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1. Executive Summary

Work package 7 has started with the recruitment of Getachew Hagos GELETA, who is working on his PhD at COSYS – LEOST, Lille campus Gustave Eiffel University since 1rst of November 2023, with supervision by Marion Berbineau and follow-up committee members of Simon Collart-DUTILLEUL, Francesco FLAMMINI, and Nicola SACCO.

During the period of M1 to M22, we had discussions and online meetings with one of the safety experts from ALSTOM, Mr. Quentin Bleriot. He provides essential information regarding the parameters we used for our Virtual Coupling Train Sets (VCTS), particularly for the Cooperative Awareness Message (CAM) exchanges between two trains and also comments on the hazard analysis part of the work for the time being. Finally, we planned to work together for the main part of the PhD work, which is on the development of a methodology for the dependability analysis of wireless link CAM exchange between two trains.

During the first year of the PhD program, we focused on:

- understanding the railway control and command rules, the PhD topic, and the analysis of literature related to dependability analysis, and the methodologies related to dependability analysis. Among them, we focused on Petri Net tools. We aimed to identify the appropriate tools, such as Colored Petri Nets (CPN Tools) and the CPN IDE tool.

- Identifying existing works related to train to train communications and the evaluation of different technologies

In the second year, based on the safety standards generally considered (EN 50126, EN 50128, and EN 50129) in the rail domain for wireless communications, we performed an accurate hazard analysis of Train-to-Train (T2T) communications using Failure Mode Effects and Criticality Analysis (FMECA) and Fault Tree Analysis (FTA). Subsequently, we develop a mathematical Boolean expression to determine the probability of failures.

The purpose of conducting a hazard analysis of Train-to-Train (T2T) communication or Virtual Coupling Train Set (VCTS) using FMECA and FTA is to systematically identify, assess and mitigate possible failure modes and their impacts on system safety and operational reliability. This dual-method approach enables a comprehensive evaluation of both component-level vulnerabilities (via FMECA) and system-level causal pathways leading to hazardous events (via FTA), thereby supporting the development of robust safety measures for autonomous train operations. The analysis aims to identify how to enhance the safety assurance process for critical communication-based train control systems.

After that, we designed a model for the T2T communication system using colored Petri Nets, and we analyzed the effects of message loss on safety-related wireless link performance metrics such as: End-to-End Delay, Average Inter-message gap, Percentage of safe message gaps, Throughput, Message Delivery Ratio, and Percentage of safe delivery. We have explicitly incorporated some of the mitigation strategies outlined in the FMECA: one-time retransmission in case of message loss and timestamps of the messages to ensure timelines and to detect and discard repeated messages. This analysis quantifies the performance of the proposed mitigations. By bridging the static hazard analysis with a dynamic, simulation-based dependability study, we aim to validate the effectiveness of these strategies provided by FMECA and to identify any residual risks.
This first model has not taken into account 5G NR V2X characteristics. We introduced these characteristics in the last few months.

The scientific contributions from M1 to M22 can be summarized into three main points:

1. State-of-the-art and methodological groundwork:

- Review of railway control and command rules, and literature on dependability analysis methodologies.
- Identification and selection of appropriate modelling tools, with focus on Coloured Petri Nets (CPN tools and CPN IDE).
- Review on existing works related to wireless communications standards for train to train communications and VTCS. This work will be included in a journal paper in preparation. A comparative table between wireless technologies has been prepared.

2. Hazard analysis of Train - to – Train (T2T) communications:

- Application of FMECA and FTA methods- to analyze failure modes and hazards in wireless Train-to-Train, VCTS communication.
- Development of Boolean expressions to quantify failure probabilities and support safety assurance for critical communication-based train control.

3. Dynamic modelling and validation of mitigation strategies:

- Design of a Coloured Petri Net model for T2T communication
- Performance evaluation of wireless link under message loss scenarios using metrics such as delay, throughput, and delivery ratio.
- Implementation and assessment of mitigation strategies, for instance, one-time retransmission, timestamping to validate the effectiveness of hazard analysis recommendations and identify residual risks.

Therefore, the next plan is to improve the model to include 5G NR V2X characteristics and multiple retransmissions within a fixed time period, called the acceptable time interval. This will make sure that important safety messages are delivered on time before an emergency braking happens. Also, changing how often trains send messages will help test the communication system in more realistic situations. This is important for setting clear rules for VCTS use in railways, such as the maximum number of times a message can be resent in one interval. Those improvements will help make the VCTS both safer and more efficient.

In parallel, we will also explore the potentialities and retransmission performances of 5G side link in the T2T context to take them into account. This will be done thanks to collaboration with Railenium and SNCF-Voyageur in the WP6 of the project IAM4RAIL. Based on these results, we have explored how to “tune” the CPN model with 5G NR key performance indicators.

2. Current Status of the PhD candidate

The PhD candidate began his doctoral studies on November 1, 2023, and is now entering the third year of their PhD program. Over the past two academic years, the candidate has successfully completed all courses and training modules required by the University of Lille’s doctoral program regulations. In total, the candidate has completed fifteen (15) training modules, corresponding to 92 hours / 106 credits, thereby fulfilling their educational obligations in line with the requirements for doctoral studies. The number of completed modules within the block and skills descriptions are:

- Block 1: Conceiving and elaborating a research and development procedure
- Block 2: Setting up a research and development, study and prospects procedure
- Block 3: Promoting and transferring the results of a Research and Development
- study and prospects, procedure
- Block 4: Scientific and technological vigilance on an international scale
- Block 5: Training and sharing scientific culture
- Block 6: Monitoring teams dedicated to Research and Development, studies and

4. prospects activities

The candidate also participated in International Activities from July 15 to July 24, 2025, in the Summer International School on "The European Railway System" (2nd edition – 2025), held in Rome. The program included lectures, seminars, and technical visits covering a wide range of topics, such as:

- European research and innovation in railways,
- Artificial intelligence applications in railway operation,
- Safety management systems and risk assessment,
- Evolution of railway signalling and ERTMS/ETCS,
- Competition in the high-speed railway market,
- Digital Automatic Coupling technologies,
- Guided visits to railway control centres, maintenance facilities, and industrial partners (for example, RFI traffic control centre, Alstom, and metro line C construction site, etc.).

Generally, the candidate actively engaged in the academic and professional sessions, strengthening both their technical expertise and international research network in the railway sector.

3. Collaboration with industrial partners

During the second year of the PhD, collaborations with Alstom has been established with a senior expert in safety Quentin BLERIOT. We exchange documents and he reviewed part of the candidate's work. The exchanges will continue.

In addition, the candidate's work is complementary to the work performed in IAM4RAIL project in collaboration with Railenium and SNCF-Voyageur. In this project, Railenium and UGE are developing the concept of train-to-train communications for virtual coupling. 5G sidelink performances have been analysed versus various constraints as for example the latency and the distance between trains. Discussions will be established before the end of 2026.

The participation to the 7th Smartracon seminar will be also an opportunity to present de work to ERJU representatives. Contacts with CAF has not been yet established due to lake of time.

In addition, in the PhD work, we will also consider Pod to Pod communications in the PODS4RAIL project. Thus the PhD is really sharing his work in different Eu projects.

4. Background

The basic idea behind virtual coupling is to increase railway capacity (number of trains on the network) by running trains synchronized together (well well-known example of TGV). Today, the virtual coupling consists of coupling two trains (also called consists in the rail terminology) or two wagons (or coaches). Currently, the coupling of two wagons is performed in the garage, and it is a fixed mechanical coupling and the connection of the wired embedded communication network called TCMS. For the coupling of two trains, the principle is the same, but this coupling is generally done in a station (for example of the coupling of two TGVs in a station).

In the current virtual coupling specifications, the aim is to couple two trains thanks to a wireless vehicle-to-vehicle (V2V) communication. Furthermore, the platooning strategy of trains involves assigning trains to various platoons, choosing where and when to join and depart the platoon, controlling stopping at stations and other tasks. In this case, a wireless communication system will facilitate information sharing between two vehicles. In this coordinated movement, each train considers the speed and braking behavior of the train ahead, enabling them to travel more closely together thanks to the respect of the conventional Absolute Braking Distance System (ABDS). Since this coordination relies on the real-time exchange of critical data between train sets through a wireless communication system (WCS), assessing the wireless system’s dependability is essential to ensure the safety of VCTS operations and to develop a methodology to conduct dependability analysis of wireless communication links.

The safety of the wireless system is traditionally based on a safety layer implemented above the wireless system at the application layer. The characterisation of the safety level is related to the wireless link performances in terms of packet loss rates, latency, and end-to-end delay. The railway safety standards such as EN50126 (railway applications specification and demonstration of RAMS), 50129 (Railway applications Communication, signalling and processing systems Safety-related electronic systems for signalling), and 50159 (Railway applications Communication, signalling and processing systems Safety-related communication in transmission systems) provide this guarantee by the RAMS (Reliability, Availability, Maintainability, and safety) operating safety guidelines. Therefore, the dependability analysis is necessary to design this safety application. In this PhD, we considered a cutting-edge wireless system designed normally for vehicle-to-vehicle wireless communications: the 5G sidelink standard (5G NR V2X), which is not totally standardized.

Choice of the wireless technology (PODS4RAIL D11.1)

Wireless communication plays a critical role in enabling reliable and low-latency connectivity between trains and supporting infrastructure in the virtual coupling process. Although Vehicle-to-Vehicle (V2V) communication has been extensively studied in the automotive domain (Mannoni et al., 2019), (Chatzoulis et al., 2023), many of the insights are transferable to the rail sector. Over the years, different frequency bands have been explored, including the 400MHz band, the 5.8 GHz band with ITS-G5 technology, and millimetre-wave bands. Each spectrum range offers distinct benefits and limitations in terms of latency, bandwidth, propagation characteristics, and coverage factors that must be carefully balanced for mission-critical railway applications.

In this context, our focus is on the emerging 5G sidelink standard, known as NR V2X (5G V2X, 2024). This technology is designed for direct communication between vehicles and natively aligned with the 5G New Radio (5G NR) framework, which forms the foundation of the Future Railway Mobile Communication (FRMCS). Leveraging NR 5G for Train-to-Train (T2T) communication holds significant promise, but its performance depends on multiple operational parameters, including train separation distance, mobility profiles, track topology, and potential interference from both coexisting wireless systems and adjacent trains. Key performance indicators such as message loss rate, end-to-end delay, and application-level throughput are crucial for evaluating system reliability. Any degradation in these metrics can delay the transmission of safety-critical information, including braking commands, speed adjustments, or emergency alerts, thereby posing risks to operational safety. Additional challenges specific to the railway environment, such as high-speed mobility, multipath fading in tunnels or urban areas, and stringent reliability requirements imposed by signalling systems, further complicate wireless deployment. Ensuring deterministic latency and ultra-reliable connectivity in such conditions remains one of the central challenges in realizing robust wireless communications for the rail domain.

The choice of a wireless system for virtual coupling application is not yet defined. In the R2DATO project an architecture for the communications has been defined but the technology has been chosen. In IAM4RAIL project Task 6.4.1 conducted within WP6, a technology based on 5G NR V2X is under development for the TRP 4 demonstrator of Train-to-train communications.

The PhD work focus on 5G NR V2X. The choice for this technology is based on literature analysis related to vehicular applications and also works on going in the Marion Berbineau's team in other projects (Ferromobile, Iam4RAIL, PODS4RAIL). The following Table 1 (from Pods4rail - D11.1) gives some comparison elements.

Whatever is the environment in which the trains are, the communication unit will benefit from an adaptive solution that will be able either to combine several technologies; either to reconfigure itself in order to cope with weak or absence of radio coverage, short range or long-range needs as well as various latency, end-to-end delay, availability and throughput requirements. Various candidate technologies are available today for vehicular to everything (V2X) communications in the road and rail domains for safety and non-safety related applications.

For V2X applications in the road domain, ETSI ITS-G5 standard based on IEEE 802.11p and .11bd has been developed. Release 1 based on .11p has been evaluated in different road scenarios, as well as in the rail domain (Gómez et al., 2018) (Bigñotte et al., 2023). A big benefit of IEEE 802.11 is the backward compatibility between .11p and .11bd devices. If a .11p device is present, the .11bd devices can communicate in a degrade mode with the previous generation. A wireless access for vehicular environment with IEEE 802.11p is suitable for highly dynamic vehicle to everything environments, without the need of specific infrastructure, and with self-configurable devices. It is based on the Physical and MAC layers of the IEEE 802.11a adapted to vehicular communications, including enhanced capabilities for reliable authentication and connections in dynamic and timely critical contexts.

A V2X communication standard based on cellular radio is published by 3GPP. C-V2X (Cellular Vehicle-to-everything) started based on 3G, further developed with release 14 and 15 under the umbrella of 4G and up from release 16 called 5G V2X (Liu et al., 2025) (Maglogiannis et al., 2022) (Molla et al., 2025) (Maaloul et al., 2021) (Ghodhbane et al., 2022) (Narouwa et al., 2024). 4G and 5G support side link communication that will directly connect the nodes and avoid connections with the core network. The side link communication enables direct T2T and V2V communication based on 5G sidelink standard under development. Sidelink for direct device-to-device and V2X over 5G and beyond (5G Sidelink), is based on 5G technology allows establishing direct communication but without cellular infrastructure. This approach provides high versatility and flexibility for dynamic communications with a robust and secure device-to-device data exchange. It allows different spectrum configurations, from license to non-license bands, bringing adaptability to a high range of devices. This will ultimately provide benefits in terms of interoperability and scalability.

Millimetric waves for short range communications are also a promising technology (Berbineau et al.,

2023) (Mabrouki et al., 2022) (Soliman et al., 2019). The IEEE 802.11 and the 3GPP 5G NR standards support mmWave in two major frequency bands between 24 GHz and 70 GHz with large available bandwidths. Large bandwidth below 10 GHz can be archived with ultra-wideband (UWB) communication based on IEEE 802.15.4. Multiple channels with 500 MHz or 1 GHz bandwidth are available.

Long range solutions such as LORA or TETRA could be beneficial in some specific use cases. For very short-range RFID and optical technologies could be considered (Molla et al., 2024). 5G is rapidly evolving towards 6G. 6G corresponds to the integration of several technologies that will enhance drastically connectivity everywhere. Among them, we can mention the use of low earth orbit (LEO) satellite constellations (EUSPA, 2023) is planned in combination with 3GPP 5G NR for rail and road applications when terrestrial infrastructure deployment is too expensive. The European Union is pushing to launch European constellation such as IRIS2 for mission critical applications such as the Pods4Rail system. In addition, networks hybridization such as TN (Terrestrial Network) and NTN (Non-Terrestrial), mmWave access points associated with 5G networks.

In addition, ISAC and RIS (Reflective Intelligent Surfaces) (Habib et al., 2023) technologies offered by 6G network in a near future should be also taken in consideration (Liu et al., 2024).

Table 1: Comparison of communication Standards

Technology	Frequency ranges or bands	Frequency (GHz)	Bandwidth (MHz)	Data Rate	Range	Latency (ms)	Tx Power (dBm)	Mobility	Protocol / Standards	Supported V2X modes
4G LTE		0.45-5.9	1.4-20						3GPP Rel. 12/13	V2I
4G LTE-V2X	ITS	5.9	10, 20	27 Mbps	1 km	15	23	Yes	3GPP Rel. 14/15	V2X
5G NR	FR1	0.4-7	5-100		400 m			Yes	3GPP Rel. 15	V2I
5G NR	FR2	24-100	50-2000	10 Gbps	100 m	1		Limited	3GPP Rel. 16/17	V2I, TU-to-CU
5G NR V2X	ITS	5.9	10, 20, 40		2 km		23	Yes	3GPP Rel. 16/17	V2X
5G NR V2X	FR2	24-100	50-2000		100 m	1		Limited	3GPP Rel. 18	V2X
6G	FR1	0.4-7	5-100			0.1		Yes	3GPP Rel. 21	V2I
6G	FR2	24-100	50-2000	100 Gbps	100 m	0.1		Limited		V2I, TU-to-CU
6G	FR3	7-24			1 km	0.1		Yes		V2I
6G	THz	100-3000		1 Tbps	10 m	0.1	-	No	IEEE 802.15.3d	TU-2-CU
6G V2X	ITS	5.9						Yes		V2X
6G V2X	FR2	24-100	50-2000					Yes		V2X
Wi-Fi 6		2.4, 5	160	9.6 Gbps	150			Limited	IEEE 802.11ax	V2I, TU-to-CU
Wi-Fi 6E		2.4, 5	160	9.6 Gbps	150			Limited	IEEE 802.11ax	V2I, TU-to-CU
Wi-Fi 7		2.4, 5, 6	320	46 Gbps	150			Limited	IEEE 802.11be	V2I, TU-to-CU
Wi-Fi 8		2.4, 5, 6	320					Limited	IEEE 802.11bn	V2I, TU-to-

										CU
ITS-G5 rel 1	ITS	5.9	10	27 Mbps	1 km	10	23	Yes	IEEE802.11p	V2X
ITS-G5 rel 2	ITS	5.9	10- 20		2 km	1	23	Yes	IEEE802.11bd	V2X
ITS-G5 rel 2	ITS	65	2000					Yes	IEEE802.11bd	V2X
UWB		3-10	500, 1000	1 Gbps	100 m	1	-41.3	Yes	IEEE802.15.4	V2X
RFID		0.125-0.96	-	Up to 640 kbps	~10 m	1	-	Limited	ISO/IEC 18000	V2X
NB-IoT (Cat-NB1/2)		0.9, 1800	0.2	26 kbps(DL), 62kbps(UL) / 127kbps(DL) 159kbps (UL)	Rural: 35 km; Urban: 8 km	1000	20, 23	limited	3GPP Rel. 13/14(NB-IoT)	-
LoRa		0.433, 0.868 (EU)	0.125, 0.25, 0.5	50 kbps	Urban: 5 km; Rural: 35 km	1000	14–20	Yes	LoRaWAN 1.0/1.1	V2I
ETSI TETRA								Yes		V2X
LEO Satellite Com			5-400	1 Gbps	-	20-100	-	Yes	Starlink, IRIS², OneWeb	V2I, V2N

The following tables extracted from PODS4RAIL D11.2 give the requirements for V2X services: LTE-V2X and 5G NR V2X. These KPI are very important to take into account in the virtual coupling development and the safety analysis.

LTE V2X/ITS-G5

Table 2: Requirements to support V2X scenarios (LTE-V2X)

Comm mode	Payload (Bytes)		Tx Rate (Msg/sec)	Max E2E latency (ms)		Reliability (%)	Range (m)
	CAM	DENM					
V2V	50-300	1200	10	100*		**	***
V2I	50 - 300	1200	10	100		**	***
V2N	-	-	10	1000		**	***
V2P	-	-	10	100		**	***

* Maximum latency for pre-crash sensing : 20 ms
** high reliability without requiring application-layer message retransmissions.
*** capable of supporting a communication range sufficient to give the driver(s) ample response time (e.g. 4 seconds).
Support absolute velocity = 250 km/h
Relative velocity : 500 km/h

Reference

3GPP; Technical Specification Group Services and System Aspects; Study on LTE support for Vehicle to Everything (V2X) services (Release 14)
Or
LTE; Service requirements for V2X services (3GPP TS 22.185 version 19.0.0 Release 19)
Available: https://www.etsi.org/deliver/etsi_TS/122100_122199/122185/19.00.00_60/ts_122185v190000p.pdf

5G NR V2X

Requirements to support enhanced V2X (eV2X) scenarios (5G NR-V2X)
Categories of eV2X services:

- Vehicles Platooning
- Advanced Driving
- Extended Sensors

- Remote Driving

Table 3 : Summary of eV2X service requirements for the Highest degree of automation.

Category	Scenario	Payload (Bytes)	Tx Rate (Msg/sec)	Max E2E latency (ms)	Reliability (%)	Data Rate (Mbps)	Range (m)
Platooning	Cooperative driving	50-1200	30	10	99.99	-	80
	Reporting needed for platooning	50-1200	2	500	-	-	-
	Information sharing for platooning	-	-	20	-	50	180
Advanced Driving	Cooperative collision avoidance between UEs	2000	100	10	99.99	10	-
	Information sharing for automated driving between UEs	-	-	100	-	53	360
	Information sharing for automated driving between UE and RSU Emergency trajectory alignment between UEs	-	-	100	-	50	360
	Emergency trajectory alignment between UEs	2000	-	3	99.999	30	500
	Intersection safety information between an RSU and UEs	UL: 450	UL:50	-	-	UL: 0.25 DL: 50	-
	Cooperative lane change	12000	-	10	99.99	-	-
	Video sharing between a UE and a V2X application server	-	-	-	-	UL:10	-
Extended sensors	Sensor information sharing between UEs	-	-	3 - 50	95 - 99.999	10 - 1000	50 - 1000
	Video sharing between UEs	-	-	10	99.99	90 - 700	200 - 400

Remote driving	Information exchange between a UE and a V2X Application Server	-	-	5	99.999	UL : 25 DL : 1	-

Table 3: Performance requirements for Vehicles Platooning

Scenario	Degree	Payload (Bytes)	Tx Rate (Msg/sec)	Max E2E latency (ms)	Reliability (%)	Data rate (Mbps)	Range (m)
Cooperative driving	Lowest degree of automation	300 - 400	30	25	90	-	-
	Low degree of automation	6500	50	20	-	-	350
	Highest degree of automation	50-1200	30	10	99.99	-	80
	High degree of automation	-	-	20	-	65	180
Reporting needed for platooning	N/A	50-1200	2	500	-	-	-
Information sharing for platooning	Lower degree of automation	6000	50	20	-	-	350
	Higher degree of automation	-	-	20	-	50	180

Reference

3GPP TS 22.186 V19.0.0 (2025-10: 3GPP; Technical Specification Group Services and System Aspects; Enhancement of 3GPP support for V2X scenarios, (Release 19)
or
https://www.etsi.org/deliver/etsi_ts/122100_122199/122186/18.00.01_60/ts_122186v180001p.pdf

5. List of Submitted and Accepted Papers to International Conferences

1. Getachew Hagos GELETA, Marion BERBINEAU, Simon Collart-DUTILLEUL, Francesco FLAMMINI, Nicola (2025). Modelling and Analysis of Safety Metrics With Colored Petri Net for Train-to-Train Wireless Communication in the Case of Virtual Coupling. SmartRaCon Scientific Seminar No. (SRC7SS), Stuttgart, Germany, October 15-16, 2025. Accepted.

   This work proposes a Coloured Petri Net (CPN) model to assess the dependability of train–to–train (T2T) wireless communication for virtual train coupling using 5G NR V2X. It defines evaluation metrics, formulates equations, and analyses their safety implications for T2T communication. The framework enables studying network parameters, such as message loss rate, to support safety-critical wireless link design for virtual coupling.
2. Getachew Hagos GELETA, Marion BERBINEAU, Simon Collart-DUTILLEUL, Francesco FLAMMINI, Nicola (2025). CPN-Based Modelling to assess the dependability of Train-to-Train Wireless Communication for Virtual Coupling. 6th International Conference on Reliability, Safety, and Security of Railway Systems, RSSRail, Pisa, Italy, November 26-28, 2025. Accepted.

   This work is an extension of the previous work; it includes the simulation and evaluation of safety-related metrics of the wireless link, such as end-to-end delay, average inter-message gaps, percentage of safe gaps, Throughput, Message Delivery Ratio, and Percentage of safe delivery. These metrics are analysed under a variety of environmental conditions, particularly different message loss rates, to assess their impact on communication reliability and safety performance in virtual coupling scenarios.
3. Getachew Hagos GELETA, Marion BERBINEAU, Simon Collart-DUTILLEUL, Francesco FLAMMINI, Nicola (2025). A Colored Petri Net Model to assess dependability of Train-to-Train 5G NR V2X Communications for Virtual Coupling. The Transport Research Arena (TRA) 2026 - Call for Papers (Rail and Transport Innovation) Budapest, 18–21 May 2026. Accepted for full paper submission.

   As an extension of the second work, while the initial evaluation considers only a single retransmission in case of message loss, this extension explores scenarios with multiple retransmissions before triggering emergency braking, providing deeper insights into the trade-off between communication reliability and timely safety actions.

6. Conclusion

The PhD candidate is making very good progress in his doctoral research. He has successfully completed all educational obligations required by the Doctoral School (15 training modules, 92 hours / 106 credits) and actively participated in international academic activities, including the Summer International School on *"The European Railway System"* (2nd edition – 2025, Rome).

In terms of research dissemination, the candidate has already submitted three papers to international conferences, all of which have been accepted for publication, and he is currently preparing a journal paper for submission in the coming months. His work is therefore progressing fully in line with the research plan defined in previous meetings. During the CSI evaluation (Comité de Suivi Individuel de thèse – 2ème année), involving professors from the Doctoral School, follow-up committee members, and supervisors, it was confirmed that the candidate is on track to successfully complete his PhD within the expected timeframe.
Overall, the candidate has nearly fulfilled the requirements for the completion of the PhD, and his progress is highly satisfactory. Everything is advancing as planned, and the supervisory team remains confident in the timely and successful conclusion of his doctoral studies.

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8. Annexes

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CPN-Based Modeling of Train-to-Train Wireless Communication in the case of Virtual Coupling for Dependability analysis

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Abstract. The Virtual Coupling of Train Sets (VCTS) is widely regarded as a transformative concept for enhancing railway capacity and operational flexibility. However, VCTS implementation requires safe exchange of critical data both between trains and control centers and directly between train sets. The wireless communication technology supporting VCTS must therefore meet stringent performance and availability requirements. Furthermore, a dedicated safety layer at the application level is essential. Existing systems, such as Euroradio, which facilitate centralized train-to-ground communication, are currently not suitable for supporting the decentralized nature of VCTS. This paper introduces a modelling and simulation framework based on Colored Petri Nets (CPNs) to evaluate the dependability of Train-to-Train (T2T) wireless communication in a VCTS context, with a focus on 5G NR V2X technology. We begin by outlining the VCTS concept and its architectural components. Next, we discuss methodologies for dependability analysis and present our CPN-based model of T2T communication, including the performance metrics used. The simulation results show that as MLR increases, system reliability degrades significantly, underscoring the importance of robust error handling and quality-of-service mechanisms. Given the absence of specific requirements related to the wireless link for VCTS, our study references automotive benchmarks specifically, 3GPP V2X and 5G AA requirements as a practical basis for analysis. We can observe that under low MLR conditions, the system satisfies the performance requirements defined in these requirements.

Keywords: Virtual Coupling of Train Set (VCTS) · Train-to-Train (T2T)· Coloured Petri Nets (CPN)· Train Control and Monitoring System (TCMS)· Cooperative Awareness Message (CAM)· Dependability Analysis

1 Introduction

As railways evolve toward smarter and more automated systems, one groundbreaking concept gaining traction is Virtual Coupling of Train Sets (VCTS). Imagine trains moving in a synchronized way, travelling close together with precision, much like a convoy of autonomous cars. VCTS makes this possible by enabling trains to operate at shorter intervals without physical coupling in close coordination, significantly enhancing the capacity of existing railway lines [1] [2]. However, unlike traditional railway systems that rely on fixed blocks of track for safety, VCTS requires the adoption of the moving block system [3]. Think of it as a dynamic safety zone around each train, constantly updated based on real-time data exchanges. Trains share critical information like speed, location, and braking curves not only with each other but also with the rail infrastructure. These exchanges, known as Cooperative Awareness Messages (CAM), help each train to adjust its speed and position, ensuring they stay safely spaced while moving almost like a single unit. However, this high level of coordination brings a major challenge: communication availability and reliability. To function safely, VCTS depends on uninterrupted high-speed data shared between trains (Train-to-Train or T2T) and between trains and control centers (Train-to-Ground or T2G). But real-world railway environments with tunnels, cuttings, vegetation, interference, and high-speed movement can cause signal fluctuations and degradations that will affect radio availability and reliability, which threaten system dependability.

Several European research projects, such as X2RAIL3, R2DATO, and IAM4RAIL are actively exploring the VCTS concept and related communication technologies, including the Wireless Train Backbone [4]. Additionally, the manufacturer CAF has developed a practical LTE-based demonstrator as part of the CONNECTA project [5], showing the potential of this wireless technology in real-life railway operations. Whatever the chosen wireless system, a dedicated safety layer should be added in the application layer. Existing safety protocols, such as Euroradio, which facilitate centralized train-to-ground communication, are currently not suitable for supporting the decentralized nature of VCTS. In order to find the key parameters of this safety layer protocol, the dependability analysis of the wireless link should be done.

To assess the dependability of the wireless communication link for VCTS operation, a detailed model of the CAM exchanges is needed to analyze possible weaknesses and support the development of effective mitigation strategies. This paper presents a preliminary model for T2T communications using 5G side link (V2X) technology. The model is developed using Colored Petri Nets IDE (CPN IDE), a tool for simulating and analyzing complex systems. The rest of this paper is organized as follows: First, Section 2 introduces the VCTS and its overall architecture. Section 3 illustrates how trains function within a virtual coupling setup, exploring the underlying processes. Next, Section 4 discusses the hurdles of wireless communication in rail environments. Section 5 explains the European safety standards, and Section 6 presents different methods used for dependability analysis. Section 7 reviews current research and related technologies. Section 8 explains the use of Colored Petri Nets for modelling T2T communication.

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Section 9 discusses the equations and definitions for the current considered metrics. Section 10 analyses the simulation results, and Section 11 summarizes the conclusions and future works.

2 The Virtual Coupling Train Set and Architecture

VCTS system combines onboard sensors, communication modules, and control systems to achieve accurate synchronization and maintain operational safety [6]. By using advanced technologies, VCTS enables multiple trains to function as a single coordinated unit while ensuring a safe separation is maintained between them. An overview of the VCTS system architecture is illustrated in Figure 1.

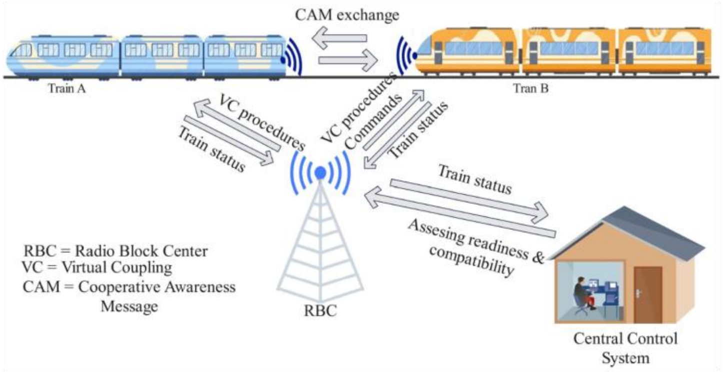

Fig. 1. Virtual Coupling Train Architecture

It includes three main elements: Onboard subsystems, a communication network, centralized control system. The onboard subsystems include the train control and monitoring system (TCMS) serving as the central intelligence of each train. The TCMS manages essential functions such as speed regulation, braking, and door operations. Within the VCTS framework, it is adapted to support inter-train communication and coordination.

- Communication Unit: this component enables wireless data exchange between trains, transmitting critical information such as speed, location, and braking instructions.
- Positioning System: technologies like the Global Navigation Satellite System (GNSS) are employed to determine each train's precise location within the virtual convoy.
- Sensors: devices including accelerometers, odometers, and wheel speed sensors collect real-time data on train dynamics to support safe and accurate operation.

- Communication Network: A wireless communication infrastructure enables continuous data exchange between trains and with the ground-based systems, forming the backbone of the VCTS.
- Centralised Control System: In some configurations, a centralized control unit oversees the entire VCTS operation. This system gathers data from all participating trains and can:
  - Optimize train routing and scheduling.
  - Provide redundant communication paths during connectivity disruptions.
  - Put into action further safety measures in emergency cases

3 Operation of Trains within a Virtual Coupling Framework

Figure 2 depicts the message exchange sequence involved in the VCTS between Train A and Train B. The process is initiated by the central control system (CCS), which dispatches virtual coupling procedures to evaluate whether the two trains are ready and compatible for coupling. As part of this assessment, both Train A (the lead train) and Train B (the following train) transmit their operational data to the CCS. Upon verifying these parameters, the CCS instructs Train B to begin the virtual coupling. Train B then aligns its movement with Train A by continuously adjusting its parameters through real-time communication. This initial stage is critical to confirm that both trains are properly synchronized and that the communication link is stable.

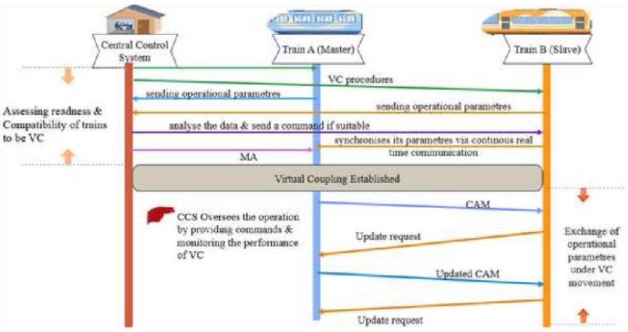

Fig. 2. Operation of trains under Virtual Coupling

After the virtual coupling is successfully established, Train A takes on the role of the master train MT), while Train B operates as the slave train (ST) within the coupled formation. The CCS continues to supervise the process, issuing high-level commands and monitoring the overall performance of the virtual link. Train A sends real-time updates, including its speed, position, and control instructions to Train B through the wireless communication channel. Using this data, Train B

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continuously adjusts its speed and following distance to stay precisely aligned with Train A. During this phase, the system carefully monitors the end-to-end delay of messages exchanged between the trains. If a message does not reach its destination or becomes corrupted, a retransmission protocol is activated, prompting the sender to resend the message until the receiver confirms successful delivery with an acknowledgement. In order to respect safety rules, the message should be received within a given interval to avoid emergency braking.

4 Wireless Communications in the rail domain and associated challenges

Numerous wireless technologies have been explored for Vehicle-to-Vehicle (V2V) communication in platooning scenarios [7]. For Train-to-Train (T2T) communication specifically, several options have been assessed, including LTE and LTE-V2X [8], millimetre-wave bands for high-speed V2V links [9], and ITS-G5 operating in the 5.8 GHz band [10]. All of these technologies have their own pros and cons in terms of latency, bandwidth, coverage, and dependability as summarized in [11]. For example, LTE-V2X provides good coverage but may encounter latency issues in congested areas, while millimetre-wave technologies offer high data rates but are more vulnerable to environmental effects.

In this study, we consider the 5G sidelink standard (NR-V2X), which is currently under development. NR-V2X is aligned with 5G New Radio (5G NR) the foundation of Future Railway Mobile Communication Systems (FRMCS) [12]. The performance of NR-V2X for T2T communication is influenced by various factors, including the distance between trains, potential masking effects, and possible interferences from surrounding wireless systems and nearby trains. The performance of wireless communication is measured considering key performance indicators (KPI) such as packet loss rate, end-to-end delay, and error-free throughput at the application level. These indicators can critically affect the transmission of time-sensitive information, such as braking commands or speed adjustments. Consequently, the safety level will also be affected. The overall performance of the 5G V2X sidelink technology in the railway environment will impact the safety layer design. Euroradio protocol is a well-known safety layer implemented for ERTMS/ETCS. It concerns train-to-ground data exchanges. A specific safety layer should be designed for VCTS.

5 Safety Aspects and Norms

The risk analysis phase plays a critical role in identifying and assessing potential hazards that may arise during a system's operational phase. In the railway industry, this process typically adheres to the EN 50126 and Common Safety Method for Risk Evaluation and Assessment (CSM-RA) standards [50126, 50126-2, implementing-regulation]. EN 50126 outlines the overall safety management framework, while CSM-RA provides specific regulatory guidance for implementation.

When wireless communication is introduced to enhance an existing railway system, the original system can serve as a baseline reference, as noted in [13]. The focus then shifts to evaluating new hazards introduced by the wireless technology, weighing them against the safety benefits the new system brings. For communication-specific safety in the railway domain, standards like EN 50159 are essential. This standard offers a structured approach for analyzing and demonstrating the safety of communication systems used in railway operations. A distinctive feature of railway applications is that safety is inherently managed at the application level. Common message-related faults in such systems include: repetition, deletion, insertion, sequencing, corruption, and masquerade. These types of errors must be rigorously analyzed and mitigated to ensure the safety and reliability of railway communication systems.

The safety of a system is evaluated with the safety integrity level (SIL) defined by the International Electrotechnical Commission's (IEC) standard IEC 61508, which concerns other domains than Railway. As mentioned previously, EN 50126, EN 50128, and EN 50129 standards are considered to meet railway-specific requirements. For continuous operation, SIL-1 requires at most 10^{-5} probability of failure per hour (PFH). SIL-2, 3, and 4 require at most 10^{-6}, 10^{-7}, and 10^{-8} PFH, respectively. As far as we know, the relation between the safety requirements for the wireless link and the control-command system does not exist. The aim of our work is to provide a methodology to establish this relationship in the case of T2T communications.

6 Methodologies to analyze dependability analysis

The analysis of dependability of railway applications employs a variety of methodologies to assess key factors such as reliability, availability, maintainability, and safety (RAMS). This section highlights several prominent approaches and related research.

Failure Mode Effects and Criticality Analysis (FMECA) [14] is a structured methodology used for wireless communication in VCTS to find critical failure points in the communication links and how these failures could affect train operations. Fault Tree Analysis (FTA) [15] visually represents the different pathways leading to system failures. By identifying the root causes of failures, FTA helps to understand how communication breakdowns can influence train safety and operational efficiency. Markov models [16] are used to model the probabilistic behaviour of wireless communication systems, capturing the dynamic nature of wireless links. Petri Nets ([17],[18], [19], [20], [21], [22]) are a versatile modelling tool that can represent complex interactions and concurrent processes within communication systems. Petri Nets enable the analysis of performance metrics such as packet loss, system availability, and end-to-end delays, making them especially suitable for studying railway communication systems. Simulation techniques [23], including discrete-event simulations and system dynamics, are widely used to evaluate the performance of wireless communication systems within railway environments. Reliability Block Diagrams (RBD) [15] are useful for assessing the reliability of wireless communication systems, as they focus on the reliability of individual components and their combined effect on overall system performance. Combining multiple methodologies [24], such as combining FMEA, FTA, and simulation techniques, offers a more comprehensive approach to dependability analysis. These combined methods provide a deeper understanding of how different failure modes interact and how they influence the system's performance.

For our analysis of the dependability of train-to-train wireless communication for virtual coupling, we chose the Colored Petri Net (CPN) approach. CPN is particularly effective at modelling complex systems with multiple concurrent processes and discrete events. It allows us to represent interactions within the communication system clearly and capture the dynamic behaviour of wireless protocols. The use of colours in CPN aids in differentiating between various data types and states, making it easier to analyze how different scenarios impact system performance. This capability is advantageous for modelling the intricate dependencies and timing constraints in railway communication systems. Moreover, the CPN approach offers powerful analytical tools that facilitate performance evaluation and dependability analysis [25]. We can assess critical performance metrics such as end-to-end delay, message loss, and system reliability through simulations of different operational conditions.

7 Existing Works

Recent studies have applied CPN (Coloured Petri Nets) to model and analyze various components of railway communication systems. In [17], the authors used CPN to validate and verify a train-to-train distance measurement system. The analysis of virtual coupling control parameters in the [19] working CPN, focusing on optimization of system performance using formal modelling techniques. Likewise, [20] used CPN to model and enhance a high-speed flying train communication system. Further contributing to the field, [21] performed a reliability analysis of a wireless communication system in VCTS. Furthermore, [22] modelled typical train virtual coupling scenarios using CPN. These studies collectively demonstrate the increasing relevance of CPN in railway applications, offering a robust framework for evaluating system safety, performance, and reliability in complex operational scenarios.

8 The Colored Petri Net (CPN) Model

This section introduces a Colored Petri Net (CPN) model for simulating the exchange of CAMs between a MT and a ST within a virtual coupling context. The model is specifically designed to capture the impact of varying T2T communication conditions, considering 5G NR V2X sidelink. By adjusting the simulation to reflect different message loss rates based on various railway environments, the model allows detailed performance evaluation. It excludes other train control operations and assumes that only one retransmission is permitted.

This retransmission must occur within a predefined time window that ensures message delivery without error, before triggering emergency braking. This time constraint is also configurable within the simulation. So, retransmission of the CAM occurs when the MT does not receive an acknowledgement from the ST within the specified CAM period, 200 ms or due to the request of the ST in case of message loss. Each transmitted CAM data is associated with a particular sequence number, and this is shown in the model in the first place (P1, MT data ready) labelled or named as NUMxDATA. So, these sequence numbers can be used for different purposes during the exchange of CAM between the MT and ST. For instance, for confirmation, duplication, lost, retransmission, and updated CAM requests by the ST. The ST sends a numeric value of 2 for the reception confirmation of the first CAM and requests the next updated CAM (second CAM). Therefore, the entire CAM exchange or transmission protocol between the MT and ST continued in this way. The graphical CPN model illustrated in Figure 3 represents the flow of tokens and interactions between transitions and places, representing the sequence of events in CAM exchanges.

The MT initiates communication by sending a message and awaits responses, while the ST processes incoming data and replies with acknowledgements or CAM requests. The model integrates mechanisms to handle message loss (transition T4) and simulates realistic network delays through functions like @+Delay () to maintain safe train operations. And the communication process is modelled in the following steps:

1. Initiation and transmission via the network (P1 → P2 → P3 → P4): The master train generates the message, begins transmission, sends it across the network, and completes delivery.
2. Reception by Slave Train (P5 → P6 → P7): The slave train receives, processes, and confirms the message.
3. Response from Slave Train (P8 → P9): The slave sends back either an acknowledgement or a new CAM request.
4. Master Train Verification (P10 → P11): The master receives and validates the response, deciding whether further action (like retransmission or update) is needed. The arc expressions defined how tokens are created, consumed, and modified as they flow through the network. For instance,
   - 1‘a: creates one token with the value of variable a.
   - (a, t): A token consisting of a tuple of the CAM's data (a) and the timestamp (t).
   - if a = b then b+1 else b, if success () then 1‘ (a, t): A conditional expression for token manipulation.

The places represent the states of the communication system. Thus, each place (P1 - P12) describes specific stages in the communication process and is represented as a circle in the Petri Net. For example, (P1, MT data ready) represents that the master train has prepared a CAM data packet to transmit, (P3, netk tx processing) represents that the CAM data packet is travelling through the network, and (P5, ntk pack rx ST) represents that the slave train has received the CAM data packet. The transitions represent the events or actions that change the

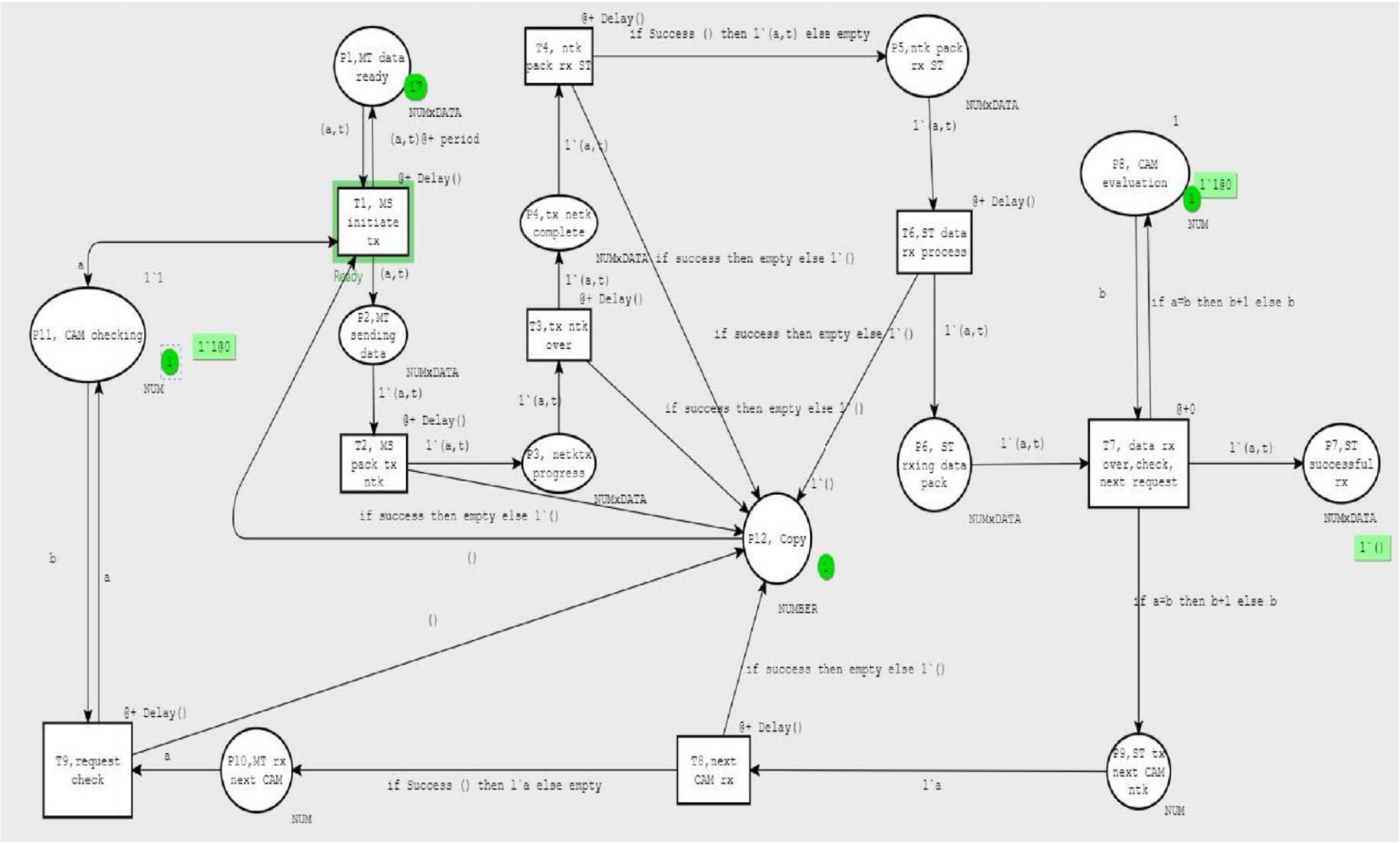

Fig. 3. Train-to-Train Data Exchange CPN Model

state of the communication system from one state to another and are shown in rectangles in the Petri Net. For example, (T1, MS initiate tx) represents that the master train initiates CAM data transmission, (T3, tx ntk over) represents that the CAM data packet transmission to the network is completed, and (T7, data rx over, check, next request) represents that the reception of CAM data is completed, checked, and generates an updated request or confirmation by the slave train. The green symbols of the places define the data types for tokens. Thus, the colour sets represent the CAM data and associated information, such as sequence number, data, and timestamp. It is conveniently labelled in each place for the readability of a CPN model, such as NUM to represent a token containing only numbers and NUMxDATA to represent a token that contains a sequence number and data. And the green rectangular shape in the first transition (T1, MS initiate tx) shows that the readiness of the transition for firing the tokens to move from the first place (P1, MT data ready), to the next place (P2, MT sending data).

To translate various environmental conditions, network congestion, software and or hardware issues, and so on, in a first approximation, we simulated different message loss rate values ranging from zero (0) to 0.97 by triggering the transition T4, under varying conditions. In future works, this message loss rate could be related to realistic values in specific scenarios, considering the 5G NR V2X link. In addition to the different message loss rate values, the model operates under specific assumptions, including a transition delay up to 5 ms and a CAM period of 200 ms as referenced in previous studies [12] [18] [26]. The CAM period is the time interval during which the master train transmits its updated CAM to the slave train. These parameters are critical for accurately reflecting the dynamics of communication in real-world scenarios. They can be modified. The transition delay is the time it takes for each transition to complete after it becomes enabled in the CPN model. The Max Delay is equal to 500 ms, which represents the maximum allowable delay to receive a CAM with no error before emergency braking. The Max Gap is the maximum time allowed between received messages before emergency braking (1000 ms). Table 1 summarizes the simulation parameters. These parameters can be varied in order to reflect different scenarios. Furthermore, due to the absence of requirements for wireless communication with VCTS at present, our study references requirements found for automotive applications, specifically for the Third Generation Partnership Project Vehicle-to-Everything (3GPP V2X) [26], [27] and Fifth Generation Automotive Association (5G AA) [12] standards. Their relevance values are summarized in Table 2.

Table 1. The input parameters

Table 2. 5G NR V2V Platooning benchmark requirement values of 3GPP and 5G AA

Parameters	Values
Message loss rate, MLR	0.0 to 0.97
CAM period	200 ms
Transition delay	0 to 5 ms
Maximum delay	500 ms
Maximum gap	1000 ms

Description	Values
Inter-packet arrival time	50 to 200 ms
CAM period with radio reliability 95%, 1 retransmission	100 to 200 ms
Latency (varied scenarios)	10 to 500 ms
Cooperative awareness for 90 - 95% radio reliability	100 ms to 1 s
Data rate per vehicle for Cooperative awareness	5 - 96 kbps
Cooperative sensing for > 95% radio reliability	3 ms to 1 s
Cooperative maneuver for > 99% radio reliability	<3 ms to 100 ms

9 Simulation Metrics and Parameter Definitions

This section outlines the definitions of the metrics used to evaluate the CPN model. It includes their corresponding mathematical formulations and highlights their relevance to safety in virtual coupling and train-to-train communication systems.

End-to-End Delay – refers to the total time taken for a message to travel from the MT (T1) to the ST (T7). In the context of wireless communication, it represents system latency, the time required for data to reach its destination. This metric is especially vital in real-time applications, where on-time data delivery is necessary to ensure the information remains actionable. Minimizing delay is crucial for time-sensitive operations. Its mathematical expression for single and multiple messages is summarized in equations 1 and 2, respectively.

$$\text{End-to-End Delay} = t_{\text{receive}} - t_{\text{sent}} = T7_{\text{timestamp}} - T1_{\text{timestamp}} \tag{1}$$

where: $t_{\text{receive}} = T7_{\text{timestamp}}$ is the received time of the message by the slave train and $t_{\text{sent}} = T1_{\text{timestamp}}$ is the time of the message sent by the master train.

$$\text{Average End-to-End Delay} = \frac{(\sum(T7_{\text{timestamp}} - T1_{\text{timestamp}}))}{(\text{Number of T7 messages})} \tag{2}$$

Thus, the average end-to-end delay becomes the mean of these delays across all messages.

Average Inter-Message Gap - states the mean interval between successive messages received by the slave train. Unlike metrics that measure the transmission time of individual messages, this metric focuses on the frequency of message reception. It indicates how trains regularly exchange information such as position, speed, and braking curves, which is essential to maintain real-time situational awareness. A shorter gap implies more frequent updates, which is especially important in high-risk contexts such as high-speed operations or dense traffic. In contrast, a longer gap may be acceptable in low-risk scenarios but can lead to outdated data during emergencies, potentially increasing the risk of accidents or delays. This metric is mathematically defined based on the timestamps of messages received by the slave train, known as T7 events. The gap is calculated as the time difference between two consecutive T7 timestamps.

For the $i_{(th)}$ gap:

$$\text{gap}_i = T7_{(i+1)} - T7_i \qquad for\ i = 1, 2, 3, \cdots, n-1 \tag{3}$$

where: T7 is a sorted list of timestamps when messages are received (T71, T72, T73...) and n is the total number(#) of T7 events.

Therefore, the Average Inter-Message Gap stands for the average of all these gaps:

$$\text{Average Inter Message Gaps} = \sum_{(i=1)}^{(n-1)} \frac{T7_{(i+1)} - T7_i}{(n-1)} \tag{4}$$

Percentage of Safe Gaps – quantifies the portion of message intervals that fall within an acceptable time threshold, known as the Maximum Gap (e.g., 1000 ms). So, it effectively quantifies how often the system can maintain the communication intervals required for safe operation under varying loss conditions. A gap is considered safe if the time between two consecutive messages does not exceed this threshold, ensuring that communication remains timely and does not jeopardize safety or operational performance. This metric is crucial because even if the average inter-message gap is low, occasional excessive delays could still obstruct the delivery of critical updates. A higher percentage of safe gaps indicates more consistent and reliable communication, which is essential for preventing safety-related issues. To evaluate this, each gap is classified as safe (1) if it is less than or equal to the maximum gap, or unsafe (0) if it exceeds it.

$$\text{safe gap}_i = \begin{cases} 1, & \text{if gap}_i \leq \text{Max Gap} \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where: Max Gap is the maximum time allowed between messages to be safe (1000 ms). The percentage of safe gaps is the proportion of safe gaps multiplied by 100:

$$\text{Percentage of safe Gaps} = \sum_{(i=1)}^{(n-1)} \frac{\text{safe gap}_i}{n-1} \times 100 = \frac{(\#\text{ of gaps} \leq \text{Max Gap})}{n-1} \times 100 \tag{6}$$

where n is the total count of messages received. Collectively, these metrics evaluate both the regularity and reliability of communication, ensuring that trains consistently receive the timely updates necessary for safe and efficient operation.

Throughput – denotes the number of error-free messages successfully delivered during the entire simulation period, measured in messages per second. This metric reflects how efficiently messages are transmitted from the master train to the slave train over time. High throughput indicates the system's ability to handle a large volume of message exchanges quickly, which is essential for real-time functions such as train coordination. Throughput can be represented as messages per second using Equation 7 or, when considering message size, as bits per second using Equation 8.

$$\text{Throughput} = \frac{\text{number of T7 events}}{\text{Total simulation time}} \tag{7}$$

where: Total simulation time = max (T7)-min(T1)

$$\text{Throughput} = \frac{\text{number of T7 events} \times \text{message size}}{\text{Total simulation time}} \tag{8}$$

Message Delivery Ratio (MDR) – represents the ratio of messages that the slave train successfully receives out of the total messages sent. This metric reflects the reliability of the communication system in ensuring message delivery, which is vital for safe train operation. A high MDR signifies that nearly all messages are reaching their destination, supporting effective and safe coordination. In contrast, a low MDR suggests frequent message loss, which can compromise safety and lead to potential delays or accidents.

$$MDR = \frac{\text{number of successfully delivered messages}}{\text{Total number of messages sent}} = \frac{\#\text{ of T7 events}}{\#\text{ of T1 events}} \tag{9}$$

MDR can also be written in terms of Message Loss Rate (MLR) as: MLR is the proportion of messages that are lost (nor delivered at the slave train) out of all messages sent.

$$MLR = \frac{\text{Number of lost messages}}{\text{Total number of messages sent}} \tag{10}$$

where:

$$MLR = \frac{\text{Total number of sent messages - Number of delivered messages}}{\text{Total number of messages sent}}$$

$$MDR = 1 - \frac{\text{number of delivered messages}}{\text{Total number of messages sent}} = 1 - MLR \tag{11}$$

Percentage of Safe Delivery – indicates the proportion of messages that reach the slave train within the maximum permissible delay (Max Delay: 500 ms), making them timely and usable for real-time decision-making. A message is considered safely delivered if it arrives quickly enough to allow timely action, such as braking to prevent a collision or adjusting speed. Timeliness is crucial; even successfully delivered messages are ineffective if they arrive too late. For instance, an emergency braking alert must be received almost immediately. A high percentage of safe deliveries demonstrates that the communication system is not only dependable but also responsive enough to support critical safety functions in real time.

$$\begin{aligned} \%\text{age of Safe Delivery} &= \frac{\#\text{ of messages delivered within time limit}}{\#\text{ of successfully delivered messages}} \times 100 \\ &= \frac{\#\text{ of T7 events where } (T7 - T1) \leq \text{Max Delay}}{\#\text{ of T7 events}} \times 100 \end{aligned} \tag{12}$$

Combined, the Message Delivery Ratio and Percentage of Safe Delivery provide a comprehensive measure of both the reliability and timeliness of train communication, key factors in preventing accidents and ensuring smooth, efficient operations.

10 Results and Discussion

The simulation graph in Figure 4 illustrates the relationship between end-to-end delay, average Inter-message gap versus message loss rate in the context of T2T communication for CAM exchange. The graphs show that the end-to-end delay and average inter-message gap remain relatively low, stable and consistent below 100ms for MLR values below approximately 0.3 and 0.2, respectively. And then, they slightly increase with increasing message loss rate up to 0.6 MLR value, indicating minimal retransmission overhead. However, as the MLR increases beyond 0.6, the delay and gap increase rapidly due to the retransmission required to ensure successful message delivery. This exponential growth indicates that the communication reliability and continuity significantly degrade or deteriorate. In T2T communication scenarios, where CAMs must be delivered in real-time to support situational awareness and safety applications, such delays and high message gaps can severely impair system performance. Therefore, maintaining a low MLR is essential. Below the MLR value of 0.2, the end-to-end delay is below 100 ms, and the inter-message gap becomes lower than the periodicity of 200 ms, even if there is one retransmission of the message in case of loss.

Moreover, Figure 4 also shows the evolution of the end-to-end delay and average inter-message gap versus MLR. Our scenario considers messages sent sequentially, ensuring each is received before sending the next message to maintain strict timing and avoid overlaps or missed messages. This concept would naturally lead to the end-to-end delay and average inter-message gap being almost similar. The results are compliant with 5G NR V2X requirements in the vehicular context (Table 2).

Figure 5 illustrates how the percentage of safe gaps varies with the MLR. As shown in the graph, the percentage of safe gaps is nearly 100% at low message loss rates (MLR < 0.4), indicating highly reliable and timely message delivery. However, as the MLR increases beyond 0.4, the percentage of safe gaps begins to decline suddenly and approaches 0% as the MLR near to 1. This behaviour reflects the diminishing capacity of the system to maintain communication intervals that fall within the acceptable safety margins as reliability degrades. The results emphasize that the proposed communication model performs more than ($>$) 95% reliably at low to moderate MLR levels. This also achieves the requirements we proposed in Table 2 in the case of vehicular applications. However, at higher MLRs, the decline in safe gaps signifies openings in safety thresholds, emphasizing the critical need to limit message loss in real deployments through robust error correction, redundancy, or prioritization mechanisms.

Figure 6 shows the impact of message loss rate on the system throughput. The graph shows a step decline in throughput as the MLR increases. At very low

MLRs (close to 0), the system achieves its maximum throughput, approximately 55 msg/s, indicating highly efficient and reliable data transmission. However, as the MLR increases beyond nearly 0.1, throughput rapidly degrades, falling below 10 msg/s by the time MLR reaches 0.2. Beyond this point, the throughput goes near zero, suggesting that the network becomes practically unusable for real-time communication. This behaviour emphasises the critical dependence of throughput on network reliability because throughput serves as a direct indicator of how effectively the communication channel supports the intended message flow. When throughput drops significantly, even if some messages are delivered with low delay, the volume and consistency of message delivery are inadequate, which is unacceptable for safety-critical applications. This result aligns with the benchmarks stated in Table 2, which targets very high reliability ($> 95\%$).

Figure 7 presents the relationship between message delivery ratio (MDR) and message loss rate. As expected, the graph shows a linear and inverse proportional relationship. When the message loss rate is 0, the MDR is 1 (in other words, 100% of the messages are delivered successfully). As MLR increases, MDR declines, reaching nearly 0 when MLR approaches 1. This behaviour shows that as more messages are lost, fewer are delivered successfully, which is a direct and spontaneous relationship. From the graph, it's clear that the system performs well only when MLR is minimal (under ≈ 0.1) or with reliability $> 95\%$. Beyond this point, MDR degradation becomes critical, indicating a loss of reliability. This analysis aligns with the trends observed in the above Figure 4, 5, and 6, where delay, message gaps, safe operation, and throughput all deteriorated as MLR increased. We can observe that, below the MLR value 0.1, the results meet the requirements stated in Table 2 demanded by 3GPP V2X and 5G AA standards for real-time vehicular control systems and cooperative awareness.

Figure 8 shows the relationship between MLR and the Percentage of Safe Gaps, which indicates how effectively messages are delivered without compromising system safety. As illustrated in Figure 8, the percentage of safe delivery remains consistently high (nearly 100%) for lower MLR values (approximately MLR $<$ 0.3). This suggests that at lower message loss rates, the communication ensures almost all messages are delivered within acceptable safety margins if we refer to the requirements stated in Table 2. In the reverse case, as the MLR increases beyond approximately 0.3, the percentage of safe delivery begins to decline more noticeably. The degradation becomes steep when MLR exceeds 0.5, and by the time MLR approaches 1.0, the percentage of safe delivery rapidly declines to 0%. This steep decline illustrates the system's inability to maintain reliable communication under high message loss rates, harshly undermining operational safety.

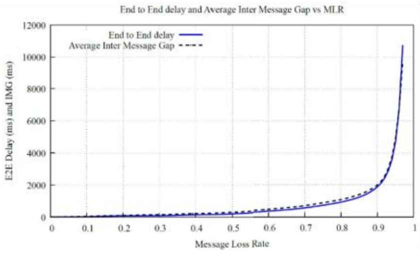

Fig. 4. End-to-End Delay, Average Inter-message gap versus Message Loss Rate

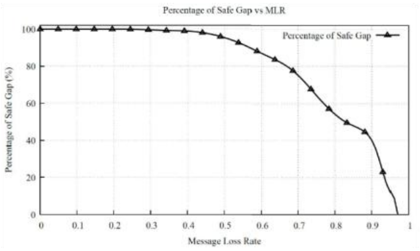

Fig. 5. Percentage of Safe Gap versus Message Loss Rate

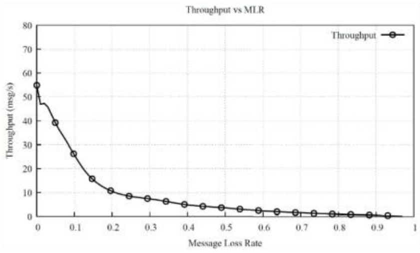

Fig. 6. Throughput versus Message Loss Rate

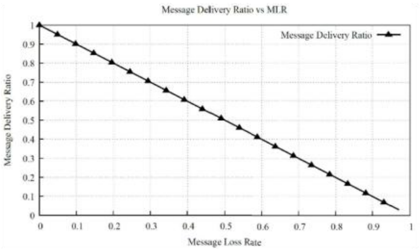

Fig. 7. Message Delivery Ratio versus Message Loss Rate

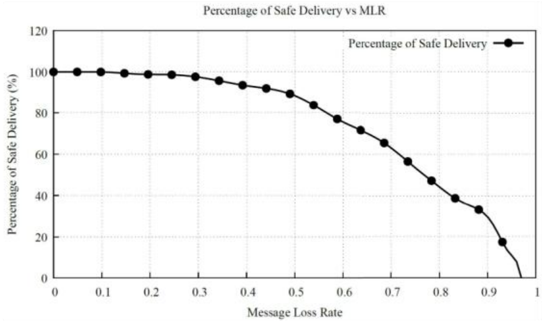

Fig. 8. Percentage of Safe Delivery versus Message Loss Rate

11 Conclusion

This study presented a simulation model of the CAM exchanges for T2T communications in the VCTS process. This model is based on the colored CPN IDE tool and considers only one retransmission. This model is a tool to evaluate the dependability of Train-to-Train (T2T) wireless communication based on 5G NR-V2X. We focus in particular on the impact of message loss rate (MLR) on key safety-related performance metrics such as end-to-end delay, inter-message gaps (intervals), throughput, message delivery, and safe communication reliability. These first simulation results were analyzed to quantify how increasing MLR affects the chosen metrics. As expected, the increase of MLR affects the metrics and shows deterioration of the CAM exchanges. These results show that it will be important to increase the number of retransmissions or to add other mechanisms, such as error corrections and prioritization mechanisms. The paper shows that the proposed CPN-based model allows the analysis of the CAM exchanges during the VCTS process. We observed that the results are compliant with 5G NR V2X requirements in the case of V2V communications. In future work, the model can be extended to account for multiple retransmissions within a bounded time interval called an acceptable time interval of messages, ensuring that safety-critical messages are delivered reliably before triggering the emergency braking. Additionally, varying the transmission periodicity between trains will allow a more realistic evaluation of the communication performance under different operational scenarios. This will be vital for defining potential requirements adapted to the VCTS operation and the railway environments, such as the maximum allowable number of retransmissions per periodicity interval, thereby supporting both safety and efficiency in VCTS implementations.

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CPN-Based Modelling to assess dependability of Trainto-Train Wireless Communication for Virtual Coupling

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Abstract

This work presents a Colored Petri Net (CPN)-based model and simulation framework to evaluate the dependability of Train-to-Train (T2T) wireless communication in the context of virtual coupling of trains using 5G NR V2X technology.
This work includes definitions of each metric considered for evaluation, presents the corresponding mathematical equations, and discusses the impacts of these metrics for the safety aspects of virtual coupling in trains or train-to-train communications. The model provides a foundational tool for analyzing the impact of network parameters such as Message loss rate, on the communication performance and safety metrics. It aims to facilitate the design of a safety process for the wireless link essential for virtual coupling of trains.

Keywords: Virtual Coupling of Train Set (VCTS), Train-to-Train (T2T), Coloured Petri Nets (CPN), Train Control and Monitoring System (TCMS), Cooperative Awareness Message (CAM), Dependability Analysis

Introduction

As the railway industry advances towards more efficient and automated systems, Virtual Coupling of Train Set (VCTS) has emerged as a promising solution to increase the capacity of the railway network by allowing a smaller distance between trains [1], [2], [3]. Similar to the automotive domain, VCTS, or platooning, enables multiple trains to operate closely together in a coordinated manner. The coupling of two train sets will be achievable only through the deployment of the moving block concept [3], which allows trains to run close together and exchange regular mission-critical data such as speed, position, and braking curves among train sets, as well as between the trains to be coupled and the infrastructure. These messages are referred to as Cooperative Awareness Messages (CAM). Based on the exchanged CAM, trains adjust their speed to maintain a safe distance between coupled trains. The implementation of VCTS presents several challenges. In particular, the communication system must ensure seamless connectivity between trains (Train-to-Train, T2T) and between trains and ground stations (Train-to-Ground, T2G) to facilitate real-time data exchanges and coordination. However, variability in wireless signal quality due to environmental factors such as interference, tunnels, and mobility poses significant risks to communication reliability. Developments on VTCS have recently been performed in European projects such as X2RAIL3, R2DATO, and IAM4RAIL, alongside the Wireless Train Backbone solution [4], [5], [6]. The safe operation of VCTS will depend on the safety level of the wireless message exchanges. This necessitates an analysis of the dependability of the considered wireless communication link. Thus, developing a comprehensive model for dependability analysis is essential to identify potential vulnerabilities and propose effective mitigation strategies.

This paper aims to propose a preliminary model for T2T communications based on 5G side link (V2X) using the CPN (Colored Petri Net) Tool. The rest of the paper is organized as follows: First, Section 2 introduces the VCTS and architecture. Section 3 discusses the operation of trains within a virtual coupling framework, detailing the processes and interactions involved. Next, Section 4 addresses wireless communications in the rail domain and associated challenges, highlighting the key technological hurdles faced in implementing reliable communication systems. Section 5 examines safety aspects and norms, Section 6 explores methodologies to analyze dependability, presenting various analytical techniques used to ensure system reliability. Section 7 reviews existing works, summarizing relevant research and developments in the field. Section 8 introduces Colored Petri Nets, discussing the details of modeling and analyzing the model of T2T data exchanges using Colored Petri Nets. Section details theoretical explanations, definitions, and mathematical equations of the metrics considered. Finally, we conclude and present future works.

The Virtual Coupling Train Set and architecture

VCTS utilizes wireless communication systems to maintain a virtual link between two or more trains, allowing them to operate closely together while remaining physically independent. It integrates onboard sensors, communication modules, and control systems, ensuring precise coordination and safety [4]. The VCTS uses various technologies to enable trains to operate as a single, virtual unit while maintaining a safe distance between them. Below is an explanation of the main components involved in its architecture:

I. Onboard Subsystems:
  - Train Control and Monitoring System (TCMS): This is the brain of the individual train, managing functionalities like speed control, braking, and door operations. In a VCTS, the TCMS is modified to handle communication and coordination with other trains in the virtual set.
  - Communication Unit: This unit facilitates communication between trains using a wireless technology to transmit and receive data related to speed, position, and braking commands.
  - Positioning System: A Global Navigation Satellite System (GNSS) or other positioning technology to provide accurate location for each train within the convoy.
  - Sensors like accelerometers, odometers, and wheel speed sensors gather real-time data on train movement.

II. Communication Network:
  - The wireless network enables communication between trains and with the ground.

III. Centralized Control System:

In some VCTS architectures, a central control system might be implemented to monitor and manage the overall operation. This system would receive data from all trains in the VCTS and could potentially:

  - Optimize train scheduling and routing.
  - Provide backup communication channels in case of network issues.

- Implement additional safety measures.

The architecture generally considered is shown in Figure 1.

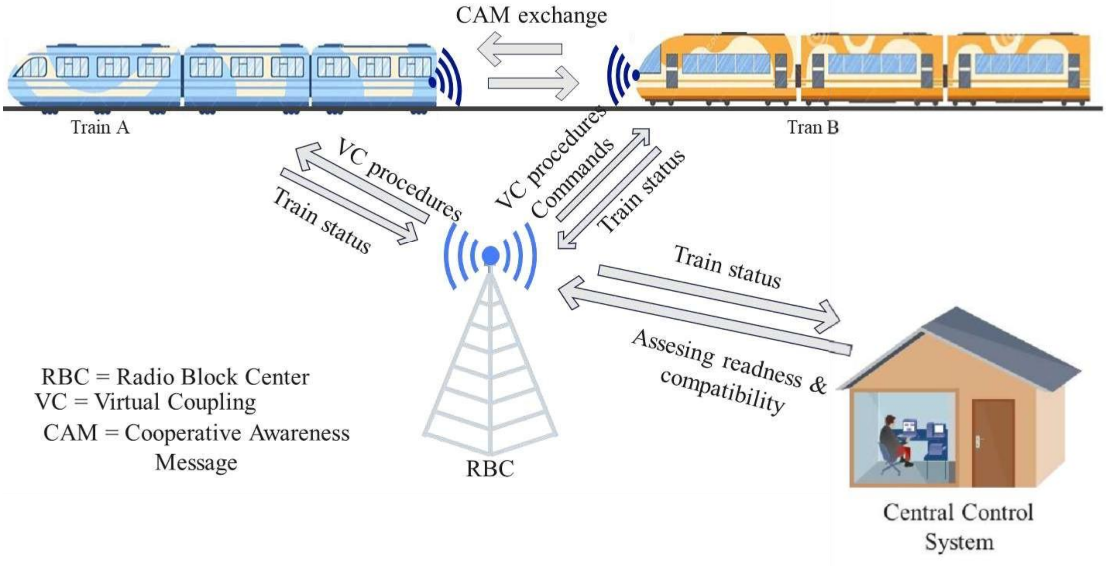

Figure 1: Virtual Coupling Train Architecture

Operation of Trains within a Virtual Coupling Framework

The general VCTS concept and functional layers are described for example in [3]. Figure 2 illustrates the exchanges of messages during the VCTS process between Train A and Train B. It begins with the central control system (CCS) by sending the virtual coupling producers to assess the readiness and compatibility of the trains to be virtually coupled. This involves Train A, the lead train and Train B, the following train, sending their operational parameters (speed, position, and acceleration) to the CCS. Then, the CCS sends a command to Train B, the following train, to initiate the virtual coupling process. Train B then synchronizes its parameters with Train A through continuous real-time communication. This initial phase ensures that both trains are in optimal condition for coupling, and it verifies the robustness of the communication link by checking parameters like signal strength, data integrity, and end-to-end transmission delay.

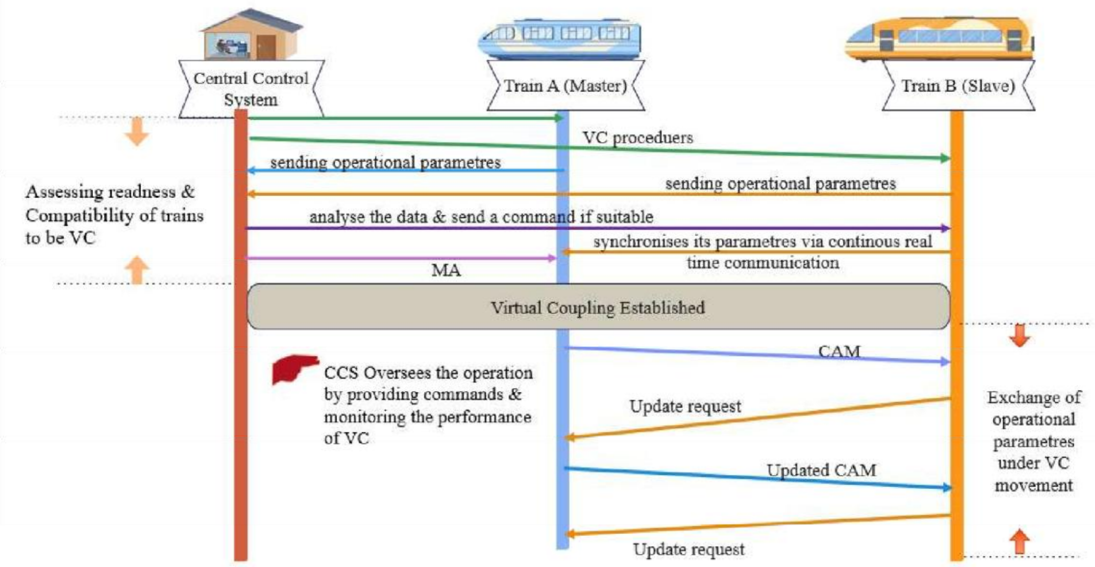

Figure 2: Operation of trains under Virtual Coupling

Once the virtual coupling is established, Train A assumes the role of the master, while Train B functions as the slave in the coupled set. The CCS oversees the operation by providing supervisory commands and monitoring the performance of the virtual coupling. Train A continuously transmits its speed, position, and control commands to Train B. Train B uses this information to adjust its speed and distance, ensuring precise following of Train A. Low latency and high reliability for the wireless link are crucial for maintaining the safety and integrity of the coupling. During this phase, the end-to-end transmission delay of messages exchanged between the trains is critically monitored. If a message is lost or corrupted, a retransmission mechanism could be triggered, requiring the transmitting train to resend the message until an acknowledgment is received from the receiving train. The period of time during which the retransmission is possible before emergency braking is defined by the safety requirements.

Wireless Communications in the rail domain and associated challenges

Various wireless technologies have been compared for Vehicle-to-Vehicle (V2V) communications [7], [8], particularly in the automotive domain. Different frequency bands have been investigated since several years, such as the 400 MHz band [9], the 5.8 GHz band with ITS-G5 system |10], [11] and the millimetric waves bands [12], [13]. Each technology presents its own advantages and limitations in terms of latency, bandwidth, coverage.

In this work, we consider 5G side-link standard (NRV2X) under development for vehicular applications [14]. It is compatible with 5G New Radio (5GNR), which is the backbone of the FRMCS (Future Railway Mobile Communication Systems) [15]. The performance of 5GNRV2X for T2T communication depends on a lot of parameters such as the distance between trains and the presence of interference from other wireless systems and adjacent trains. Packet loss rate, End-to-end delay and throughput at the application level are key metrics in assessing the performance as they can disrupt the timely delivery of the critical messages such as braking instructions or speed updates and jeopardize safety.

Safety aspects and norms

The preliminary step to be conducted in the dependability analysis is the risk analysis that identifies and evaluates risks that may occur during the operation phase of a system. The usual methodologies of the railway domain follow the Common Safety Method Risk Analysis (CMSRA) and EN 50126 standards. The EN 50126 defines the global safety strategy, while the CSM provides the implementation regulation. When railway wireless communication is used to improve an existing railway system, this existing railway system could be used as a reference following [16]. In this case, the discussion will focus on the new hazards introduced that should balance the new safety mitigation that the new technology will allow. The railway communication safety analysis specific to the railways should be based on specific railway regulation documents such as EN 50159, which proposes an approach to address and demonstrate communication safety. One of the characteristics of railway applications is that safety is achieved through applications. Message-related errors are mainly: repetition, deletion, insertion, sequencing, corruption and masquerade. We will align our work on this standard. The safety of a system is evaluated with the safety integrity level (SIL) defined by the International Electrotechnical Commission’s (IEC) standard IEC 61508, which concerns other domains than Railway. As mentioned previously, EN 50126, EN 50128, and EN 50129 standards are considered to meet railway-specific requirements. For continuous operation, SIL1 requires at most 10^{-5} probability of failure per hour (PFH). SIL-2, 3, and 4 require at most 10^{6}, 10^{-7}, and 10^{-8} PFH, respectively. As far as we know, the relation between the safety requirements for the wireless link and the control-command system does not exist. The aim of our work is to provide a methodology to establish this relationship in the case of T2T communications.

Methodologies to analyze dependability analysis

The dependability analysis in railway applications involves various methodologies that assess reliability, availability, maintainability, and safety (RAMS). This section outlines several key methodologies and relevant research works that contribute to the understanding and enhancement of dependability in wireless links for railway systems.

- Failure Mode Effects and Criticality Analysis (FMECA) [17] is a systematic approach used to identify potential failure modes within a system and assess their impact on overall system performance. In the context of wireless communication for VCTS, FMECA can help identify critical failure points in communication links and their effects on train operations.
- Fault Tree Analysis (FTA) [18] applies a top-down approach that visually represents the pathways leading to system failures. This methodology is particularly useful for analyzing complex systems like VCTS, where multiple interdependent components interact. By identifying the root causes of failures in wireless communication, FTA aids in understanding how different failure events can affect train safety and operational efficiency.
- Markov models [19] are employed to analyze the stochastic behavior of wireless communication systems. These models can capture the dynamic nature of wireless links, including variations in signal quality and connectivity due to environmental factors. ● Petri Nets [20] are a powerful modelling tool that can represent concurrent processes and complex interactions within communication systems. This approach allows researchers to evaluate performance metrics such as packet loss, end-to-end delay, and system availability.
- Simulation techniques [21], including discrete-event simulation and system dynamics, are widely used to analyze the performance of wireless communication systems in railway environments. These approaches allow researchers to model various scenarios to assess their impact on system dependability.

- Reliability Block Diagrams (RBD) [22] provides a graphical representation of the reliability of a system by illustrating the relationships between different components. This methodology can be applied to wireless communication systems to assess the overall reliability based on the reliability of individual components.
- Combining multiple methodologies, such as FMEA, FTA, and simulation techniques [23] can provide a more comprehensive analysis of dependability. Hybrid approaches allow for a more nuanced understanding of the interactions between different failure modes and their effects on system performance.

In our work, the CPN approach is chosen due to its powerful capacity to model complex systems with concurrent processes and discrete events. CPN allows for a clear representation of interactions between different components within the communication system, enabling us to capture the dynamic behavior of wireless communication protocols. The use of colors in CPN facilitates the representation of different data types and states, making it easier to analyze varying scenarios and their impacts on system performance. This feature is particularly beneficial for modelling a train communication system's complicated dependencies and timing constraints. Additionally, the CPN approach provides robust analytical tools that support performance evaluation and dependability analysis, we can assess critical metrics such as endto-end delay, message loss, and system reliability by simulating various operational conditions.

Existing works

Recent researchers have used CPN for modeling and analyzing various aspects of railway communication systems. In [25], the authors employed CPN to validate and verify a train-totrain distance measurement system. Their approach highlighted the advantages of CPN in managing complex system interactions and ensuring reliability in safety-critical applications. Virtual coupling control parameters are analyzed in [26] using CPN, focusing on optimizing system performance through formal modelling techniques. Similarly, [27] utilized CPN to model and optimize a high-speed flying train communication system, demonstrating the flexibility of CPN in addressing diverse communication scenarios within the railway domain. In [28] the authors further contributed to the field by conducting a reliability analysis of a wireless communication system in a VCTS, strengthening the utility of CPN for assessing system dependability. Moreover, [29] modeled typical train virtual coupling scenarios using CPN, emphasizing vehicle-to-vehicle communication's role in enhancing train control systems. These studies collectively illustrate CPN's growing significance in railway applications, providing a robust framework for evaluating system safety, performance, and reliability in complex operational environments.

The Colored Petri Net (CPN) Model

This section presents the model of Cooperative Awareness Message (CAM) exchange between a master train (MT) and a slave train (ST) in a virtual coupling scenario using CPN. The model considers only the T2T communication link between the MT and ST. It does not explicitly model other train control functions. The T2T link is assumed to be a 5G NR-V2X side link. The message loss rate depends on the environmental scenario, and for this first step, we consider only one possible retransmission. The retransmission should be done within a time period that corresponds to the maximum time allowed to receive a message with no error before emergency braking. This time period is also a parameter that we can vary in the simulations. The number of retransmissions can be modified in future works.

The graphical representation of the CPN model and token flow is presented in Figure 4, referring to the Train-to-Train data exchange CPN model. This figure illustrates the interaction between places and transitions, capturing the sequence of events involved in CAM exchange between the MT and ST. Thus, the Master train initiates communication by sending data packets and receiving acknowledgments or requests. The Slave train receives data, processes it, and responds with acknowledgments or CAM requests. Thus, the system ensures reliable communication through checks and retransmissions. The model also includes mechanisms for message loss (T4). CAMs are used for real-time updates and safety-critical information exchange between trains. Delays and conditions (e.g., @+Delay()) account for real-world network latency and ensure the system remains in a safe operational state. According to the model, the communication between the master train and slave train works in the following ways of steps:

1. Initiation and transmission (P1 → P2 → P3 → P4): The Master train prepares data (P1), starts transmission (P2), and the data travels through the network (P3) until transmission is complete (P4).
2. Reception by Slave (P5 → P6 → P7): The Slave train receives the message (P5), processes it (P6), and confirms successful reception (P7).
3. Response from Slave (P8 → P9): The Slave generates and sends acknowledgements or CAM requests (P8, P9).
4. Master Verification (P10 → P11): The Master receives and checks these responses (P10, P11), deciding on updates or retransmissions.

In order to translate various environmental conditions, network congestion, software and or hardware issues, and so on, in a first approximation, we simulated different message loss rate values ranging from zero (0) to 0.99. In future works this message loss rate could be related to realistic values in specific scenarios considering 5GNR V2X link. In addition to the different message loss rate values, the model operates under specific assumptions, including a transition delay up to 5 ms and a CAM period of 200 ms as referenced in previous studies [30]. The CAM period is the time interval during which the master train transmits its updated CAM to the slave train. These parameters are critical for accurately reflecting the dynamics of communication in real-world scenarios. They can be modified. The transition delay is the time it takes for each transition to complete after it becomes enabled in the CPN model. The Max Delay is equal to 500 ms, it represents the maximum allowable delay to receive a CAM with no error before emergency braking. The Max Gap is the maximum time allowed between messages before emergency braking (1000 ms). Table 1 summarizes the simulation parameters. These parameters can be varied in order to reflect different scenarios.

Table 1: The input parameters

Parameters	Values
Message loss rate, MLR	0.0 to 0.99
CAM period	200 ms
Transition delay	0 to 5 ms
Max. delay	500 ms
Max. gap	1000 ms

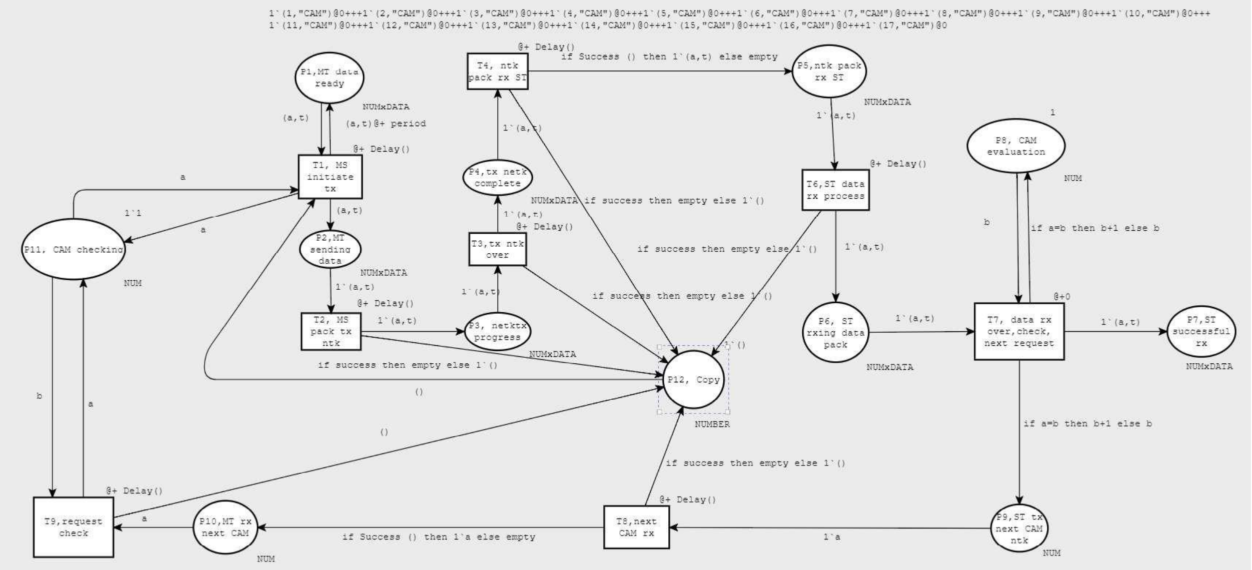

Figure 4: Train-to-Train Data Exchange CPN Model

About the Metrics

This section explains the definitions of each metric considered for evaluation with the CPN model. It presents the corresponding mathematical equations and discusses the importance of these metrics for the safety aspects of virtual coupling in trains or train-to-train communications.

End-to-End Delay – is the time a message takes to travel from the master train (T1) to the slave train (T7). As in wireless communications, this metric reflects the latency of the system how long it takes for information to reach its destination. It is critical in applications like realtime communication, where timely delivery ensures the information remains relevant. Low delay is essential for real-time decision making, such as reacting to an obstacle or coordinating with another train, because high delay can result in outdated information, potentially leading to collisions or operational errors.
For a single message:

$$End - to - End\ Delay = t_{receive} - t_{sent} = T7_{timestamp} - T1_{timestamp} \ \ldots\ldots\ldots\ldots\ (1)$$

Where: $t_{receive}$= $T7_{timestamp}$ is the message received time by the slave train and

t_{sent}= $T1_{timestamp}$ is the time of the message sent by the master train.

For multiple messages:

$$Average\,End - to - End\ Delay = \frac{\sum(t_{receive} - t_{sent})}{Number\ of\ messages} = \frac{\sum(T7_{timestamp} - T1_{timestamp})}{Number\ of\ T7\ messages} \ \ldots\ldots\ldots\ldots\ (2)$$

The average end-to-end delay is the mean of these delays across all messages.

Average Inter-Message Gap - is the average time between consecutive messages received by the slave train. It focuses on the timing pattern of message receptions rather than the transit time of individual messages. It shows how frequently trains are communicating, which is critical for sharing real-time updates like position, speed, or safety alerts (emergency braking). Thus, a smaller gap means trains are getting updates more often, which is vital in high-risk situations like dense traffic or high-speed travel. A large gap might work in less critical scenarios, but could lead to outdated information in emergencies, including the risk of collisions or delays. According to our model, this metric can be defined with equations. We are tracking messages received by a train at specific timestamps called T7 events. Therefore, the gap between two consecutive messages is the difference in their timestamps.

For the i_{th} gap: $gap_i = T7_{i+1} - T7_i \quad for\ i = 1, 2, 3, \ldots, n - 1$ .... (3)

Where: T7 is a sorted list of timestamps when messages are received ($T7_1$, $T7_2$, $T7_3 \cdots$) and n is the total number of T7 events.

The Average Inter-Message Gap is the average of all these gaps:

$$Average\ Inter\ Message\ Gaps = \sum_{i=1}^{n-1} \frac{T7_{i+1} - T7_i)}{n-1} \ \ldots\ldots\ldots\ldots\ \ldots\ldots\ldots\ldots\ldots\ldots\ (4)$$

Percentage of Safe Gaps – This measures the proportion of time gaps between messages that are lower or equal to the Maximum Gap. A safe gap is one where the time between messages is below a maximum threshold (for instance, 1000 ms), ensuring that delays don't compromise safety or efficiency. This ensures reliability. Even if the average gap is small, some gaps might still be too long, delaying critical updates. A high percentage of safe gaps confirms that communication is consistently timely, reducing the chance of safety issues.

A gap is safe if it is less than or equal to the maximum gap. Count a gap as safe (1) or not (0):

$$safe\ gap_i = \begin{cases} 1, if\ gap_i \le Max\ Gap \\ 0,\ \ otherwise \end{cases} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (5)$$

Where: Max Gap is the maximum time allowed between messages to be safe (1000 ms).

The percentage of safe gaps is the proportion of safe gaps multiplied by 100:

$$Percentage\ of\ safe\ Gaps = \sum_{i=1}^{n-1}\left(\frac{safe\ gap_i}{n-1}\right) x\ 100 \ldots\ldots\ldots\ldots. (6)$$

$$Or\ simply\!:\quad Percentage\ of\ safe\ Gaps = \frac{Number\ of\ gaps \leq Max\ Gap}{n-1}\ x\ 100 \ldots\ldots\ldots. (7)$$

Where n is the total number of messages received.

Together, these metrics balance frequency and consistency, ensuring trains have the up-todate information they need to operate safely and efficiently.

Throughput _ Is the rate of successful message deliveries (with no error) over the total simulation time, in messages per second. This metric shows how many messages are successfully sent from the master train to the slave train over a given period. High throughput ensures that a large volume of messages can be exchanged quickly, which is critical for realtime applications like train coordination. It can be expressed in two forms: messages per second or bits per second (if message size is considered).

Messages per second:

$$Throughput = \frac{Number\ of\ successfully\ delivered\ messages}{Total\ time} = \frac{Number\ of\ T7\ events}{Total\ simulation\ time} \ldots\ldots\ldots. (8)$$

Where: $\text{Total simulation time} = \max(\text{T7}) - \min(T1)$

$$Throughput = \frac{Number\ of\ successfully\ delivered\ messages\ x\ message\ size}{Total\ time}$$

$$= \frac{Number\ of\ T7\ events\ x\ message\ size}{Total\ simulation\ time} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (9)$$

Message Delivery Ratio (MDR) – measures the proportion of messages successfully delivered by the slave train out of all messages sent. It shows how reliable the communication system is in ensuring messages reach their destination, which is critical for maintaining safe train operations. A high ratio indicates that most messages are successfully delivered, which is essential for safety, whereas a low ratio indicates that most messages are missing, then increasing the risk of accidents or operational delays.

$$MDR = \frac{Number\ of\ successfully\ delivered\ messages}{Total\ number\ of\ messages\ sent} = \frac{Number\ of\ T7\ events}{Number\ of\ T1\ events} \ldots\ldots\ldots\ldots\ldots (10)$$

Percentage of Safe Delivery represents the percentage of delivered messages that arrive at the slave train within a maximum allowable delay (Max Delay: 500ms), ensuring that they are actionable for real-time decisions. A safe delivery means the message arrives quickly enough to be acted upon, such as avoiding a collision or adjusting speed in time. Even if a message is delivered, it must arrive in time to be useful. For example, a message about an emergency brake needs to be received almost instantly. A high percentage ensures that the communication system is not only reliable but also fast enough to support real-time safety decisions.

$$Percentage\ of\ Safe\ Delivery = \frac{Number\ of\ messages\ delivered\ within\ time\ limit}{Number\ of\ successfully\ delivered\ messages}\ x\ 100$$

$$= \frac{Number\ of\ T7\ events\ where\ (T7-T1) \leq Max\ Delay}{Number\ of\ T7\ events}\ x\ 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Together, the metrics message delivery ratio and percentage of safe delivery ensure that trains can communicate both reliably and quickly, which is vital for preventing accidents and maintaining efficient operations.

Conclusion

This paper presented a comprehensive model for analyzing the dependability of 5G NR V2Xbased T2T link in the context of VCTS using Colored Petri Net. The paper details the VCTS context and process, the background and the methodology considered. The CPN model is described with the different theoretical foundations and metrics considered, and the simulation parameters. The future works will focus on extensive simulations and analysis with the CPN.

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A Colored Petri Net Model to assess dependability of Train-to-Train 5G NR V2X Communications for Virtual Coupling

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Abstract

To increase railway system capacity, efficiency and safety, the Virtual Coupling of Train sets (VTCS) is a promising solution. This enables multiple trains to operate closely together as a platoon, in a coordinated manner [1] [2] in the context of moving block concept [3]. VTCS necessitates that the trains exchange mission-critical data such as speed, position, and braking curves. These messages are referred to as Cooperative Awareness Messages (CAM). The implementation of VCTS presents several challenges. In particular, the communication system must ensure Train-to-Train (T2T) and train-to-Ground (T2G) seamless connectivity to allow real-time CAM exchanges and coordination. Distance between trains, speed, interference, tunnels, radio impairments will affect the communication reliability. Therefore, it is crucial to develop a methodology to analyze the dependability of the T2T link to design safety rules for this link at application layer such as the number of message repetitions allowed during a given period before emergency braking. We will present a new Colored Petri Net (CPN) model to evaluate the dependability of a 5G NR V2X based communication between two trains in the context of VTCS. The study focuses on analyzing how the message loss rate (MLR) can impact safety and the design of VTCS operation.

Keywords: Virtual Coupling of Train Set (VCTS), Train-to-Train (T2T), Coloured Petri Nets (CPN), Train Control and Monitoring System (TCMS), Cooperative Awareness Message (CAM), Dependability Analysis