future IP2 projects will start additional research and development work streams taking the results of this present X2Rail-3 project. These future projects will also allow concepts developed in the phase of this X2Rail-3 project to be further implemented to higher technical readiness level (TRL)."

The logo of X2Rail-3 is shown in Fig. 2-1 and the overall concept to fulfil the above-mentioned targets is shown in Fig. 2-2.

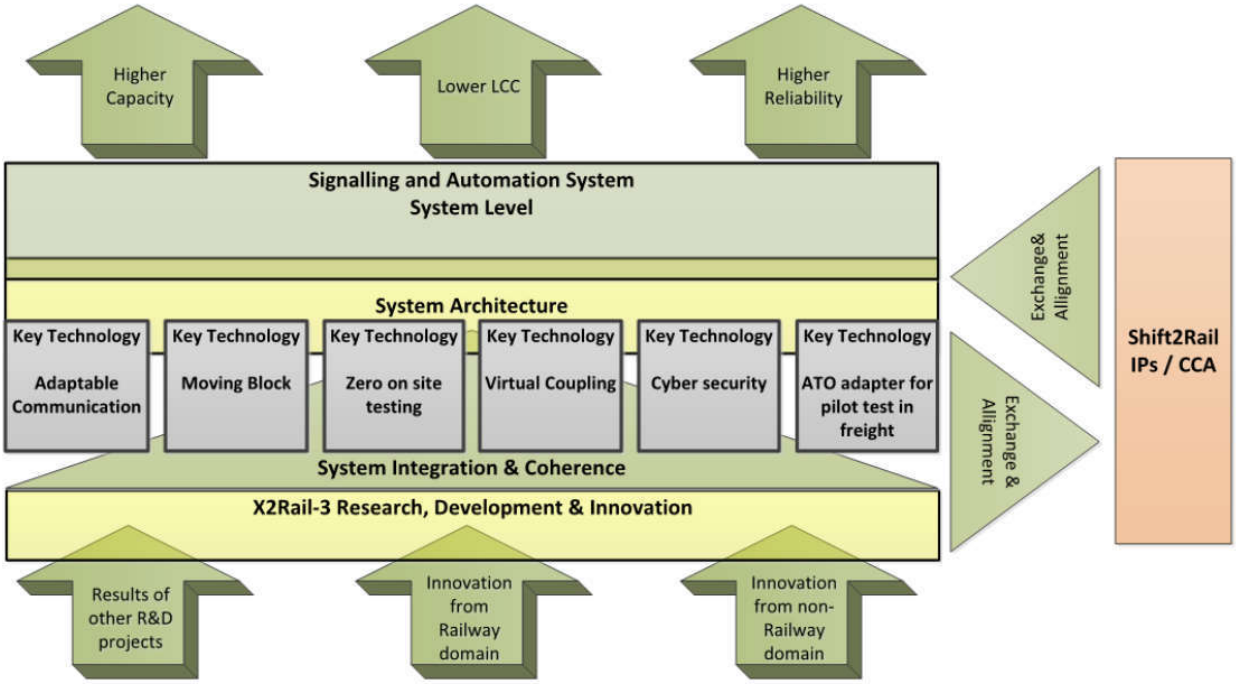

Figure 2-2: Overall concept of the X2Rail-3 Project [1]

In the following sections are the WPs described which are related to the innovation. The No. of the WP (WPx) as well as the related No. of the so-called technical demonstrator (TDy) is given to show the relation between the work done in X2Rail-3 and the overall Shift2Rail IP2 program [2].

2.2.2 Adaptable Communications

Current ETCS and CBTC communications are suffering from several drawbacks, e.g. in adapting to different communication environment settings and requirements. Therefore, the objective of "Adaptable Communications for all Railways" (TD2.1 / WP 3) is to demonstrate that a new Communication System will be able to overcome these drawbacks and deliver an adaptable communications system that can be used for train control applications in different market sector environments. The basic idea is to bring all the different radio access technologies – e.g. GPRS, EDGE, LTE, WiFi, Satellite, etc. – into a bearer independent solution of IP-based technology. By integrating these technologies into different prototypes and demonstrators, the aim is to demonstrate the multi-bearer access system capabilities, which are required for the intended migration of legacy systems to enhance throughput, safety and security functionalities. Thus, current as well as future needs of signalling systems, interference resilience and radio technology evolution aspects can be supported. Based on the specifications and technology guidelines from the project X2Rail-1, different demonstrators will support the business case study about the potential shift from "network as an asset" to "network as a service" model vision. Testing in the laboratory will validate the communication layer potentials considering the communication needs and the unified communication system combining different access networks. In preparation of the follow up project the field test strategy will be provided for the demonstrators started in X2Rail-3

2.2.3 Moving Block

Additional important technical demonstrators shall be developed in the field of Moving Block (TD 2.3 / WP4). These demonstrators are implementing the requirements defined in X2Rail-1 and detailed in X2Rail-3 in a laboratory environment. These laboratory preparations are focusing on various suitable railway applications. Further, processes required for testing of Moving Block approaches shall be investigated in co-funded collaboration with MovingRail and Zero On-site testing. In addition, Change Requests from LinX4Rail are analysed in order to demonstrate the close alignment with Hybrid L3 and RCA supporting the newly defined Change Management Process from the Program Board.

2.2.4 Virtually Coupled Train Sets

With the focus on the key technology "Virtually Coupled Train Sets" (TD 2.8 / WP6 & WP7) a comprehensive study about suitable new concepts is carried out. The objective of these approaches is to increase track capacity by enabling that trains can run within their absolute or event relative braking distance and to allow a flexible train composition on the move by virtual coupling and uncoupling of train convoys. Implementations of this technology must not have negative impact on the level of safety. Therefore, the project actions contain definitions of system behaviour, architecture, functions, applicability and safety level analysis.

2.2.5 ATO over ETCS

In TD 5.6 / WP10, "ATO over ETCS" aims at developing a demonstrator for autonomous freight train operation. The main objective of this pilot test it to support freight ATO demonstration activities in projects ARCC (IP5, WP1) and X2Rail-1 (IP2, WP4) in terms of engineering and planning for the GoA2 demonstrator. Further, field tests shall be done to obtain feedback about improvement potentials with specific focus on freight operations. The testing also shows the interoperability of the solutions of different suppliers.

2.2.6 Zero On-Site Testing

Apart from the technical development focused key technologies, the topic of "Zero On-Site Testing" (TD 2.6 / WP5) is about transferring testing and validating from railway environment into a simulation and testing framework of a laboratory. Tree different demonstrators are provided focusing on topics like connecting 3 different labs, a prototype for validation and stress testing as well as a prototype for subsystem and integration testing. For the implementation of the prototypes the necessary FFFIS interface specifications have been defined and agreed and can pave the way for future standardization. Test cases have been identified using common data model verified by means of formal verification. This aims to create a simulation and testing environment that supports automated laboratory testing and validation. Thus, the need for field tests will be dramatically reduced.

2.2.7 Cyber Security

Cyber Security (TD 2.11 / WP8 & WP9) concludes the spectrum of key technologies in X2Rail-3. Within the project, the main objective is to define a railway specific cyber security system with high availability, authentication and integrity for preventing attacks and discovering errors.

With the aim of reducing costs of infrastructure maintenance and enhancing time to market, interoperability and compatibility, the project supports a "Security-by-Design" standard for different railway applications. Finally, a network of Railway Cyber Security Experts as a base for a railway dedicated Computer Security Incident Response Team (R-CSIRT) shall the established. In addition to providing guidelines for the assessment specific demonstrators have been defined to support the activities in the area of Adaptable Communications, CONNECTA as well as TD2.10 providing new approaches for the Smart Wayside Objects.

2.2.8 System Integration & Coherence

As the functionalities and technologies of CCS Systems are always highly interdependent, X2Rail-3 has set up a dedicated work group where technical experts will come together to ensure technical coordination and system integration within the project. The related transversal work package (WP2) will ensures coherence within X2Rail-3 project, but also with the past X2Rail-1 and X2Rail-2 projects and the future X2Rail-4 and X2Rail-5 projects within IP2. In order to ensure the consistency with the ETCS core concept and to facilitate that the outputs from the project will be well prepared to enter smoothly the ERTMS CCM process, the liaison with corresponding ERTMS Users Group and UNISIG groups will also be ensured.

2.3 Methodology

Improving the railway system performance is in the focus of X2Rail-3. Based on the results of previous project X2Rail-1, the project initializes the demonstration of new technologies challenging the conventional signalling and automation systems. Aiming at a drastic change of railway operation, X2Rail-3 sets up a system approach for complete Shift2Rail IP2. Results from past and current research projects as well as technology innovations will be reviewed and integrated into the technical sub-systems. Considering the system nature of railway signalling and automation systems the projects links the different technical work streams to provide synergies and benefits at system level. The project work packages are cross-referenced with key system technologies of signalling and automation. In summary, based on the results of X2Rail-1, the project contains all the preparatory work required for the Shift2Rail IP2 demonstrators, whereas most of the technology sub-system domains of X2Rail-3 can be considered as X2Rail-1 continuations. The Virtual Coupling concept is newly introduced aiming at running train traction units much closer one another. As mentioned before, the other sub-systems focus on signalling, automation, testing, radio communications and cyber security aspects. Together, they represent the enabling technologies for advanced signalling and automation functionalities being handled in individual interconnected work streams. Each work stream focuses on a different technical sub-system, e.g. radio block centres, on-board units, wayside objects or TMS interlockings. This structure allows to power the new technologies up fast and to synchronize the X2Rail-3 activities with the progress in other IP2 projects. This overall methodology approach enables addressing of new laboratory test environments, facilitation of authorisation, approval and time-to-market processes. In order to learn from technology sectors outside the classic railway domain, non-railway domain experts are incorporated in the X2Rail-3 project activities to ensure adaptation of technologies and innovations to the railway system domain.

2.4 Impact

The project X2Rail-3 will provide innovations and demonstrations for building blocks of future advanced rail traffic and train control systems based on the current ERTMS/ETCS basis. Hence it supports the rapid and broad deployment of those systems by offering improved functionalities and standardised data and physical interfaces based on common operational concepts. The migration from legacy systems will be facilitated by reducing overall costs, adapting it to the needs of the different rail segments by enhancing flexibility as well as to the needs of a multimodal smart mobility system. The impact from X2Rail-3 needs be understood in the entire series of the projects from X2Rail-1 up to X2Rail-5. It continues to develop results from X2Rail-1 and will itself be continued in X2Rail-5. Especially it identifies possible solutions for virtual coupling and demonstrates prototype activities for ATO applications in freight rail transport.

In the following sections are potential impacts with respect to higher flexibility, improved performance and better efficiency discussed as specific examples.

2.4.1 Higher Flexibility

In some low-density areas is the demand for rail transport significantly variable over time and sometimes difficult to plan over months or years. E.g. the pandemic situation has shown that the demand from students to go to school or university from the living areas around cities which is sometimes the largest peak can decrease to almost zero. A potential approach can be here to use virtual coupled train sets together with adaptable communications to have a quick reaction to changing demands up to almost real-time provision of the required train capacity but avoiding almost empty trains. As a further step the transport on very low demand lines can be done on demand e.g. after "booking a train" in advance. This approach paves the way to fully automatic operation in GoA4 in later step.

2.4.2 Improved Performance

Another example of improvement potential in today's rail system are lines which are connecting around larger stations. Here is a need of low trackside investments in the outer branches of the network a high capacity or low headways in the lines at the main station in the middle. Here can the moving block concept help to achieve higher capacity as well as higher availability in the lines with a dense timetable as well as have a reduced trackside equipment at the outer line segments. The ACS can further help to reduce LCC by providing the required level of safety as well as ensuring the required level of service in an adopted way: High level of quality and availability where needed and reduced complexity where acceptable.

2.4.3 Better Efficiency

Generally, the railway system can be improved to make best use of the capabilities which are there as well as reducing efforts. Consequently, it is to be analysed where higher degrees of automation and digitalisation can help to improve the exactness of the train operation and reduce cost e.g. for approval which both again help to lower the LCC of the CCS systems.

The operation of freight trains is another approach to improve operation by ATO over ETCS. Here it needs to be mentioned that the dynamic behavior of freight trains can differ much more than for passenger trains. One freight – moved by the same locomotive - train can have 100 meters length and 100 ton weight another 2.500 tons and 750 meters. Both of them could have complex internal dynamic effects which lead to n-dimensional control problem. The demonstration can be understood as a proof of concept – The control concepts will have a need for refinement.

Another area of high effort in the rail system and especially for CCS system is today the validation and approval procedures. Especially the testing required for the homologation and put into service is very much time and effort consuming in the real environment. Here intends the Zero on-site Testing to move tests as far as possible from field into the lab. This will lead to a high number of positive effects on the cost: Tests can be done all the time e.g. only during work hours (and not in the middle of the night as field test often are) as well as 24/7 automatically. Critical situations can be tested with much less risk. Repeating a test run can be done within very short time. Scarce resources as test trains and their specific drivers can be used much more selective. Those and many more positive aspects justify the long and complex discussions to accept the tests in lab as basis for the approval. The innovative technology as well as the definition of common architecture and interfaces are done in X2Rail-3.

2.5 Conclusion

The project X2Rail-3 is the third of the projects in the X2Rail-Series of five projects. It is bridging the Start – Up activities from X2Rail-1 with the final field demonstrations in X2Rail-4 and X2Rail-5 and provides therefore important results providing different demonstrators in Lab and Field. The technical focus of the research and development of innovations is given to the areas of Adaptable Communication Systems, Moving Block, ATO over ETCS for Freight, Cybersecurity and Zero On-site Testing. The provided prototypes will give important feedback to the prepared specifications and technology definitions. In addition, standardization will be supported due to additional FFFIS specifications in the area of simulation and testing as well as operational experiences gained in the field testing of ATO. The study about Virtually Coupled Train Sets has the objective to show that trains will be able to run much closer to one another and to dynamically modify their own composition. The results in this area will open new innovation possibilities for future operational concepts in a demanding mobility environment. By performing all those activities X2Rail-3 prepares the next steps for future advanced CCS Systems to be done in Shift2Rail e.g. in the project X2Rail-5 and later in the Europe's Rail Joint Undertaking.

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2.7 Acknowledgements

This project X2Rail-3 has received funding from the Shift2Rail Joint Undertaking (JU) under grant agreement No 826141. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Shift2Rail JU members other than the Union.

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2.8 Authors

Bettina Dötsch (Dipl.-Ing. BA) holds an engineering degree in computer science from the Berufsakademie in Stuttgart. She joined Thales in 1986. Since joining Thales GTS (Ground Transportation Systems) in 1989 she has gained experience in different areas of the Main Line Business like Safety, Quality and Product Strategy. Form 2010 till 2013 she was working as Design Authority in the Thales HQ in Paris. Starting 2015 she joined the Shift2Rail research project representing Thales in IP2 and acting as coordinator for X2Rail-3.

Bettina.Doetsch@thalesgroup.com

Dr.-Ing. **Michael Meyer zu Hörste** holds a PHD in mechanical engineering from the Technical University of Braunschweig. He has joined DLR Institute of Transportation Systems in 2001 bringing already 6 years of railway research experience with him. He is expert in railway operations, command, control and signalling systems, especially ERTMS/ETCS as well as train localisation. Currently he is working the business development of the DLR Institute of Transportation Systems. He was a major contributor in building the DLRs ETCS test laboratory RailSiTe®. He is chairman of the ERTMS Reference Labs Association since 2012. He is fellow of the Institution of Railway Signalling Engineers (FIRSE) since 2012. He is member of the Shift2Rail governing board and coordinator in the DLR for Shift2Rail.

Michael.MeyerzuHoerste@dlr.de

Dipl.-Ing. **Christian Rahmig** graduated at the University of Technologies in Dresden in the field of Transportation Engineering with focus on Transport Telematics. He joined DLR Institute of Transportation Systems in the year 2009, where he contributed to a lot of national and international projects focusing on multi-sensor data fusion, on-board positioning, digital maps and data models for usage in railway applications. Since 2015, he works as business developer for the Institute, at first for the Railway Department and since 2021 for the Department of Information acquisition and data modelling.

Christian.Rahmig@dlr.de

3 Antenna Integration in Railway Environment

Naveen Kumar, IRT RAILENIUM, Famars, France;
Divitha Seetharamdoo, COSYS-LEOST, Université Gustave Eiffel, Villeneuve d'Ascq, France

3.1 Introduction

Railways are one of the most energy-efficient modes of transport for long distances. The most important factors in railway travel are usually speed and cost. A key component of a fast and efficient rail network is the communication system whose performance is dependent on the antennas used. Antenna integration in railway environment presents many challenges equally important to railways; it includes considerations such as safety, ease of deployment and maintenance, footprint, separation distance from other systems, and cost-effectiveness. When considering antenna integration in railway environment, it is necessary to account for the high level of electromagnetic interference and the importance of minimizing the impact on signal quality [1]. Antenna performances is largely dependent on frequency range and impact of obstacles and consequently on the changes in impedance and radiation.

This article will discuss some factors affecting antenna performance in a railway environment, how they affect antenna performance, and what can be done to prevent or mitigate the effects.

3.2 Antenna Integration Constraints

Railway environments are complex and include railway infrastructure in close proximity to one another. There are many constraints that arise from the inclusion of a railway system within an urban setting [2]. This article will discuss these constraints which may affect the effectiveness of antennas with regards to their range, efficiency, directionality and placement.

3.3 Train Rooftop Structure

Many trains have a curved roof top which has an impact on antenna operation, particularly for wireless communications. The roof top can also have metal bars. The antenna mounted away from the center line of the train will exhibit worst performance due to obstruction due to the curvature of the roof.

Figure 3-1: Example: Exaggerated Curvature of train rooftop [3]

3.3.1 Antenna positioning on rooftop

Space availability on the train rooftop is limited and with increasing number of communication systems there is a scarcity of space. This gives rise to problem to find optimum position for antenna systems to avoid any performance degradation. Moreover, the structures on the train rooftop such as air-conditioning unit, pantographs, curved roof, strengthening bars, sunken roof etc. affects the antenna radiation performance.

Another factor to consider is the separation distance between antenna systems operating in the same frequency band. If the separation distance is not enough then the interference issue degrades the system performance. The separation distance is decided as per the operating frequency for example GSM-R works at 900 MHz with wavelength of 0.33 m, so the separation distance should be at least five time of the wavelength i.e. 1.65 m. For antenna systems operating in different frequency bands, this separation distance can be smaller as there is low risk of interference.

3.3.2 Ground plane size

For most of the antenna structures such as monopole, microstrip patch etc., there is a general requirement of minimum ground plane for desired antenna operation. The dimensions of the ground plane depends on the operating wavelength. If the ground plane size is smaller than required, then the antenna resonance and radiation efficiency gets affected. This can be understood by following example of a monopole antenna operating at 900 MHz band. It can be observed from Figure 3-2 that for smaller ground plane size (l_g = 50mm), the antenna shows no resonance. As the ground plane size is increased the impedance matching improves and the resonance shifts to lower side of the frequency spectrum. When the ground plane size is optimum (l_g =150 mm), the resonant frequency is in the desired band of 900MHz and required bandwidth is also covered by the antenna. The ground plane size should be λ/4 in every direction, where λ is the wavelength at resonant frequency.

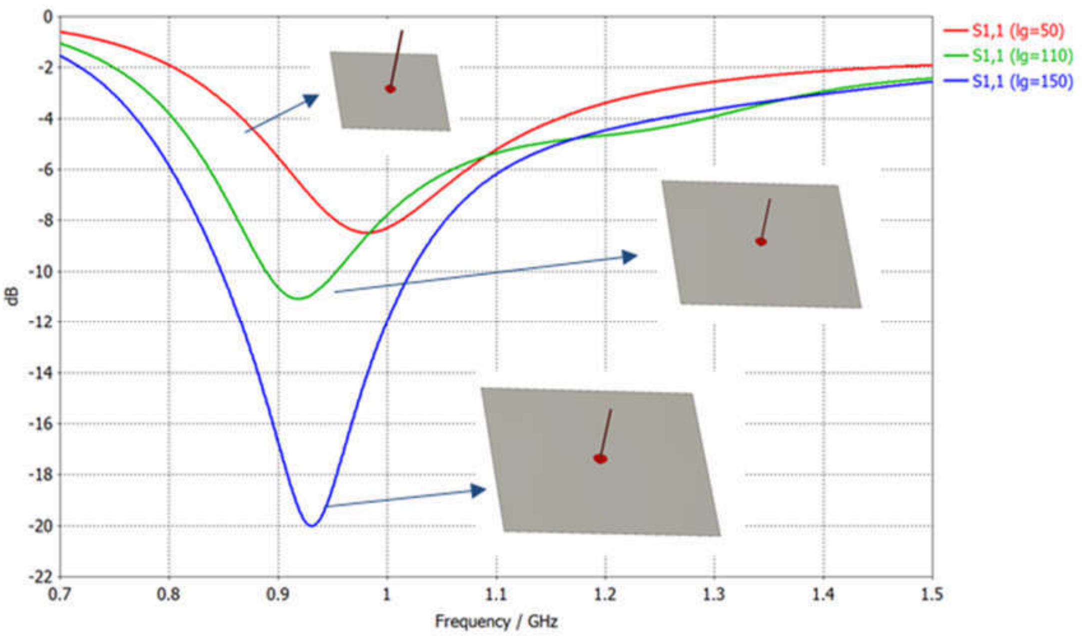

Figure 3-2: Example: S-Parameter plots for different ground plane sizes

3.3.3 Radome size and material

A radome structure is used to provide environmental protection to the antenna structure and it is made up of such materials which exhibit minimal attenuation to the electromagnetic signals from the antenna [4]. The size of the radome depends on the overall dimensions of the antenna and the application platform. Few popular materials are amorphous thermoplastic polyetherimide (PEI), ASA (acrylic ester-styrene-acrylonitrile), fiberglass, and PTFE.

The separation distance between the radome and the antenna need to be optimal such that the antenna performance does not get degraded [5]. The dielectric properties of the radome affects the radiation pattern shape and the resonant frequency of the antenna. The minimum separation distance can be calculated from the equation given below:

$$d_m = \lambda_0/2 \qquad (1)$$

where d_m is the minimum distance between radome and antenna and λ_0 is the wavelength at resonant frequency.

3.4 Mitigating decrease in antenna performances due to integration constraints

3.4.1 Electromagnetic Cloak

The space constraint on the train rooftop affect the antenna system positioning and separation between systems. With increasing number of communication standards to be supported by on-board train communication system, the space constraint becomes more severe. One of the possible solutions is to use electromagnetic cloak which is an engineered structure to reduce scattering cross-section (SCS) [6]. So, in the case of an antenna being affected by an object or another antenna close by, a cloak can be employed around the object so that the antenna properties will not get affected. Metamaterials can be used to design a cloak which can be used to reduce SCS of an object/antenna [7].

3.5 Conclusion

In this paper, we presented and discussed few antenna integration constraints in the railway environment. The simulation analysis of the effect of ground plane size of the antenna showed that ground plane should be $\lambda/4$ in size in all directions to achieve optimal antenna performance. The degradation in the antenna performance due to some of these constraints can be mitigated by using electromagnetic cloaking technique. This technique gives us a solution to integrate and install the antenna near to other antenna systems and/or structures on the train rooftop.

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3.7 Acknowledgements

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3.8 Authors

Naveen Kumar is a research engineer in Railenium, currently working on antenna specifications and design for adaptable communication system (ACS) in Shift2Rail project. He has completed Ph.D. from Thapar Institute of Engineering and Technology, Punjab, India in 2021; Master of Engineering from Panjab University, India in 2013; and Bachelor of Technology from Punjab Technical University, India in 2009. His research interests are antenna design, MIMO antennas, Metamaterials, and Wireless Communication.

naveen.kumar@railenium.eu

Divitha Seetharamdoo is a researcher in the LEOST laboratory of the COSYS department, University Gustave Eiffel, Lille campus. Her research interests are the modeling and design of metamaterials for various applications such as antennas for communication systems and radars, and electromagnetic compatibility. The application context of her research is mainly in the field of transport (connected and automated vehicles) and smart city. She has made numerous contributions in the field of the integration of antennas in complex environments and of techniques for associating metamaterials with antennas to improve their performance during integration and miniaturization.

divitha.seetharamdoo@univ-eiffel.fr

4 SDN-based slicing and network resource distribution in train-to-ground railway communication

Eder Ollora Zaballa, DTU Fotonik, Lyngby, Denmark

4.1 Introduction

Software-Defined Networks (SDNs) were initially focused on networks such as Data Centers (DC), and most of the initial research outcomes have these networks as an initial point of the design. First-wave SDN networks were based on southbound protocols like OpenFlow [1], enabling vendors to create bare metal switches that allow an external centralized control plane to program the forwarding tables and collect traffic statistics. Openflow is a model that offers both a match-action abstraction and an interface that provides a well-known communication protocol for the control and data plane layers.

From the original publication of Openflow, the concept of SDN started to cover new scenarios and use cases. As the research work analyzed additional features of SDN networks and as southbound protocols evolved to new versions, additional use cases appeared. Apart from focusing on DC-based use cases, new use cases appeared on optical networks, wireless networks, carrier-grade networks, Network Function Virtualization (NFV), assisting Radio Access Networks (RANs), etc. Railway networks do generally not incorporate innovative and state-of-the-art network technologies due to component interworking issues. In addition, the fixed-function appliances used in railway networks prevent them from being flexible, consequently restricting programmable bare-metal switches to be added to either train or ground networks. Incorporating SDN-based network programming to the railway architectures opens up new possibilities for railway networks to expand the control plane applications (e.g., add firewall functionalities on demand).

4.2 Related work

As mentioned in the Introduction, railway networks have never been a natural area for SDN-related investigation. Therefore, the available research when mixing SDN and railway networks is limited to a handful of industry research and academic papers. Focusing on the private sector, NEC published a white paper in the NEC technical journal [2] listing the most common issues found on railway stations when construction works occur. The authors mention problems such as significant network configuration changes, IP address reassignment, requirements for fast service deployment, and short time window constraints when construction work was being conducted. As a result, NEC Corporation (NEC) decided to deploy an SDN-based solution for a Tokyo train station. Incorporating OpenFlow switches allowed the network control plane to be aware of any changes in the network topology. The network managers were also able to reduce the time needed for network configuration, and the virtual tenant network (VTN) functionality avoided any issue related to IP address duplication.

In terms of the research work conducted in the last years, a few researchers presented new case studies for SDN and railway networks. The existing research that shares some features with the work of SDN in X2Rail-3 was published in 2016. Gopalasingham et al. [3] presented an SDN-based architecture for a Train-to-Wayside Communication System (TWC). The proposed architecture offers both mobility management and a dynamic Quality-of-Service (QoS). The difference between this proposal and the one depicted in the current paper (as part of X2Rail-3) is that the OpenFlow switches are part of the Adaptable Communication System (ACS) and the train local area network (LAN). The QoS differentiation offered is similar in both proposals, but the one on X2Rail-3 is based on the slicing methodology applied by the ONOS SDN controller (SDNC). Since the SDN architecture implemented on X2Rail-3 uses several ACS systems, the SDN controller can select which ones to use and which interfaces to use from each ACS.

Sen et al. [4] proposed an SDN architecture to provide WiFi-based backhaul connectivity for trains. The main difference with the ACS-based SDN proposal of X2Rail-3 is that slicing and QoS are part of the features provided by the SDN controller. Besides, Sen et al. propose to use the SDN controller at train and wayside, compared to the only core controller proposed by Gopalasingham et al. [3]. The X2Rail-3 proposal uses an external core controller too, although the controllers support cluster-based communication. Still, improvements and changes to this configuration are discussed in the Future Work section. Finally, Franco et al. [5] describe a train-to-ground (T2G) communication architecture based on SDN and transport-level Multipath Transmission Control Protocol (MPTCP) techniques. The results show that including MPTCP and the SDN controller application DynPaC improves the response against failures and better data rates than legacy switch-based tests. Furthermore, the SDN proposal on X2Rail-3 included additional features compared to the ones described by Franco et al. [5], such as adding a cluster of controllers and train-based Openflow virtual and hardware switches.

4.3 SDN integration and testbed

Incorporating SDN architectures into train and ground networks implies integrating the virtual and physical OpenFlow switches with the existing train hardware. In X2Rail-3, the SDN virtual and physical switches have been incorporated as part of the train LAN and the ACS. Both have been integrated into different architectures and testbeds in this paper, but both virtual and physical OpenFlow switches can run together in future tests.

4.3.1 Virtual SDN switches as part of the ACS

In the first case, portrayed in Figure 4-1, the SDN switches are part of the ACS. The Open Virtual Switch (OVS) is the OpenFlow switch part of the ACS. The primary purpose of the switch is to forward the traffic via different interfaces that represent possible wireless interfaces such as WiFi, LTE or 5G. It does so by establishing a secure end-to-end tunnel based on IPSEC. The other end switch decrypts the traffic and forwards each packet to the appropriate application or service.

The SDN controller and the OpenFlow switch are connected via a secure Virtual Private Network (VPN) since both entities are located in different testbeds. In-band OpenFlow might be necessary when the controller and the SDN are located in different premises, and control and data traffic share the same gateway. However, an out-of-band OpenFlow might be possible if a secondary wireless interface is used only for control traffic.

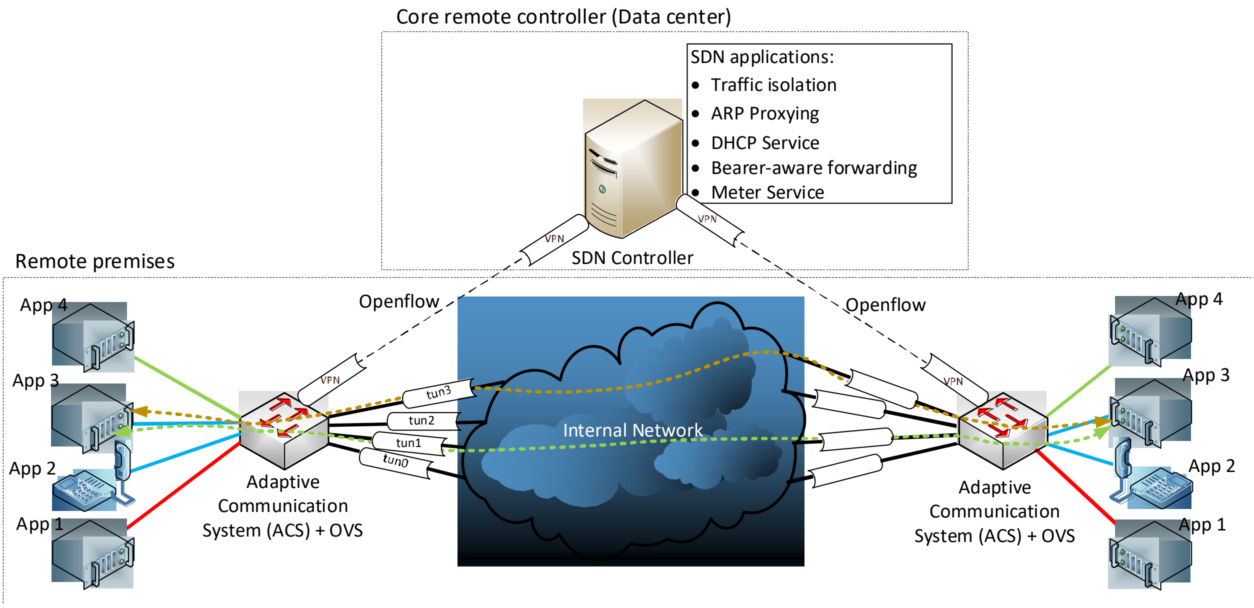


Figure 4-1: Integrating the virtual OpenFlow switches as part of the onboard ACS in the first testing scenario.

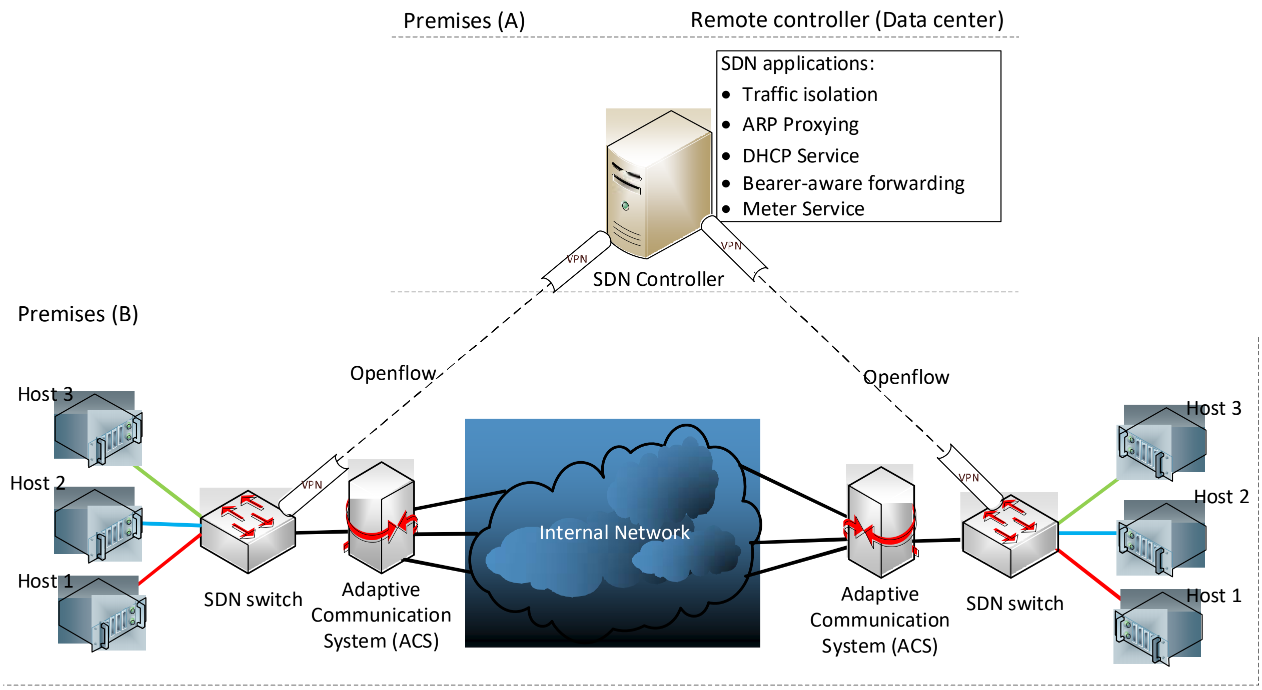


Figure 4-2: Integrating the physical OpenFlow switches as part of the train LAN in the second testing scenario.

The ACS tunnel management sends a REST request with a JSON format to the SDN controller to set up a connection. Then, the SDN controller extracts the information added to the connection flow, such as the metrics, relevant addressing parameters, main and backup tunnel IDs, etc. The parameters are translated to configuration objects that represent flows in the controller slicing application. When the configuration is added to the controller, it installs flow rules on the switch to forward the traffic to the next hop properly. It also installs meters if necessary and keeps track of the connection to install the backup path if an interface is down or poor performance. Therefore, the controller can shift the tunnel path of an established connection at runtime. This is achieved by submitting new OpenFlow rules that will replace the actions of old ones. The slicing application also isolates traffic from traffic belonging to different slices. An example of this process is present in the Appendix (Listing 3-1).

4.3.2 Physical SDN switches as part of the train LAN

In this integration, the OpenFlow switch was an HP Aruba 2930F, and it was part of the train LAN. When the Openflow switch was part of the ACS, it was possible to implement bearer-aware traffic forwarding. In this case, the OpenFlow switch cannot select any of the ACS interfaces to use, but instead, it can only select which of the train ACS is used to forward the traffic from each slice flow. The SDN controller connects to the switches using the same type of VPN used in Figure 4-1. This VPN is used to interconnect testbed premises, allowing to secure the communication channel between the controller and the switches. However, securing the connectivity among premises cannot be replaced with the OpenFlow encryption using TLS. This is because the VPN secures the traffic between premises, but not end-to-end, switch-to-controller.

Although this second scenario includes physical SDN switches instead of the virtual ones and the switches located differently, the SDN controller application functionality is the same. However, as stated before, when configuring the SDN switch, it is essential to consider that the main and backup tunnels associated with forwarding the traffic from a slice will only reference the ACS to be used and not the interface on the ACS.

4.4 Results and discussion

In both cases, the test procedure first verified that the SDN controller could detect all the switches since the OpenFlow traffic is tunneled using the end-to-end VPN. Then the slices could be both created using CLI commands or via the REST API. Once the slice was created, it was possible to associate a flow configuration with a slice. Then assign an appropriate treatment for that flow: main and backup interfaces (first test case), select the ACS or load balance (second test case), rate limit flows (metering), isolate addressing and communication between slices, etc.

Figure 4-3 shows the rate limitation imposed by the SDN switches and commanded by the SDN controller. The bottom two red boxes forward and rate-limit the traffic from 192.168.112.30 to 192.168.112.29. The single red box on top shows the flow rule for the traffic on the other way. Thus, only one-way traffic (bottom red boxes) is rate-limited.

Figure 4-4a shows the effect of flow rules in Figure 4-3, and the rules affect the traffic. The tests with iperf send from one endpoint to another with a rate of 1Mbit/s. The server reports a rate of 535 Kbit/s from the client, demonstrating that the SDN slicing application can distribute the available resources among slices and flows at runtime. In this way, when the resources from a particular wireless technology are scarce, some of the slices might be rate limited. This case is shown in Figure 4-4b, when one of the slices is drastically rate limited to accommodate critical slices (slice 2, red) that require most of the available resources. As shown, slice 1 is limited to

150 Kbit/s and slice 2 to 750 Kbit/s. Slice 2 continues with the same rate, and when the available resources are better, the SDN controller changes the limit of slice 1 to 500 Kbit/s.

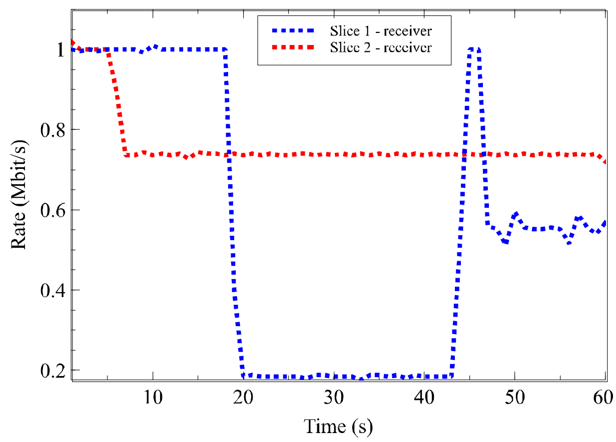
SELECTOR	TREATMENT	APP NAME
ETH_TYPE:bddp	imm[OUTPUT:CONTROLLER], cleared:true	*core
(No traffic selector criteria for this flow)	transition:TABLE:100, cleared:false	*drivers.hp.HPPipeline
ETH_TYPE:lldp	imm[OUTPUT:CONTROLLER], cleared:true	*core
IN_PORT:7, ETH_DST:C4:00:AD:15:39:52, ETH_SRC:C4:00:AD:17:00:2A, ETH_TYPE:ipv4, IPV4_SRC:192.168.112.29/32, IPV4_DST:192.168.112.30/32	imm[OUTPUT:1], cleared:false	dk.dtu.x2rail.slice
ETH_TYPE:ipv4	imm[OUTPUT:CONTROLLER], cleared:true	*core
IN_PORT:1, ETH_DST:C4:00:AD:17:00:2A, ETH_SRC:C4:00:AD:15:39:52, ETH_TYPE:ipv4, IPV4_SRC:192.168.112.30/32, IPV4_DST:192.168.112.29/32	imm[OUTPUT:7], metered:METER:1, cleared:false	dk.dtu.x2rail.slice
ETH_TYPE:arp	imm[OUTPUT:CONTROLLER], cleared:true	*core
(No traffic selector criteria for this flow)	transition:TABLE:200, cleared:false	*drivers.hp.HPPipeline

Figure 4-3: Non-metered traffic and metered flow rules on the ONOS SDN controller.

```
root@x2r-appl-ob:~# iperf -u -c 192.168.112.29 -b 1m -t 10 -i 1 -l 500
------------------------------------------------------------
Client connecting to 192.168.112.29, UDP port 5001
Sending 500 byte datagrams, IPG target: 4000.00 us (kalman adjust)
UDP buffer size:  208 KByte (default)
------------------------------------------------------------
[  3]  local 192.168.112.30 port 34082 connected with 192.168.112.29 port
5001

[ ID] Interval       Transfer     Bandwidth
[  3]  0.0- 1.0 sec   123 KBytes  1.00 Mbits/sec
[  3]  1.0- 2.0 sec   122 KBytes  1.00 Mbits/sec
(...)
[  3]  9.0-10.0 sec   122 KBytes  1.00 Mbits/sec
[  3]  0.0-10.0 sec  1.19 MBytes  1000 Kbits/sec
[  3]  Sent 2501 datagrams
[  3]  Server Report:
[  3]  0.0- 9.5 sec   653 KBytes   565 Kbits/sec   0.000 ms 1163/ 2501 (0%)
```

(a)



(b)

Figure 4-4: (a) A client connecting to the server with 1 Mbit/s rate and server reporting 565 Kbit/s. (b) The reported rate at the server from two different slices with different requirements.

Additionally, some wireless interfaces might offer better latency results when some areas are better covered than others. In this way, the ACS-based switch can forward traffic when the expected outcome regarding available resources or latencies is better.

4.5 Future work

One of the main concerns when testing train-based SDN networks is that the control plane traffic needs a reliable channel to keep consistent communication between the control and the data plane. In our test case, the control traffic traversed fixed networks, so no wireless interface was involved. However, even if the ONOS SDN controller application supports distributed control planes (i.e., ONOS instances running as a cluster), this would not solve the problem of having the control traffic transport protocol from failures. This means that if the control plane interface fails, the TCP connection would need to be reset several times, becoming an unreliable part of the SDN network. This issue can also be identified in the design described by Gopalasingham et al. [3].

Future tests in X2Rail-5 will look into integrating local controllers and remote controllers using a hierarchical organization. In this way, a core controller from a higher hierarchy level can manage the train controller for configuration and data reporting. Local controllers then can manage the OpenFlow control traffic and provide a reliable control plane organization. Figure 4-5 shows how the controller organization and deployment transition from X2Rail-3 (left) to X2Rail-5 (right) will happen.

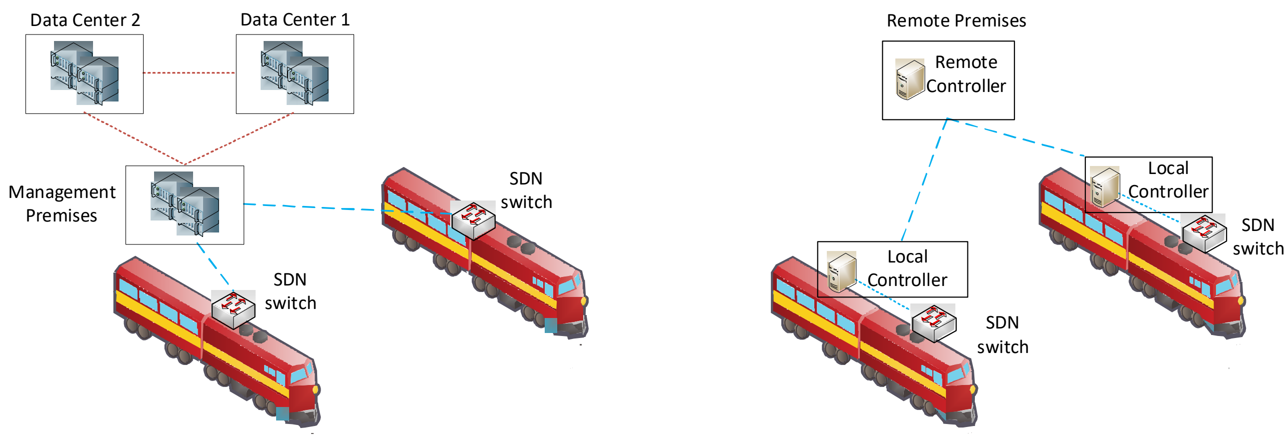


Figure 4-5: Transitioning from a remote, centralized and cluster-based controllers (left figure) to a hierarchically organized local and remote controllers (right figure).

4.6 Conclusion

When analyzing SDN networks, it is well known why DC networks, campus networks, or ISP networks are among the most popular use cases for SDN. However, including wireless interfaces for the control traffic complicates deploying an architecture where the control plane is physically separated from the data plane and remotely located. Even though integrating SDN in train-to-ground communication networks is challenging, we have demonstrated that the outcome is promising. The slicing application's design, integration, and development show that the different training and wayside/ground networks can be segregated into different groups or sliced. These slices isolate the communication among the entities from different slices and distribute the resources among them. Furthermore, the results show how the ONOS SDN controller has been able to rate-limit train to ground traffic at runtime when the resources vary and also manage the proper interface output. With future features in X2Rail-5, the slicing application will support a hierarchical controller organization, preventing unreliable wireless channels for the control traffic.

4.7 Appendix

```
Step-1:    function changeForwarding (event)
           {
              if ( event.reason == (LINK_DOWN || PORT_DOWN) ||
                        event.reason == config.CHANGE) {
                 newTunnel ← getBackupTunnel(config)
                 newPath ← calculatePathWith(newTunnel)
                 oldFlows  ← getInstalledRulesForMainTunnel()

                 //Install new rules with a different priority
                 installRules(path, priority+1) //alternatively with priority-1

                 for f in oldFlows: //Remove old flows not used
                    removeFlow(f)
              }
              return
           }
Step-2:    Attach changeForwarding() as topology change listener. It will run when LINK_DOWN, PORT_DOWN or configuration change
involve a main tunnel.
```

Listing 3-1: Steps SDNC follows after a network event and new forwarding rules have to be installed.

4.8 References

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4.9 Acknowledgements

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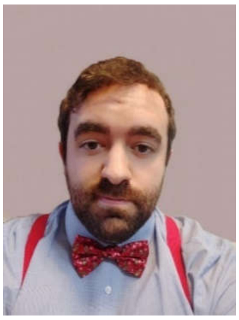
4.10 Author



Eder Ollora Zaballa is a third-year Ph.D. student in the Network Technologies and Service Platforms group at the Technical University of Denmark. He studied the Telecommunications Engineering BSc at the University of the Basque Country. He has previously been involved in the European project NGPaaS. His research interest focuses on control and data plane programming (ONOS, Openflow, P4, and P4Runtime), distributed control planes, slicing, telemetry, and network security within SDN networks.

eoza@fotonik.dtu.dk

5 Adaptable Communication System in regional and freight demonstrator including Channel Emulator Tool

Nerea Fernández-Berrueta , Jon Goya, Jaizki Mendizabal; CEIT, San Sebastián, Guipúzcoa, Spain

5.1 Introduction

The study of the radiolocalization

This work describes the CET (Channel Emulator Tool) integrated into a regional and freight demonstrator as one of the prototypes being developed in X2RAIL-3 WP3 Adaptable Communication System (see Figure 5-1) as part of TD of IP2 Advanced Traffic Management and Control Systems in the frame of Shift2Rail.

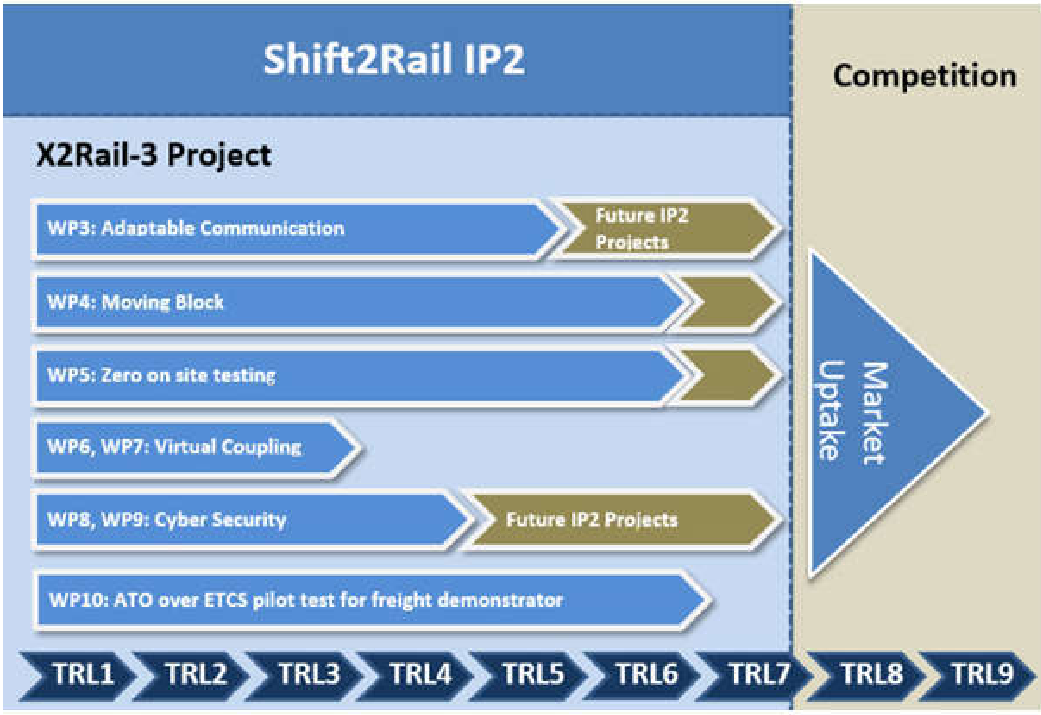


Figure 5-1: WP3 in the X2Rail-1 project

The objectives of this work package are to cover the definition, development and test of prototypes and demonstrators for the adaptable communication system in response to ETCS and CBTC system requirements, cover operational voice services as well as supporting enhancements of the signalling system foreseen by other TDs and other railway communication needs (critical video, critical data).

In order to develop and test the Adaptable Communication System (ACS), three different demonstrators have been proposed within this specific work:

- Mainline
- Regional and freight
- Urban

In this abstract, the focus is on the regional and freight one due to CEIT collaboration in this demonstrator. First, the description of the demonstrator where the CEIT prototype is integrated; the regional and freight demonstrator. Then, the article gives a short explanation of the prototype itself and its main goal. Moreover, the general functioning of the prototype is explained, precising that some possible inputs of the prototype can be given by another tool called Channel Characterization Tool: a system that can measure different impairments along a track; therefore, allowing replaying the real scenario in this prototype. Finally, the integration between both, prototype and demonstrator is detailed. Furthermore, the results of this integration are shown and some conclusions are exposed.

5.2 Demonstrator

The demonstrator selected to work with is focused on the regional and freight scenarios. It consists of the integration of different prototypes to get as close as possible to the on-site testing. Figure 5-2 shows: satellite communications, voice dispatcher, emulator being the communication channel, ETCS application and of course the ACS that the WP wants to test itself.

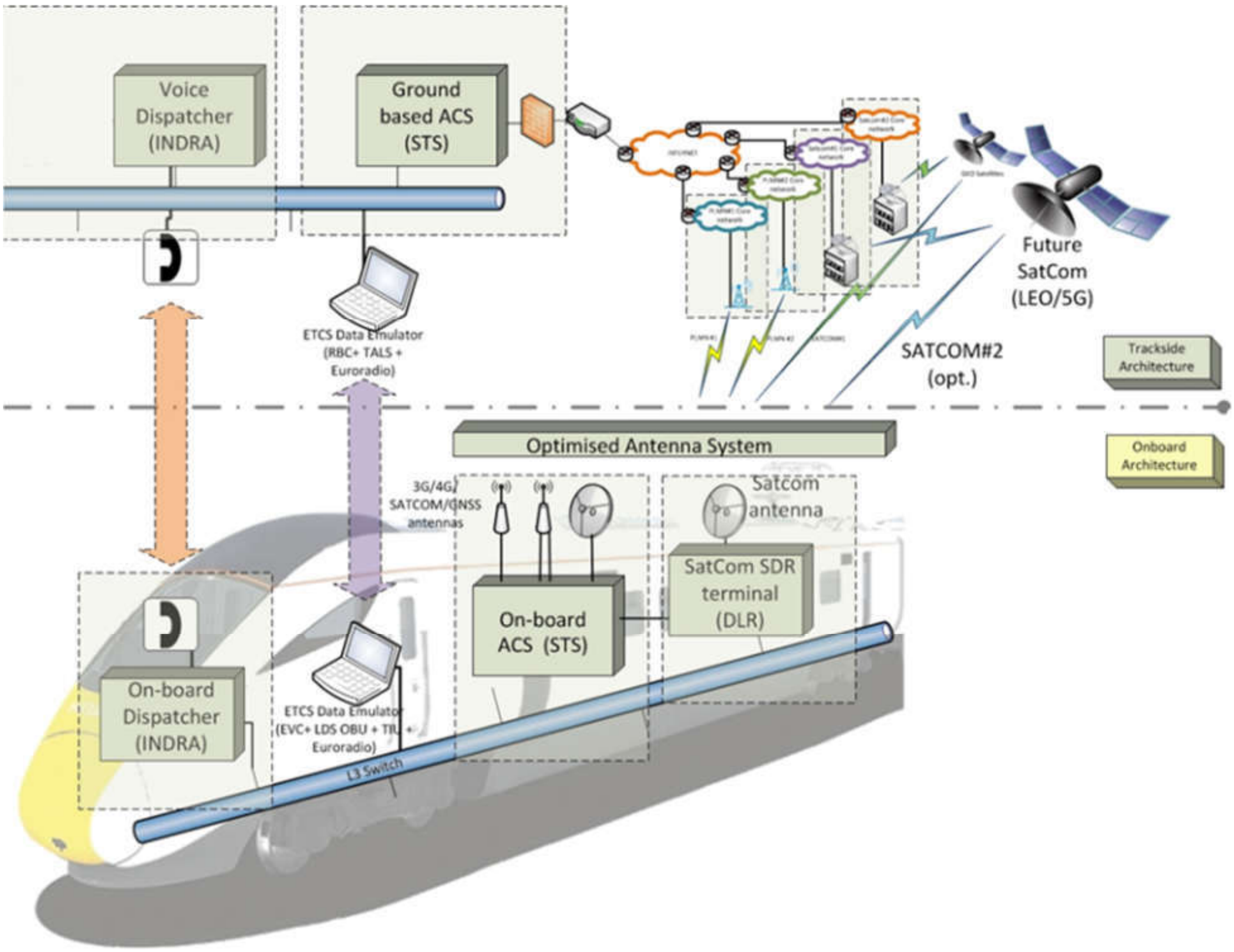


Figure 5-2: Integration of the emulator in the demonstrator

5.3 Prototype

In the context of TD2.1 Adaptable Communications Systems (ACS) for railways, the channel emulation prototype has some objectives such as:

- To test the ACS layer.
- To test different applications in different communication channels.
- To shift the more realistic scenarios to the laboratory the better.
- To analyse how railways environment can affect the communication.
- To introduce impairments in the communication channel in order to study the behaviour of the applications, both current applications and the ones that will be developed in the future.

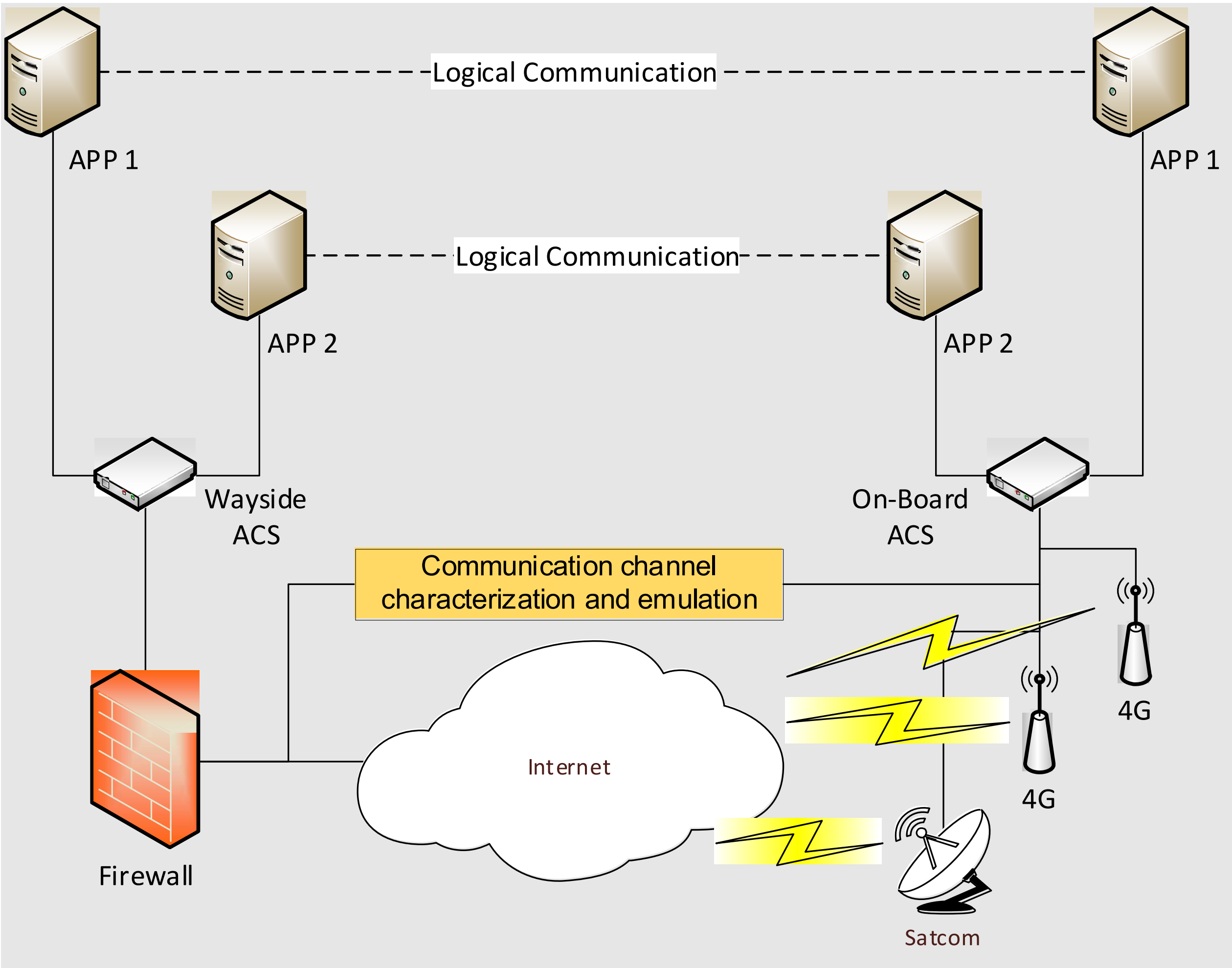


Figure 5-3: CET placement

Channel Emulator Tool is placed between the ACS on the on-board side and the ACS on the trackside replacing the different technologies of the real communication channel through the track. One important point to take into account is that these communication channels are varying through the track. The communication channel is affected by several interferences or impairments differently in each of the environments (e.g. urban, rural area) [1].

In order to achieve these goals, the communication channel has to be emulated. The impairments that can be emulated are the following ones:

- Delay in ms
- Bandwidth
- Packet loss
- Jitter

In order to emulate a communication channel with the already mentioned impairments, the user must configure it accordingly by sending the proper parameters. To make this configuration more intuitive, the user can configure it by accessing a web page as Figure 5-4 shows.

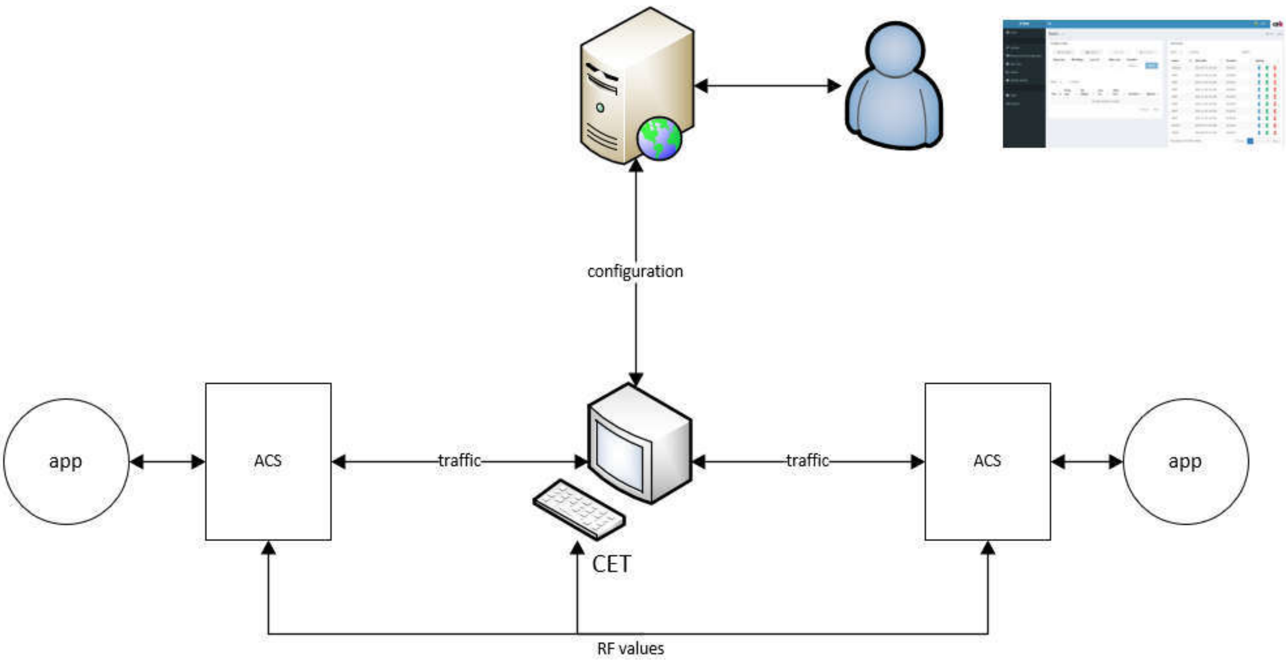


Figure 5-4: Schema of CET

Moreover, two different ways of configuration are available for the user:

1. Static configuration: the user configures the emulator with the different IP impairments for a whole time slot. The impairments are configured based on time. Additionally, other aspects have to be taken into account in the static test. The static test, which are loaded to the emulator from the web site, can be created from different perspectives: synthetic scenarios (totally made up), real scenario from measurements on-site with the Channel Characterisation Tool and hybrid ones (both of them).

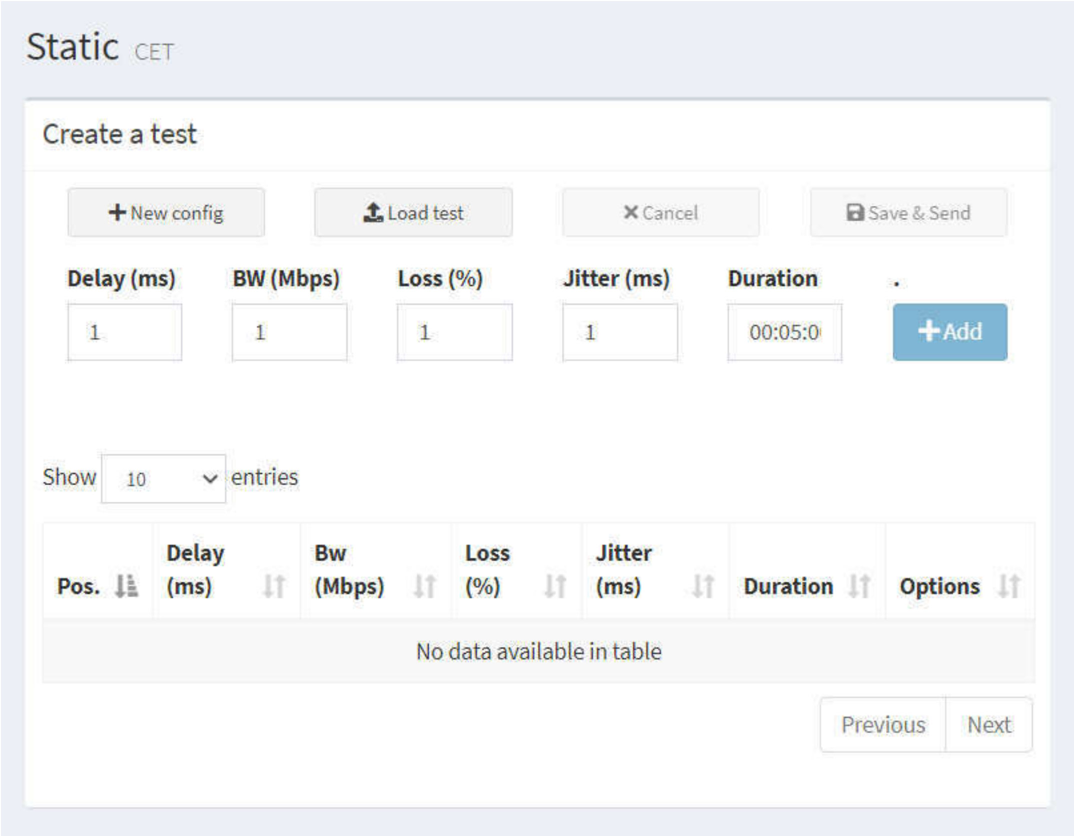


Figure 5-5: static test

2. Dynamic configuration: the user is continuously interacting with the emulator by changing the configuration whenever it wants. This is useful if, e.g., the user wants to modify something from the static test or it wants to test everything dynamically. Moreover, this dynamic information can be saved, therefore, it becomes another static test that can be loaded.

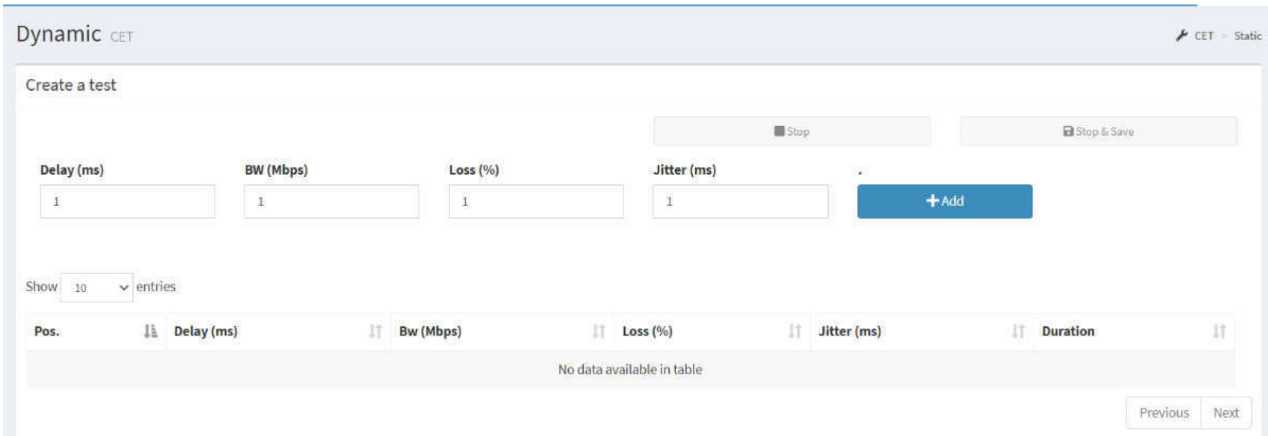


Figure 5-6: dynamic test

As the Channel Characterization Tool (CCT) has already been mentioned as part of the inputs of the CET in static mode, a brief explanation of the tool is explained hereafter.

The main goal of the Channel Characterization Tool [2], is to measure on-site the different parameters of each channel available and to see how the environment affects the channel.

This tool allows analysing the communication channel by measuring different parameters, providing a temporal and spatial characterisation of the communication channel. In this manner, the results of the different measurements and the position can be mapped.

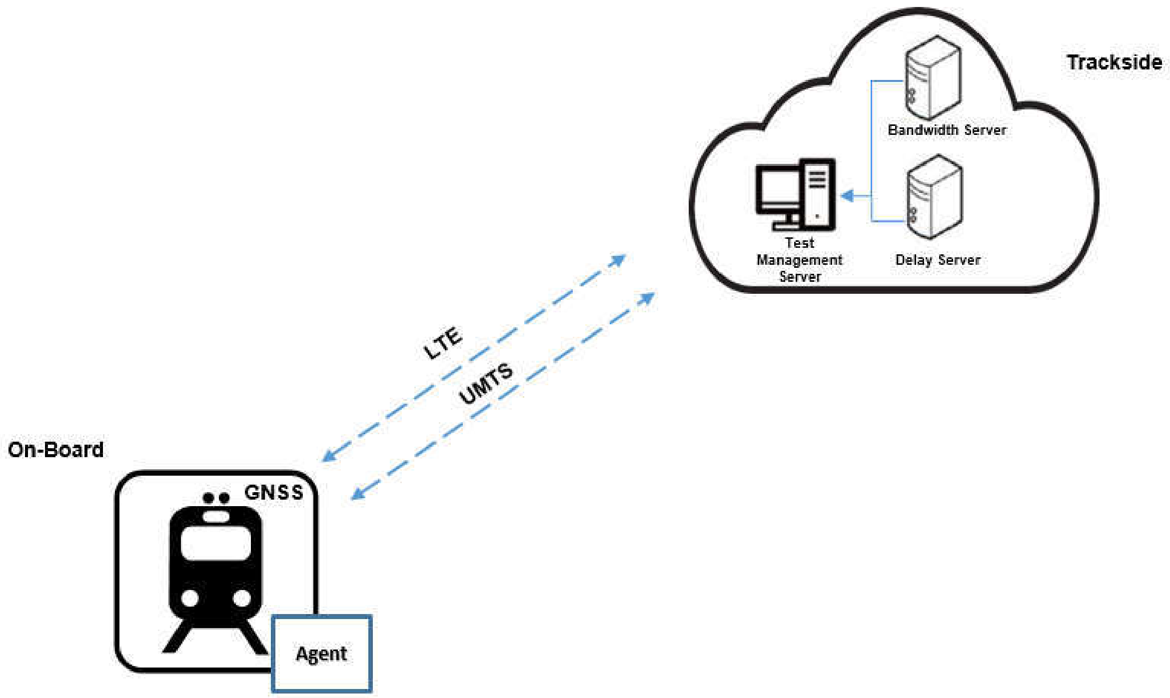


Figure 5-7: CCT

Moreover, the results of the tool provide inputs to CET if needed for testing with a real scenario condition on the lab. In this way, the testing of a given application can be replayed in the lab under real scenario condition to analyze its behaviour.

5.4 Integration in the urban and freight demonstrator

The previous section explained what the emulator is and how it works. However, the emulator needs other subsystems to work with to achieve the previously mentioned goals. One of these subsystems is the ACS. The ACS is directly connected to the CET and it exchanges both control and traffic information from, e.g. the different applications: ETCS, voice, etc.

As one of the objectives is to shift the best from on-site (Figure 5-7) to laboratory testing (Figure 5-8), it is necessary to emulate the communication channel with different IP impairments but as well to emulate the radio values from modems and antennas. Therefore, in order to get the closest to the real world, CET is giving Radio Frequency values such as RSSI (Received Signal Strength Indicator) when, at the same time, emulating the communication channel.

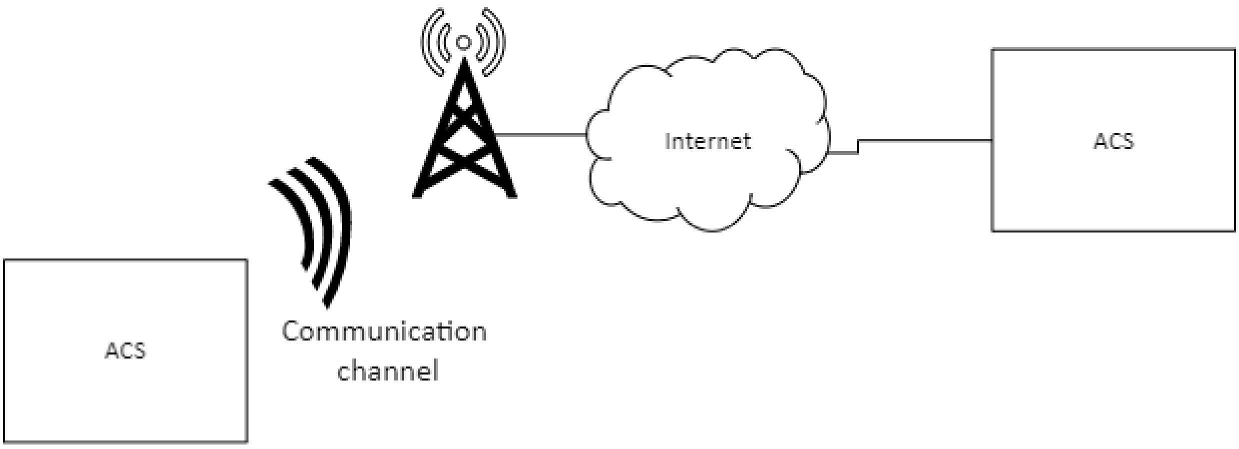


Figure 5-8: On-site testing

Figure 5-9: Laboratory testing

When receiving these RF values, the ACS can take different decisions. These RF values vary depending on the technology, not every technology has the same parameters. The ACS takes the decision based on how these RF values are, if they are beside the decided threshold, the behaviour of the system changes, e.g., vertical handover.

The Channel Emulator Tool differs from other network emulators as it is focused on the application. CET is being implemented with aim of using it for the railways environment. This is not a common aspect in the emulator environment; normally the commercial emulators have been designed and implemented for a general-purpose, with no special focus in any application. [3]

5.5 Testing

After the definition and implementation of the demonstrator, two different functions of the whole system, prototype integrated in the demonstrator, have to be tested.

1. The first test is the integration between the demonstrator, specifically the ACS, and CET. The criterion to pass this test is that the traffic sent by the ACS passes through CET and return to the ACS.

2. The second one, the scenario where the user configures CET to insert a specific in a given channel. The criterion to pass this test is that the traffic of one of the application of the demonstrator, in this case the ETCS application, sent through the ACS is delayed by the sum of the delay that the traffic has in normal condition and the configured delay.

5.6 Results

The integration between the demonstrator and the prototype has been remotely due to the covid19 situation. It was successful; the traffic sent by the demonstrator was passing through the emulator. The traffic from the demonstrator passing through the CET was delayed not because of the configuration a specific delay but due to the remote connection between Spain and Italy This delay was taking about 3.4 seconds. Moreover, during the test, the connection remains stable (0 disconnections).

In the delay testing scenario, it can be stated that the traffic was delayed because of the emulator. In every test, a Euroradio connection from the on-board unit to the wayside unit across the two ACS was established. ETCS messages from the on-board to the trackside were having a delay in the application (configured delay + delay of the remote connection).

5.7 Conclusions

Current railways communication channels are getting obsolete, such as ERTMS using GSM-R, due to, e.g., low data rate or high latency. Because of this reason, new communication channels for railways have to be tested and deployed. Additionally, the deployment and testing on-site are expensive. Therefore, one alternative is to shift on-site to the laboratory and test the different applications through some devices that emulate these technologies acting as the communication channel. The Channel Emulator Tool is responsible for emulating these communication channels.

CET emulates the different type of communication channel having as result the behaviour of the application that the user wants to test. In this way, the user knows how the application could behave along the track using a given communication technology before going on-site. Moreover, the ACS is an important element in the new technologies for railways, it takes the important decisions depending on the communication channel through the track, e.g. vertical handover.

By changing different configurations of the CET, different functions of the ACS can be tested before going on-site testing saving costs and time.

5.8 References

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5.10 Authors

Nerea Fernández-Berrueta received the M.Sc. degree in Telecommunications Engineering from Faculty of Engineering in Bilbao (University of the Basque Country) in 2016. She joined the CEIT-BRTA Research Centre in San Sebastián in 2017, and she is currently a PhD student within the Transport and Sustainable Mobility group. Her research activity lies in the field of railway signaling specially in zero on-site testing and adaptable communication systems.

nfernandez@ceit.es

Jon Goya received the M.Sc. degree in telecommunications engineering in 2011 and the Ph.D. degree from the Universidad de Navarra in 2016. He is currently a Lecturer with the TECNUN, Universidad de Navarra, and also a Researcher with the CEIT. His professional research activity lies in the simulation of on-board positioning system and performance analysis for railway. He has participated in FP7 projects coordinated by CEIT and is now actively participating in H2020 European funded, such as AIOSAT, and Shift2Rail projects in Railway signaling and Positioning topics: X2RAIL-2 and FR8RAIL.

jgoya@ceit.es

Dr. **Jaizki Mendizabal** received his M.Sc. and Ph.D. degrees in Electrical Engineering from TECNUN (University of Navarra, San Sebastián, Spain) in 2000 and 2006 respectively. He joined Fraunhofer Institut, Germany) and SANYO Electric Ltd, Japan as RF-IC designer. Nowadays, he is at CEIT-BRTA, in San Sebastián (Spain) where his research interests include communications and electronic systems. He is lecturing "Communications Electronics" and "Communications via Radio" at TECNUN (University of Navarra).

jmendizabal@ceit.es

6 ETCS radiocommunication link laboratory testing saboteur

Nerea Fernández-Berrueta , Jon Goya, Jaizki Mendizabal, CEIT, San Sebastián, Guipúzcoa, Spain

6.1 Introduction

X2RAIL-3 WP5 Zero on-site testing (see Figure 6-1) is part of TD of IP2 Advanced Traffic Management and Control Systems in the frame of Shift2Rail and has the main objective of shifting on-site testing to laboratories to reduce testing cost and time.

This work describes the communication saboteur device integrated into the laboratory testing environment as one of the prototypes being developed in X2RAIL-3 WP5 Zero on-site testing. The objective of the Saboteur is to test the communication link in presence of faults.

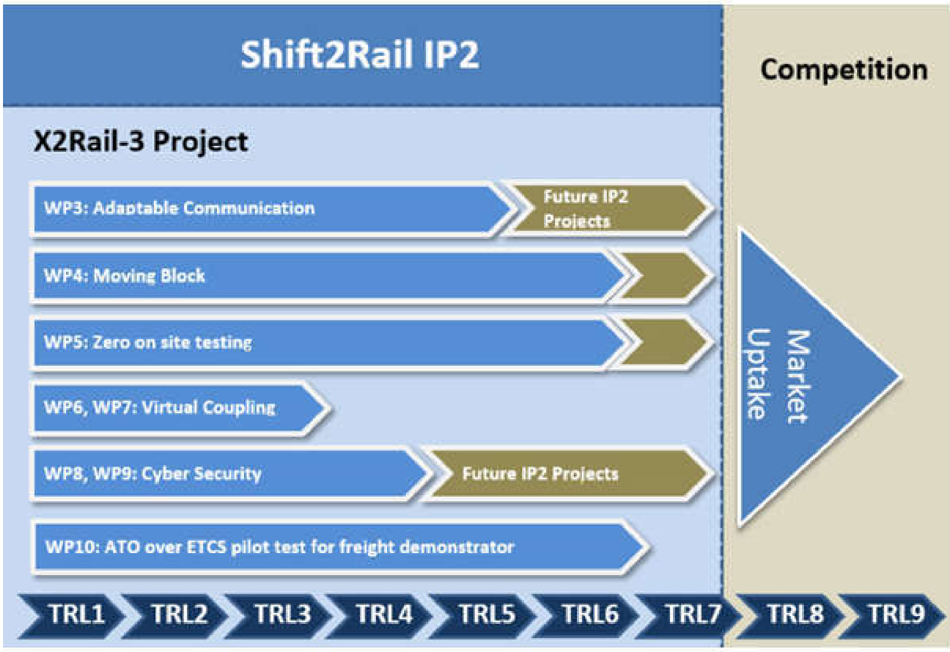

Figure 6-1: WP5 in the X2Rail-1 project

This abstract introduces briefly the ETCS laboratory testing environment, and the different prototypes defined and developed for testing it. In this abstract, the focus is on one prototype, directly related to the testing of the communication channel. Then, the integration of all the subsystems which form the prototype is explained, especially the saboteur subsystem, developed by CEIT. Additionally, the results of testing are given, and some conclusions are established.

6.2 ETCS laboratory testing environment

The ETCS application uses GSM-R as the communication channel. However, GSM-R is getting obsolete. Therefore, the WP3 corresponding to TD2.1. Adaptable Communication System is working on new communication systems to replace the GSM-R technology. Nevertheless, the

X2RAIL-3 WP3 dealing with future adaptable communications is not the only one including the future communication system since X2RAIL-3 WP5, as the work package responsible for the Zero on-site testings, has also included this aspect in one of its prototypes.

The WP5, Zero on-site testing, defines different prototypes in order to test several scenarii for the ETCS application:

- Prototype 1: Performance validation and stress testings are focused specifically on the GSM-R network and the next-generation network as defined in TD2.1, on integration and system level.
- Prototype 2: Testing activities with distributed test environments.
- Prototype 3: Subsystem and integration testings.

The prototype 1 is shown in Fig. 6-2. The ETCS environment focuses on the laboratory testing of the communication channel, and consists of different subsystems for a correct functioning in order to get the closest to the on-site:

- TCL (Test Control and Logging)
- RBC (Radio Block Center)
- OBU (Onboard Unit)
- ACS (Adaptable Communication System)
- IXL (interlocking)
- Saboteur

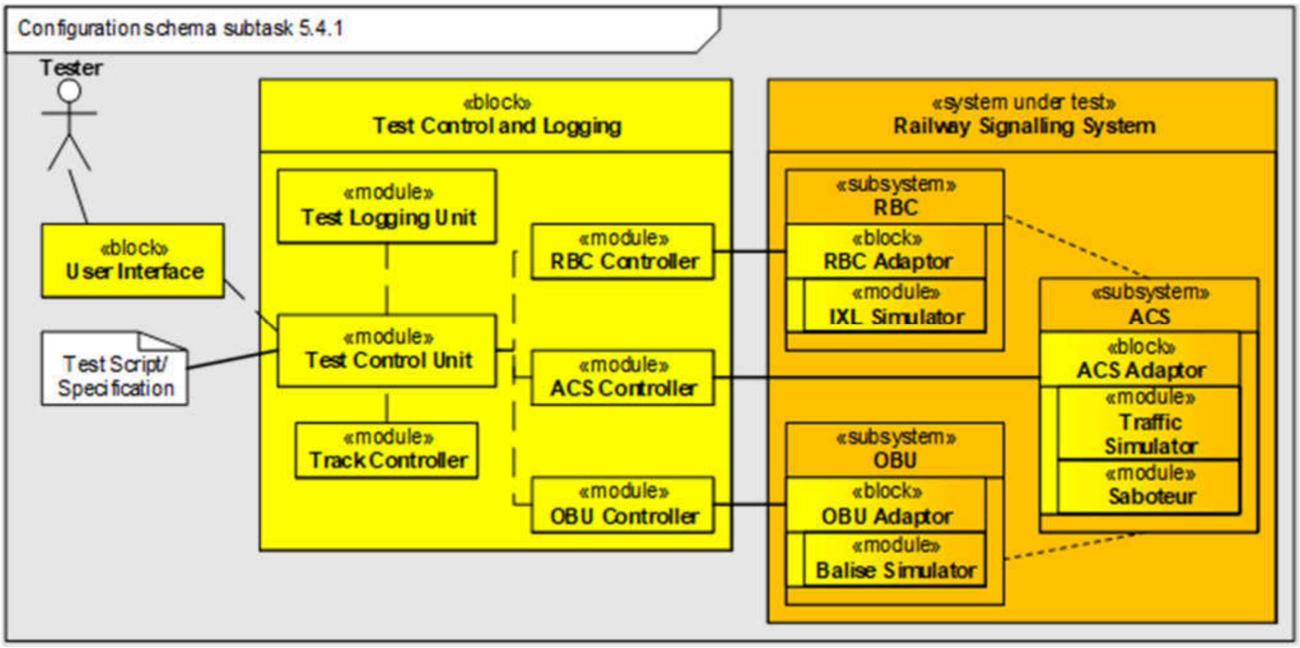

Figure 6-2: Prototype schema [1]

Specifically, the work of CEIT in this work package is focused on the saboteur subsystem and on the communication between the saboteur and the ACS shown in Fig. 6-2.

6.3 Communication link Performance Validation and stress testing

In this chapter, prototype 1 is described and specifically one of its subsystem: the saboteur subsystem. Moreover, because of the COVID-19 situation, the whole prototype could not be totally integrated. Thus, only the interaction between saboteur and ACS was completely covered. This integration is described and the result of testing is shown.

6.3.1 Saboteur description

The saboteur is a subsystem of the prototype which goal is to inject faults in testings in order to stress the environment, modifying the communication link performance parameters such as delay. The objective is to control the behaviour of the ETCS application when faults are injected. It can be configured by external subsystems through configuration messages specifying the fault that has to be injected. Moreover, it can be activated or deactivated depending on the test that the user wants to configure: the activation implies a later configuration message and a fault injection. The deactivation restores a state equivalent to an ETCS laboratory testing environment without faults injection.

In this first step of the prototype in the WP5, the fault is a delay.

The saboteur splits into two different visions: the control plane and the data plane.

- The control plane refers to the different messages that arrive at the saboteur as the messages previously mentioned: configuration, activation and status.
- The data plane refers to the application traffic from e.g., RBC or OBU. The behaviour of this traffic depends directly on the configuration set in the control plane, it will be delayed in order to arrive at the destination if the fault injection is configured.

6.3.2 Prototype

The prototype is composed of different subsystems previously mentioned and shown in Figure 6-3. The subsystems of the prototype were provided by different companies: KT, SIE and CEIT. Specially, CEIT is providing to the saboteur subsystem.

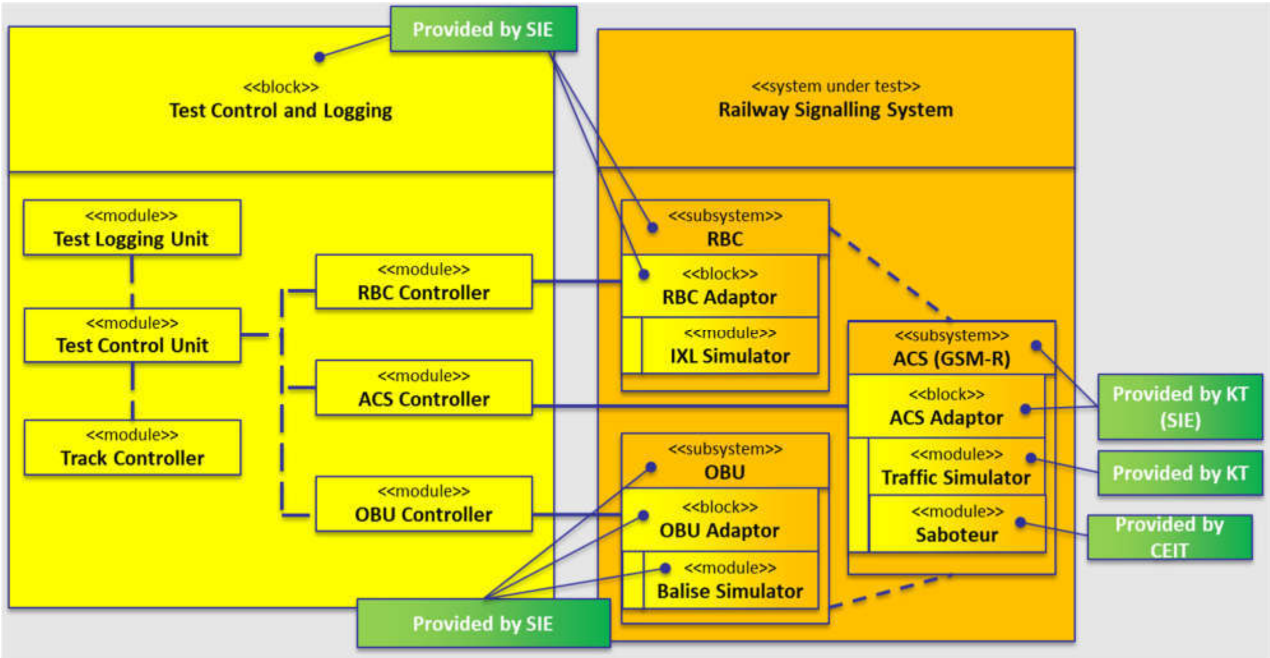

Figure 6-3: Prototype 1 Performance Validation and stress testing [1]

Integration between the saboteur and the rest of the prototype

The CEIT work in this prototype was the integration of the saboteur and the interconnection between the ACS and the saboteur, shown in Figure 6-3.

Therefore, the communication between the different subsystems has been defined and implemented based on XML-RPC (Extensible Markup Language-Remote Procedure Call) protocol. This protocol was chosen because XML-RPC may be the simplest and most commonly used in a wide area of applications.

In order to activate and send the fault injection to the saboteur, some messages have been defined and implemented to be sent from the TCL simulator to the ACS [2].

- SABOTEUR.activate: switches on/off the saboteur
- SABOTEUR.configure: contains the configuration parameters for the saboteur
- As well, the ACS, due to the interaction with the saboteur, replies to the TCL:
- SABOTEUR.activateResponse: responds to the activate message with the status of the saboteur.
- SABOTEUR.configureResponse: responds to the configure message

The TCL and the ACS interacts according to the messages defined in [2]. Then the ACS interacts with the saboteur sending the corresponding information in order to inject the desired faults.

6.3.3 Testing

Two different functions have to be tested:

1. The first one is the integration between the ACS and the saboteur. The criterion to pass this test is that the traffic sent by the ACS has to pass through the saboteur and return to the ACS.

2. The second one is the scenario where the ACS configures the saboteur to insert a delay fault injection. The criterion to pass this test is that the delay (checked by the ping tool) must be equal to the sum of the delay in normal condition and the configured delay.

6.3.4 Results

The saboteur connects directly to the ACS therefore, an integration was needed. This integration ACS-Saboteur was successful: everything was connected in the data plane (traffic from the application was passing through the saboteur) and control plane (configuration messages were arriving at the saboteur and configuring it).

However, due to the COVID-19 situation, the rest of the prototype was not completely integrated. For this reason, the saboteur configuration messages are sent by a TCL simulator (just sending the FFFIS messages to the ACS), instead of the real TCL. Additionally, the traffic was sent by the ACS in order to test the saboteur behaviour in the data plane.

The results obtained by the integration of the saboteur with the ACS and the testing of it is described in this section.

The integration step between the ACS and the saboteur is fulfilled when traffic is passing through the last subsystem as Figure 6-4 shows. The 6 ms delay is due to going through the saboteur.

```
Envoi d'une requête 'Ping'  172.21.167.170 avec 32 octets de données :
Réponse de 172.21.167.170 : octets=32 temps=6 ms TTL=62
Réponse de 172.21.167.170 : octets=32 temps=6 ms TTL=62
Réponse de 172.21.167.170 : octets=32 temps=5 ms TTL=62
Réponse de 172.21.167.170 : octets=32 temps=7 ms TTL=62
```

Figure 6-4: checking the delay before configuring any fault injection [1]

Additionally, Figure 6-5 shows how the simulated TCL has the possibility of sending different messages to the ACS concerning the control plane. For the test of the injection of faults, first, the message SABOTEUR.activate has to be sent and then the SABOTEUR.configure is used with the desired configuration

```
-------------------- STUB TCL --------------------
 0: quit
 1: CMD.checkPDIVersion
 2: CMD.checkDTVersion
 3: INIT.configure
 4: INIT.Activate
 5: INIT.getState (sab.status)
 6: SABOTEUR.configure
 7: SABOTEUR.activate
 8: LOGGING.activate ON
 9: LOGGING.activate OFF
10: LOGGING.request NO-DELETE
11: LOGGING.request DELETE
12: close "LOGGINGresult.log"
13: ...
Choice?:
```

Figure 6-5: selection of the control message [1]

Figure 5-6 shows the reception of the configuration message (Received sab.configure message) and the injection of the fault in the saboteur (Insert delay).

```
INFO 2020/10/09 13:37:05  Received sab.configure
INFO 2020/10/09 13:37:05  ID 2 action 0 fault 4 delay 100 direction 1
INFO 2020/10/09 13:37:05  Insert delay
INFO 2020/10/09 13:37:05  Send 100 ms delayed data via ens3interface
INFO 2020/10/09 13:37:05  Delay of 100 ms configured
INFO 2020/10/09 13:37:05  Delay successfully configured
```

Figure 6-6: configuration in the saboteur [1]

The result of testing an ETCS application was not reached because of the covid19 situation, the integration had to be remotely being some functionality not available. Because of that the altenative to know that the saboteur was delaying according to the delay configured was the ping tool. Figure 6-7 shows how the traffic passing through the saboteur after the configuration is delayed by the number of ms specified in the configuration message.

```
Envoi d'une requête 'Ping'  172.21.167.170 avec 32 octets de données :
Réponse de 172.21.167.170 : octets=32 temps=106 ms TTL=62
Réponse de 172.21.167.170 : octets=32 temps=107 ms TTL=62
Réponse de 172.21.167.170 : octets=32 temps=107 ms TTL=62
Réponse de 172.21.167.170 : octets=32 temps=106 ms TTL=62
```

Figure 6-7: delay fault injected [1]

If a comparison between Figure 6-6 and Figure 6-7 is done, it can be stated that the current delay is the one already configured (100 ms): 106ms from the delayed scenario vs -6 ms from the no faults injected one.

6.4 Conclusions

Laboratory testing is needed to save costs and time comparing with the on-site testing. For this objective, an effort to shift the closest to the best into the laboratory is necessary. The WP5 has the objective of shifting the most the best form on-site to laboratory being its main focus in the ETCS environment. Because of that, different prototypes were defined, one of them being focused on the communication channel, especially in the next generation of communication systems.

The first prototype is the responsible for the performance validation and stress testing and focused especially on the GSM-R network and the next-generation network which allows checking the behaviour of the ETCS application. The delay of one application is an important fault to be taken into account, delaying one of the messages of a safety-critical application as ETCS can be critical in terms of human lives and economic aspect. Within X2RAIL-3, this prototype is in the first step of deployment. Nevertheless, due to the covid19 situation the ETCS application could not be sent trhough the whole prototype, passing trhough the saboteur. Therefore, there is room for progress; further activities are already planned in X2RAIL-5. Focusing on the saboteur, its improvement will be the extension to other fault injections such as packet loss, both individually and several fault injections together. In this way, different behaviours can be tested and checked.

6.5 References

[1] X2RAIL-3, Deliverable D5.3 Verification Report of the Prototypes

[2] X2RAIL-3, Test Environment Definition, FFFIS for ACS Adaptor

6.6 Acknowledgements

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6.7 Authors

Nerea Fernández-Berrueta received the M.Sc. degree in Telecommunications Engineering from Faculty of Engineering in Bilbao (University of the Basque Country) in 2016. She joined the CEIT-BRTA Research Centre in San Sebastián in 2017, and she is currently a PhD student within the Transport and Sustainable Mobility group. Her research activity lies in the field of railway signaling specially in zero on-site testing and adaptable communication systems.

nfernandez@ceit.es

Jon Goya received the M.Sc. degree in telecommunications engineering in 2011 and the Ph.D. degree from the Universidad de Navarra in 2016. He is currently a Lecturer with the TECNUN, Universidad de Navarra, and also a Researcher with the CEIT-IK4. His professional research activity lies in the simulation of on-board positioning system and performance analysis for railway. He has participated in FP7 projects coordinated by CEIT and is now actively participating in H2020 European funded, such as AIOSAT, and Shift2Rail projects in Railway signaling and Positioning topics: X2RAIL-2 and FR8RAIL.

jgoya@ceit.es

Dr. **Jaizki Mendizabal** received his M.Sc. and Ph.D. degrees in Electrical Engineering from TECNUN (University of Navarra, San Sebastián, Spain) in 2000 and 2006 respectively. He joined Fraunhofer Institut, Germany) and SANYO Electric Ltd, Japan as RF-IC designer. Nowadays, he is at CEIT-BRTA, in San Sebastián (Spain) where his research interests include communications and electronic systems. He is lecturing “Communications Electronics” and “Communications via Radio” at TECNUN (University of Navarra).

jmendizabal@ceit.es

7 Integrate operational data related to the temporality of the driver's actions in the test architecture

Philippe Richard, IRT RAILENIUM, Famars, France;
Simon Collart-Dutilleul, COSYS-ESTAS, Université Gustave Eiffel, Villeneuve d'Ascq, France

7.1 Introduction

The main objective of the X2RAIL-3 Work-Package (WP) 5 called Zero On-Site Testing (ZOST) is to transfer a maximum of tests that are performed on site to the laboratories. Indeed, on-site tests are expensive, and the risks, as accident, are higher than in labs. During X2RAIL-1, to help achieve this goal, a test architecture has been defined and some requirements have been raised. Among these requirements, some suggest integrating operational data in the tests. Indeed, during field tests, these operational data are irremediably present, and this ensures that in the real world, the tests performed with functional data remain valid. These operational data concern the railway infrastructure (track description), the GSM-R (Global System for Mobile communications – Railways) capacities... but also data related to the human operator, in this case, the driver. In the rest of this paper, we will focus on this last family of data.

In X2RAL-3, we constructed the data in relation to the driver's action time to the DMI (Driver Machine Interface). This paper will first present the 2 solutions considered to quantify these data. Then, a first illustration of the impact of other system component parameters on the data related to the human operator will be discussed. Then, a discussion around the data format will be done, allowing the testing laboratory to process the information and the statistical framework able to provide a realistic set of data.

7.2 Data definition

The first step is to determine what data is needed, i.e. the interactions with the DMI, in order to be able to quantify or measure the parameters to associate them with figures. It is thus necessary to define the use case that will allow to identify the interactions and consequently determine the areas of the DMI used. The use case, that will be performed on the test architecture of the WP, must allow realizing a test as realized today, from the subset definition and with functional data. However, it must also be compatible with the inclusion of operational data, in our case, the driver's action duration. Then, the results of the two tests will be compared to identify the possible variations.

7.2.1 Use case definition

Thus, as we mentioned, we want to perform an identical test twice on the test architecture prototype defined in [1]. The first time, it will be carried out in the same conditions as today [2], i.e. by the robot with its own temporality and a second time by integrating operational data that allows simulating, as precisely as possible, the temporal constraints which would be present during a human interaction, please see [3] for more details on test specifications. The test sequences of the subset 076 are very numerous, so we have looked for sequences integrating multiple interactions with the DMI. Our choice was therefore oriented towards a phase with several interactions, the start of mission. In order to confirm the definition of these 2 tests, we conducted a preliminary test on the ERTMS platform of the University of Gustave Eiffel. This platform is not equipped with a robot so the tests must be performed by human operators, in this case. The panel of subjects is not extensive, and the people involved are new to ERTMS testing, but the objective was to illustrate the problem we were trying to explore, i.e. the generation of false negatives or positives results when a human performed the test. It took many attempts for the subjects to successfully complete the test. The main constraint was the time available to enter the information and interact with the DMI. It is necessary to specify that these are the tests as provided by the platform, compliant Subset 026 and subset, without any modification of parameters.

The selection of the use case allows us to determine the areas of the DMI to consider, defined in [4]. These areas are mainly those with buttons, as the procedure under test is the start of mission using the “fixed train’s data entry”. In this case, the driver selects only one option. On the other hand, using “flexible train’s data entry”, the driver enters every bit of train data by themselves, leading to a lot of clicks on the screen and much keyboard striking. Sequences of keyboard pressing are intentionally avoided in this study as they lead to a particular scenario where the human is much quicker than the robot.

Now that the zones are identified, it will be possible to estimate or measure the action times of the operator which is at the heart of our problematic. Indeed, what we want is to inject into the simulation platform the action time of the operator. By action time we mean the time between the appearance of the stimulus and the end of the required action.

Our problematic can be summarized in a simple equation (1).

$$Duration_{action\_data\_test} = Duration_{action\_human} + Duration_{action\_system} \quad (1)$$

With $Duration_{action\_system} = Time_{system\_under\_test} - Time_{local\_delay\_architecture}$

and $Duration_{action\_human} = Time_{reaction\_human} + Time_{movement\_human}$

The $Duration_{action\_system}$ can be measured or extracted from the technical documentations. However, the $Duration_{action\_human}$ must be quantified from the literature (estimation) or from the field (measurement). The next section explores these two ways to quantify this duration by determining $Time_{reaction\_human}$, $Time_{movement\_human}$.

To perform tests, on this use case, on the test architecture with injecting operational data, in our case duration of action, it is necessary to determine the values of this data. We have opted to estimate these values from the literature. Indeed, the health crisis prevented us from carrying out measurements on simulators.

7.2.2 Data construction from the literature

Reaction Time

The first way to quantify these parameters is through the literature. The duration of a human action (1) can be decomposed in three times, the reaction time, the time of movement and the necessary time for the system to respond to the human action (2).

$$Duration_{action\_human} = Time_{reaction\_human} + Time_{movement\_human} \quad (2)$$

So, we have to determine $Time_{reaction\_human}$ and $Time_{movement\_human}$. The $Time_{reaction\_human}$ represents the time between the occurrence of the stimulus and the beginning of the movement to respond to this stimulus. In the literature, we did not find any data directly linked to the DMI, but we can estimate it from other domains of study. In the context of our use case, the only stimulus that we considered is visual. We can also make the hypothesis that, for an icon, the stimulus can be considered as simple. For this kind of stimulus, [5] and [6] indicate that the time to react is about 190ms. [7] obtains similar results with a mean time of 166 ms ± 20 ms. [8] also exposed the mean time to press a key in response to a light. The author notes that the mean times are different for a man and a woman with respectively 220 ms and 260 ms. In this work, we've focused our study only on a simple stimulus and considered that this hypothesis covered a pictogram information. For our test, we have chosen to take the minimum value from the literature as the minimum value, so 146 ms (166 ms - 20 ms), and to take a bound rounded to 300 ms (260 ms is an average and we do not know the standard deviation) for the maximum bound. We know that some stimuli on the DMI are textual messages. In this case, the time will probably increase.

Movement time

The second element to calculate the duration of action is the time of movement. We did not find element in the literature directly linked to the interaction with the DMI. Thus, we hoped to calculate it by using Fitt's law [9]. Fitt's law was originally designed for moving a cursor with a mouse on a screen, but it is also valid for moving the arm or hand. The Fitt's law is defined by the equation (3):

$$T = a + b * \log_2(1 + \frac{D}{W}) \quad (3)$$

Where: T: Time of movement; a and b: coefficients; D: distance of the target; W: Width of the target and $\log_2(1 + \frac{D}{W})$ represents the index of difficulty (ID).

W are available in [4] for all areas of the DMI. D can be extracted from the rolling stock specification. Concerning a and b, these coefficients are directly dependent of the interaction. The best solution would be to measure movement times with humans in the context of interaction with an DMI. Unfortunately, these measurements were not feasible in the context of this study, for the reasons discussed in the following section. And as we mentioned, we do not find data linked to the DMI in the literature. Thus, we searched data linked to a « similar" interaction and opted for an interaction with a touch screen, such as a tablet or smartphone.

In this domain, studies are available. [10] determine these coefficients for touch tablet and the results purposed 2 intervals, one for a=[325; 390] and one for b=[52;75].

7.2.3 Data construction from a simulator

It was planned to perform the duration measurement from the simulation trace analysis as in [11]. Simulation data are stored in a SQL compatible relational database where the simulation events are time stamped. From this set of data, Büchi automata can be used for analyzing traces [12]. In a second time, we planned to compare our experimental data to the one that can be produced from the theoretical formulas of the state of the art. As it was not possible to access to the simulation tool regarding the pandemic context, we were only able to compare old experimental data of [11] with the theoretical data.

As a synthesis, the initial idea was to assess the experimental data using the state of the art, but performed a reverse checking. We checked that the state-of-the-art-based formulas produced a set of data that is similar to our old set of data. As an evidence, not all the theoretical data can be assessed such a way, because the considered scenarios do not really match. The main contribution to this checking phase is to verify that our test architecture does not contain a design singularity forbidding us to use the classical formulas.

7.2.4 Data constructed

As we mentioned before, we were not able to measure the duration of action of driver, so we estimated it from the literature. The Table 7-1, presents the input data extract from [4], [5], [6], [7] and [8].

Table 7-1: Input data for calculation

Data linked to DMI	
Area	C1
Button	/
W	1,3
L* (From outside DMI)	50
L* (From inside DMI)	3
Type of information	Pictogram

Fitt's Law Coefficient	
a_min	a_max
325	390
b_min	b_max
52	75

Time_reaction_human	
Pictogram	
Min	Max
146	300

Time_local_delay_architecture		Delay_distributed_architecture	Time_system_under_test	Duration_system	
From outside	From inside			From outside	From inside
1100	400	0	0	1100	400

From inside represents a movement between to successive actions on the DMI. From outside represents a movement between an external position to the DMI screen.

By using the Fitt's law and the input data in Table 7-1, we were able to determine min and max time_of_movement for the area C1 (cf. Figure 7-1) of ERTMS DMI [4] and (see Table 7-2).

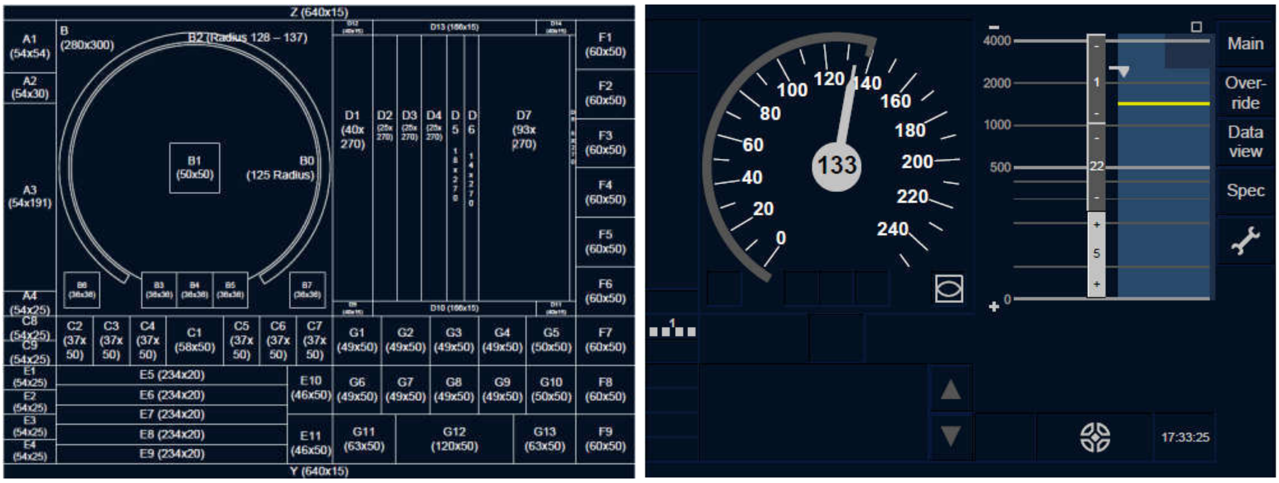

Figure 7-1: Areas of the DMI (extracted from [4])

Table 7-2: Time calculated for movement time

Time_movement_human			
Area C1			
Min		Max	
From outside	From inside	From outside	From inside
600,7235155	414,7429019	787,6781473	519,4368777

By using equation (1), we can calculate the duration of action for the area C1 (Table 7-3)

Table 7-3: Duration of action calculated for area C1 on DMI

Area C1					
From outside			From inside		
min	max	avg	min	max	avg
-0,33045237	0,11457393	-0,10793922	0,17736767	0,51503785	0,34620276

All the data is present in an Excel file and all input data can be modified. Of course, the Excel does not contain only data for the area C1 but for all required area of our use case. From this Excel file, we can generate the XML file that will be used as input in the test architecture.

7.2.5 Integration of operational data in the test framework

The problem described in this section is the following:

- Using the knowledge acquired on the field and formalizing it in order to be able to use it in a realistic simulated scenario.
- From a pragmatic point of view, agnostic models and open data format are needed.

Ontologies are known to be an efficient tool for knowledge engineering. Ontologies show the properties of a subject area and describe how they are related altogether, by defining a set of concepts and categories that represent the subject. Standardization bodies and their stakeholders decided to organize consistency on a unique and shared Data Dictionary: OntoRail

(RailTopoModel RTM) is an ontology presenting railway infrastructure topologies from a functional point of view and it is using UML. RailTopoModel has become such an IRS (International Railway Standard) in 2016 and is now referred as IRS 30100.

There may be a gap between efficient data processing and conceptual knowledge description. Main railway infrastructure managers agree on using UML, as a good tool for modelling the knowledge. They suggest generating an XSD in order to process data using XML files. IFC-RAIL, Eulynx, RTM, OntoRail, Lynx4rail agreed on using UML/SysML models. The proposed methodology is to build an XSD file from the UML classes; thus, specifying a corresponding XML format. If validating an XML with regard to an XSD is easy, generating this XSD is a critical task. The main contribution of RailML 3 is providing schema based on the RailTopoModel specification. Based on ISO 19148, RailSystemModel (RSM) is a UML conceptual model aiming to be a universal description of objects in the railway industry [13]. To our knowledge, the duration of operations performed by workers is still not integrated in this model.

For this reason, some specific XML files have to be generated. As we want to produce statistic data from data exploiting the simulation traces, Excel file are used. Using the Excel software, table data are processed and provide mean value and typical validity range for operation data. The result table of the Excel files are exported in an XML format that can be easily processed in order to populate the scenario values to be used by a lab testing the compatibility to the subset 26, using the framework of the subset 94 and playing scenarios of the subset 76.

7.3 Conclusion

In this paper, we proposed a methodology to quantify the duration of action when the driver is interacting with a DMI. The objective is to operationalize the time for the robot to replace the human operator during the test. This was an opportunity to illustrate the impact of some parameters on others and that it seems relevant to use methods to generate the operational data of the test automatically, for more details see [2].

This methodology can be criticized. Indeed, the first criticisms, already mentioned before, are the generation of values in itself based on literature on studies not covering the railway field and in particular the DMI. Also, the value attributed to the architecture time is most probably overestimated compared to the reality, especially when the robot is already in position on the DMI (from inside), whereas for the operator, the movement time is reduced. Nevertheless, for this last point, the platform expert can easily modify the value in the excel file before generating the XML file.

Another limitation is also present. The study is focused on the interaction with the DMI without considering the other tasks of the human operator's activity. In the real world, the maximum value of reaction time is probably higher. The DMI emits a sound when it requests an action from the driver. It is therefore conceivable to start from the hypothesis that to the maximum visual reaction time it is required to add the reaction time to an audio stimulus. [5] estimates this time at around 160ms. Another hypothesis would be to determine the upper limit from the maximum time allowed by the system to perform the action when it exists.

Depending on the level of accuracy expected, it may also be possible to be more representative of the future population of drivers who will use the equipment. Indeed, the literature indicates that the experience [6] and the gender [4] influence the reaction time in particular. With the global profile of the client railway company's population, it would be possible to weight the times according to it.

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7.6 Authors

Dr. **Philippe Richard** (M) received his PhD in Automation and Computer Engineering from the University of Valenciennes and Hainaut-Cambresis (France) in 2012. He is currently contributing to two European projects (X2RAIL-5 WP5 and 8 and TAURO) and two national projects (TC-Rail (train remote driving) and autonomous train). In these last two projects, he coordinates 3 work packages. He also contributed to the expertise of a human factors study for the merging of the ERTMS/ETCS level 1 and the national system. His main competences are Human Machine-System, Human Factors (estimation of human error, analyse of consequences, detection of human error risk on the line…) applied to the railway domain. He performed studies, focused on human operator, on IFSTTAR ERTMS/ETCS simulator in accordance with SUBSET-026 of EUAR. He was involved in the conception of numerical simulators dedicated to research and learning in the railway domain: COR&GEST and MissRail®.

philippe.richard@railenium.eu

Dr. **Simon Collart-Dutilleul (M)** obtained his PhD degree from the Savoie Mont Blanc University (France) in 1997. He is a senior researcher at an equivalent professor level of the Gustave Eiffel university. He is a scientific expert of Discrete Event Systems (DES) and Formal Methods (FM). He has been involved in various national and European projects. He was the coordinator of the ANR granted PERFECT project dealing with formal methods, safety and ERTMS implementation. He is the scientific leader of the ERTMS –regional project of the IRT - Railenium. He authored and co-authored more than 130 scientific papers. Dr. Simon Collart-Dutilleul is also an industrial safety expert concerning the SUBSET-076 of EUAR.

simon.collart-dutilleul@univ-Eiffel.fr

8 Simulating the Impact of ETCS L2 and Improved Coupling Mechanisms on Station Capacity

Leander Flamm, Michael Meyer zu Hörste; German Aerospace Center (DLR), Institute of Transportation Systems, Braunschweig, Germany
David Gill, Simon Chadwick; Siemens, Chippenham, UK

8.1 Introduction

This work was conducted as part of Innovation Programme 2 (IP2: Command, Control and Signalling) of the Shift2Rail project IMPACT-2 (Indicator Monitoring for a new railway PAradigm in seamlessly integrated Cross modal Transport chains – Phase 2) in work package WP4 "KPI". Its objective is to measure the impact of innovations defined in Shift2Rail on Life-Cycle Cost (LCC), Reliability & Punctuality, and Capacity of the railway system, with this work focussing on track capacity. [1]

The capacity of a passenger railway system is defined as the number of passengers that can be transported in the peak hour. Therefore, it is composed of the passenger capacity of each train, the number of trains operating coupled as one trainset, and the track capacity (trains per peak hour) limited by how fast trains can run after each other. The technology developed in IP2 has major effects only on the track capacity, which is why this work focusses on the simulation and calculation of track capacity [2].

The KPI in IMPACT-2 are defined as the difference between a baseline scenario, representing the existing state of technology pre Shift2Rail, and a future scenario including the innovations enabled by Shift2Rail. The baseline scenarios are described in [3]. The scenarios aim to give a rational example of a line showing the maximum effect of the innovations rather than representing a statistical European average or a specific existing line. Because railway operations can differ greatly depending on the use case, four different System Platform Demonstrators (SPD) are defined to represent different environments:

- SPD1: High Speed
- SPD2: Regional
- SPD3: Metro
- SPD4: Freight

Going by real-world examples, SPD3 is not expected to have any train coupling or decoupling during operation, and is thus addressed by improving train following times using moving block systems. This calculation is done separately and thus out of scope for this work. The operations of SPD4 vary greatly from those used in passenger transport and are therefore out of scope as well.

8.2 Scope Conditions

The main innovations of IP2 for track capacity are resulting in a faster and more reliable coupling of trains and the use of cab-based train control instead of physical signals at fixed block positions. Both in general and especially after the addition of moving block train following, the capacity of a given line is limited by the station capacity rather than track capacity between stations [4]. This is reinforced by coupling and decoupling trains, which result in longer station dwell times. As a consequence, a simulation of station operations is conducted to calculate the overall line capacity.

Beginning with the requirements of the baseline scenario, a basic track layout is defined matching the operational requirements of both the regional and the high-speed SPD. It has to be noted that the track layout has a substantial effect on the realisable capacities and results may vary greatly in real-world situations differing from this layout. Still, the track layout shown in Figure 8-1 was decided to be both generic enough and rational from an operational standpoint.

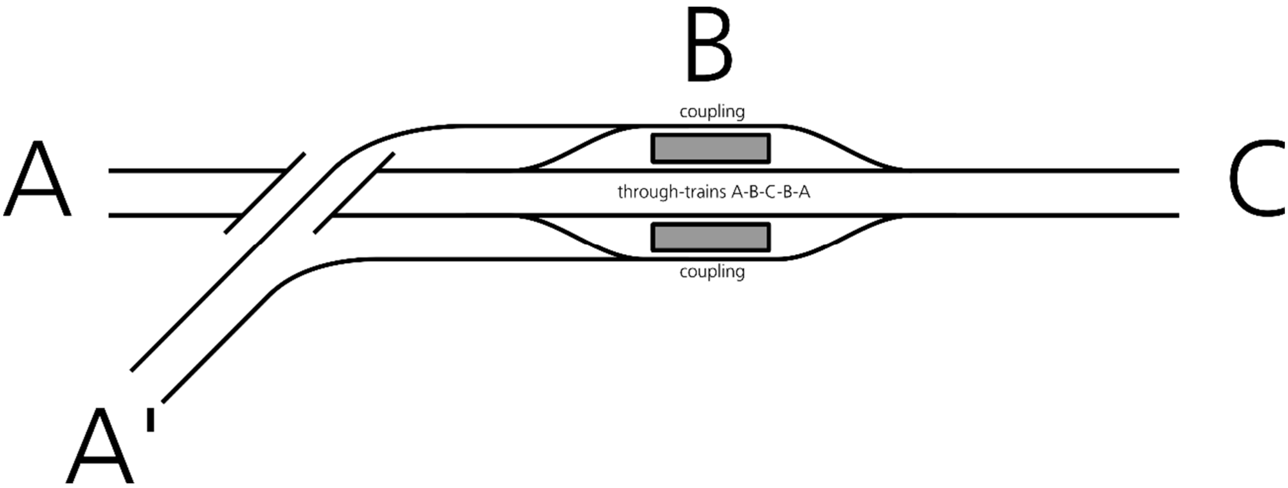

Figure 8-1: Station layout for the regional and high-speed SPD

The track layout has to allow trains running from A over B to C with only a short stop in B as well as trains from A and A' coupling in B for a combined run to C. In the opposite direction, trains from C can be split in B to continue to A and A' separately. To prevent other effects of the track layout being measured in the simulation, a flyover is used to diverge the tracks to A and A'.

The train parameters are chosen as defined in the baseline scenarios in [3]. Where detailed information on train dynamics is missing, reasonable values of real-world trains are filled in. The resulting values are given in Table 8-1.

Table 8-1: Train parameters for both scenarios

	Regional	**High-Speed**
Length	70 m	200 m
Vehicle mass	140 t	450 t
Maximum speed	160 km/h	330 km/h
Emergency deceleration	1.17 to 1.29 m/s² dep. on speed	1.10 to 1.21 m/s² dep. on speed
Tractive effort	150 kN	300 kN
Traction power	2600 kW	8000 kW
Operational mode	Coupling of three trains in B	Coupling of two trains in B

8.3 Simulation Approach

A microscopic simulation of train dynamics is combined with an analytical calculation of event sequences and timings to derive the capacity per station track. With those two values, a basic timetable is constructed assuming alternating operation of coupling and through trains to give the overall capacity.

As moving block systems in stations and especially when reaching fixed track elements such as points are not yet defined, a system of short fixed blocks is used to identify improvements by using cab signalling instead of fixed signals. The exact positions of the chosen block tiling and train detection sections are shown in Figure 8-2.

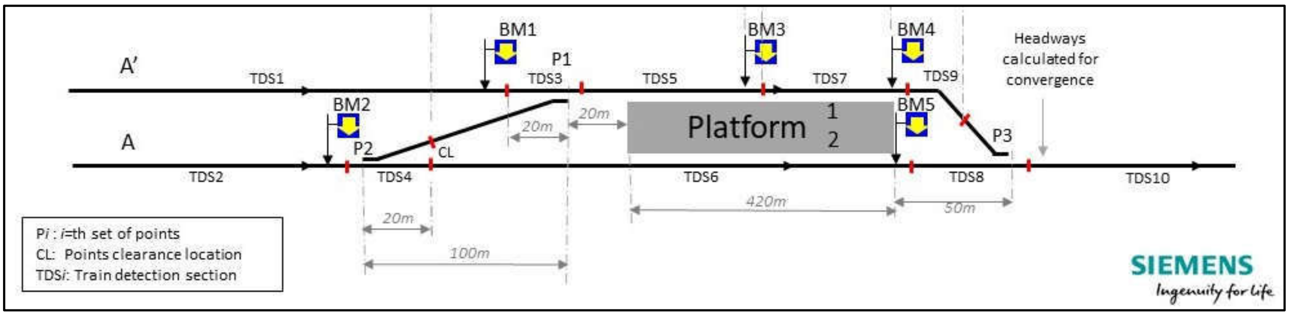

Figure 8-2: Block tiling and train detections sections used in the simulation

Signalling delays with and without point movement are calculated by adding the effects of:

- Train detection output change
- Interlocking processing of train detection
- Interlocking processing for route setting
- Point movement, locking, and detection (if necessary)
- RBC transmission times

- RBC calculation of movement authority
- RBC communication to the train
- Processing and update of the driver interface on the train

This gives the full delay between one train leaving a train detection section and a following train receiving the updated movement authority as 11.6 seconds (with point movement) respectively 6.6 seconds (without point movement). This includes improvements made by innovations in IP2. Further, the following event timings are defined:

- Train coupling delay: 60 seconds (improved according to IP2)
- Train dwell time with open doors for passenger boarding: 60 seconds (regional), 120 seconds (high-speed)
- Driver response time: 5 seconds

With these timings and the train dynamics mentioned above, the timings of a full operational cycle are calculated. An operational cycle consists of a coupling train on platform 1 (see Figure 8-2) followed by a stopping train at platform 2 and the next coupling train on platform 1 again. As the timetable assumes alternating operation of coupling and stopping trains and only depicts peak hourly traffic, this suffices to calculate the expected station capacity.

The operational cycle was assembled from a set of transit times calculated using a Siemens Mobility in-house railway simulation tool. Key static locations correspond to the Train Detection section boundaries that detect clearance of track crossovers. Key dynamic locations correspond to ETCS supervision locations that vary in relation to the train speed. For a fixed geometry of the station area, the signalled capacity is dependent on the speed that trains approach the station, as this dictates the safe braking distance computed by the ETCS onboard unit. The set of transit times was captured in a spreadsheet calculation from which the maximum signalled capacity (trains per hour) was determined and analysed.

8.4 Results

As described above, the regional and high-speed SPDs differ in the number of trains that are coupled in B. While in the regional SPD, three trains are coupled together, the high-speed SPD only requires two trains to be coupled. Because the case of three trains coupling in a single station is very rare in reality, both cases are calculated for the regional scenario.

The simulation and event calculation result in complete event timings for an operational cycle. The events are shown in a systematic headway graph (not to scale; not showing train dynamics) in Figure 8-3.

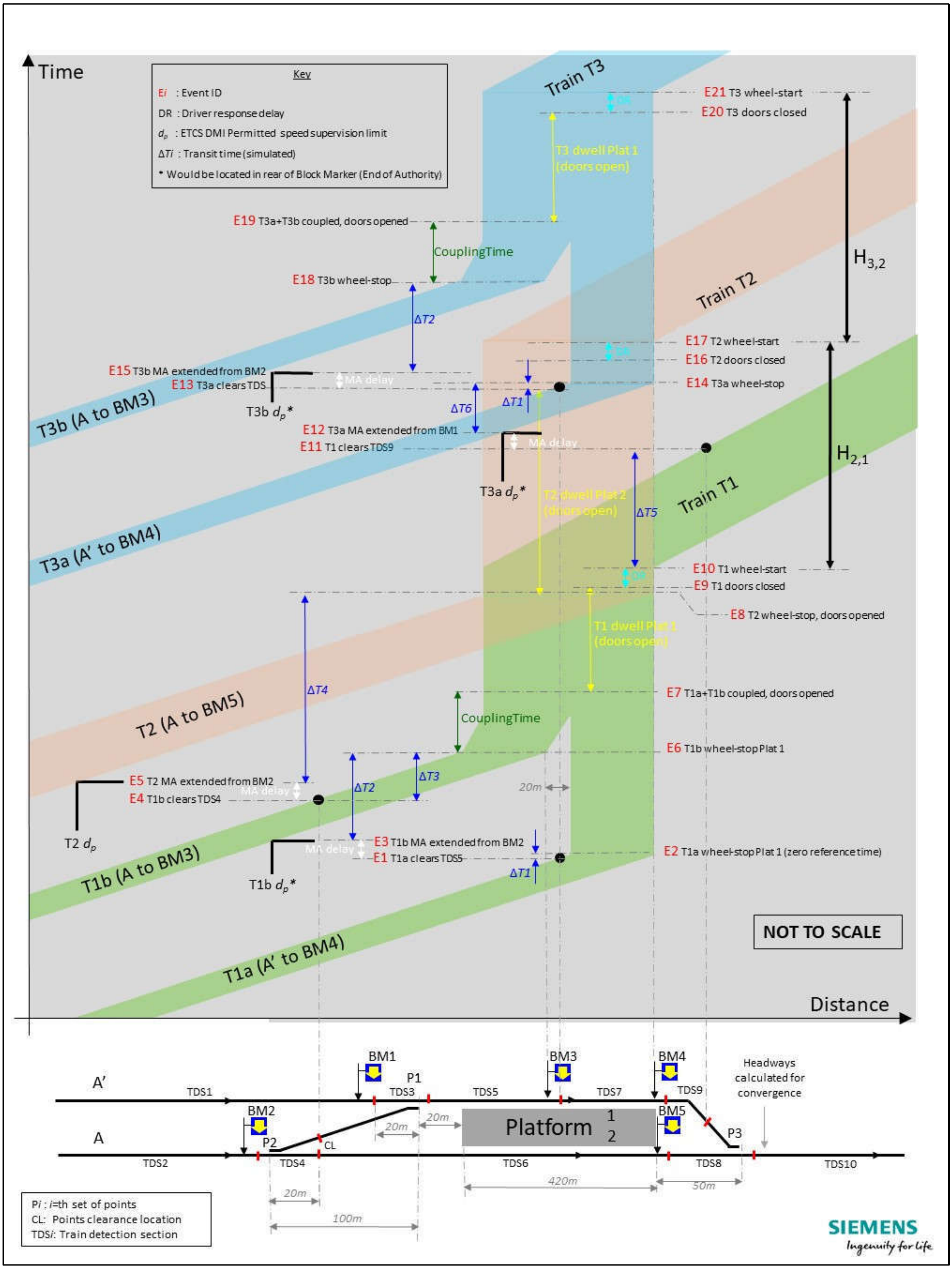

Figure 8-3: Systematic headway graph (not to scale; not showing train dynamics)

For the regional SPD, a minimal cycle time of 344 seconds between two trainsets of two coupling trains is calculated and 433 seconds between two trainsets of three coupling trains. This cycle time contains all events between the wheel stop of the first train (e.g. T1a) and the wheel stop of the next train on the same platform (e.g. T3a), including coupling and departure of T1, arrival and departure of T2 on the other platform, and the arrival of T3a. This resembles a maximum station capacity of 10.5 (two regional trains coupling) respectively 8.3 trains per hour per direction (three trains coupling).

To evaluate the improvement resulting form the innovations of Shift2Rail, these values are compared to current-day capacities. For this, minimal headways of coupling trains were analysed throughout Europe. It has to be noted that the following headways are not currently used and are based on arrival and departure of the coupling trains. The headway results from the assumption of two minutes between departure of one train and arrival of the next on the same platform as can be seen in many real-life situations, albeit without coupling procedures. The real-life examples are:

- DB Regio AG, RE 40/41, Neukirchen (b Sulzb): 9 min headway (arr. 11:36, dep. 11:43, +2)
- Southern, Portsmouth – London, Horsham: 11 min headway (arr. 12:11, dep. 12:20, +2)
- BLS AG, R 6822/RE4170, Spiez: 8 min headway (arr. 13:44, dep. 13:50, +2)

All examples are of two trains coupling at a station. For a comparison with the currently possible headways, the shortest headway from Spiez is used as reference. This gives a current capacity of 7.5 trains per hour (two trains) respectively 5.5 trains per hour (three trains, extrapolated).

As a result, the simulation shows an improvement from 7.5 to 10.5 train per hour or 39 % for two trains coupling and from 5.5 to 8.3 trains per hour or 52 % for three trains in the regional scenario.

Because this result compares simulated operations with real-world examples, the following has to be considered:

- A real timetable uses time buffers to allow for robust operations. This is partly corrected by assuming minimal headways for the real-world examples that are not used in current timetables and focus on the coupling train itself. Still, the simulation does not account for any delays and thus will calculate a higher capacity than probably used in reality.
- Event timings that do not rely on technical functions, e.g. passenger boarding times, are estimated and have a relevant impact on the results. Therefore, estimates on the higher end were used to achieve reliable results.
- The track layout was optimised for evaluating the impact of signalling and coupling on the station capacity. To that end, all unnecessary path crossings were eliminated, to not evaluate the effect of those instead of the effects of technology improvements. Still, other track layouts can have substantial effects on the actually achievable station capacity.

For the high-speed SPD, only the case of two trains coupling was evaluated. There, a minimal cycle time of 535 seconds was calculated, resulting in a station capacity of 6.7 trains per hour per direction. In the case of two ICE trains coupling in Hamm (Westf.) in Germany, the minimal headway with the above -assumption of directly following trains equals 12 minutes, resulting in a capacity of 5 trains per hour. This gives an improvement of 34 % for the track capacity in trains per hour.

8.5 Conclusion

The simulation and calculation done to evaluate the track capacity with innovations from Shift2Rail shows that significant improvements can be made in comparison to current-day operations. It focusses on the station operations as these are determining the total line capacity when assuming moving block operation on the track between stations. With a generic track layout and conservative assumptions for operation, train, and signalling parameters, the impact of faster coupling times as well as cab-based signalling with shorter train detection sections can be identified to vary between 34 % and 52 %. Both the regional and high-speed SPD profit from those innovations. The effects are enlarged if more than two trains are coupling at the same station, showing that the effects stack when applied on multiple trains.

Some limitations apply as the simulation cannot represent real operations with all dependencies but instead focusses on one station on its own. Further, the choice of the track layout affects the results substantially. While the track layout was chosen with great care to be as generic as possible, this can result in vastly different capacities when applied to existing, differing track layouts.

8.6 References

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8.7 Acknowledgements

This project X2Rail-3 has received funding from the Shift2Rail Joint Undertaking (JU) under grant agreement No 826141. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Shift2Rail JU members other than the Union.

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for Research & Innovation

8.8 Authors

Dipl.-Ing. **Leander Flamm** finished his studies in Transportation Engineering with focus on railway systems at TU Dresden in 2016 with his Diploma thesis on external costs in freight traffic. He worked on the certification of railway safety systems at CERSS Kompetenzzentrum Bahnsicherungstechnik in Dresden before joining DLR in 2017. There he is research associate and project manager in the department Evaluation of Transport in the Institute of Transportation Systems in Braunschweig. Research focus lies on the automation of railway transport both defining technical requirements and evaluating the impact on operations and costs. To this end, an extensive knowledge on microscopic simulation of railway operations was gathered and used to measure the impact of multiple new transportation technologies. Further interests lie in modelling passenger flow in transport networks, timetabling, and evaluating economic and ecologic aspects of transportation systems.

Leander.Flamm@dlr.de

Simon Chadwick Simon Chadwick joined Westinghouse Signals, now Siemens, in 1983, working on the safety-critical software development for ATP and Interlocking systems and data preparation tools for those systems. Later work included design work on the architecture of new interlocking systems. He is currently working within Siemens Mobility in the UK on new signalling systems and is leader of X2Rail-5 WP4 “Moving Block” within Shift2Rail.

Simon.Chadwick@siemens.com

David Gill is with Siemens Mobility Limited at Chippenham in the UK where he is Technical Authority for system performance and modelling within New Technology group. He has 35 years of experience in the railway industry and holds a doctorate in Electrical & Electronic Engineering from the University of Birmingham. His research thesis addressed the application of computer-based mathematical algorithms to the optimal design of signalling and train control systems for high-capacity mass transit railways. He is currently involved with Siemens projects for the deployment of ETCS Level 2 on UK mainline railways. He is a Chartered Engineer and member of the Institution of Engineering and Technology and Institution of Railway Signal Engineers.

David.Gill@siemens.com

Dr.-Ing. **Michael Meyer zu Hörste** holds a PHD in mechanical engineering from the Technical University of Braunschweig. He has joined DLR Institute of Transportation Systems in 2001 bringing already 6 years of railway research experience with him. He is expert in railway operations, command, control and signalling systems, especially ERTMS/ ETCS as well as train localisation. Currently he is working the business development of the DLR Institute of Transportation Systems. He was a major contributor in building the DLRs ETCS test laboratory RailSiTe®. He is chairman of the ERTMS Reference Labs Association since 2012. He is fellow of the Institution of Railway Signalling Engineers (FIRSE) since 2012. He is member of the Shift2Rail governing board and coordinator in the DLR for Shift2Rail.

Michael.MeyerzuHoerste@dlr.de

9 Safety and Performance analysis of virtually coupled train sets (VCTS)

Siddhartha Verma,IRT RAILENIUM, Famars, France;
Mohamed Ghazel, COSYS-ESTAS, Université Gustave Eiffel, IFSTTAR, Villeneuve d'Ascq, France
Marion Berbineau, COSYS, *Université Gustave Eiffel, IFSTTAR, Villeneuve d'Ascq, France*

9.1 Introduction

The VCTS concept is currently under development in the framework of the Shift2Rail program (https://shift2rail.org). The platooning strategy consists of assigning trains to different platoons, determining when and where to join and leave the platoon, managing stopping at stations, etc. In this context, the wireless communication system is a crucial module for correctly setting and managing the virtual coupling operation. The main objective of this work is to analyse the impact of the wireless communication system key performance indicators, such as the end-to-end delay and the packet error rate, on the performance of the VCTS operation in view of some targeted safety integrity level. The impact of parameters, such as, for instance, the size of the platoon is also considered in our analysis. The outputs of our study will support the choice for an appropriate communication system to be used in the virtually coupled train set (VCTS) context.

9.2 Concept of virtual coupling

Virtual coupling (see [Canesi, S. and al. (2020), Flammini, Francesco and al. (2018)]) aims to replace the conventional mechanical coupling by wireless connectivity, as shown in Figure 1. The headway between the trains is maintained with the help of real time periodic exchange of relevant information, such as location, speed, acceleration, etc. Virtual coupling aims to increase the capacity in two ways (see [Canesi, S. and al. (2020)., Flammini, Francesco and al. (2018)]). Firstly, it decreases the headway between trains (utilising cooperative breaking as shown in Figure 9-2b unlike absolute braking, which doesn't consider real time parameters/status of the preceding vehicle), and secondly, it enables on-the-fly coupling to reduce the waiting time on platforms.

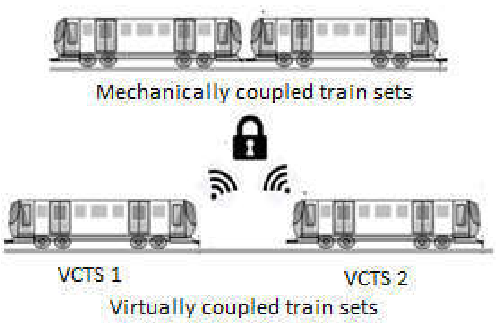

Figure 9-1: Mechanically vs Virtually coupled train sets

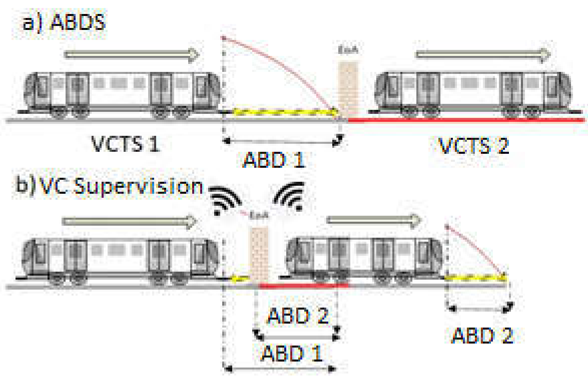

Figure 9-2: Absolute Braking Distance vs Cooperative Braking Distance supervision

9.3 VCTS functionalities

We have categorized the movement of virtually coupled train sets **(VCTS)** based on different phases of operation, inspired from five functionalities in [Canesi, S. and al. (2020)]), into four functionalities that are aided by wireless communication, as shown in Figure 9-3.

1. **Virtual Coupling Set Up** – the RBC (Radio Block Centre) / Zone Controller (or strategic layer **(SL)** when considering the functional layer categorisation of the VCTS as mentioned in [Canesi, S. and al. (2020), we cannot mention the categorisation details based on functionality because of copyright issues]), initiates the virtual coupling. The SL communicates and exchanges the relevant information such as the list of vehicles to be contacted, when and where to join the platoon etc. with slave 2 (which wants to join the existing platoon). After the slave 2 accepts the request, the SL communicates the platooning strategy to all the VCTS units. Thereafter, slave 2 communicates its mission data (braking characteristics, train length) with the master, and in return, the master communicates the aggregate mission data of the platoon with each VCTS unit.

2. **Transition from ATP (Automatic Train Protection or signalling or train protection) system to VCTS supervision** - once the slave 2 has been granted the permission to join the platoon, it approaches the platoon under ATP supervision (absolute braking distance supervision-ABDS) until the handover position. After the handover position, the platoon moves under virtual coupling supervision (co-operative braking distance supervision - **CBDS**) based on the information **exchanged** within the platoon.

3. **Supervising Train Separation Distance** - supervising train separation distances based on co-operative braking requires continuous exchange of co-operative awareness messages (**CAM**), which consist of information such as speed, location, braking curve etc. Based on the CAM, following trains accelerate or decelerate to maintain a safe headway from the preceding train.

4. **Termination of Virtual Coupling Session** – When the slave reaches a safe distance (based on the ABDS) from the preceding train, the termination of virtual coupling session can be initiated by slave or master.

The functionality 'Supervising Train Separation Distance (STSD)' supervises the platoon's movement based on co-operative braking and, thus, is the most impacting in terms of safety and performance. Therefore, in this work, we will consider this functionality for safety and performance evaluation. The other functionalities are transitional, as they allow for establishing coupling or decoupling; they are safety critical as well but not in the scope of this work.

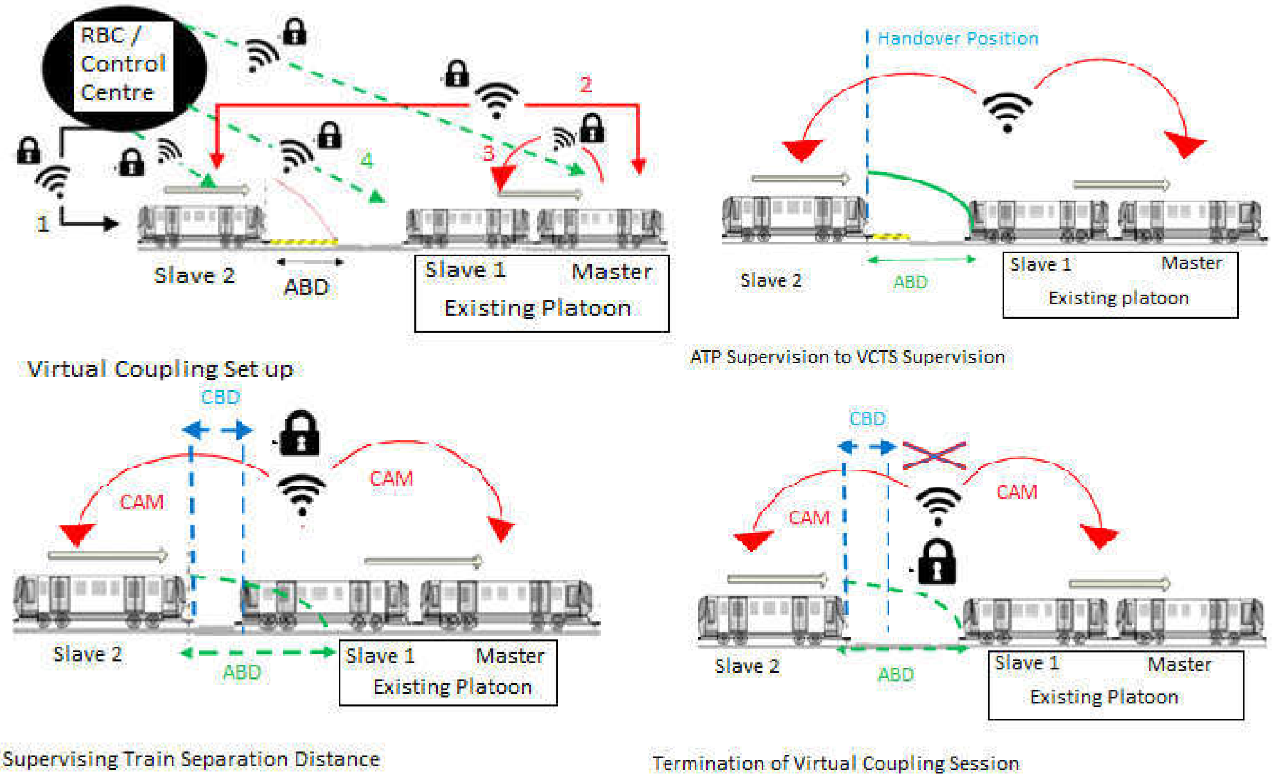

Figure 9-3: Virtually Coupled Train Sets - Functionalities

9.4 CAM dissemination strategy

CAM (co-operative awareness messages) are exchanged between each VCTS unit via direct communication (one-hop), as shown in Figure 9-4. Therefore, a total of ‘n X (n-1)’ (where n is the number of VCTS units inside the platoon) CAM exchanged between VCTS units during a single period (period for exchanging CAM). If anyone of these CAM is missed or delayed, then we consider the system to be down for that period, as shown in Figure 9-5. If the system is down for ‘m’ consecutive periods (m can be parameterized), then we consider the system as failed.

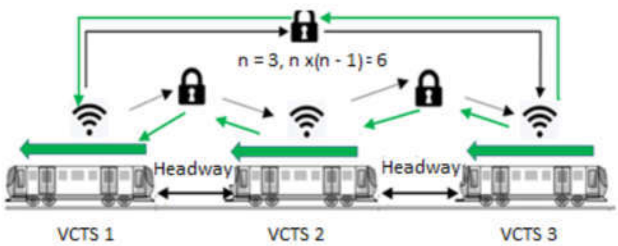

Figure 9-4: Dissemination- one hop full mesh type

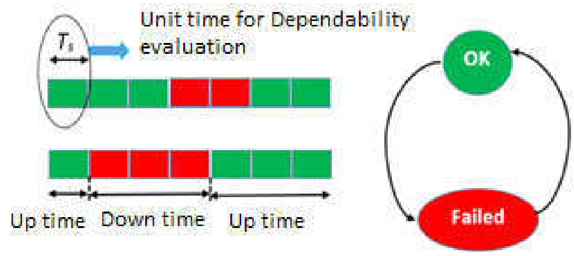

Figure 9-5: Dependability state of the communication system

We will consider two mitigation strategies that were proposed as a result of Failure Modes, Effects and Criticality Analysis (FMECA) analysis for our evaluation. **Acknowledgement** – an acknowledgement (**ack**) message is sent back to the sender after receiving the CAM. **Retransmission** - If the sender does not receive an acknowledgement message back from the receiver within some ack timeout, it then resends a copy of the original message.

9.5 Modelling the use case with Stochastic Petri Nets

Petri Nets (**PN**) are referenced by **IEC 61508** as a suitable notation for reliability analysis. A PN model holds 2 basic nodes, as in Figure 9-6- **Places**: model local states or conditions e.g., token at place p2 represents the state when the msg is received. **Transition**: model local events e.g., message transmission and the associated delay. The delay can be deterministic or stochastic (**SPN** - Stochastic Petri Net). In SPN and PN, all tokens are identical. In coloured SPN (SCPN), tokens can have arbitrarily defined attributes (colours), as in Figure 9-7. Because of this, SCPN can model large and complex systems in a compact manner which would not be possible with SPN.

We will model the virtual coupling supervision scenario as shown in Figure 9-8 with the help of Stochastic Petri Nets (see [Talebberrouane, M. and al. (2016)]). 'CAM IJ' (where I, J belong to {1,2,3} represents the messages exchanged between VCTS'I' as a sender and VCTS'J' as a receiver).

In our case (3 VCTS units), each VCTS unit sends CAMs to the other two VCTS units. When the VCTS units receive the CAM, they send an acknowledgement message back to the sending VCTS unit.

If the received message is inconsistent due to some transmission error (due to Bit Error Rate) or if it is received after the message obsolescence deadline, then the receiving VCTS unit will consider the messages as invalid and will not send an acknowledgment message back to the sending VCTS unit.

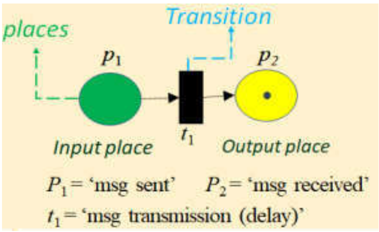

Figure 9-6: Basic nodes of a Petri Net

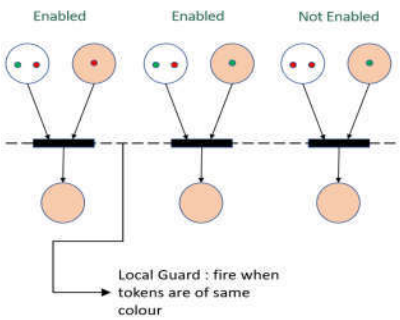

Figure 9-7: Stochastic Coloured Petri Net

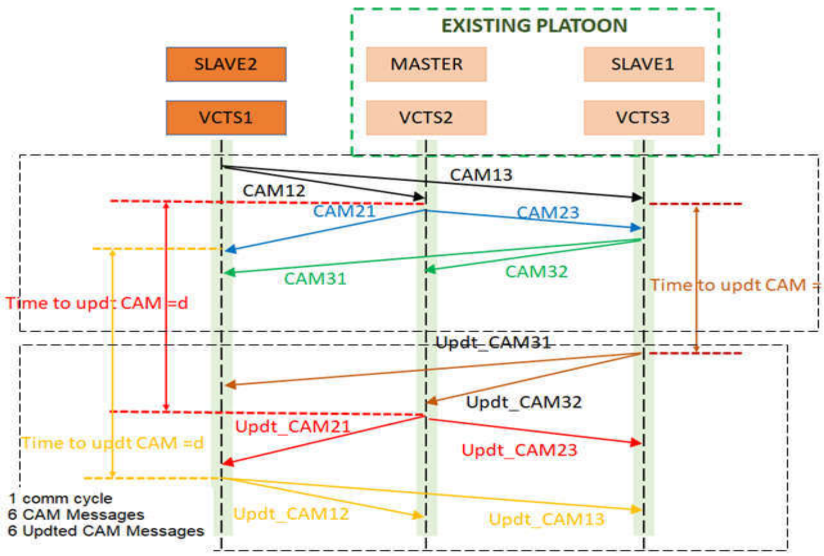

Figure 9-8: Exchange of cooperative awareness messages

In case the sending VCTS unit does not get an acknowledgement message back from the receiving VCTS units within some ack timeout, the sending VCTS unit sends a copy of the original message. The retransmission is repeated until an ack is received back or all the copies are exhausted.

As soon as a VCTS unit receives a CAM, it takes a deterministic time 'd' to evaluate the control signal and send the updated CAM back to sending VCTS unit.

If the sending VCTS unit receives this updated CAM, then the system is considered 'UP' for that period. If any one of these updated CAM is not received by the sending VCTS unit, then the system is considered as 'DOWN'.

9.6 Analysis and Results based on the SPN model

The reliability of the communication system, as assigned by safety integrity level in terms of tolerable hazard rate, must be assured for a safe VCTS operation. Therefore, we are presenting an evaluation approach that shows how the reliability of the communication system is impacted by different parameters such as the Transmission Error, Transmission Delay and the 'number of VCTS units inside the platoon'.

Considering the assumption that all the communications between VCTS units are identical and independent from each other, we can evaluate the dependability parameters for the simplest case, and then use that result to analytically evaluate more complex cases. In our future work we will consider dependence among communication between different VCTS (such as resource allocation), such a complex scenario requires modelling with SCPN. The input values for our evaluation such as transmission error (due to packet error), transmission delay, message obsolescence time etc were taken from paper [Nguyen, Khanh. Beugin, Julie. and al. (2014)] and corresponds to LTE communication network in a communication-based train control system.

For example, we simulated (using TimeNET tool, which uses SPN/SCPN for modelling and Montecarlo for simulation; see [Kelling, C., German and al. (1996)]) downtime (D-the fraction of time the system is down) for a single CAM (1 CAM within a period), and the obtained result is D1 = 0.0112 %.

A platoon with two VCTS units exchanges two (n X (n-1) = 2) CAM within a period. Therefore, the downtime (D) for such a platoon is given by $D_2 = 1 - (1 - D1/100)^2 x100$ % = 0.022 %.

A platoon with three VCTS units exchanges six (n X (n-1) = 6) CAM within a period. Therefore, the downtime (D) for such a platoon is given by $D_2 = 1 - (1 - D1/100)^6 x100$ % = 0.067 %.

Figure 9-9 represents the impact of transmission error (PET) and the 'number of VCTS units inside a platoon' on the availability of the communication system. We can notice that the downtime increases as the number of VCTS units inside a platoon increases. The trend is as expected. Each curve belongs to a specific transmission error. The dash curve with a higher transmission error (PET) lies above representing a higher down time.

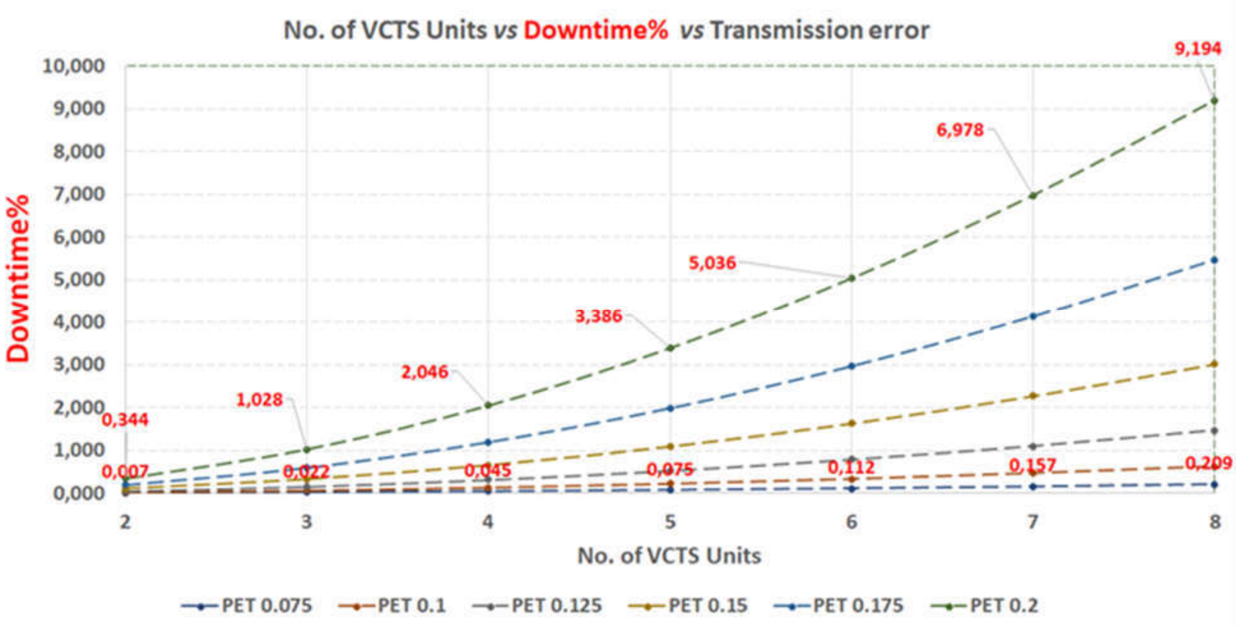

Figure 9-9: Impact of platoon size and packet error on dependability attribute

Figure 9-10 represents the impact of the transmission delay (DL) and the 'number of VCTS units inside a platoon' on the availability of the communication system. The downtime increases as the number of VCTS units inside a platoon increase. The trend is as expected. Each curve belongs to a specific transmission delay. The dash curve with a higher transmission delay lies above representing a higher down time.

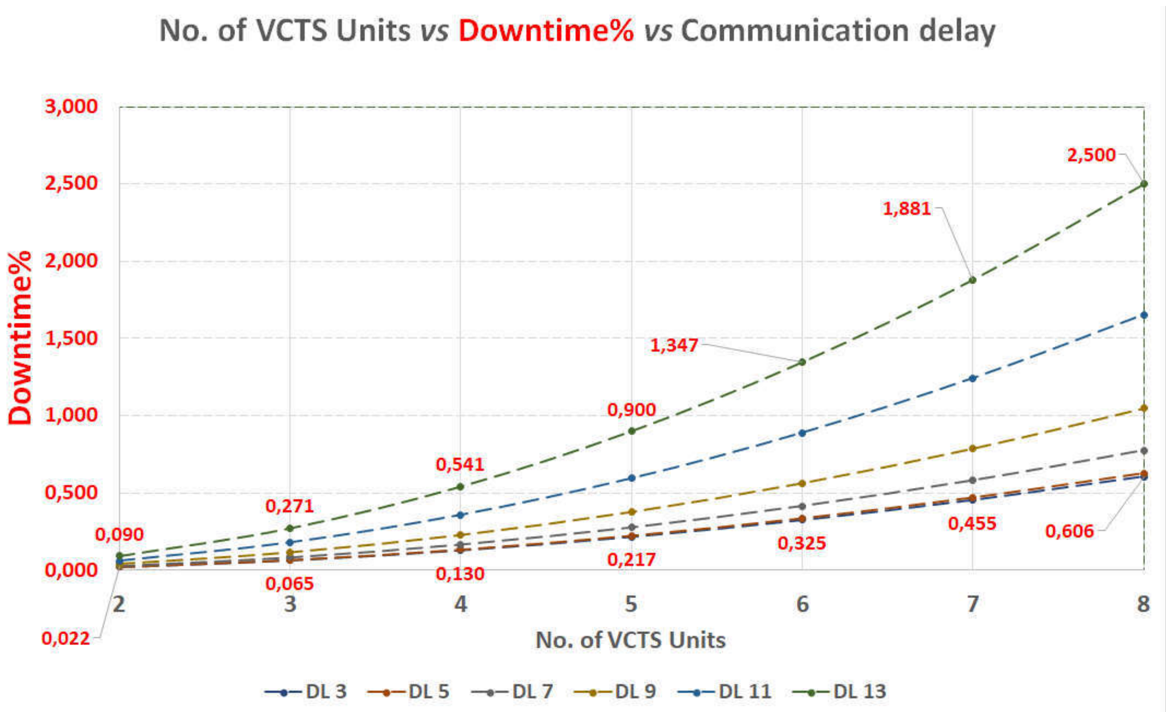

Figure 9-10: Impact of platoon size and communication delay on dependability attribute

9.7 Conclusion and Future Works

In the present work, we proposed an evaluation approach for the reliability of the communication system to assure the safety and performance of VCTS operation. A number of assumptions have been considered for our evaluation. For example, we considered the same transmission error and transmission delay between each pair of VCTS units inside a platoon irrespective of the distance between them. This assumption becomes susceptible, especially in the case of one-hop communication, for the communication of leader to distant followers inside a platoon, as shown in Figure 9-11.

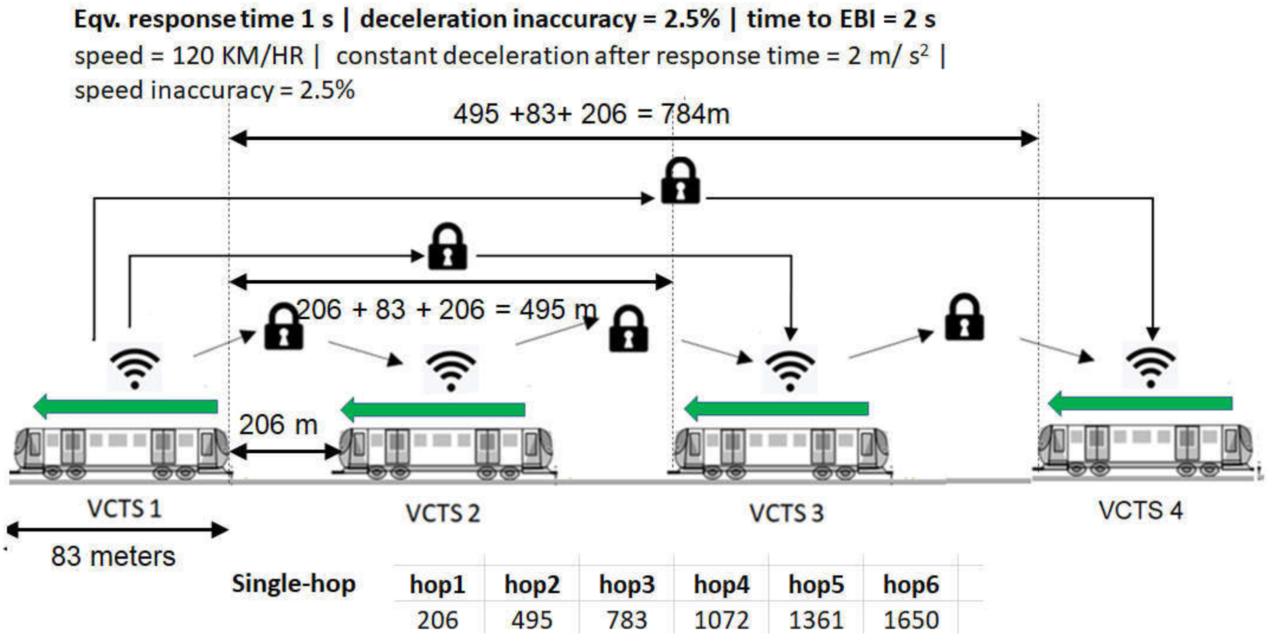

Figure 9-11: One hop communication

The minimum headway required between VCTS units for a virtually coupled platoon's safe operation is the guiding factor for choosing appropriate communication technology and dissemination strategy. The minimum safe headway depends on various factors (see [Canesi, S. and al. (2020), Flammini, Francesco and al. (2018)]) such as the operational speed of platoon (up to 400 km/hr), speed inaccuracy, braking system response time (pneumatic, electromechanics, electronic control), braking capacity (1-2 m/s2, brake modulation), time for service braking before emergency brake intervention (EBI), phase of virtual coupling operation (VC set up to ATP /VC Supervision handover, movement under VC supervision, VC Supervision to termination of VC), etc. Based on the combination of all relevant factors, appropriate communication strategy and data dissemination strategy needs to be evaluated.

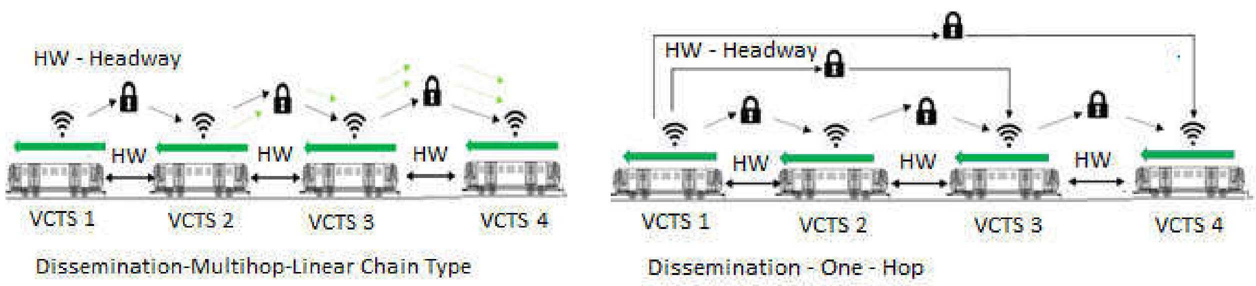

Figure 9-12: Dissemination- one hop vs multi hop

Apart from the data dissemination strategy discussed earlier, in our future work we will evaluate and compare other data dissemination strategies, such as 'one-hop communication' (see [Hardes, Tobias and al. (2019), Kai, Li. Wei and al. (2020)]), 'multi-hop linear chain type communication' (see [Mittag, Jens. Thomas and al. (2009)]) proposed in connected vehicles (as shown in Figure 9-12) and other strategies. One hop communication discussed in this document considers a one-hop communication between all VCTS units, e.g., master to all followers and all followers to master. Whereas in ([Hardes, Tobias and al. (2019), Kai, Li. Wei and al. (2020)]), the master communicates to all followers, but no follower communicates to master. The dissemination strategy in this document provides redundancy, especially in case of communication failure between a leader and RBC / Control Centre.

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9.9 Acknowledgements

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9.10 Authors

Siddhartha Verma is a research engineer at Railenium, Villeneuve d' Ascq. He obtained his bachelor's degree in Mining Machinery Engineering from ISM Dhanbad, India in 2011 and master's degree in system design from FH Kaernten, Austria, (2013-16). He worked as an assistant manager at Reliance Power Limited for procurement of heavy duty equipment and operational support (2011 -13, Mumbai, India) and as a research engineer for safety-security co-engineering at Austrian Institute of Technology, Vienna, Austria (2017-2019).

siddhartha.verma@railenium.eu

Mohamed Ghazel is a Research Director with the University Gustave Eiffel - COSYS department (previously at IFSTTAR) and is the deputy Director of the ESTAS team. He received the Master and Ph.D. degrees in Automatic Control and Industrial Computer Sciences from the École Centrale de Lille in 2002 and 2005, respectively; and the HDR (Habilitation à Diriger des Recherches) from University Lille Nord de France in 2014. His research mainly focuses on the engineering, safety and interoperability of transportation systems using discrete event models and formal methods. Dr. Ghazel is a member of the IFAC technical committees TC 7.4 on Transportation Systems and TC 9.2 on Social Impact of Automation and has been involved in several French national and European research projects.

mohamed.ghazel@univ-eiffel.fr

Marion Berbineau received the Engineer degree from Polytech'Lille (EUDIL) in informatics, electronics, automatics, in 1986, and the Ph.D. degree in electronics from the University of Lille, France, in 1989. She was the Director of the Leost Laboratory, from 2000 to 2013, and the Deputy Director of the COSYS Department, from 2013 to 2017. She is currently the Research Director of Université Gustave Eiffel (previously Ifsttar and Inrets), since 2000. In addition to research activities and supervision of Ph.D. students, she coordinates railway research at Université Gustave Eiffel. She is the Pole Leader of the Intelligent Mobility pole of European Railway Research Network of Excellence (Eurnex). Her current research interests include wireless communications for connected and automatic vehicles (trains and cars) (radio propagation, channel characterization and modeling, MCM, MIMO, ITS-G5, GSM-R, LTE, and 5G NR). She is also the Project Leader of the Emulradio4Rail Project in the framework of Shift2Rail IP2 and involved in several other projects (X2RAIL3, X2RAIL4, and X2RAIL5).

marion.berbineau@univ-eiffel.fr

10 Concept and Performance Analysis of Virtual Coupling for Railway Vehicles

Moritz Schenker, Riccardo Parise, German Aerospace Center (DLR), Institute of Vehicle Concepts, Stuttgart, Germany
Javier Goikoetxea, Construcciones y Auxiliar de Ferrocarriles, S.A. (CAF), Beasain, Spain

10.1 Introduction

Today's operational principles for train headway are based on absolute braking distance (ABD) for collision protection. These train protection systems rely on trackside information and mostly utilize train-to-ground (T2G) communication. The most common national and international systems which are currently applied and in development are fixed and moving blocks [1]:

- Fixed blocks (European Train Control System (ETCS) Level 1 and 2 and most national signalling systems): A track is divided into sections, called blocks, which can only be occupied by one train at the same time. The succeeding train has a maximum movement authority up to the beginning of the next occupied block where it must be able to stop, irrespectively of the position of the train that is currently occupying that section.
- Moving blocks (e.g. ETCS Level 3): The end of authority is directly associated to the rear end of the front train, which allows for shorter headways than in fixed blocks. Each train determines its safe rear end with on-board train integrity and positioning equipment.

Due to the limitation of ABD, the system reaches a state, where it becomes increasingly more complex and less robust to add additional services to the schedule in order to increase the capacity and cover a growing demand in railway transportation. Infrastructural measures can provide additional capacity but are often costly and limited by the available space. Another option to operatively increase capacity in a network is to join trains on a common stretch. This Joining trains is currently enabled through mechanical coupling (MC), which causes additional standstill times during coupling and decoupling and, creatinges a sensitive rendezvous within the timetable, possiblye disrupting operation when one of the trains is delayed. Furthermore, compatibility is a known issue, since many manufacturers utilize different standards.

Virtual coupling combines the best of both approaches, shortening the headway between trains and coupling them to a single train set, by going one step beyond current train protection systems and at the same time avoiding the disadvantages of an MC. The headway between trains is aimed to be further decreased by considering the dynamics of both trains and changing the paradigm to a relative braking distance (RBD) instead of ABD. For this, a fast and secure communication link between trains is required, which can be established with a direct train-to-train (T2T) communication, avoiding a centralized system and reducing delays. A reliable T2T communication together with accurate on-board sensors is the basis of the virtual coupling system. A concept of virtually coupled train sets (VCTS) is developed and analysed in work packages 6 and 7 of X2Rail-3 (Grant Agreement No. 826141[2]), a Horizon 2020 project of the Shift2Rail (S2R) Joint Undertaking, for "Advanced Signalling, Automation and Communication

System". The first results of the concept as well as a preliminary performance analysis are presented hereafter.

10.2 Goals of Virtual Coupling

The main goals VCTS aims to achieve can be summarized as [2]:

- Increasing line capacity by reducing the headway
- Increasing operational flexibility by ensuring interoperability between all railway vehicles
- Improving the use of the existing platforms by utilization of several platform tracks
- Reducing costs by:
    - Utilizing on-board equipment and electronic systems instead of building new tracks or applying major infrastructural changes
    - Reducing maintenance cost in relation to the best use of the line and platforms

Hereby, VCTS tries to take railway operation to the next level, while at the same time keeping the necessary modifications small and cost-efficient. These goals funnel into the overall aim of S2R to increase the competitiveness of the railway with respect to other transportation means.

10.3 The Concept of Virtual Coupling

The concept of virtual coupling is based on the paradigm change called "Breaking the braking wall" [1], which refers to the shift from train protection based on the ABD to an RBD principle. Metaphorically, this wall represents the maximum End-of-Authority, which follows the rear end of the leading train. End-of-Authority is the point where a succeeding train has to be able to stop in any case in an ABD-based system. ABD systems assume that, in the worst case, a train may stop instantaneously, which is justified by the lack of information of the braking capabilities and status of the other trains. By virtually coupling two or more trains of any train type, trains can communicate their braking capabilities and positions in real time, enabling a cooperative movement. The figurative wall can then be removed and the trains can drive closer together at RBD (see Figure 10-1).

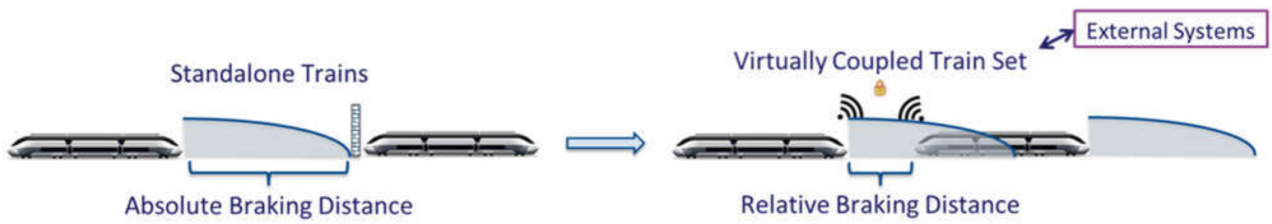

Figure 10-1: Paradigm change "Breaking the braking wall": From absolute to relative braking distance [3] (train graphic by DLR, NGT Project)

Today, when coupling trains mechanically, the distance between them is fixed, and forces are transmitted by the physical link, naturally preventing collision. Additionally, the physical link enables data transfer and a connection of the brake pipes for synchronised braking. The VCTS concept transfers the functions of the mechanical link to an electronic, wireless link. With this concept, fast coupling and decoupling are enabled, even including efficient on-the-fly manoeuvres while driving. Due to the missing mechanical link, the trains inside the platoon may have different dynamic states at any time. Thus, the challenge of virtual coupling is to ensure a safe distance between trains while allowing them to drive closer together than ABD. Therefore, some new elements are required:

- For data transfer, a direct **T2T-communication** needs to be established. It needs to provide a continuous, reliable and safe exchange of critically relevant information such as the current train dynamics, trajectories and braking capabilities. Using different communication technologies for different ranges, this T2T-link is the basis of cooperative platoon movement. Additionally, a VCTS still needs T2G-communication with external systems (e.g. traffic management, signalling).

- The trains forming the platoon need to be aware of themselves and of their environment at all times. Thus, in addition to the odometry system with its estimation of the absolute status for each train, real-time distance, relative speed and relative acceleration between the trains needs to be supervised through **on-board sensors**. Together with the supervision of the absolute state (including braking and acceleration capabilities and weight of train and current track conditions, if available), these values are also exchanged via the T2T-link. These sensors can also ensure safe operation and fast reactions in case the T2T communication fails or is delayed.

- Finally, the actual **distance control** needs to be safely executed on each train. For this, an interface of the VCTS system with traction/braking control units is required.

These three on-board components are the basis for the VCTS **platoon management**. The VCTS concept is aimed to be widely applicable and thus mostly independent from the underlying signalling system. This is possible, as the main components enabling the concept are implemented on-board. To the external systems, a VCTS is then seen as one single train that follows the rules of the underlying signalling system. The distance management below ABD within the platoon is controlled by the on-board VCTS system without interference from the trackside system. Thus, the ABD paradigm is not explicitly violated, which would require a more fundamental change of the signalling system. However, it is necessary to provide additional information (such as current VCTS length, status and number of coupled trains) to the existing trackside system and adjust the corresponding train protection and interlocking functionalities to ensure safe operation with a variable train length and gaps within the VCTS.

10.3.1 Functional Layer Architecture and Main Functions

The elements and interfaces of the VCTS system introduced above provide various functionalities within the VCTS concept. These functionalities can be grouped into different classes. In the proposed concept, these classes are organized in a vertical layer structure, presenting distinct levels of abstraction: from a macroscopic view of the whole railway network down to the microscopic movements of single trains. Four functional layers and their interfaces are defined in X2Rail-3 D6.1 [1], as shown in Figure 10-2.

- **Services**: The top level is in charge of managing service requests and serves as an integrated mobility-as-a-service platform. It provides external interfaces to the users, e.g. individuals accessing the booking systems or platforms for other modes of transportation.
- **Strategic**: Upon service requests, this layer defines the composition, ordering and de-/coupling instructions for a potential VCTS, based on compatibility, destinations and schedules. This layer can provide functionalities to maximise capacity in terms of traffic management by planning and supervising traffic flow, identifying and reacting to conflicts and delays. It furthermore provides feedback to the services layer.
- **Tactical**: On this layer, the actual platoon movements and manoeuvres such as coupling and decoupling are coordinated. It is meant to execute the strategy from the layer above via T2T communication and provides feedback with the current status of a platoon. Unexpected events and degraded modes need to be accounted for within the tactical layer by prearranged, safe procedures. Based on the underlying signalling system, the tactical layer is responsible for defining the speed and acceleration targets and the headway between trains. Here, the coupled operation and connected manoeuvres can be optimised with respect to energy or time consumption.
- **Operational**: The lowest layer, implemented on each vehicle, is in charge of the local control of each unit and has to ensure the safe execution of the commands from the tactical layer. Hereby, the headway is controlled based on target values and safety-limits, while at the same time supervising the stability of the platoon. The safety-critical functions of VCTS on the train level are allocated on this layer.

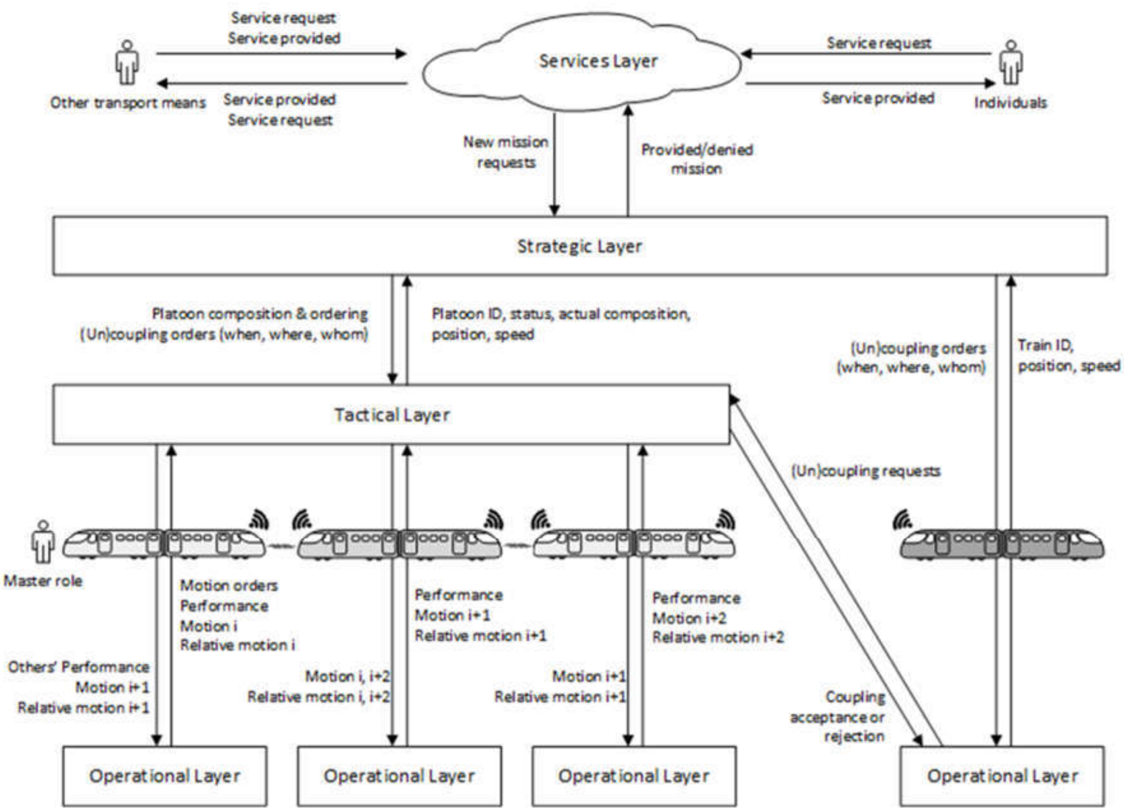

Figure 10-2: VCTS and functional layers [1]

Work packages 6 and 7 of X2Rail-3 are focussed on the operational and tactical layer and interfaces to the strategic layer (highlighted by the dotted box in the Figure 10-2). This is where the main elements of VCTS, as introduced above, are allocated. This part of the functional layer architecture is responsible for five main functions, as shown in Figure 10-3: Protection against collision inside the platoon, VC set-up, coupled driving, VC termination and interaction with external systems. The implementation of these functions is described in the next section.

10.3.2 VCTS Two-Stage Implementation Approach

The VCTS system requires some fundamental changes in railway operation. In order to facilitate the implementation of the concept into existing operation, a stepwise implementation of VCTS functions with increasing complexity is targeted. [4]. Thus, the goal is to provide a VCTS solution that is widely compatible and allows for a near-term introduction with the utilization of two stages. The implementation of the main functions within these two stages is illustrated in Figure 10-3.

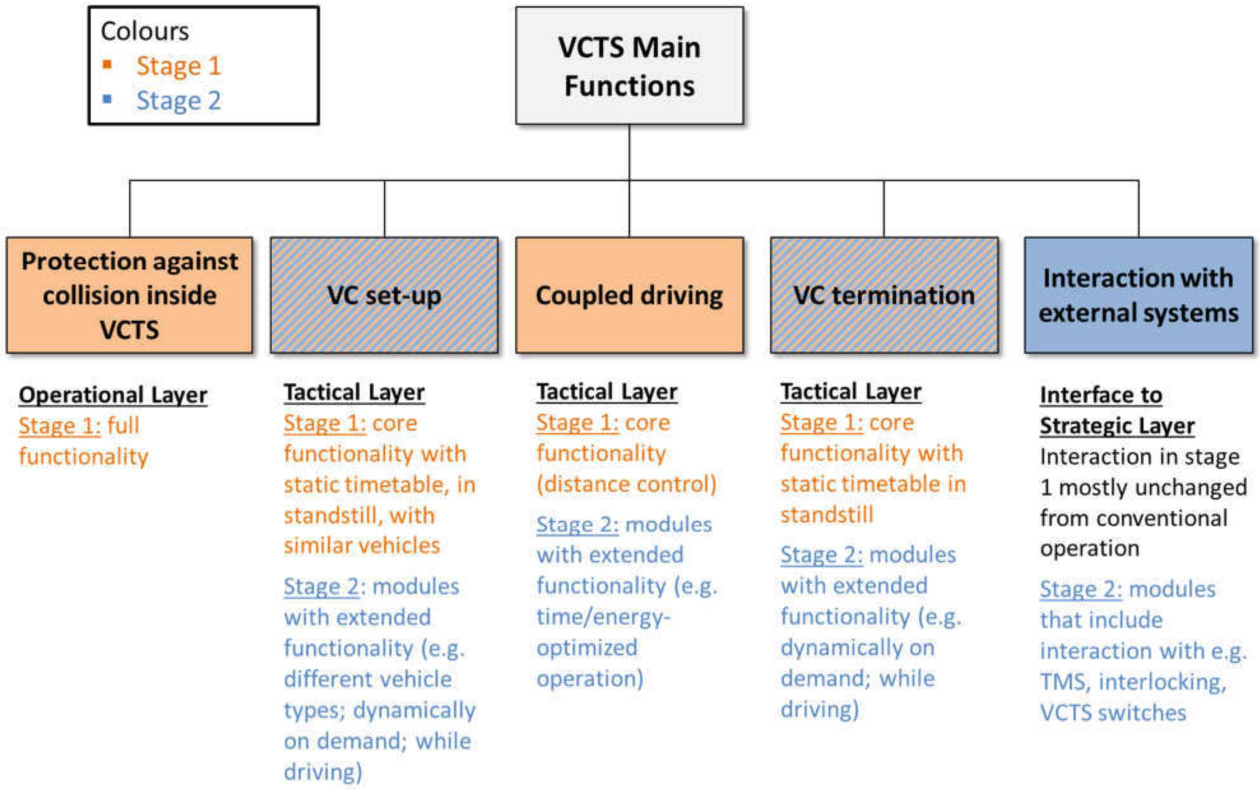

Figure 10-3: The allocation of the five main VCTS functions in the two-stage implementation approach. [4]

- Stage 1: The first step is a minimum-complexity implementation of the core functionality of VCTS. It builds on the established procedure of MC executed in standstill according to the timetable, but with significantly reduced de-/coupling times due to the removal of the mechanical link. This mainly includes the implementation of the safety-critical function to protect the units inside the platoon from collision (full operational layer) and a first, simple distance control during coupled driving with similar vehicles (tactical layer). The interaction with external systems remains similar to a mechanically coupled train (through the lead unit), now including a variable length train set length and gaps in between VCTS units.

- Stage 2: Here, the goal is to provide smaller modules with additional functionalities to the VCTS core that can be added simultaneously or successively. They aim to further utilize the advantages of VCTS with smooth and efficient operation. While the operational layer was fully introduced in stage 1, this concerns the extension of tactical layer and the interfaces with the strategic layer. On-the-fly coupling and decoupling manoeuvres can be introduced as well as calling with one VCTS at multiple platforms, i.e. splitting a long VCTS before a station to stop at different platforms and re-joining the trains behind the station. Furthermore, optimisation of the platoon tactics and additional interactions with external systems can be implemented.

10.4 Performance Analysis

Based on the concept introduced in the previous chapter, a first analysis of the possible VCTS performance was conducted. Following the goals described in the beginning, the VCTS concept has the potential to improve rail operations by combining benefits that usually contradict each other: **Capacity, flexibility and robustness**. The replacement of MC and the reduction of headway in general cannot only lead to a higher network throughput, they also open up possibilities for a more flexible and robust operation. Coupling compatibility issues can be resolved, sensitive MC rendezvous are avoided and some of the capacity gains can also be traded for additional robustness. Additionally, VCTS provides the ability to dynamically arrange and dissolve platoons based on real-time information for more flexibility.

While flexibility and robustness are crucial advantages, in the first analysis, we focussed on a preliminary quantification of capacity gains, since capacity is one of the main S2R key performance indicators (KPIs). Various studies of the IMPACT scenarios [5] for high-speed and regional operation showed that a VCTS Stage 1 implementation (replacing MC), considering only reduced coupling and decoupling times, can lead up to a doubling of the capacity [6]. The exact capacity gains depend on the underlying signalling system, with most cases yielding approximately 10 - 50% improvements compared to MC [6]. However, even more important for capacity improvements than reduced de-/coupling times is the paradigm shift from ABD to RBD as introduced in the previous chapter. In order to quantify possible improvements compared to operation with an ABD protection system, RBD is analysed hereafter.

In general, RBD is the required distance between trains that guarantees safe braking to standstill. In an ideal world without any delays and perfect precision in both measurements and control, the RBD would be zero. In this theoretical case, when both trains travel at the same speed, they could follow the same braking curve and thus never change the distance between them. However, in reality, there are multiple factors of influence that cause deviation from this ideal behaviour and require additional safety margins in the RBD. This can be latencies in communication and control, imprecision in speed and distance measurement, differences in braking capabilities, built-up times or speed levels, etc. For three specific, isolated factors, this behaviour is demonstrated in the following:

- **Reaction delay (RD)**: Δt_{RD} is the elapsed time between brake application of two trains, regardless of the reason for the delay. It may be caused by communication latency, brake build-up time or any other reason that delays brake force application of the rear train. If only this RD is considered, the rear train will travel at initial speed v_0 for Δt_{RD} seconds after the front train started braking and then follow the same braking curve. The required safety margin in the RBD due to this factor is:

$$RBD_{RD} = \Delta t_{RD} \cdot v_0$$

- **Position inaccuracy (PI)**: $\Delta s_{\mathrm{inacc}}$ is the difference between the assumed position of a train (measured or estimated) and its actual position due to the inaccuracy in the determination method. This implies when the front train brakes, it might be closer to the rear train than measurement suggests. The inaccuracy applies for both trains, therefore, the necessary margin covering the worst case results to:

$$RBD_{\mathrm{PI}} = 2 \cdot \Delta s_{\mathrm{inacc}}$$

- **Speed inaccuracy (SI)**: $\Delta v_{\mathrm{inacc}}$ is the difference between the measured speed of a train and its actual speed due to the inaccuracy in the speed determination method. In the worst case, when the front train brakes, it might be slower than measured, while the rear train might be faster. Considering a common brake deceleration of a_brake, the margin is:

$$RBD_{\mathrm{SI}} = 2 \cdot \Delta v_{\mathrm{inacc}} \cdot \frac{v_0}{a_{\mathrm{brake}}}$$

When these effects are combined, they result in a joint headway. This value does not correspond to the pure sum of the margins above, as e.g. SI and RD interact with each other. An algorithm was set up to calculate the RBD, considering RD, PI, SI, different speed levels and braking capabilities. The RBD was determined for the four railway scenarios defined in Table 10-1, considering an additional safety margin of 15%, and compared to the ABD for the same application. The results of this comparison are depicted in Figure 10-4. It is evident that there is a significant reduction in distance. Depending on the scenario the values range from -64 to -81%, which yields an indication for the potential capacity improvements by headway reduction with the paradigm shift from ABD to RBD.

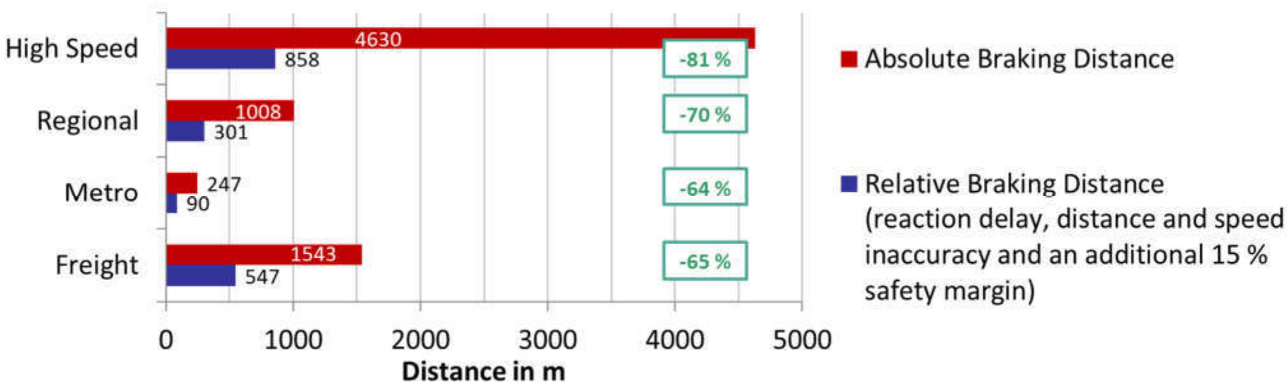

Figure 10-4: Comparison between ABD and RBD for four different railway scenarios [3].

Table 10-1: Railway scenarios based on IMPACT reference cases [5] and additional assumptions.

Service [5]	**a in m/s²**	**v_0 in km/h [5]**	**Δt_{RD} in s**	**$\Delta s_{\mathrm{inacc}}$ in m**	**$\Delta v_{\mathrm{inacc}}$ in km/h [7]**
High Speed	-0.75	300	3	20	7.7
Regional	-0.75	140	3	15	4.3
Metro	-1.00	80	1.5	10	3.1
Freight	-0.25	100	8	15	3.5

10.5 Outlook: Development and Migration Roadmap

Together with the preliminary safety analysis in [6], the performance analysis showed that the VCTS has the potential to heavily increase railway network capacity in a safe way. Therefore, a subsequent feasibility analysis was conducted [4]. Here, critical aspects in the VCTS implementation concerning the technological and operational subsystems were identified. The most notable are:

- Precise and safe supervision and exchange of the distance, relative speed and relative acceleration between virtually coupled units,
- variably controllable brakes with fast and precise system response,
- availability of suitable T2T-communication technologies and the respective frequencies and
- reliable supervision of the integrity of each train within the platoon and the platoon length (length of the virtually coupled trains and the current distance between them).

For these aspects, mitigation measures were identified together with S2R experts from the respective domains. For all of the abovementioned points, ongoing developments in other S2R-projects or the industry were identified to provide suitable technologies and systems in the near future [4]. And although additional general, non-technological obstacles exist, such as locked-in effects, these obstacles were not identified as showstoppers. With the demonstration of feasibility, an introduction strategy was developed, proposing the next steps in VCTS implementation [4]. These steps are summarized in a qualitative roadmap in Figure 10-5.

The proposed next steps are grouped into three main categories: Development (I), testing (II) and roll-out (III). This includes the next tasks in the X2Rail-3 project in terms of system requirements specification as well as potential successor projects with the aim of a demonstrator to prove the concept, ultimately leading to a roll-out facilitated by the two-stage approach described in the concept above.

10.6 Conclusions

It can be concluded that VCTS developed in X2Rail-3 provides a concept to increase capacity, flexibility and robustness of a railway network avoiding infrastructural changes by focussing on on-board equipment and operational tactics. VCTS enables decreased headway and coupling times, efficient and dynamic manoeuvres and interoperability by coupling compatibility between any train types. A safe realisation of this concept is possible with the right system design and control mechanisms [6]. Furthermore, the VCTS system is not tailored to a single signalling system, enabling multiple different application cases and avoiding additional barriers in railway operation. In conclusion, VCTS presents a concept to contribute to an increased competitiveness with respect to the road transportation by enabling more efficient freight and passenger transportation over the railway network.

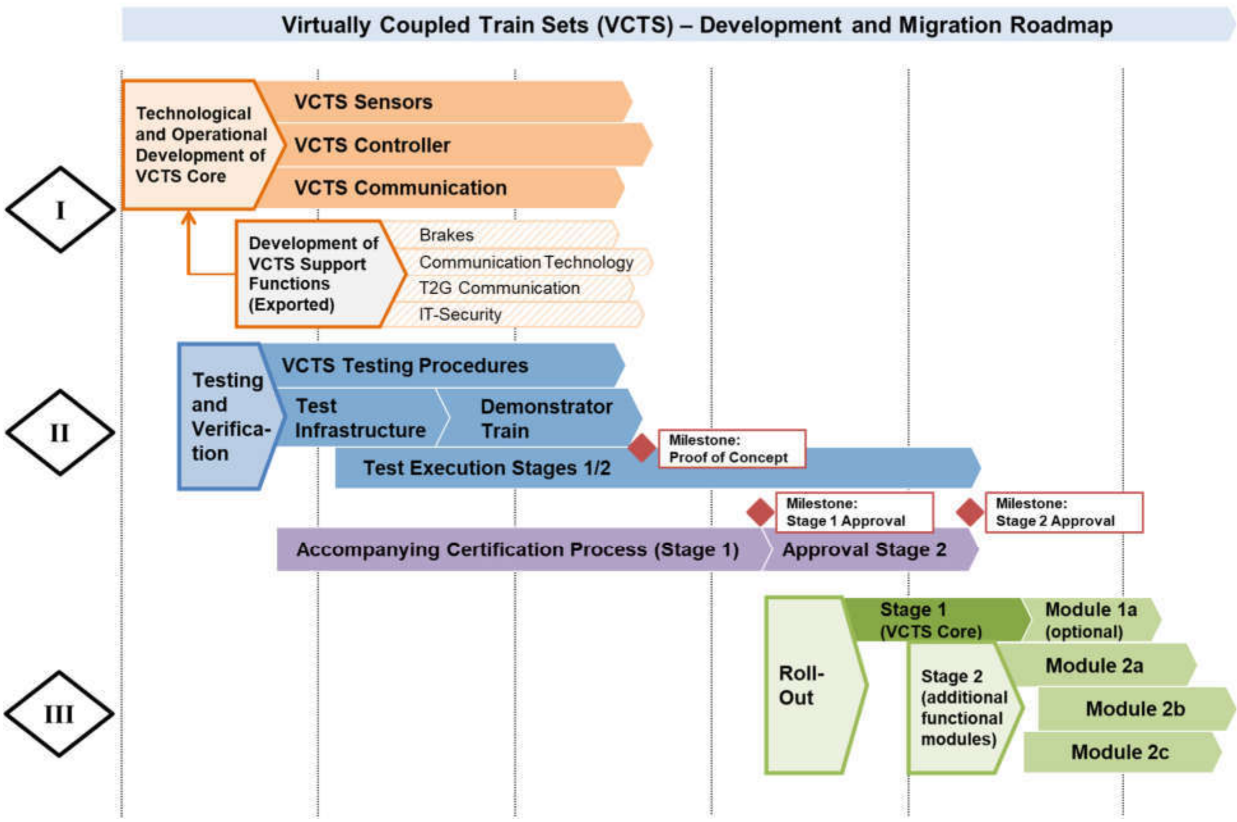

Figure 10-5: Further steps in the VCTS development as a qualitative migration roadmap [4].

10.7 Acknowledgements

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10.9 Authors

M.SC, **Moritz Schenker** finished his studies in physical engineering at TU Berlin in 2019 and joined the Institute of Vehicle Concepts at German Aerospace Center (DLR) in Stuttgart in the same year. As a research associate, he is currently working on the concept, performance and impact analysis of virtual coupling within X2Rail-3. Furthermore, his focus in the DLR Next Generation Train project is on simulation and optimization of railway trajectories and the control of hybrid propulsion systems.

Moritz.Schenker@dlr.de

M.SC, **Riccardo Parise** completed his under-graduation in Mechanical Engineering at the University of Campinas (UNICAMP) in 2017. He is with the German Aerospace Center (DLR) in Berlin since 2018, where he works mainly with the concept of Virtual Coupling in the project Next Generation Train and the European Joint Undertaking Shift-2-Rail.

Riccardo.Parise@dlr.de

Javier Goikoetxea, Dipl.-Ing. joined CAF in 1997 after finishing his studies in mechanical engineering at Tecnun in San Sebastian. Currently he holds the position of Senior Technology Strategist at the Technology Division of CAF. He has been involved in developing advanced technological products for CAF such as the SIBI tilting system, the COSMOS TCMS product or the OARIS high speed train. Javier has a large experience in managing national and international research projects and represents CAF at the ERRAC Steering Committee and UNIFE R&I Committee. Within the Shift2Rail initiative Javier is the Coordinator of the Innovation Programme 1 - Cost-efficient and reliable trains.

jgoikoetxea@caf.net

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