Deliverable D3.1
Virtual Coupling Communication Solutions Analysis

Project Acronym:	MOVINGRAIL
Starting Date:	01/12/2018
Duration (Months):	25
Call (part) Identifier:	H2020-S2R-OC-IP2-2018
Grant Agreement No.:	826347
Due Date of Deliverable:	Month 10
Actual Submission Date:	25-09-2020
Responsible/Author:	Bill Redfern (PARK)
Dissemination Level:	Public
Status:	Draft

Reviewed: No

Document history		
Revision	*Date*	*Description*
0.1	03-07-2020	First draft for comments and internal review
0.2	24-09-2020	Second draft
1.0	25-09-2020	Issued

Report contributors		
Name	*Beneficiary Short Name*	*Details of contribution*
John Chaddock	PARK	Primary Curation. Identification and collation of source documentation. Document review.
Bill Redfern	PARK	Literature review and solutions research. Requirements identification. Analysis of requirements and potential solutions. Descriptions and conclusions.
John Marsden	PARK	Literature review and solutions research.
Michael Duffy	PARK	Literature review and solutions research.
Mark Cooper	PARK	Literature review and solutions research. Analysis. Format/editing.
Andrew Wright	PARK	Document review.
Lei Chen	UoB	Document review.
Mohamed Samra	UoB	Document review.
Paul van Koningsbruggen	Technolution	Document review.
Rob Goverde	TUD	Document review, quality check and final editing.

Funding

This project has received funding from the Shift2Rail Joint Undertaking (JU) under grant agreement No 826347. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Shift2Rail JU members other than the Union.

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Executive Summary

This document is MOVINGRAIL Work Package 3 deliverable D3.1 virtual Coupling Communication Solutions Analysis. Work Package 3 on Communication Technology for Virtual Coupling aims at assessing wayside/on-board communication structures already proposed by Shift2Rail projects (e.g. CONNECTA, X2Rail-1, Safe4Rail) so to propose analytically determined systems for safe and effective communication for Virtual Coupling. This first deliverable of Work Package 3 concentrates on the identification of Virtual Coupling communication requirements, identification of appropriate and current technical Virtual Coupling communication solutions and analysis of these candidate solutions for their suitability against the requirements.

The first sections of the document provide background and technological basis of the systems where virtual coupling may be applied. Of note these systems will generally have, or be migrating to, the European Rail Traffic Management System (ERTMS) or have Communication Based Train Control (CBTC).

The methodology applied to the analysis to identify suitable candidates for virtual coupling communication solutions, identify the applicable requirements and assess the compliance of the candidates is explained.

A literature review of Shift2Rail and open source research was carried out to identify references to communication systems candidates in the virtual coupling sphere. Similar technologies were traced to generic groupings and governing standards. Radio solutions no longer current were rejected. Given the rapid rate of change in the communications field the latest incarnations of the technology were taken forward.

The candidate technologies considered worthy of further analysis included LTE/ Cellular mobile technology (the 3PP standards), TETRA and Wi-Fi evolutions.

Analysis revealed that evolution from GSM-R to 5G in accordance with the aims of the Future Rail Mobile Communications System project presented the best path forward for elaboration into a communications proposal for virtual coupling for the European rail network and that 5G is also appropriate, for consistency and economy, for the other sectors.

Abbreviations and Acronyms

Abbreviation/Acronym	Description
3GPP	Third-generation Partnership Project
AP	Access Point
ATO	Automatic Train Operation
ATP	Automatic Train Protection
BSSID	Basic Service Set Identifiers
CAMs	Co-operative Awareness Messages
CBTC	Communications Based Train Control
CCSA	China Communications Standards Association
COTS	Commercial-Off-The-Shelf
CSMA	Carrier-Sense Multiple Access
C-V2X	Vehicle-to-everything (V2X) using cellular
D2D	Device-to-Device (D2D) communication in cellular networks is defined as direct communication between two mobile users without traversing the Base Station or core network.
DMO	Direct-Mode Operation
DMU	Diesel Multiple Unit
DPSK	Differential Quadrature Phase Shift Keying
DSRC	Dedicated Short-Range Communication
EBI	Emergency Brake Intervention
EIRENE	European Integrated Railway Radio Enhanced Network
EMC	Electro-Magnetic Compatibility
eMLPP	Multilevel Precedence and Pre-emption Service
EMU	Electric Multiple Unit
EoA	End of [movement] Authority
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
ETML	European Traffic Management Layer
EVC	European Vital Computer
FRMCS	Future Rail Mobile Communications System
GNSS	Global Navigation Satellite System
GoA	Grade of Automation
GSM	Global System for Mobile Communication
GSM-R	Global System for Mobile Communication – Railway
HSR	High-Speed Rail
IEEE	Institute of Electrical and Electronic Engineers
IoT	Internet of Things
ITS	Intelligent Transportation Systems
ITS-G5	Intelligent Transportation System, generation 5
ITU	International Telecommunication Union
LEU	Lineside Equipment Unit

LRT	Light Rail Transit
LTE	Long Term Evolution
MAAP	Multi-Annual Action Plan
MORANE	Mobile Radio for Railway Networks in Europe
Moving block	Contrasts with fixed block. In a moving block the "block sections" are not tied to specific locations but can be adjusted continuously.
MOVINGRAIL	MOving block and VIrtual coupling New Generations of RAIL signalling.
MTBF	Mean Time Between Failures
NR	New Radio
P2P	Peer to Peer
PARK	Park Signalling Limited
PMR	Personal Mobile Radio
RAT	Radio Access Technology
RBC	Radio Block Centre
RCS	Radio Communication System
REC	Railway Emergency Call
ROI	Return on Investment
RRT	Rail Rapid Transit
S2R	Shift2Rail
SBI	Service Brake Intervention
SDS	Short Data Service
SPD	System Platform Demonstrator
STC	Streetcars
STDMA	Self-organised Time Division Multiple Access
SvL	Supervised Limit
SWOT	Strengths, Weaknesses, Opportunities, Threats
T2I	Train to Infrastructure
T2N	Train to Network
T2T	Train to Train
TBTC	Transmission-Based Train Control
TDMA	Time Division Multiple Access
TETRA	TErrestrial TRunked RAdio
TIMS	Train Integrity Monitoring System
TMO	Trunk Mode Operation
TPWS	Train Protection and Warning System
TRL	Technology Readiness Level
UIC	International Union of Railways
V2D	Vehicle-to-device
V2E	Vehicle-to-environment, mostly used for cellular communications using base stations.
V2G	Vehicle-to-grid

V2I	Vehicle-to-infrastructure
V2N	Vehicle-to-network
V2P	Vehicle-to-pedestrian
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-everything (V2X) communication is the passing of information from a vehicle to any entity that may affect the vehicle, and vice versa. Can be WLAN-based (802.11p), and/or cellular-based (C-V2X, LTE/5G).
VCTS	Virtually Coupled Train Set
VGCS	Voice Group Call Service
VOBC	Vehicle On-Board Controller
WAVE	Wireless Access in Vehicular Environments, IEEE 802.11p
WLTB	WireLess Train Backbone

1. Objective

The objective of this deliverable is to analyse the current technical communications solutions, that could be exploited to implement virtual coupling on a real railway. This analysis has been performed on a theoretical basis, and resulted in an assessment of the state-of-the-art in communications systems that are candidates for implementation in a final virtual coupling solution.

1.1. S2R Context

This report forms Deliverable D3.1 of MOVINGRAIL, which contributes to Task 3 of the Virtual Coupling Technical Demonstrator TD2.8 – Feasibility Analysis of Virtual Coupling. This report will specifically analyse potential communications systems as solution candidates. It will consider scenarios that will form the System Platform Demonstrators (SPDs) that are defined by S2R in the Multi-Annual Action Plan (MAAP). These scenarios form the market segments discussed in MOVINGRAIL Deliverable D4.1 "Market Potential and Operational Scenarios for Virtual Coupling", i.e. High Speed, Main Line, Regional, Urban and Freight (Ref [1]).

1.2. Requirements

To compare candidate solutions, high-level requirements have been placed on the communications system required for Virtual Coupling, and from these requirements criteria have been set, and potential communication solutions evaluated against these criteria. We have also taken note of MOVINGRAIL's original call (S2R-OC-IP2-01-2018) which defines some of the criteria for the analysis of potential solutions.

1.3. Literature Review

To identify the candidate solutions, a literature review has been undertaken which looked at existing innovations by projects within S2R as well as looking at research and innovation within the field of autonomous vehicles. The literature review also looked at open research in the fields of rail, autonomous road vehicles, and communications in general. From this literature review the most promising communication system candidates have been chosen to be investigated in further detail. The literature review included documents released under collaboration agreements with complementary projects (CONNECTA-2, X2RAIL-3).

1.4. Factor and SWOT Analysis

A safety, performance, cost and extendibility factor analysis was then performed on the solution candidates. This factor analysis considered the criteria derived from the high-level requirements, identified earlier. A SWOT analysis has been undertaken on potential candidate solutions, looking at their potential suitability for virtual coupling applications. Because TD2.8 is being developed to Technology Readiness Level (TRL) 3, the analysis of the solution candidates has been theoretical in nature.

1.5. Critical Review

Following this we performed a critical review of the analyses undertaken in this deliverable to identify any deficiencies or weaknesses that may have occurred and the effect these may have had on the process and the outcome. From this we aimed to identify areas in which more information is needed or into which further analysis was required.

2. Background

MOVINGRAIL is a research project funded by the Shift2Rail Joint Undertaking (S2R JU) of the European Commission in response to the open call S2R-OC-IP2-01-2018.

This document is Deliverable 3.1 (D3.1) of MOVINGRAIL, and is part of Work Package 3 (WP3): Communication Technology for Virtual Coupling.

This section provides a brief background about the MOVINGRAIL project, and WP3.

2.1. MOVINGRAIL

Train-centric signalling systems represent the most promising technology for increasing railway capacity, and reducing railway life-cycle costs. These systems include moving block signalling, which enables trains running at absolute braking distance, and virtual coupling that even aims at running at relative braking distance, with train sets virtually coupled into a convoy.

MOVINGRAIL aims to support the further development of train-centric signalling systems by introducing and applying a multidimensional analysis framework to assess train-centric signalling from the operational, technological and business perspectives. This is applied to moving block and virtual coupling at different levels, highlighting the differences to traditional fixed block signalling.

Work Package 3, Communication Technology for Virtual Coupling, aims at assessing wayside/on-board communication structures already proposed by Shift2Rail projects (e.g. CONNECTA, X2Rail-1, Safe4Rail) so to propose, from the results of the analysis, systems for safe and effective communication for Virtual Coupling. An extensive review of these projects has been performed to collect specifications of proposed communication systems.

WP3 will:

- Identify appropriate Virtual Coupling technical communication solutions by reviewing previous studies and projects and analysing these against requirements for this work package.
- Assess and identify proposals for Virtual Coupling technical communication solutions facilitating business analysis and exploitation road map.
- Investigate the application, solutions and dynamics of automated car driving and evaluate the applicability to the railway field.

2.2. Technology in the Railway Markets

Other MOVINGRAIL work packages (e.g. WP4) have considered the application of virtual coupling across the market sectors (high speed, main line, regional, urban/sub-urban and freight). Here we are mainly concerned with technological and contextual differences between the market sectors that have influence upon the virtual coupling communication requirements. §3.1.2 discusses these differences.

Whilst the analysis in this work package has been weighted by an assumption that virtual coupling technology will expand on and fall back to the 'conventional' control system used by the market sector it does not preclude the possibility of the virtual coupling control and or communications system being stand alone.

See reference [1] for further details on the European railway markets.

2.2.1. High Speed

High Speed Railways (HSRs) are railway systems that travel at speeds of 200 km/h and faster, usually on dedicated lines, and using a fleet of dedicated, and similar, trains. Lines are designed to connect multiple urban centres.

The control technology for High Speed lines is the same as for conventional main line, however high speed lines require in-cab signalling with ATP. The European rail networks are transitioning to ERTMS.

2.2.2. Conventional/Main Line

Main line services are essentially for long distance national and international trips connecting cities within a region or across regional boundaries acting as the principal arteries of the rail system. Main line generally refers to a route between cities as opposed to a route providing suburban or metro services. Main lines may be operated under shared access by a number of railway companies, with sidings and branches operated by private companies or single railway companies.

Signalling is currently conventional fixed block, usually with three or four aspect lineside signals to achieve required headways. The European mainline rail networks are transitioning to ERTMS.

2.2.3. Regional

Regional railways are defined as rail-based high-performance suburban transit systems which operate along the rail lines/routes spreading between urban and suburban area [2]. They serve as a backbone for local public transport (particularly for commuters) in many countries worldwide.

The trains consist mainly of DMU or EMU with a large variance in top speed (80-200 km/h) and capacity (from 2-car-DMU to 8-car-double-deck-EMU) depending on the network.

Conventional signalling systems are in use on the regional lines. Lines that form part of the European rail network are transitioning to ERTMS.

2.2.4. Urban/Suburban

The major sub-markets or the urban/suburban sector include tramways or Streetcars (STC), Light Rail Transit, metro (subway) and Rail Rapid Transit. LRT and STC systems have light weight high performance vehicles. The systems are self-contained without inter-running with other systems (with the exception of systems using tram-trains to extend the network). Metro and RRT tend to have longer trains, typically 4 to 10 cars. Combined systems are not unusual.

2.2.4.1. Metro (Subway) or Rail Rapid Transit (RRT)

The metro is a rail-based high-performance urban transit system where trains operate along the dedicated lines/routes with rail tracks usually including underground sections, i.e. with tunnel alignment in large densely populated urban areas [2]. The lines constituting the network are an exclusive right-of-way enabling frequent, punctual, reliable, and fast transport services compared to other urban mass transport systems.

Signalling technology in the metro sector can be conventional two aspect fixed block signalling (e.g. London Underground), however it is common for metro systems to employ Communication

Based Signalling (CBTC). For example the London Docklands Light railway has since 1994 used the Thales (since 2007, previously Alcatel) SelTrac moving block transmission-based train control system was introduced. Transmission is between trains' VOBC and the control centre via inductive loop.

The Thameslink programme upgraded the core section of the Thameslink network across central London to an ATO system operating over ETCS level 2, i.e. signalling is in-cab and communications are via GSM-R. Trains run at GoA 2 in the Thameslink core.

Rapid Rail Transit (RRT) is closer to conventional rail than Metros and overlaps with Regional but with higher performance and is more focused on serving cities and conurbations. RRTs often include inter operation with other modes.

Compared to the LRT, the RRT system provides much higher transit capacity, travel speed, internal comfort, reliability, punctuality and safety of services [20].

2.2.4.2. Light Rail Transit (LRT)

The light rail is a rail-based high-performance urban transit system operating along predominantly reserved grade-separated Right-Of-Ways, although some systems share streets with car traffic. It usually includes 1 to 4 electric railcars carrying up a capacity of up to 220-600 passengers [20]. Speeds are generally up to 100 km/h. The services are provided according to a fixed schedule at stops/stations, which are rarer than those at bus and tramway systems. The LRT system has generally long distances with more distant, i.e. less frequent, stations along the entire length of its lines.

2.2.4.3. Tramway or Streetcar (STC)

Trams are classic streetcars. They operate partly on segregated tracks and partly on street on roads shared with automotive traffic.

The control scheme for tramways is line-of-sight, very similar to automotive driving. Trams are designed to have similar braking performance to road vehicles. For line-of-sight safety depends, like car driving, on the driver's ability to see and react to hazards. For line-of-sight operation a minimum number of Tram Signals are provided to regulate the trams at junctions and single lines. Point Indicators are provided to allow passage over points. At road junctions (note Tramways do not normally have 'level crossings') the road Traffic Light Controller will generally operate the Tram Signals. Conventionally, to satisfy integrity requirements and enable degraded mode working, separate Point Indicators are provided. Point calling will often be by the approach of the tram, with very limited route setting. Sprung, rather than motorised, points are common on tramways. There are normally integrated control centres for tram systems. Line of Sight systems/areas do not have a signaller and the 'controllers' primary role is the timetable regulation of the service.

2.2.5. Freight

Although there are some lines specifically dedicated to freight traffic, usually with less infrastructure than for passenger lines, freight services for at least part of the journey will frequently be made on conventional mainlines.

Lines that form part of the European rail network are transitioning to ERTMS.

2.3. ERTMS

The European Rail Traffic Management System (ERTMS) is a suite of standards for digital railway signalling systems. The aim of the standards is to introduce interoperability across the European rail market, both in terms of train operation, and in terms of signalling procurement. This is all with the ultimate aim of improving the competitiveness of the rail sector. ERTMS is constructed of three principal components: Global Systems for Mobiles – Railway (GSM-R), European Train Control System (ETCS), and European Traffic Management Layer (ETML) [3].

2.3.1. ETML

European Traffic Management Layer (ETML) makes up the traffic management component of ERTMS. ETML is intended to optimise train movements and timetables, as well as provide route planning. This is all with the intention of improving train running, and information for operational staff, as well as customers. ETML is not yet fully defined, and development is still ongoing. It is likely that ETML will, for the European rail network, have a role managing the virtual coupling/uncoupling of trains.

2.3.2. GSM-R

Global Systems for Mobiles – Railway (GSM-R) is the standard in which track-to-train communications are undertaken. GSM-R is identical to the second generation mobile standard GSM, with a number of additional railway specific functions. A simplified GSM-R system diagram is shown in Figure 1 below, Table 1 shows a summary of GSM-R Quality of Service requirements : [4], and Table 2 shows a summary of 2G GSM technical properties.

The GSM-R specifications were finalised in 2000, based on the European Union-funded Mobile Radio for Railways Networks in Europe (MORANE) project. The specification is being maintained by the International Union of Railways project ERTMS.

The EIRENE Functional Requirements Specification (FRS) version 8.0.0 and System Requirements Specification (SRS) version 16.0.0 address the complete GSM-R system requirements, containing in particular the requirements that are relevant to interoperability of the rail system within the European Community, according to the Directive 2008/57/EC.

The most recent updates introduced Internet Protocol based new Core Network architecture, enabling the system to use either Packet Switching or Circuit Switching and introduced other functionalities for the network and the terminals.

The EIRENE Specifications requirements which are relevant for interoperability in Europe are referenced in the Annex A of the CCS TSI as mandatory.

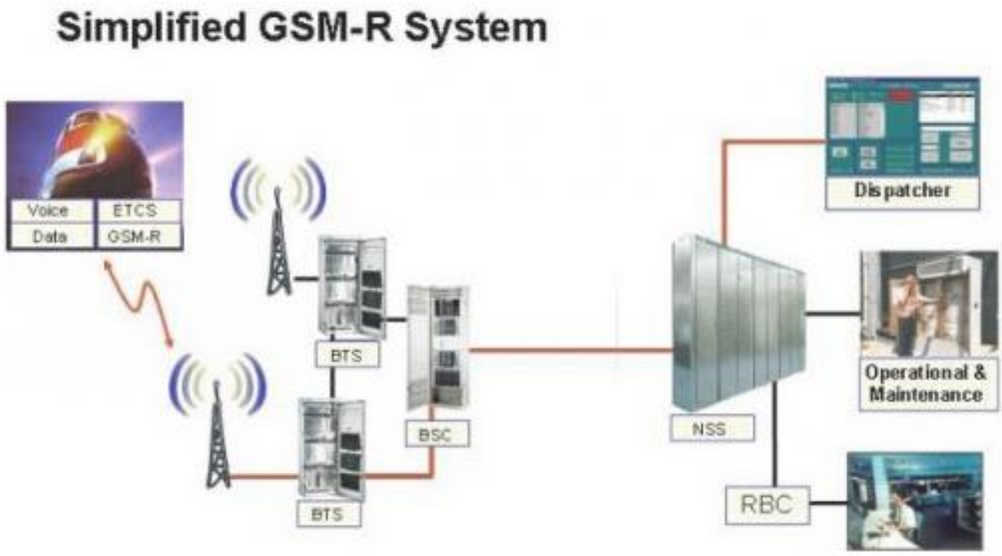

Figure 1 - Simplified GSM-R System *[5]*

Table 1 - Summary of GSM-R QoS Requirements

Requirements	
Connection establishment delay	< 8.5 s (95%), <= 10 s (100%)
Connection establishment error ratio	< 10^{-2} (100%)
Connection loss rate	< 10^{-2} / h (100%)
Transfer delay of user data frame	<= 0.5 s (99%)
Transmission interference period	< 0.8 s (95%), < 1 s (99%)
Error-free period	> 20 s (95%), > 7 s (99%)
Network registration delay	<= 30 s (95%), <= 35 s (99%), <= 40 s (100%)
Call setup time	<= 10 s (100%)
Emergency call setup time	<= 2 s (100%)
Duration of transmission failures	< 1 s (99%)

Source reference: [4], Document Review Item 140

Table 2 - Summary of 2G GSM technical properties

Properties	
Frequency Band	900MHz, 1800MHz
Transmission Data Rate	>= 2.4 Kbps, <=9.6 Kbps
Handover Effective Time (between Base stations)	>300 ms
Latency	>300ms, <1000ms
Cell range	35Km

Source reference: [6]

2.3.2.1. Additional Railway Functions

GSM-R uses dedicated frequency bands.

GSM-R includes Voice Group Call Service (VGCS) functionality which allows a number of users to participate in the same call established on a purely geographic basis. This includes for Railway

Emergency Call (REC) which allows a train driver from a single button press to send a stop message to local trains. The Multi-Level Precedence and Pre-emption Service (eMLPP) allows RECs to be given the highest precedence.

GSM-R includes functional number management, a feature that allows a signaller to call a train driver using the trains identity (headcode).

2.3.2.2. Obsolescence

GSM is now considered a legacy system being superseded by progressive developments under the 3GPP standards framework. The UIC Radio Communications group under Future Rail Mobile Communications Systems (FRMCS) initiative is specifying the successor to GSM-R. Migration to FRMCS is expected to commence in 2022. The ability of the rail industry to continue to support GSM-R beyond roughly 2030 is doubtful [7].

2.3.3. ETCS

ETCS is the train control element that manages movement authorities and provides automatic train protection. ETCS works by issuing movement authorities to trains when the safety of the movement has been established. The movement authorities are transmitted using an agreed protocol over GSM-R, meaning that all ERTMS fitted trains are compatible. ETCS also provides a standard way to display movement authorities in-cab to the driver, reducing the training required and reducing the need for trackside signals. ETCS is split into multiple levels, with each level providing a higher level of standardisation, and a reduction in the need for trackside equipment.

2.3.3.1. ETCS Level 1

Within level 1, a train receives information from a track-mounted balise which, in turn, receives information from the interlocking or signal via a Lineside Equipment Unit (LEU). The information received by the balise from the interlocking will include the state of the signals such that it can infer the extent of the movement authority that is to be given to a passing train. The decision on the extent of the movement authority is determined by a LEU, which then interfaces with the balise to set the message to be sent to the passing train. The information received by the train from the balise will include speed limits, gradient information and the extent of the train’s movement authority.

Within a level 1 system, a balise (or, more accurately a group of balises) will be placed at a location where a movement authority could end, for example at a wayside signal, and also on the approach to such a place so that the balise could inform a train if a signal has “stepped-up” to a less restrictive aspect, and thus the movement authority has been extended. The locations of the balises is therefore derived from the block sections. In order to calibrate the on-board odometry of a train, other balises can also be placed at intervals along the track (in the UK they are typically not more than 4 km apart). All balises provide the train with location. Because ETCS Level 1 systems do not have continuous communication loops within the track (Euroloop) can be used for infill especially on the approach to signals, to provide information to the train when a signal aspect ‘steps up’.

At ETCS Level 1, the flow of information is unidirectional; no information is passed from the train to the Control Centre. The radio system (GSM-R) only provides voice call services.

The information received by the ETCS equipment on-board the train is sufficient for Automatic Train Protection (ATP) to be implemented, whereby the train speed is supervised and the train can

be slowed or stopped, without the driver's intervention, if the ETCS equipment determines that the train will exceed a speed limit, or will not otherwise stop before the end of the movement authority.

Within a level 1 system, trackside detection of trains will still exist, as will wayside signals, and the track will still be divided into block sections that cover a fixed length of track.

Level 1 systems improve safety, by providing automatic train protection, but also has a negative impact on network performance and capacity as a signal stepping up is not conveyed to the train until it reaches a balise or loop.

2.3.3.2. ETCS Level 2

Within a level 2 system, the balises are now normally standalone, and are not connected to the interlocking system or any other off-train system. The balises therefore they do not receive any information. The information that passes from the balise to a passing train will be the same each time and will not contain any transient information about the situation of the line. This means the information could contain information about things that do not change, such as location, gradients and approaching changes in ETCS level, but could not convey movement authority.

Within a level 2 system, a balise (or, more accurately a group of balises) will be placed at a location where a movement authority could end, for example at a wayside signal. Balises will also be placed on the approach to such a location, but will be used to calibrate the train's on-board odometry. This is to ensure that the train's ETCS will be able to apply braking in time to stop the train, before it reaches the end of its movement authority. The location of the balises is therefore derived from the block sections. As with level 1, and in order to calibrate the on-board odometry of a train, other balises can also be placed at intervals along the track (in the UK they are typically not more than 4 km apart).

Trains will receive movement authority and speed limits by radio signal, through GSM-R. The information is sent to the trains by a Radio Block Centre (RBC). The RBC is connected to, and receives route locking information from, the interlocking. The RBC manages the connection between the interlocking and the ETCS equipment on-board the trains.

As trains enter an area that a given RBC controls, it is instructed to register with the RBC by fixed balises on the track. The RBC, using the route-locking information from the interlocking system, and knowledge of the locations of trains that have registered with it, determines what a train's movement authority should be and then issues appropriate movement authorities to the trains within its area.

Within a level 2 system, trackside detection of trains still exists, but the wayside signals become optional in many situations. Wayside signals however will remain necessary if trains that are not fitted with ETCS are expected to run on the track. The track will still be divided into block sections that cover a fixed length of track.

Less infrastructure is needed for level 2 systems (no signals) and capacity improvements are obtained because of the continuous in-cab signalling and continuous ATP.

2.3.3.3. ETCS Level 3

The distinction between ETCS level 2 and level 3 is the movement of train detection from the trackside, and onto the train. This is principally achieved by the addition of a Train Integrity Monitoring System (TIMS). The TIMS device is fitted on the train and is used to ensure that the train is still complete and that the individual vehicles have not separated from one another. The train integrity is then continuously reported back by the ETCS equipment onboard the train to the RBC via GSM-R, as well as the precise train positioning.

ETCS fitted trains still receive their movement authorities from the RBC in a similar way to ETCS level 2, and therefore there is no need for wayside signals. Because of the continuous reporting of the trains' locations, there is no need to split the railway up into fixed block sections, although virtual block sections can be defined. Moreover, as trains' locations are updated, other trains movement authorities can be continuously updated to any location. This concept enables moving block operation, with trains separated only by their absolute braking distance rather than being separated by the need to have only one train in each distinct and fixed block.

Whilst the ETCS level 3 concept is for operation without Trackside Train Detection, it is proposed that some systems will retain trackside train detection, allowing for the movement of unfitted trains, to aid recovery from onboard train equipment failures, over points and crossings etc. Such system could be equipped with Trackside Train Detection only in specific locations, or throughout the area of control [8]. ETCS level 3 can therefore support fixed block, full moving block and hybrid systems.

Because there is no concept of a fixed location where movement authorities could end, balises are only located periodically for the calibration of on-train odometry. Level 3 systems offer further capacity improvement.

2.4. CBTC

Communication Based Train Control (CBTC) is the control system of choice for the Metro sector.

2.4.1. CBTC Characteristics

A CBTC system is a continuous automatic train control system utilising high-resolution train location determination, independent of track circuits; high-capacity bidirectional train-to-wayside data communications; and capable of implementing automatic train protection (ATP) functions, as well as optional automatic train operation (ATO) and automatic train supervision (ATS) functions [9].

CBTC systems have evolved from earlier transmission-based train control (TBTC) which made use of inductive loop transmission techniques for track to train communication, introducing an alternative to track-circuit based communication. Since the early 2000's modern CBTC systems utilise bi-directional radio communications. Figure 2 shows a functional block diagram of a typical CBTC system [10].

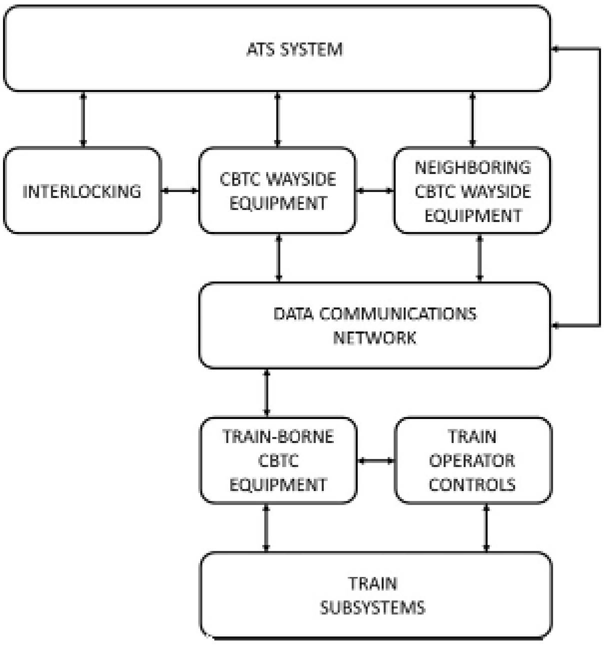

Figure 2 - Functional block diagram for a typical CBTC system *[10]*

The train continuously sends its current speed, direction, and location to the wayside over the radio connection. Based on this information received from all trains currently on the track, as well as a train's braking capability, the CBTC wayside equipment calculates the maximum speed and distance the train is permitted to travel and sends this to the train. Based on this information, the train's onboard ATC equipment continuously adjusts the train speed and maintains the safety distance to any preceding trains.

A typical CBTC architecture will divide the systems into zones, each zone having its own Zone or Wayside Controller, which is responsible for maintaining safe train separation in its zone. Dividing the wayside network into multiple, independent zones, improves availability if one or more zones experience failures.

CBTC systems are available from the major rail manufactures e.g. Siemens have NexTEO (for SNCF RER's E-line) and Thales have SelTrac (for Transport for London: District, Circle, Hammersmith & City and Metropolitan lines).

Metro systems differ from mainline railways in that they serve specific urban geographic areas, and are usually segregated with no inter working. Metros often have a vertically integrated structure combining operations, maintenance, control systems and telecommunications. These factors all favour an integrated system-wide radio system bespoke to that system.

It could be argued that CBTC systems are closer to achieving virtual coupling, with many metros already utilising moving block.

2.4.2. CBTC Communications

The trend in CBTC communication has been to migrate from loops and balises (TBTC) to local radio systems most notably employing Wireless LAN (WLAN) IEEE 802.11, either Commercial-Off-The-Shelf (COTS) or bespoke systems. Many systems have integrated infill via leaky feeder, loops or

balises particularly to deal with areas of difficult propagation such as tunnels. Historically there has been a general lack of standardisation for CBTC, the result of which is that nearly all existing CBTC installations are incompatible, proprietary systems.

Responsibility for data communications lies with Radio Communication System (RCS): The RCS is typically a combination of software and hardware, including radios and antennas, and can either be a completely independent system or integrated into the Vehicle On-Board Controller (VOBC).

The trackside is divided into multiple overlapping Wi-Fi cells, each served by one Access Point (AP). The APs are connected to the wayside components through the trackside backbone network. A typical configuration of the trackside backbone network is a star-topology though ring topologies, which minimise cable runs, are becoming popular (see Figure 3 below). Most recently there has been movement towards LTE based communication for CBTC radio. [10]

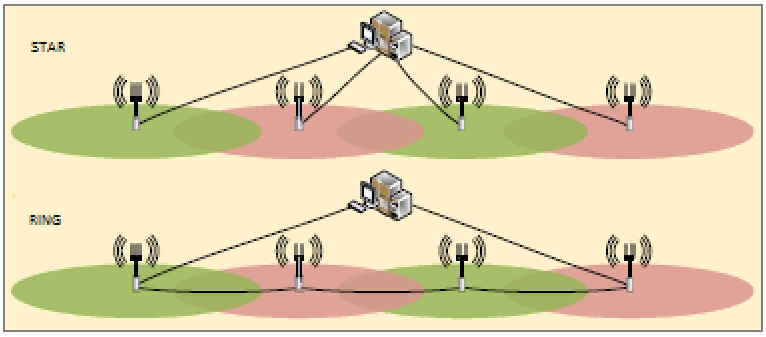

Figure 3 - Star vs. Ring based trackside backbone network *[11]*

2.5. Wireless Train Backbone

Other Shift2Rail projects including CONNECTA are looking at the issues around wireless connection between train vehicles, the WireLess Train Backbone (WLTB). Though this technology is primarily aimed at eliminating the wired connection between vehicles there is clearly an overlap with virtual coupling, since WLTB will provide a form of short range T2T communication. MOVINGRAIL deliverable D3.3 “Proposals for Virtual Coupling Communication Structures” will consider the use of WLTB in the virtual coupling train control architecture.

3. Virtual Coupling

Virtual Coupling is a train-centric control system whereby trains are connected by electronic signals such that they travel in the same direction along the same route, at the same speed and have, with some delays imposed by communications latency, the same braking characteristics as each other. Trains thus coupled are referred to in the literature as in a "platoon" or "convoy". Virtual Coupling is envisaged as the next generation of signalling system with the aim of increasing capacity on congested railways.

Currently most train control philosophies use Absolute Braking Distance which is calculated to the rear of train ahead assuming it is stationary (zero velocity), whereas Relative Braking Distance (see Figure 4) takes into account the velocity of the train ahead and is synonymous to the way road vehicles are driven.

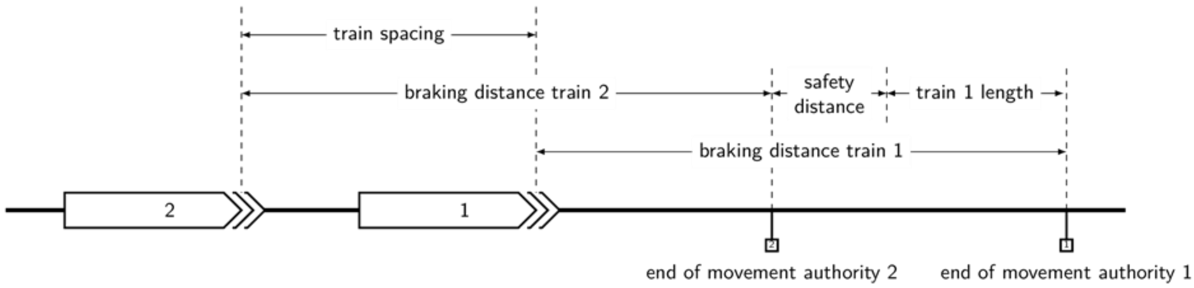

Figure 4 – Trains separated by Relative Braking Distance

In Virtual Coupling each train is aware of the speed, acceleration and position of the train ahead, and of other trains in the convoy, by the exchange of Cooperative Awareness Messages (CAMs). Each train is therefore able to calculate its own braking curve in order to ensure that it will attain and match the velocity of the train ahead, to avoid it colliding with it. This allows the train following to travel at its relative braking distance to the train ahead, rather than the absolute braking distance that would have been maintained with conventional train control such as ETCS level 3 Moving Block.

If the trains are travelling at the same velocity, the relative braking distance of the following train is zero metres and therefore the actual distance between the two trains is determined by only the safety margin. The safety margin is not yet formally defined but would need to consider, amongst other things: The latency of communications between the trains; errors in speed and velocity measurement; and impact of track gradients.

This relative braking distance calculation assumes that the deceleration of the train ahead can be matched or exceeded by the train following. This assumption will fail if the train ahead should collide with an "immovable object" and stop in a sudden and uncontrolled fashion, in less than its normal emergency braking distance.

In order to implement Virtual Coupling, the train ahead must be aware of the braking characteristic of the train following, and the train following must be aware of the velocity and location of the train ahead. With this information shared, the train ahead can ensure that its own braking characteristics are never better than those of the train following such that the train ahead never decelerates more rapidly than the train following is able. This implies that the train ahead might need to cooperatively degrade its own braking performance. With the information provided to the

train behind, it can match the speed of the train ahead, and remain within its relative braking distance. Alternatively, a following train may maintain a bigger distance to a train ahead with faster deceleration capabilities according to the relative braking distance.

Virtual coupling requires accurate positioning see §3.1.1. TIMS devices are also required, as for ETCS level 3. For the European rail network it has been suggested that for a platoon of trains the leading train will receive an ETCS movement authority and that all following trains within the platoon will have a "Virtual Coupling Movement Authority" which will give the train authority to be virtually coupled to the train ahead. For other sectors it is also envisaged that virtual coupling will sit with the train control system normally in use, such as CBTC.

The motivation for virtual coupling is the prospective improvement in capacity that can be achieved.

There is clearly a close synergy between automotive platooning and railway virtual coupling. There are also significant differences between these areas relating to poor braking (due to steel wheel on steel rail adhesion), the long length of trains, high mass and inertia including significant lags and the inability of trains to manoeuvre. These differences translate to very large distances when virtual coupling commences and a gulf in the target safety integrity levels.

Another significant difference between the road and rail domains is that, for roads traditionally safety is placed with the driver (who is in control of a highly responsive machine with the ability to mitigate hazards, e.g. by swerving); whereas from the very early days of railways the need for safety signalling (because of the limited braking and lack of mitigations to the driver) was apparent. Hence new automotive technologies, such as platooning, do not have a core safety system to build upon and are predominantly standalone driver aids.

3.1.1. Train Localisation

It is likely that virtual coupling will require greater positional accuracy than other forms of train control. Railway control systems use longitudinal lineage (track distance from last reference point) to carry out speed control curve calculations. For ETCS systems accuracies of 4m +5% of distance are achieved, however virtual coupling will require close accuracy even when far from the reference positions. Other projects are looking at the use of Global Navigation Satellite System (GNSS) and Augmented GNSS. Although this technique requires communication it is considered out of the scope of this analysis.

3.1.2. Virtual Coupling Sector Differences

It is inevitable that there will be some differences between the markets (High Speed, Mainline, Regional, Urban and Freight) in their requirements for virtual coupling. The aim should be for maximum commonality as this will lead to the lowest costs.

High Speed, Mainline and Regional railways which form part of the European rail network are transitioning to ERTMS. We assume that virtually coupling trains will be initially controlled under ETCS Level 3 and will therefore be capable of receiving connection establishment (convoy joining) information from a centralised regulation system by means of a network connection. Furthermore, these trains can be expected to be fitted with FRMCS (Future Rail Mobile Communications System). For these trains it would appear that Train to Infrastructure communication (T2I) has only limited

potential, because point control and locking will remain with an interlocking, and the speeds and distances involved would prevent cooperation with road traffic at grade crossings.

For High Speed and mainline railways, the speeds involved and mass of these trains mean that absolute braking distances are large, e.g. 1250 m from 180 km/h. A consequence of this is that the initial stages of a virtual coupling will require exchange of CAMS telegrams over distances unsuitable for direct (side link) communication.

Metro systems stand out as different. Traditionally these systems, normally self-contained, have utilised bespoke radio solutions for voice. Their control systems are often communication based, however currently radio plays only a small part in train control systems. For train control purposes metros tend to utilise local inductive loop/balise communications. For consistency with other modes metros could employ the same peer to peer radio for the direct communication needed for virtual coupling as 'mainline', however this would build on the metro's control framework and not ETCS.

LRT, and trams in particular, are very different and very close to automotive. Similar issues, such as splitting of a platoon because of traffic signal change, arise and hence this sector has the potential to benefit from T2I communication. This sector is also more likely than the others to use communications to establish ad-hoc autonomous joining.

It is also the only mode which is susceptible to the possibility of the direct (V2V) radio path being blocked by an intervening road vehicle, see Figure 5. In the automotive sector it is proposed that this issue is resolved by reflections, however the effectiveness of this approach remains an open point.

Figure 5 – Blocking of direct path by intervening vehicle in automotive sector

3.1.3. Virtual Coupling Open Safety Challenges

An open safety point, which will require resolution, is whether existing safety levels can be maintained in the event of the lead train suffering an incident. The concern is, in the case of a rear-end collision, the performance of virtually coupled trains against mechanically coupled trains given the mechanical couplings role in the crashworthiness of the train.

A further open safety point is the conflict between a lead train normally using maximised braking, say because of an ATP trip, with a requirement for a lead train to moderate its braking to match a following train may result in an unresolvable requirements conflict.

4. Methodology

4.1. High Level Requirements

Currently, the high-level requirements are ill-defined for virtual coupling with work ongoing within complementary Shift2Rail projects (CONNECTA-2, X2RAIL-3). However, virtual coupling is generally agreed to be defined as trains running closer than their absolute braking distance, but outside of their relative braking distance, and still not collide [12]. This is for the purpose of running trains closer together, and thus increasing the capacity of a railway without adding further rail lines.

A literature review of public domain (and private where accessible) Shift2Rail information and related open source information was assessed for relevance to virtual coupling. Initial scan reading of this documentation was used to provide a ranking of documents for detail review (Appendix A – Source Document Review Table). Identified research documents are referenced by their line item number in the Source document review table. Documents that were ranked as relevant to virtual coupling were then subject to detail review to extract relevant requirements.

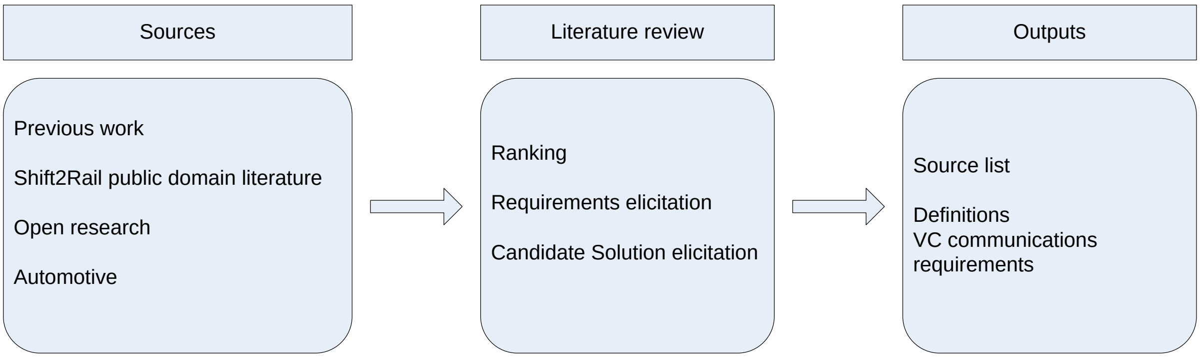

Figure 6 - Virtual Coupling Communications Requirements road map analysis

Of particular relevance was User & System Requirements (Telecommunications) [13] from X2Rail-1 with virtual coupling within the scope of Automatic Train Control. However, due to the rapid rate of change in the telecommunications field it was necessary to carry out a cross check with the latest standards and the work arising from the UIC Future Rail Mobile Communications System (FRMCS) working group. The information captured was used to produce the virtual coupling requirements set in §5.

4.1.1. Additional Input Material

At a relatively late state in the analysis process additional input material was received from the complementary projects (CONNECTA-2 and X2Rail-3).

From CONNECTA-2:

- D1.1 – Specification of evolved Wireless TCMS [14]

From X2Rail-3

- D6.1 Virtual Train Coupling System Concept and Application Conditions (Draft) [15]

This additional material allowed improvements to be made to the analysis in this document.

4.2. Solutions Capture

Various solutions have been proposed from both academia and industry to solve the problem of direct peer-to-peer communications. These proposals have been published by both Shitft2Rail projects and in the wider research domain, including autonomous vehicle communications, and Internet-of-Things applications.

To ensure that all potential solutions are captured, a literature review of all of these fields was carried out. From this literature review, candidates for virtual coupling communication systems were captured.

The candidates were parsed for references to communications technology in a Virtual Coupling context. The identified technologies were filtered for overlaps and technology evolutions. Similar technologies were traced to generic groupings and governing standards. Radio solutions no longer current were rejected. Given the rapid rate of change in the communications field the latest incarnations of the technology were taken forward for further analysis and review (see §6).

4.3. SWOT and Factor Analysis

For each proposed solution, an assessment of its strengths and weaknesses, and also of any opportunities that it might introduce, and of any foreseeable threats to its effectiveness was undertaken. This is to identify how a solution candidate could fit in to a roadmap for implementing virtual coupling on a real railway.

To perform the factor analysis, the factors considered were the criteria derived from the high-level requirements that were arrived at using the methodology defined in section 4.1. Each solution candidate has been analysed using these factors to facilitate comparison and critical review.

5. High Level Virtual Coupling Communications Requirements

The specific needs of virtual coupling will impart requirements on the communications system that is chosen. The full requirements for the entire virtual coupling system are currently not well defined, or quantified. A literature review of Shift2Rail and open source research was carried out to identify references to communication systems candidates in the virtual coupling sphere.

5.1. Literature review for Virtual Coupling communication requirements

Line ref	Category	Source	Notes
11	CONNECTA-1	D3.1 - Drive-by-Data Requirement Specification	Train inauguration. NG-TCN shall provide the sole communication platform.
12	CONNECTA-1	D3.2 - Drive-by-Data Technology Evaluation Report	Two classes are defined by the standard, class A defined for a frame frequency of 125 µs and latency of 2 ms, and class B for a frame frequency of 250 µs and a latency of 50 ms (IEEE 802.1BA). A class C, defined for a frame frequency of 1 ms, is actually under consideration. Latency time definition.
28	CONNECTA-1	Connected Trams demonstrator brochure	The WLTB is based on LTE technology due to its maturity and its efficient radio access management. Compared to 802.11-based wireless networks, the LTE technology deploys a radio access scheduling, avoiding possible collisions between different users in the wireless network.
45	X2Rail-3	Virtual Coupling concept Safety and performance analysis	Nil
60	X2Rail-1	D3.1 User & System Requirements	Contains full requirements capture adopted from FRMCS User Requirements Specification (URS).
72	Roll2Rail	D2.1 Specification of the Wireless TCMS	Train to Train Communication: Connection (link) between communication devices at the interface between two trains when these trains are virtually coupled. TCMS Function Domain considered ETCS (European Train Control System) and ATP (Automatic Train Protection).
73	Roll2Rail	D2.2 Characterisation of the Railway Environment for Radio Transmission	Use-case Virtual Coupling. New technologies in the 60 GHz range like IEEE 802.11ad and machine-to-machine type communication systems as being defined in 4G and 5G may also be considered.
75	Roll2Rail	D2.3 State of the Art in Radio Technologies and Recommendation of Suitable Technologies	Nil
76	Roll2Rail	D2.5 Architecture for the Train and Consist Wireless	Considers that selected (LTE) methodology for 'discovery' with regards to coupling/uncoupling leaves future possibility for virtual coupling.
77	Roll2Rail	D2.7 Simulations of the Selected Suitable Technologies	Wireless communications between consist to consist will need to coordinate with the Virtual Coupling concept. This means that two backbones will exist, one for the communication within the TCMS domain, which can be also safety related, and another for the

			regular train backbone communication of the other domains.
79	Safe4Rail1	System Integration Requirements	6 WP1ramsmain_6 System integration layer should support stepwise network operation and frame dissemination operation. Note: this is to support system verification and virtual coupling.
80	Safe4Rail1	Initial Drive-by-Data Draft Concept Design	Nil
95	Open Research	Analysis of Platooning Train Operations Under V2V Communication-Based Signalling: Fundamental Modelling and Capacity Impacts of Virtual Coupling	The signalling architecture of Virtual Coupling builds on the basic modules of ETCS Level 3 and 4 and introduces a vehicle-to-vehicle communication layer (V2V comm) on top of it. Risks can be mitigated if Virtual Coupling can supervise both the relative and the absolute braking curves. In this way, the safe distance from a converging junction would be supervised directly by Virtual Coupling without the need of many communication switches.
96	Open Research	A multi-state train-following model for the analysis of Virtual Coupling railway operations	ETCS Level 3: Trains have a radio-based Vehicle-to-Infrastructure (V2I) communication with the Radio-Block Centre (RBC) reporting train position updates every few seconds (usually every 1 to 5 s). V2V: Additional on-board antennas are hence considered to enable such a communication. For simulation modelling: The MA and the MAVC are broadcasted with an update interval of 1s and a communication delay of 1s.
98	Open Research	Hybrid vehicular communications based on V2V-V2I protocol switching	Vehicular Ad-hoc NETworks (VANETs) are emerging as the preferred network design for intelligent transportation systems. Discussion of switching strategies between V2V and V2I. Dated (2011) so 3G max.
99	Open Research	On the Performance of TETRA DMO Short Data Service in Railway VANETs	Tetra performance.
100	Open Research	A Railway Collision Avoidance System Exploiting ad-hoc Inter-vehicle Communications and Galileo	Nil
102	Open Research	5.9 GHz inter-vehicle communication at intersections: a validated non-line-of-sight pathloss and fading model	Nil
103	Open Research	ITS-G5 Channel Models for High Speed Train-to-Train Communication	Nil
104	Open Research	Wide Band Propagation in Train-to-Train Scenarios - Measurement Campaign and First Results	Nil
105	Open Research	On the Ability of the 802.11p MAC Method and STDMA to Support Real-Time Vehicle-to-Vehicle Communication	Consequently, applications have different requirements on the values of the parameters deadline and reliability.

106	Open Research	Performance Comparison Between IEEE 802.11p and LTE-V2V In-coverage and Out-of-coverage for Cooperative Awareness.	Comparison of the performance of two technologies for cooperative awareness: IEEE 802.11p/ITS-G5 and LTE-V2V. These results revealed that there is not an optimal technology for every condition and that the adoption of a given technology depends on the specific application requirements, especially in terms of communication range and packet size.
109	Open Research	A location-based MAC protocol for safety-of-life vehicle-to-vehicle communication	Nil
110	Open Research	Direct Vehicle-to-Vehicle Communication with Infrastructure Assistance in 5G Network	What is expected for (from 5G) V2V communication is 5 times reduced E2E latency with much higher reliability compared with the current 4G network. V2V traffic with 10 Hz periodic transmission of a packet of 1600 Bytes
111	Open Research	A Survey of Channel Measurements and Models for Current and Future Railway Communication Systems	One of the candidate technologies for the wireless connection is UWB (Ultra Wideband) such as the IEEE 802.15.4a standard. New technologies at 60GHz carrier frequencies like IEEE 802.11ad and machine to-machine type communication systems as being defined in 4G and future 5Gmay also be considered.
112	Open Research	A Feasibility Study and Development Framework Design for Realizing Smartphone-Based Vehicular Networking Systems	802.11 LTE
113	Open Research	3GPP LTE Versus IEEE 802.11p/WAVE: Which Technology is Able to Support Cooperative Vehicular Safety Applications?	TABLE I: BEACONING PARAMETERS Beaconing rate 10 Hz Beacon size (L) 300 bytes Beacon delivery deadline 100 ms
116	Open Research	Towards Railway Virtual Coupling	Considers VC as part of ERTMS (L4). Evolution of GSM-R through LTE and 5G. In Virtual Coupling scenarios, train-to-train communication becomes essential to maximise the probability of message delivery compared to train-to-track only (i.e., fully infrastructure based). In fact, Virtual Coupling requires extremely low reaction times and hence latency to synchronise multi-vehicle behaviours. Possible topologies include: “fully connected”, in which the RBC communicates with the entire train fleet merged into a platoon and each train, in turn, forwards some information to its neighbours; “chain-like”, in which the RBC communicates with the first train of the platoon that, in turn, forwards the messages to the following train like in multi-hop/mesh routing.
121	Open Research	Increase of Capacity on the Shinkansen High-Speed Line Using Virtual Coupling	The close distance between two trains, which could be, for example 10 m.
140	Open Research	Communications Technologies for Vehicles	QoS-Aware Radio Access Technology (RAT) Selection in Hybrid Vehicular Networks QoS-aware RAT selection algorithm is proposed for HVN. The proposed algorithm switches between

			IEEE802.11p based ad hoc network and LTE cellular network by considering network load and application's QoS requirements. Performance Analysis of ITS-G5 for Dynamic Train Coupling Application. In order to realise dynamic train coupling, position and speed information must be reliably exchanged between trains with very low latency. In Europe ITS-G5, which uses IEEE 802.11p technology for radio access, has been chosen for C-ITS. IEEE 802.11p offers the ability of direct communications between vehicles, i.e. ad hoc communications, for up to a few kilometres. Doppler shift, relating to train velocity, contributes to the bit error rate. Discusses LTE railway specific features.
146	Open Research	Communications Technologies for Vehicles	The Viability of TETRA for ETCS Railway Signalling System. Standardisation Roadmap for Next Train Radio Telecommunication Systems 3GPP Its scope has enlarged later on, to encompass public safety services and Machine-Type Communications (MTC). It targets now vehicular domain (V2X). next generation (5G) aims at including from its very beginning, requirements for broadband public access … vehicular services Measurement and Analysis of ITS-G5 in Railway Environments With these measurements a proper usage of ITS-G5 in a railway environment is proven. For certain applications within a coverage of up to 1200m this communication standard is able to handle the diverse environments along a rail track

5.2. High Level Requirements

To be able to compare potential solution candidates for use as the communications system for virtual coupling, the high-level requirements have been defined below, based on the engineering judgement of the authors and the results of the literature review.

Documents identified in the literature review (§1.3) as potentially containing requirements on virtual coupling communications were analysed with any requirements relevant to virtual coupling communications extracted and presented in §5.1.

A comprehensive baseline for Virtual Coupling communication requirements was found in the X2RAIL-1 document D3.1 User and System Requirements (Telecommunications) [16], however, the FRMCS User Requirements Specification has moved on considerably since the analysis in that document (Current version: 5.0.0 19/02/20) [17].

The authors have taken this into account along with other ad-hoc identified requirements to produce the high-level requirements for Virtual Coupling Communications (Refer to §5.1).

This allows the solution candidates to be evaluated side-by-side, using comparable metrics of communications systems.

5.2.1. Virtual Coupling Functional Requirement- Performance

The primary requirement for virtual coupling is the desired separation between trains, in terms of distance and time. The intention of virtual coupling is to reduce this as far as possible, while maintaining a safe, reliable and economically practical operation of the railway. The safe operation of the railway will thus depend on the relative braking distance, plus some safety margin, to separate trains, as opposed to separation by absolute braking distance.

This implies that the End of Authority of a following train will now have a non-zero speed associated with it, and that this speed will be the speed of the preceding train. Under this method of operation, the minimum distance between trains is determined by the relative braking distance, plus a safety margin, plus any latency in updating the movement authority of the following train.

This implies that to maximise the capacity of the railway, the latency of the communications needs to be as short as possible, and the frequency of messages to update the movement authority need to be as high as practicable. It is also generally agreed that this implies that trains following one another will directly communicate (i.e. train-to-train communications), as opposed to movement authorities being managed by an RBC.

The review of previous research into requirements for virtual coupling communications identified that the 'new' functional requirement of virtual coupling communications, above the needs of moving block, is that of direct communication i.e. T2T.

There was found to be consistency in the topic set for the communication criteria to be applied to virtual coupling functional requirements i.e. Communication Type, Symmetry, Distribution, Latency, Bandwidth, Link Reliability, Setup, Availability and Speed (of travel) amongst the research documents and, in particular, between X2Rail and FRMCS.

5.2.2. Virtual Coupling Non-functional Requirement- Reliability

Because a train can now travel at some speed, while remaining quite close to its End of Authority, if the End of Authority is not regularly updated, then the train will exceed its authority, and have to stop. If the communications between trains is not reliable enough, this could happen frequently. This implies that for a virtually coupled railway to be a success, the communications between trains needs to be sufficiently reliable to ensure that the movement authority is regularly updated. Where the communications do fail, how quickly it can then recover to resume virtual coupling operation is also important.

The topic set for the communication criteria to be applied to virtual coupling non-functional requirements is: Network Security Risk, Upgradability, Longevity, Maintainability, Return On Investment (ROI), Backward Compatibility, Installability and Equipment reliability (MTBF).

5.3. Criteria to Analyse Solution Candidates

5.3.1. Basic Functionality

The virtual coupling communications system must be capable of providing symmetric (50/50 up/down) bi-directional data exchange with direct peer to peer (T2T) capability, along with network connectivity (T2N) to the control centre and distant trains.

5.3.2. Latency

A train that is using virtual coupling needs to receive timely and frequent information about the speed, location, acceleration and etc of any train ahead of it on the track, so that it can adjust its own speed in order to maintain a safe distance, and avoid colliding with the train ahead. In order to utilise the full capacity of a virtual coupled railway, trains need to be operated as closely together as can be safely achieved.

For the purposes of comparison, we define latency as the time between one train announcing its position and speed, and another train receiving that information, such that it can act on it.

For virtual coupling communications the latency must be LOW, i.e. immediate, less than 100ms [18].

5.3.3. Bandwidth and Spectral Efficiency

In today's modern wireless world, there is an increasing number of devices and systems all competing for the same electromagnetic environment. Electronic systems are having to be developed with more stringent EMC requirements to ensure that they can still function correctly in this new world. The communications system that is chosen will need to efficiently use its allocated band of the spectrum.

Usually bandwidth, i.e. anticipated rate of data transfer, is measured in units of bits per second per hertz. However, it can also be thought of in terms of the number of messages that could be simultaneously in transit between vehicles within an allocated frequency band.

The bandwidth, i.e. the anticipated rate of data transfer, for Virtual Coupling is LOW (e.g. from the automotive sector the size of the most common messages in V2X communications falls between 150 bytes and 900 bytes, being transmitted with a periodicity of 1-10Hz. i.e. less than 72kilobaud per train [19])

5.3.4. Link Reliability

To ensure the safety of a set of virtual coupled trains, if a train behind does not receive an update on the status on the current speed and position of the train in front, it will need to assume that the train in front is decelerating at the maximum rate. This means that in the situation where train to train communications breaks down, the train in rear will need to apply the emergency brake. This will result in discomfort for the passengers of this train. This imparts a reliability requirement on the communications system.

For the purposes of this discussion, the reliability that we are concerned about is the ability of the communications medium to deliver individual messages to the correct train within a defined timeframe. This includes the ability of the link to handle unexpected disturbances such as interferences.

For the Virtual Coupling communications system, the required link reliability is HIGH. The communication link for virtual coupling needs to be available 99.99% of the time.

5.3.5. Setup Time

We assume that, for trains on the European rail network, coupling trains will be initially controlled under ETCS Level 3 and will therefore be capable of receiving connection establishment

information from a centralised regulation system by means of a network connection. Therefore, the setup time (time to establish communication session) required for the Virtual Coupling communications system will be NORMAL. We note that previous X2RAIL-1 assessments had this property as IMMEDIATE. The implications on recovery time should also be considered.

For Urban systems we consider that Metros will also be under the control of a traffic management system however it is trams (SCT) where the potential for coupling following discovery of other trams within the vicinity exists. The discovery would be achieved via ad-hoc network (V2I) requiring IMMEDIATE setup time.

5.3.6. Range and Speed

The effect of speed of travel on the radio communications needs to be considered e.g. doppler shift. For virtual coupling the required speed of travel is HIGH (0 - 500km/h).

A simple calculation for a train stopping from 180 km/h at a braking rate of 1 ms^{-2} shows that the braking distance is 1250 m. This shows that even for modern trains with good braking rates, the communication from one train to another will need to be made over a long range.

Within the context of Virtual Coupling, a discussion of range cannot be limited to merely the geographical distance between two trains, but must also consider the situations in which the trains might be. This is because radio signals interact with the environment. The geographical range of a signal at a particular power level will be reduced in any environment where there are objects for the signal to diffract, refract or reflect on. This will be especially true in heavily wooded areas, tunnels or heavily-built-up areas.

5.3.7. Peer-to-peer (P2P)

Quaglietta et al in 'multi-state train following model' [20] assumed that the communications data path for an ETCS level-3 solution is considered to be too long and therefore, a train-to-train communications path is considered desirable for virtual coupling.

This is different to ETCS level 3, where the train in front communicates its position to an RBC, which reinterprets this position and issues a movement authority to the train behind. It is not defined, however, that the communication needs to be direct from transmitter on one train to receiver on another, but could be via a cellular network of base stations.

For this discussion a peer-to-peer network is one in which messages from one train to another train are not interpreted or modified by any intermediate system through which they might pass. The significant feature of a peer-to-peer network is that the communication between peers is not arbitrated, moderated, or modified by steps in the communication path.

The automotive sector has identified critical situations e.g. where direct communication can be blocked by intervening vehicles. For rail curvature within tunnels may create a similar critical situation that will need addressing in the system design.

5.3.8. Congestion Management/Multiple Access

The intention of virtual coupling is to increase the capacity of a fitted railway. This implies that the density of trains will increase, and thus the density of radios communicating using the same network will also increase. For railways at a lower speed, this will be especially marked, as trains

could be very close together, and the radio environment may more closely resemble a highly populated area with many mobile phones, or an IoT fitted swarm of devices.

This means that any communications system will need to be able to continue to deliver messages promptly and reliably, even when there are a large number of trains communicating with one another. For the purposes of this discussion congestion is determined by the number of vehicles within communication range of one another such that the signals between one set of virtually coupled trains could be received by other unrelated sets of virtually coupled trains. The congestion of a network is a function of message transmission time and message frequency.

5.3.9. Technology Readiness

For a system to be cost effective to implement, the risks associated with implementing the technology need to be minimised, wherever possible. For virtual coupling to be implementable, the technology that underlies the chosen communications system needs to be proven, and available at an appropriate cost. Technologies that are still in the early stages of concept development may not succeed which may impart unacceptable risk onto a realisation of the virtual coupling system.

For this study, an assessment of whether the proposed technology is ready for deployment or the amount of time, effort and money that would be required to make it ready for deployment will be considered.

5.3.10. Longevity

Because of the highly integrated nature of a railway system, with its many interfaces and interactions, the railway can be slow to implement a new technology. Therefore, when new technologies are chosen to base a new method of operation on, it is important that the technology is new enough that it will not become obsolete before full implementation is achieved. It is important to remember that railways have a tendency to take longer to implement new technologies than originally anticipated; in the UK, Train Protection and Warning System (TPWS) was intended to only be a stop-gap until ERTMS is implemented [21], however other than a few systems, no major ERTMS roll-out has occurred as of 2019.

For this study, consideration of how soon or how easily the proposed solution might become unavailable due to lack of availability of bandwidth at specific frequencies, equipment or spare parts becoming unavailable, or bandwidth pollution will be made, and an assessment made to that effect. Upgradability and obsolescence management will influence the likely longevity of the solution to be proposed.

5.3.11. Cost and Revenue

The cost components that need to be considered for each proposed solution include the costs of development, deployment, and maintenance. These things cannot be easily quantified at this stage and will not be considered in detail, nor will any attempt be made to evaluate them.

The revenue considerations will be determined by capacity and journey times. These things are considered to be beyond the scope of the present work.

5.3.12. Robustness

It is likely that the commercial viability of virtual coupling will require the maximum use of Commercial-Off-The-Shelf (COTS) equipment. It is also essential that the equipment achieves reliability and longevity in the harsh railway environment. It will therefore be necessary for the railway variants of equipment to comply with the railway domain standards including EN50121 Electromagnetic compatibility [22] and EN50125 Environmental conditions for equipment [23].

5.3.13. Security and Safety

Responsibility for the highest integrity control functions (authorisation, identity and key management) lies with the application layer (see Figure 7 – EuroRadio protocol stack) and is implemented by the safe computer (e.g. European Vital Computer (EVC)) of the train control system rather than by the communications equipment. In this regard, differences in the safety integrity targets for automotive and rail are of note. Traditionally railway control systems are required to meet the highest (SIL4) safety integrity targets particularly due to the societal expectations of rail safety. Currently the targets for automotive are somewhat lower (the order of SIL2). The reason for the acceptability of lower SILs for automotive is partly due to the complexity of the control systems needed for automotive and partly because automation even with low integrity is an improvement upon an unreliable human driver. Unlike automotive, it is natural for rail for safety responsibility to be placed with the, generally already existing, high-integrity safety computer.

The communications equipment is required to provide high availability which, where necessary, may require redundancy/duplication e.g. by provision of overlapping base stations.

The design of the communications network should be able to provide the required availability taking into account the cyber security threats.

The overall virtual coupling system must respond safely to envisaged communication system hazards, for example loss of communication must be dealt with via timeout and braking with allowance for this in the safety margin distance.

The automotive domain uses a concept of 'TRUST levels' as a measure of the required behaviours (availability, security, performance, integrity/trust and privacy) of critical communications. This has similarities to the rail domain use of integrity levels.

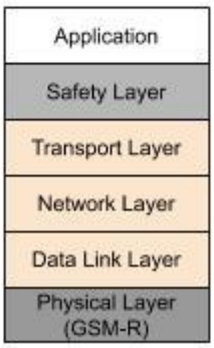

Figure 7 – EuroRadio protocol stack *[24]*

6. Communication Solution Candidates

A literature review was carried out using the method of §4.2. The literature was parsed for references to communications technology in a Virtual Coupling context. The identified technologies were filtered for overlaps (e.g. ITS-G5 and WAVE) and technology evolutions (e.g. 3G to 5G).

Following a filtering of potential candidates the candidate solutions identified for further analysis and review are:

- TErrestrial TRunked RAdio (TETRA) [25]
- 3GPP Standards [26]
- IEEE 802.11 [27]

6.1. TETRA

6.1.1. Background

TErrestrial TRunked RAdio (TETRA) was primarily developed to meet critical voice and narrowband data requirements within groups of users. TETRA is primarily designed and suitable for professional mobile radio and is characterised by its services and features especially for use by authorities and organisations with security tasks. TETRA fulfils the increased safety and security requirements of these user groups by sophisticated authorisation procedures and integrated end-to-end encryption. The first generation of networks were deployed in 1997.

Although implementation of TETRA on mainline railways (e.g. Taiwan and Kazakhstan) [28] are rare, there has been take-up of Tetra by urban / metro stand-alone systems (e.g. Transport for London (London Underground)).

TETRA and other Personal Mobile Radio (PMR) technologies are common for voice communications, and status data, but less common for signalling use.

6.1.2. Technology

Data communication is based on a $\pi/4$ DPSK (Differential Quadrature Phase Shift Keying) modulation scheme, which has a spectral efficiency comparable to GSM, but is limited by the channel bandwidth of 25 kHz.

TETRA operates in the UHF band, which provides favourable propagation conditions compared to higher frequency bands.

It provides data communication such as the Short Data Service (SDS) which can be used in Direct-Mode Operation (DMO), and this mode is particularly interesting for train-to-train communications since it allows infrastructure-less point-to-point and point-to-multipoint transmission, as well as a fast call setup.

Table 3 – TETRA Technology Summary

	TETRA
Frequency Band	For emergency services in Europe: 380-383 MHz and 390-393 MHz have been allocated. For civil systems in Europe 410-430 MHz, 870-876 MHz / 915-921 MHz, 450-470 MHz, 385-390 MHz / 395-399,9 MHz, have been allocated [29]
Voice transmission	Yes
Data Rate	<10kbit/s (standard), up to 260kbit/s (TETRA enhanced Data Service) [30]
Handover mechanisms	Standard
Technology maturity	Mature
Market structure	Multiple suppliers
Spectral efficiency	High (up 28.8 kbit/s in a 25 kHz channel)
Operation	Possible at high relative velocities of over 400 km/h

6.1.3. Operation

TETRA uses Time Division Multiple Access (TDMA) and features two modes of operation:

- TMO (trunked-mode operation) for communication between TETRA terminals and a base station
- DMO (direct-mode operation) for infrastructure-less operation. DMO also allows operating one or more terminals as a relay.

6.1.4. Issues

Short range. Data limitations. Uncertain longevity.

6.1.5. Suitability

TETRA does not have a significant footprint in the rail control or automotive sectors. There is uncertainty of TETRAs ongoing longevity.

6.2. 3GPP Standards

6.2.1. Background

The set of 3GPP (3rd Generation Partnership Project) standards have become dominant for cellular mobile communication networks.

The standards cover both public and private networks with GSM adopted as the basis for the European Railway radio system GSM-R. 2G first emerged in 1991, the fifth generation (5G, the TS 38 Series specifications) is commencing roll-out (2019). The evolution path is towards an entirely IP based protocol.

The UIC Future Rail Mobile Communications System (FRMCS) working group is targeting the 5G technology, and expects the incorporation of a majority of FRMCS requirements into the 3GPP Release 17 (5G 3rd edition) [31].

6.2.2. Technology

5G uses New Radio (NR) technology. The Radio Access Technology (RAT) is an evolution from 4G LTE.

5G NR uses two frequency ranges:

- Frequency Range 1 (FR1), including sub-6 GHz frequency bands
- Frequency Range 2 (FR2), including frequency bands in the mm Wave range (24–100GHz).

The FRMCS dedicated spectrum for critical applications will be included in the 3GPP standards, which will be enhanced by railway requirements.

5G supports two modes of operation:

- Device-to-device (Vehicle-to-vehicle and vehicle-to-infrastructure)
- Device-to-network (V2N).

Of note is the fact that direct communications V2V and V2I does not need require a base.The 5G specification incorporates direct communication between a vehicle and other devices using the PC5 interface (LTE direct). Of note 5G cellular sidelink capability is optimised for mobile operation.

6.2.3. Operation

5G moves further along the evolution path towards full IP (Internet Protocol) based data transport, see Figure 8.

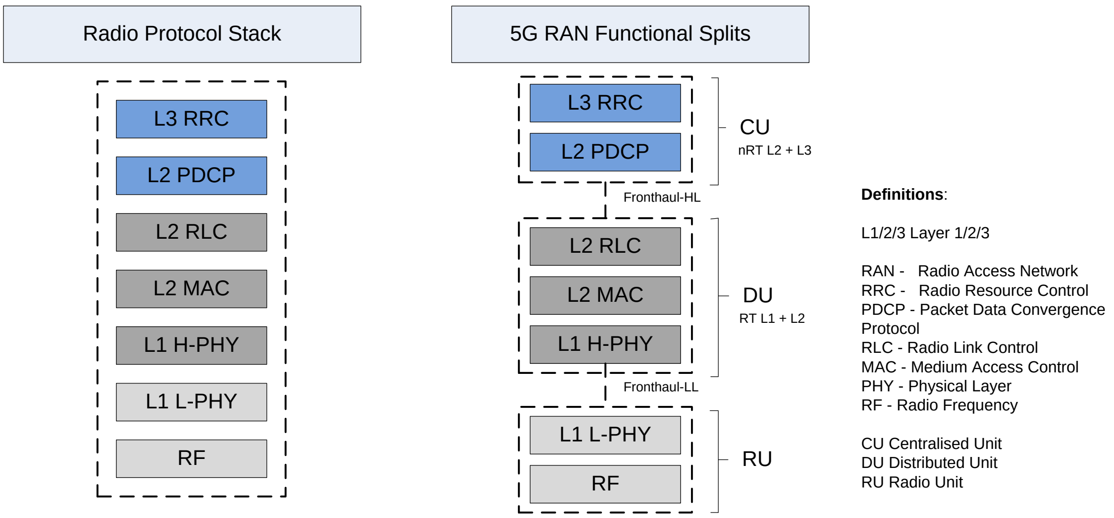

Figure 8 – 5G Radio Access Network

The 3GPP standards allow for unsymmetrical upload/download speeds with upload slower than download. However, the upload data speeds achievable with 4G (10Mbps) easily fulfils the needs of Virtual Coupling communication systems. Maximum and typical data speeds are given in tables Table 4 and Table 5 below.

Table 4 – Theoretical Maximum Network Speeds

Network Type	Download Speed (Mbps)	Upload Speed (Mbps)
3G	7.2	2
3G HSPA+	42	22
4G LTE	150	50

Source reference: [32]

Table 5 – Typical Real World Network Speeds

Network Type	Download Speed (Mbps)	Upload Speed (Mbps)
3G	3	0.4
3G HSPA+	6	3
4G LTE	20	10

Source reference: [32]

One of the key criteria in the evolution to 5G is for latency of 1ms, 50 times better than 4G (ref: [32]).

For 4G, channel bandwidths are of 5–20 MHz, optionally up to 40 MHz.

For 5G, a range of over 450m using direct mode and very large range using the network is achieved.

Operation with relative speed of up to 500 km/h is supported as a minimum requirement.

The maximum number of users supported by 5G NR FR2 is 64 – 250.

6.2.4. Issues

Cellular V2V was late into the Intelligent Transport Systems (ITS) market significantly behind Dedicated Short-Range Communication (DSRC) but is now overtaking into lead position, although 5G is still evolving.

6.2.5. Suitability

GSM-R is proven in the railway domain. Cellular communications are now ubiquitous and dominated by the 3GPP specifications. 5G is a natural successor, under FRMCS, for GSM-R. Inclusion of sidelink capability, principally for automotive applications, is in close alignment with the virtual coupling requirements, whilst its 'traditional' network connectivity via base stations well suits the larger distances involved in rail compared to road.

6.3. IEEE 802.11

6.3.1. Background

IEEE 802.11 is the protocol specification for implementing wireless Local Area Network communication (Wi-Fi).

The first version of the 802.11 protocol was released in 1997, and provided up to 2 Mbit/s link speeds. This was updated in 1999 with 802.11b to permit 11 Mbit/s link speeds.

IEEE 802.11p is an approved amendment to the IEEE 802.11 standard to add wireless access in vehicular environments (ITS-G5/WAVE), a vehicular communication system (July 2010).

The use of Wi-Fi for short-range vehicle-to-vehicle communication has been recognised in the automotive sector with IEEE 802.11p ITS-G5/WAVE variants being specifically for this purpose.

DSRC (Dedicated Short-Range Communication), which is known as ITS-G5 in Europe, uses Wi-Fi (IEEE 802.11p) communication dedicated to vehicular use.

6.3.2. Technology

Table 6 – IEE 802.11p Technology Summary

	IEE 802.11p (ETSI ITS-G5)
Access Points	Moving (150 km/h or more)
Nodes	Static/moving
Type	Master/Client – point to multipoint
Data Rate	6 – 108 Mbit/s
Average throughput	>1 Mbit/s
Range	50m – 300m
Frequency	5.85 – 5.925 GHz
Spectrum use	Unlicensed
MIMO	Not applicable
Point to point	5GHz band
Point to multipoint	Usually 2.4 GHz
Latency	40 – 200 ms

6.3.3. Operation

Figure 9 shows the WAVE protocol stack (Source ref: [33]).

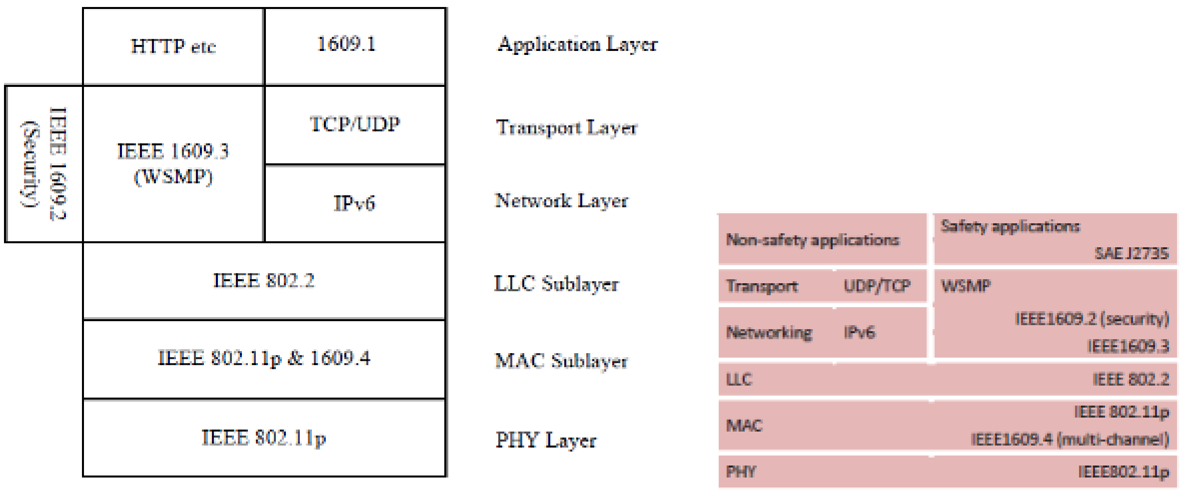

Figure 9 – WAVE Protocol stack

Note that the conventional Wi-Fi link setup with beacon scanning and multiple handshaking is too slow for use with dynamic vehicles. WAVE allows the data exchange to be setup using the wildcard BSSID, significantly reducing the setup time [34].

For smaller vehicle densities (up to 50), IEEE 802.11p standard offers end-to-end delays less than 100 ms and throughput equivalent to 10 kbps [35].

WAVE specifications include IEEE1609.2, “Standard Security Services for Applications and Management Messages”. This lines up with the principle of V2X communication security being based on signed messages using Public Key Certificates.

6.3.4. Issues

From the technical information above, particularly Table 6 – IEE 802.11p Technology Summary and Figure 9 – WAVE Protocol stack, the following issues can be identified.

WAVE range of operation is limited to several hundred metres.

Some sources raise concerns about the reliability of DSRC because of possible transmission collision and harsh channel fading with minimum reliability unspecified, and is known to be susceptible to the ‘hidden nodes in CSMA protocol’ problem [36]. It is, however, considered suitable for road safety purposes.

6.3.5. Suitability

Wi-Fi is one of the technologies of choice for direct communication (V2V) in the automotive sector. It is well suited to meet the requirements for virtual couplings direct link but less so over the longer distances required by rail.

7. Candidate Solutions Communications Requirements Compliance

In this section the ability of the solution candidates (TETRA, 3GPP and Wi-Fi) to satisfy the requirements needed for a virtual coupling communications system identified in §5.3 are captured.

7.1. TETRA

Requirement / property	**Compliance**
Symmetric 50/50 bi-directional data	TETRA was primarily developed to meet critical voice, however has narrowband data capability (<10kbits/s) and also TETRA Enhanced data service up to 260kbits/s.
Latency must be LOW, i.e. immediate, less than 100ms	End to end delay<200ms
Bandwidth	25kHz channel bandwidth Data rate upto 260kbits/s
Link reliability MTBSAF	Specifically designed for critical applications
Setup time	Supports fast call setup (150 – 300ms).
Range and speed	Operation possible at high relative velocities of over 400km/h.
Peer to peer (T2T) capability	TETRA features two modes, TMO (trunked-mode operation) and DMO (direct-mode operation). DMO provides T2T allowing infrastructure-less operation between one or more terminals.
Congestion management / Multiple access	Capable of point-to-multipoint transmission.
Technology readiness, Scalability, Migration, Upgradeability, installability	Tetra is mature and available. Few existing railway comms systems are Tetra capable as starting points for migration.
Longevity, Maintainability , Equipment reliability, obsolescence management	Whilst Tetra currently is holding its position in the fast moving communications domain, there is no evidence that it will be retained.
Cost and revenue	Several suppliers, available on the open market. Requires licensed spectrum.

7.2. 3GPP

Requirement / property	**Compliance**
Symmetric 50/50 bi-directional data	The 3GPP standards generally allow for slower upload speed. Practical achieved speeds: 4G Download 20Mbps, Upload 10Mbps. Though upload speeds are less than download, they are easily adequate for VC needs.
Latency must be LOW, i.e. immediate, less than 100ms	50ms (4G)

Bandwidth	For 4G, channel bandwidths of 5–20 MHz, optionally up to 40 MHz, providing an upload data rate of 10Mbps.
Link reliability MTBSAF	Whilst originally the 3GPP standards were for general users, they have evolved to include the needs of critical applications.
Setup time	The 5G standard specifically includes the immediate setup requirements for direct V2V communication adopted from the IEEE802.11p standard.
Range and speed	For 5G: A range of over 450m using direct mode and very large range using the network. And relative speed of up to 500 km/h supported as a minimum requirement.
Peer to peer (T2T) capability	From Release 13 direct (Sidelink) capability is required, implementation based on IEEE 802.11p.
Congestion management / Multiple access	For LTE a base station can typically support 64-128 simultaneous users.
Technology readiness, Scalability, Migration, Upgradeability, installability	3GPP standards have evolved from 2G to the latest 5G with an upgrade path provided. Manufacturers are just releasing 5G equipment into the market.
Requirement / property	**Compliance**
Longevity, Maintainability , Equipment reliability, obsolescence management	3GPP standards have evolved from 2G to the latest 5G. 5G implementation is at the start of its lifecycle, equipment using 3GPP standards is now ubiquitous with a very large user population, therefore long-term support can be expected.
Cost and revenue	Several suppliers, available on the open market. Higher frequency 5G cells have limited range. Requires licensed spectrum.

7.3. Wi-Fi

Requirement / property	Compliance
Symmetric 50/50 bi-directional data	Wi-Fi can provide data rates of 6 – 108Mbits/s
Latency must be LOW, i.e. immediate, less than 100ms	For smaller vehicle densities (up to 50), IEEE 802.11p standard offers end-to-end delays less than 100 ms.
Bandwidth	Wi-Fi frequency 5.85 - 5.925 GHz Data rates of 6 – 108Mbits/s

Link reliability MTBSAF	Wi-Fi is the technology for DSRC Safety Applications.
Setup time	802.11p amendment revised authentication without the need to establish a basic service set (BSS), to make it suitable for V2V.
Range and speed	Range 50m – 300m Moving access point 150 km/h (or more)
Peer to peer (T2T) capability	Supports Master/Client - point to multipoint.
Congestion management / Multiple access	Typical access point can support 250 connected devices. Connected devices share access point available bandwidth.
Technology readiness, Scalability, Migration, Upgradeability, installability	Wi-Fi is the ubiquitous LAN solution in all domains, including autonomous vehicles, with multiple suppliers off the shelf.
Longevity, Maintainability , Equipment reliability, obsolescence management	IEEE have actively managed the 802.11 set of standards since 1997, including ongoing updates. Wi-Fi is the ubiquitous LAN solution in all domains, including autonomous vehicles.
Cost and revenue	Several suppliers, available on the open market. Doesn't require licensed spectrum.

8. Discussion and Critical Review

It became further apparent during the course of this research of the very rapid change within the field of telecommunications. Some of the literature reviewed in the virtual coupling context was found to be already 'out of date'.

It is currently envisaged that a virtually coupled train, on the European rail network, will have stepped up from and fall back to ETCS L3, which will be the primary control for the leading train. It can therefore be expected that the trains will already be required to have capability for FRMCS, the successor to GSM-R. Work on FRMCS is leading towards a 5G solution. The 5G specifications include for LTE-direct specifically to address the needs of V2V/V2E in the automotive domain, but the parallel with rail is apparent.

MOVINGRAIL Deliverable D3.2 "Advances in Automated Vehicle Technology and Applicability to Railways" [37] suggests that rail traffic can piggy back on developments in automated car driving by building on those developments, while preserving its own characteristics and specific requirements. This, of course, applies to radio communication where reuse of automotive developments can bring the benefits of the mass market.

There is clearly a close synergy between automotive platooning and railway virtual coupling. There are also significant differences between these areas relating to poor braking (due to steel wheel on steel rail adhesion), the long length of trains, high mass and inertia including significant lags and the inability of trains to manoeuvre. These differences translate to very large distances when virtual coupling commences and a gulf in the target safety integrity levels.

The large distances require broadcast radio or very many access points, and the need for high integrity implies involvement of the train's safe computer.

The use of many overlapping access points is economically viable for geographically constrained systems, such as metros, but larger networks require broadcast capability.

The capability of the three identified communications solutions (3GPP, Wi-Fi and TETRA) to meet the defined requirements of virtual coupling (§5.2) were assessed and captured (see §7). All of the candidates could meet the requirements.

For example, Table 7 below gives a comparison of the crucial latency factor (however, in practice, control computer cycle time is likely to be dominant here in any safe implementation).

Table 7 – Ping latency and hops for Wi-Fi, LTE and UMTS *[10]*

Technology	Latency (ms)	Hops
UMTS (public network)	60ms	15
LTE (public network)	37ms	10 – 13
Wi-Fi (enterprise network)	40ms	8

An expert group at Park Signalling carried out a SWOT analysis with the results in

Table ***8***.

Table 8 – Candidate Solutions Strength, Weaknesses, Opportunities and Threats

TETRA

Strengths	**Weaknesses**
• Specifically designed for critical applications • Fast call setup • Operation possible at high relative velocities • Inherent Direct Mode operation	• Primarily developed to meet critical voice when data throughput is required • In the railway domain Tetra tends to be only used by Metro systems and predominantly for voice
Opportunities	**Threats**
• Several suppliers, available on the open market	• No evidence that it will have a long-term future

3GPP

Strengths	**Weaknesses**
• More than adequate upload and download data capability • Low latency • Both long- and short-range communication capability • Direct peer to peer capability	• Higher frequency 5G cells have limited coverage area
Opportunities	**Threats**
• Standards are evolving to incorporate critical applications • Active, ongoing development • 5G implementation is at the start of its lifecycle	• -

Wi-Fi

Strengths	**Weaknesses**
• Very low end-to-end delays • Specified for safety applications • 802.11 set of standards actively managed	• Limited communication range • Communication reliability unspecified
Opportunities	**Threats**
• Adapted for V2V	• -

Two of the candidates Wi-Fi (WAVE) and 3GPP are currently strong contenders in the automotive field and are clearly current, being subject to ongoing development and have large take up in the wider market. TETRA does not feature strongly in train control and does not have a certain future with regard to the longevity required by rail.

The distances between trains that are about to virtually couple (e.g. 1km) are much larger than for automotive platoons. These distances are beyond the capability of direct link (T2T) and therefore require trackside infrastructure (multiple access points or broadcast cells).

The UIC Future Rail Mobile Communications System (FRMCS) project is currently looking to define the successor to GSM-R and are favouring the 3GPP (5G) based solution.

We consider that 5G's ability to provide direct, cellular and network connectivity provides the overall best match for the needs of virtual coupling, and with its selection for ETCS provides a consistent common approach.

In our opinion a bespoke solution for virtual coupling communication is not required or affordable. The FRMCS project aim for the use of Commercial-Off-The-Shelf (COTS) equipment.

9. Conclusions

As previously mentioned, it became apparent during the course of this research of the very rapid change within the field of telecommunications. Some of the literature reviewed in the virtual coupling context was found to be already 'out of date'.

A method was established and described which allowed the communications requirements for virtual coupling to be elicited. Previous research into requirements for virtual coupling communications identified that the ‘new’ functional requirement of virtual coupling communications, above the needs of moving block, is that of direct communication i.e. V2V.

Suitable communications technologies suggested by the literature were investigated. The technologies looked at included TETRA, Wi-Fi, and cellular (5G/3GPP) evolutions.

Analysis revealed that evolution from GSM-R to 5G in accordance with the aims of the Future Rail Mobile Communications System project presents the best path forward for elaboration into a communications proposal for virtual coupling for the European rail network and that 5G is also appropriate, for consistency and economy, for the other sectors.

MOVINGRAIL Deliverable D3.3 “Proposals for Virtual Coupling Communication Structures” will take the communication solutions identified here forward to propose a suitable communications system architecture to support virtual coupling, and consider the use of the WLTB within a consist and the issue of safety separation of communication channels.

Further research is recommended to address the open safety points (§3.1.3) and potential use for V2I in rail.

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Appendix A – Source Document Review Table

1	Paper	Description	Virtual Coupling?	Virtual Coupling Comms?	T2G Comms?	T2T Comms?	Requirements?	Not relevant?	Technology
2	ASTRAI-WEB-B-S2R-001-01	Brochure							
3	ASTRAI-WEB-B-UNI-002-01	Newsletter ASTRAIL final							
4	ASTRAI-WEB-I-UNI-003-01	ASTRail Mid-term event							
5	CONNECTA 2	Nothing so far?							
6	connecta1 outputs								
7	CTA-WEB-B-CAF-012-01	Final conference presentation							
8	CTA-WEB-D-CAF-001-01	D1.2 - TCMS Use Cases					Lots, but not seemingly relevant		
9	CTA-WEB-D-CAF-002-01	D1.3 - Function Based Architecture (reference to appendix that we do not have?)							
10	CTA-WEB-D-CAF-003-01	D2.1 - Requirements and Specification for the T2G System			IEC 61375-2-6 (No VC reqs)				
11	CTA-WEB-D-CAF-004-01	D3.1 - Drive-by-Data Requirement Specification	Mentioned (Figure 1)	Latency requirements			IEC 61375 IEC 62580 EN 50159 EN 50155 EN 50126 EN 50128 EN 50129 ARINC 664 Part 7 Also contains many TCMS reqmts		S2R WLTB
12	CTA-WEB-D-CAF-005-01	D3.2 - Drive-by-Data Technology Evaluation Report		Some mention of latency (pg 57)		Lots of on-board wired comms			S2R WLTB
13	CTA-WEB-D-CAF-006-01	D4.1 - Architectural Requirements					Requirements to do with "open coupling" but nothing on VC		
14	CTA-WEB-D-CAF-007-01	D5.1 - System Brakes Architecture Report SySBAR							
15	CTA-WEB-D-CAF-008-02	D6.1 - Specification of the Virtual Homologation Principles							
16	CTA-WEB-D-CAF-009-01	D5.2 - Brake System Requirements							
17	CTA-WEB-D-CAF-010-01	D5.3 - Preliminary Safety Report							
18	CTA-WEB-D-CAF-014-01	D6.2 - Specification of the Simulation Framework and Train Virtualisation					requirements for simulation of train testing, but no explicit VC reqmts		
19	CTA-WEB-D-CAF-015-01	D1.4 - RAMS, Security, Legal Requirements and Norms					Reqmts for RAMS etc, no mention of VC		
20	CTA-WEB-D-CAF-016-01	D1.5 - High Level Requirements					Reqmts, none for VC		
21	CTA-WEB-D-CAF-017-01	D2.3 - Validation Plan and Report for the T2G System							
22	CTA-WEB-D-CAF-018-01	D4.3 - Application Profile Definition Guideline and Example							
23	CTA-WEB-D-CAF-019-01	D5.5 - Safety Assessment Report							
24	CTA-WEB-D-CAF-020-01	D2.4 - Report of C2C Wireless Communication Tests				Lots of data on T2T comms, using LTE. Distances up to 860m.			LTE
25	CTA-WEB-D-CAF-021-01	D6.3 - ECN-ETB Conformance Testing Protocol							
26	CTA-WEB-D-CAF-022-01	D8.3 - Contribution to Shift2Rail							
27	CTA-WEB-I-CAF-023-01	Newsletter september 2018			Details on WLTB and T2G	Details on WLTB and T2G			S2R WLTB
28	CTA-WEB-I-CAF-024-01	Connected Trams demonstrator brochure	Details on connected trams over wireless train backbone						
29	CYRAIL D1.1	Project Quality Assurance Plan							
30	CYRAIL D2.1	Safety and security requirements of rail transport system in multi-stakeholder environments					Cybersecurity requirements		
31	CYRAIL D6.1	Protection Profiles Specifications							
32	CYRAIL D7.1	Communication and Exploitation Plan							
33	CYRAIL D7.3	Brochure (Project Presentation)							

1	Paper	Description	Virtual Coupling?	Virtual Coupling Comms?	T2G Comms?	T2T Comms?	Requirements?	Not relevant?	Technology
55	ETALON-WEB-D-S2R-010-01	D7.1 Set-up Public Website							
56	X2R-DDATA-T-SIE-003-01	WP5 Innotrans Moving Block Demonstrator Presentations							
57	X2R-T6.2-D-DBA-010-01	D6.1 Current test conditions and Benchmarking report							
58	X2R-T7.3-D-CFS-006-06	D7.2 Railway requirements and standards application conditions					Smart Wayside Object Controller (& therefore associated comms to IXL etc)		
59	X2R-WP02-D-SIE-017-01	D2.3 Terminology for future signalling and automation system						Not relevant, other than for terminology!	
60	X2R-WP03-D-NRI-005-02	D3.1 User & System Requirements (Telecommunications)		Gets a mention!	Yes	Yes	Yes		S2R WLTB
61	X2R-WP04-D-SIE-002-01	D4.1 ATO over ETCS - GoA2 Specification			Relating to ATO/ETCS				
62	X2R-WP07-D-TTS-001-02	D7.1 Analysis of existing lines and economic models					Analysis of current state of the art comms and data security		
63	X2R-WP08-D-ALS-002-01	D8.1 Selection of the "Secure-by-design" standard					Comms security and standards.		
64	X2R-WP09-J-DBA-010-03	Mid-Term Booklet							
65	X2R-WP9DOC-T-DBA-011-01	X2Rail-1 Flyer							
66	X2R1-WP3-D3.3-DB-001-1.0-I	D3.3 Annex Guideline of Technology		Gets a mention, nothing more		Comms technology choices			S2R WLTB
67	X2R1-WP3-D3.3-KCC-001-1.1-I	D3.3 Communication system Specification and Technology Guideline		Gets a mention		Comms technology choices & spec			S2R WLTB
68	X2Rail-1	Deliverables for WP1?							
69	X2Rail-1	D2.1 missing?							
70	X2Rail-1	D2.2 missing?							
71	X2Rail-1	D3.2 missing?							
72	R2R-WEB-D-UNI-031-01	D2.1 Specification of the Wireless TCMS	Yes but only a link to T2T	Yes wrt T2T but much excluded from scope	No (excluded)	Yes but also excluded from scope!	Lot of communication requirements details mainly internal to consist.		
73	R2R-WP02-D-UNI-112-01	D2.2 Characterisation of the Railway Environment for Radio Transmission	Yes	Yes	Yes?	Yes	Not explicitly		S2R WLTB
74	R2R-WP02-D-UNI-113-01	D2.6 Architecture and Interface Definition for the Train to Ground Communication			Yes	Yes	In regard to requirements in IEC61375-2-6		S2R WLTB
75	R2R-WP02-D-UNI-114-01	D2.3 State of the Art in Radio Technologies and Recommendation of Suitable Technologies	Excluded	Excluded from scope but doesn't prevent use of tech.	Yes	Yes	Yes		S2R WLTB
76	R2R-WP02-D-UNI-115-01	D2.5 Architecture for the Train and Consist Wireless	Excluded but mentioned	Implication techniques selected (Release 8&9 of LTE and Standard Data Path Mode) would not be good enough for VC.	Yes	Yes, not VC.	Looks at technologies satisfying requirements from D2.1		S2R WLTB LTE
77	R2R-WP02-D-UNI-116-01	D2.7 Simulations of the Selected Suitable Technologies	Just 2 mentions. Seems to suggest LTE possible for VC (p22), then seems to say comms for VC will be higher order (p29).		Yes	Yes	Includes discussion of requirements (set in D2.1).		S2R WLTB LTE
78	Safe4Rail1 D1.1	State-of-the-Art Drive-by-Data				Yes	Requirements are mentioned		S2R WLTB
79	Safe4Rail1 D1.2	System Integration Requirements	Yes, a little.				Contains requirements including requirements at the computing platform comms interface.		

1	Paper	Description	Virtual Coupling?	Virtual Coupling Comms?	T2G Comms?	T2T Comms?	Requirements?	Not relevant?	Technology
80	Safe4Rail1 D1.3	Initial Drive-by-Data Draft Concept Design	No	A little on protocol	No	No	With regard to computing platform, Train Real Time Data Protocol for inter consist comms		
81	Safe4Rail1 D2.1	SOTA Functional Distribution Architecture Frameworks	No	No	No	No		Effect of coupling, e.g. needing common time frame, mentioned.	
82	Safe4Rail1 D2.2	Analysis functional distribution architecture solutions	No	No	No	No	At computing level	Virtual coupling of APP interfaces.	
83	Safe4Rail1 D2.3	TCMS framework concept	No	No	No	No		Touches on communication interfaces/frames.	
84	Safe4Rail1 D2.4	Report on TCMS framework instantiation	No	No	No	NO			
85	Safe4Rail1 D3.1	State-of-the-Art Distributed Simulation Framework				Simulation of comms			
86	Safe4Rail1 D3.2	Design of TCMS Distributed Simulation Framework Concept	No	No	No	No			
87	Safe4Rail1 D3.3	Design of T2G Test Environment			Yes		Yes T2G		
88	Safe4Rail1 D4.1	Requirements Definition for Brake by Wire	No	No	No	No		50159 referanced for braking system comms	
89	Safe4Rail1 D4.2	Requirements definition for Brake by Wire & Safety concept					Requirements for braking system safe communication		
90	Safe4Rail1 D5.1 ???								
91	Safe4Rail1 D5.2	Initial report dissemination and exploitation			Only mention of conferance attendance				
92	Safe4Rail1 D6.1 ???								
93	Safe4Rail1 D6.2	Risk Assessment Plan							
94	Safe4Rail2	No documents, but deliverables on https://safe4rail.eu/results/deliverables							
95	Analysis of platooning train.pdf	Analysis of Platooning Train Operations Under V2V Communication-Based Signalling: Fundamental Modelling and Capacity Impacts of Virtual Coupling	Yes						
96	Train-following model for Virtual Coupling.pdf	A multi-state train-following model for the analysis of Virtual Coupling railway operations	Yes						
97	ITSG5measurements.pdf	Measurement and Analysis of ITS-G5 in Railway Environments				Yes			ITS-G5
98	10.1.1.229.3774.pdf	Hybrid vehicular communications based on V2V-V2I protocol switching	Covers protocols and data propagation/timings associated with road-based V-2-V (and V-2-I-2-V) networks	see <-----	see <-----	see <-----			802.11
99	10.1.1.399.5199.pdf	On the Performance of TETRA DMO Short Data Service in Railway VANETs		Mentions V-2-V	DMO would also support V-2-I	DMO supports V&D connections	ETSI 300 392/ETSI 300396 series		ITS-G5
100	11126339.pdf	A Railway Collision Avoidance System Exploiting ad-hoc Inter-vehicle Communications and Galileo		V-2-V but aimed at road vehicles					
101	2016-VTM.pdf	High-Speed Railway Communications: From GSM-R to LTE-R							
102	59_GHz_inter-vehicle.pdf	5.9 GHz inter-vehicle communication at intersections: a validated non-line-of-sight pathloss and fading model		V-2-V but aimed at road vehicles					802.11
103	84275347.pdf	ITS-G5 Channel Models for High Speed Train-to-Train Communication	Yes	Yes	Potential?	Yes	ITS-G5, TETRA (ETSI)		ITS-G5
104	84275891.pdf	Wide Band Propagation in Train-to-Train Scenarios - Measurement Campaign and First Results	Yes	Yes	Potential?	Yes	ITS-G5, TETRA (ETSI)		ITS-G5
105	902414.pdf	On the Ability of the 802.11p MAC Method and STDMA to Support Real-Time Vehicle-to-Vehicle Communication		V-2-V but aimed at road vehicles	V-2-I discussion relating to AIS (shipping)				802.11

1	Paper	Description	Virtual Coupling?	Virtual Coupling Comms?	T2G Comms?	T2T Comms?	Requirements?	Not relevant?	Technology
106	Allegato_130152_.pdf	Performance Comparison Between IEEE 802.11p and LTE-V2V In-coverage and Out-of-coverage for Cooperative Awareness		V-2-V but aimed at road vehicles		V-2-V but aimed at road vehicles			802.11
107	chp_10.1007_978-3-319-38921-9_1.pdf	Roadmap Towards the Wireless Virtual Coupling of Trains	Yes				SIL2 wireless layer, SIL4 Virtual Coupler		
108	COMMAG_UNIRC.pdf	LTE for Vehicular Networking: A Survey			V-2-I but aimed at road vehicles	V-2-V but aimed at road vehicles	ETSI TR 102 962		LTE
109	CR08031FU1.pdf	A location-based MAC protocol for safety-of-life vehicle-to-vehicle communication	Yes	Yes	V-2-I but aimed at road/sea vehicles as well	V-2-I but aimed at road/sea vehicles as well			
110	Direct_Vehicle-to-Vehicle.pdf	Direct Vehicle-to-Vehicle Communication with Infrastructure Assistance in 5G Network	V-2-V but aimed at road vehicles	V-2-V but aimed at road vehicles					LTE
111	doc00027457.pdf	A Survey of Channel Measurements and Models for Current and Future Railway Communication Systems	Yes	Yes	Yes	Yes	Has details on measuring letency requirements		802.11 LTE
112	feasibility.pdf	A Feasibility Study and Development Framework Design for Realizing Smartphone-Based Vehicular Networking Systems	V-2-V but aimed at road vehicles	V-2-V but aimed at road vehicles	V-2-I but aimed at road vehicles	V-2-V but aimed at road vehicles			802.11 LTE
113	FULLTEXT01_3GPP.pdf	3GPP LTE Versus IEEE 802.11p/WAVE: Which Technology is Able to Support Cooperative Vehicular Safety Applications?	Covers protocols and data propagation/timings associated with road-based V-2-V (and V-2-I-2-V) networks						LTE 802.11
114	FULLTEXT01.pdf	Measuring and Using the RSSI of IEEE 802.11p				V-2-V but aimed at road vehicles			802.11
115	LTE_and_IEEE_80211p_for_veh.pdf	LTE and IEEE 802.11p for vehicular networking: a performance evaluation				V-2-V but aimed at road vehicles			LTE 802.11
116	railwayFSVC.pdf	Towards Railway Virtual Coupling	Yes	Yes	Yes	Yes			
117	reliable_surveillance_strategy.pdf	A reliable surveillance strategy for an autonomous Rail Collision Avoidance System				Only covers required timings/data rates for proposed German RCAS system			
118	Rico07Comparison.pdf	Comparison of Collision Avoidance Systems and Applicability to Rail Transport				Only a comparison of existing systems for other transport modes, and looks at potential applicability to Rail			
119	sensor_fusion.pdf	Application of sensor fusion to railway systems						Sensor/integration info only - no 'comms'	
120	sensors-17-01457.pdf	Towards the Internet of Smart Trains: A Review on Industrial IoT-Connected Railways						Review of technologies, only - nothing specific about application	
121	TDI010406f.pdf	Increase of Capacity on the Shinkansen High-Speed Line Using Virtual Coupling	Yes, concepts/simulation by DLR (German Aerospace Centre)						
122	VANET_Scalability.pdf	The Scalability Problem of Vehicular Ad Hoc Networks and How to Solve it						Relates only to capacity/throughput issues with larger numbers of vehicles in range of each other	

1	Paper	Description	Virtual Coupling?	Virtual Coupling Comms?	T2G Comms?	T2T Comms?	Requirements?	Not relevant?	Technology
123	VASEC.pdf	Secure Vehicular Communication for Safety Applications - A Measurement Study						Only covers performance/coverage stuff ralating to various technologies witk PK e2e encryption	
124	VTC_2013_147-39224-review.pdf	Evaluating the Feasibility of Using Smartphones for ITS Safety Applications				V2V comms			ITS-G5
125	FRMCS	FRMCS User requirements			ATC & ATO data comms, T2G & G2T voice comms				
126	IRSE ITC	ITC Report 39	Concept						
127	IRSE News	ERTMS L3 - The gamechanger						#	
128	VITE D6.2	Initial Brochure						#	
129	VITE D6.3	Final Brochure						#	
130	X2R2-TSK521-D-TRV-004-01	Formal Methods (Taxonomy and Survey), Proposed Methods and Applications						#	
131	X2R2-WP4-D-ANS-049-01	D4.1 Train Integrity Concept and Functional Requirement Specification						#	
132	X2Rail-2	Deliverables for WP1?							
133	X2Rail-2	Deliverables for WP2?							
134	X2Rail-2	Deliverables for WP3?							
135	X2Rail-3	Nothing so far...							
136	2011 Book	Conference paper				Analysis of T2T propagation in 70cm UHF band	ETSI EN 300 396-3 V1.3.1 (2006-2008), TETRA tech reqmnts for DMO; Part 2: Radio Aspects & Part 3: MS-MS air interface protocol		ITS-G5
137	2012 Book	Conference paper			Design & prototype of a T2LX comms architecture				
138	2013 Book	Conference paper						#	
139	2014 Book	Conference paper						#	
140	2015 Book	Conference paper		ITS-G5 for dymanic train coupling		Performance of IEEE 802.11p for T2T comms	ERTM/ETCS-Class 1.GSM-R I/F Class 1 Reqmnts Subset-093-V230, 10/10/2005		ITS-G5 802.11
141							EIRENE SRS V.15		
142							ETSI EN 300 396-3 V1.3.1 (2006-2008), TETRA tech reqmnts for DMO; Part 3: MS-MS air interface protocol		
143							TETRA DMO SDS		
144							ETSI EN 302 663 - Access layer spec for the 5GHz band		
145							IEEE 802.11p		
146	2016 Book	Conference paper		Concept	T2X		IEEE 802.11p WAVE (2013)		802.11
147							ETSI EN 302 663 - Access layer spec for the 5GHz band		
148	2017 Book	Conference paper				ITS-G5 channel models for high speed T2T comms			ITS-G5
149	2018 Book	Conference paper			Network based on 3GPP LTE wireless technology	Narrowband characterisation of a 2.6 GHz link in metro environment			LTE

Appendix B – T2T Communication Requirements

Communication Requirement	Description
Message delivery	Appropriate protocol mechanisms shall provide guarantee that messages are delivered to destination and/or that eventual loss of messages is detected.
Unique identification of source and destination of messages	It shall be possible to uniquely identify the source of received information (i.e.: it shall be possible to identify the master sending some specific data received by a slave), as well as the destination of transmitted data.
Adequate level of security	Techniques shall be allowed (as Encryption, CRC, etc…) to: • Detect (and eventually correct) corruption of information contained in a message • Intrusion on the communication channel (as aliasing, etc…) aimed to disturb, interrupt or modify the flow of information across the VCC • Separation of data flows; there shall be no possibility that VCTS-related traffic is mixed with other traffic, either safety or non-safety related, but anyway associated to other functions than VCTS
Delivery Time	Adequate protocol shall be arranged to allow precise determination of the worst case time to deliver messages to destination. It shall be possible to determine especially the time required, for a specific message, in the worst case, from the moment it is transmitted by source to reach the destination. An example is the information about the ongoing braking action on the master: the slave shall dimension the safety distance from the master by taking into account the worst case time for a message of ongoing brakes on master to reach the slave itself.
Timestamping/sequencing	The protocol shall allow the destination to determine the time at which the message has been sent and, together with it, the sequence of transmission in order to distinguish/discard older messages.
Status monitoring	It shall be possible to monitor the status of the communication link between master and slaves, in order to determine with predictable timing when the communication is lost/interrupted/degradated and take the necessary safety actions.

Source: [15]

Appendix C – Communications Technology Glossary

2G		
GSM	Global System for Mobile Communications	2G Standard developed by ETSI to describe the protocols for second-generation digital cellular networks used by mobile devices.
TDMA	Time-division multiple access	Radio Interface
GERAN	GSM EDGE Radio Access Network	
ETSI	European Telecommunications Standards Institute	
EDGE	Enhanced Data rates for GSM Evolution	Mobile internet network proceeding 3G.
GPRS	General Packet Radio Service	Early always on mobile internet network. IP based packet switched solution using the same air interface and access method has GSM.

3G		
3G	3G network is based on Universal Mobile Telecommunication Service (UMTS)	Mobile internet network superseding GSM, GPRS, and EDGE.
3GPP	3rd Generation Partnership Project	Standards organisation includes ETSI CCSA. GSM and related 2G and 2.5G standards, including GPRS and EDGE. UMTS and related 3G standards, including HSPA. LTE and related 4G standards, including LTE Advanced and LTE Advanced Pro. 5G NR and related 5G standards
UMTS	Universal Mobile Telecommunications Service	3G 3GPP standard for third generation mobile cellular system for networks based. Specifies a complete network system, which includes the radio access network (UMTS Terrestrial Radio Access Network, or UTRAN), the core network (Mobile Application Part, or MAP) and the authentication of users via SIM (subscriber identity module) cards.
UTRAN	UMTS Terrestrial Radio Access Network	

Uu	UTRAN external interface, connecting the Node B with the User Equipment (UE).	
Node B / NB	For UMTS network the Node B provides the connection between mobile phones (UEs) and the wider telephone network.	Base Station
CDMA W-CDMA	(Wideband) Code Division Multiple Access	Radio Interface
HSPA	High Speed Packet Access	Third-generation (3G) mobile broadband communications technology. The term HSPA actually refers to two specific protocols used in tandem, high speed downlink packet access (HSDPA) and high speed uplink packet access (HSUPA). Overtaken (incorporated) in LTE.

4G		
LTE	LTE Long Term Evolution	4G Standard for wireless broadband communication for mobile devices.
OFDMA	Orthogonal frequency-division multiple access	Radio Interface
E-UTRAN	Evolved-UMTS Terrestrial Radio Access Network	Air interface in an LTE cellular network.
eNode B / eNB	For 4G networks the eNode B provides the connection between mobile phones (UEs) and the wider telephone network.	
EPS	Evolved Packet System	Purely IP based. Both real time services and datacom services will be carried by the IP protocol.
EPC	Evolved Packet Core	The core network of the LTE system. Entirely packet switched (IP).

5G		
IMT-2020	5G Requirements	Requirements standard issued by the ITU for 5G networks, devices and services.
5G NR	5G NR (New Radio)	5G standard for Radio access technology (RAT) developed by 3GPP for the 5G mobile network. The 3GPP 5G specification is the TS 38 series.

LTE Direct	Direct communication between UEs using licensed spectrum and the global LTE ecosystem.	3GPP Rel. 12 of the LTE-Advanced standard specifies a general concept of proximity-based services (ProSe) that allows physically close devices to discover themselves and communicate via direct links. Also known has LTE Direct.
NAD	Network Access Device/NAD Modem	Essentially a cellular modem.
PC5 interface	Direct LTE/5G interface.	For V2X utilising cellular communication the direct communication between vehicle and other devices (V2V, V2I) uses so-called PC5 interface. In the 3GPP RAN specifications, "sidelink" is the terminology to refer to the direct communication over PC5.
Sidelink	In 3GPP RAN specifications terminology to refer to the direct communication over PC5.	
ProSE	Proximity Service	In system architectural level, proximity service is the feature that specifies the architecture of the direct communication between UEs. At present, efforts to commercialise ProSe are being spearheaded by the public safety and critical communications sector, amid the ongoing transition from legacy LMR (Land Mobile Radio) systems to LTE networks. Also known as LTE direct.

Non-Cellular		
DSRC	Dedicated Short Range Communication.	DSRC (known as ITS-G5 in Europe), a Wi-Fi based standard dedicated to vehicular use. DSRC uses the underlying radio communication provided by 802.11p. Rolled out in the USA, parts of Europe, and Japan, but variants differ in baud rate and protocol and are not compatible.
LMR (US) PMR (UK)	Land Mobile Radio system Private (Professional) Mobile Radio	person-to-person voice communication system. Public land mobile radio systems are made for use exclusively by public safety organisations such as police, fire, and ambulance services. Private land mobile radio for private commercial use e.g. taxis.

Wi-Fi / WLAN		
IEEE 802	Family of IEEE standards dealing with local area networks and metropolitan area networks.	Wireless LAN (WLAN) & Mesh (**Wi-Fi** certification)
IEEE 802.2	Original name of the ISO/IEC 8802-2.	
ISO/IEC 8802-2	Standard which defines logical link control (LLC) as the upper portion of the data link layer of the OSI Model.	
IEEE 802.11	Protocol specification for implementing wireless local area network (WLAN) Wi-Fi computer communication.	Part of the IEEE 802 set of LAN protocols, and specifies the set of media access control (MAC) and physical layer (PHY) protocols for implementing wireless local area network (WLAN) Wi-Fi computer communication.
ITS-G5	short-range V2X technology	Commercially available short-range V2X technology based on the IEEE 802.11 standard and standardised in Europe as ETSI EN 302 663.
MAC	Medium/Media Access Control	Data link layer that controls the hardware. MAC provides flow control and multiplexing for the transmission medium.
NB-IoT	Narrow Band Internet of Things	
LPWAN	Low Power WAN	NB-IoT or LoRaWAN.
URLLC	Ultra-Reliable Low Latency Communications	
LoRaWAN	Long Range WAN	
RAT	Radio Access Technology	
WAN	Wide Area Network	
WAVE	Wireless Access in Vehicle Environment	IEEE802.11p ITS-G5
WPA	Wi-Fi Protected Access	

TRANSPORTATION		
FRMCS	Future Railway Mobile Communication System	Is the future worldwide telecommunication system designed by UIC, in close cooperation with the different stakeholders from the rail sector, as the successor of GSM-R but also as a key enabler for rail transport digitalisation.

ITS	Intelligent Transport/Transportation Systems	
UIC	The International Union of Railways (French: Union internationale des chemins de fer)	An international rail transport industry body.
VANETs	Vehicular ad-hoc networks	A sub form of Mobile Ad-Hoc Network or MANET that provides communication between vehicles and between vehicles and road-side base stations. VANETs are created by applying the principles MANETs – the spontaneous creation of a wireless network of mobile devices – to the domain of vehicles.