Deliverable D 2.1
GSM-R or LTE, design solution

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1   EXECUTIVE SUMMARY

Based on previous projects FP7 MARATHON and more recently finished DYNAFREIGHT and FFL4E the idea of lengthening the trains to save network capacity and increase competitiveness has been developed. Distributed traction necessary for such longer and heavier trains implied for competitiveness reasons remote control of the traction units (TUs) while ensuring the safety of the train consist in all operational situations. The transmission of the orders from the leading TU to the guided TUs was initially using GSM-R being a recognized safe solution. The objective being to create consists up to 1500m with up to four locomotives in comparison with previous projects limited to 2 TUs the GSM-R solution did not offer a sufficient capacity, regarding the number of active calls, to control more than 2 TUs. The LTE radio solution was the proposed solution resolving this transmission between more than 2 TUs while reducing slightly the transmission delay in comparison with GSM-R. Moreover, it represented an interesting step easily upgradable to the future FRMCS radios system which should start to be developed in the coming years.

The safety of this radio solutions implied a close collaboration with FR8RAIL II partners in charge of providing the TUs and the DBCU (Distribute Braking Control Units) for the demonstrators as well as providing the track characteristics where theses demonstrators will be tested. These partners will have to answer to the functional requirements of M2O to ensure the global safety of the consists. As regards the radio the architecture inside the locomotive is under FR8RAIL II responsibility while forwarding to M2O the necessary characteristics of the TU and DBCU reactions to various orders transmitted from the leading TU. In particular DBCU will intervene in safety of the consists as a back-up mean of communication in degraded modes. This deliverable will focus on the various types of consists studied and on the radio solutions with their characteristics essential to simulate with TrainDy the longitudinal forces appearing in the most critical situations.

2 ABBREVIATIONS AND ACRONYMS

Abbreviation / Acronyms	Description
RCDPS	Radio Controller for Distributed power system
CCUO	Vehicle control computer
DPS	Distributed Power System
ED	Electrodynamic
TU	Traction Unit
LTE	Long-Term Evolution
LTD	Long Train Dynamics
TCMS	Train Control Management System
IP	Internet Protocol
VPN	Virtual Private Network
CSD	Circuit Switched Data
FRMCS	Future Railway Mobile Communication System
EDOR	ETCS Data Only Radio

3 BACKGROUND

The present document constitutes the Deliverable D2.1 "GSM-R or LTE, design solution" in the framework of the S2R-OC-IP5-01-2018: Radio communication and simulation of train dynamics for Distributed Power within long trains

M2O project has to build on previous FP7 Marathon and S2R FFL4E project as regards the communication solutions. Marathon project used a specific communication solution using LocCom 102 RS in the 400/500MHz with a band width of 12.5KHz of Schweizer Electronic. This enabled to couple two commercial intermodal trains driven by two electric TUs for the first test and two diesel TUs for the second test. The overall consists created were around 1500m long and ran safely on a route of 250km long between Siblin and Nimes in France.
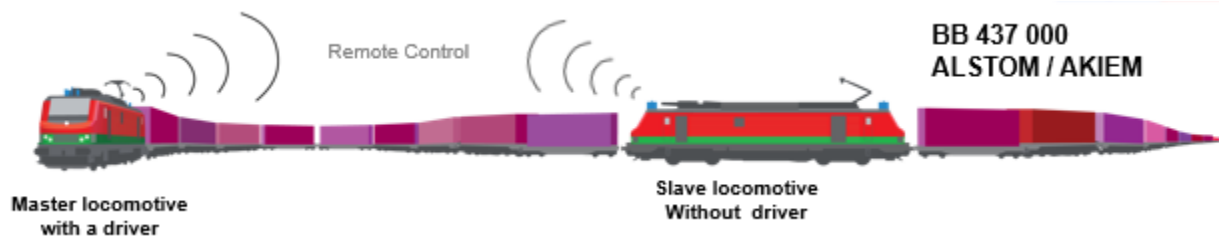
In FFL4E a GSM-R radio solution was used for the tests performed on a straight flat track between Hamburg and Bremen with test trains of 540m with 2 TUs one at each end of the consist composed of 39Fal Wagons fully loaded for a total weight of 3500T.
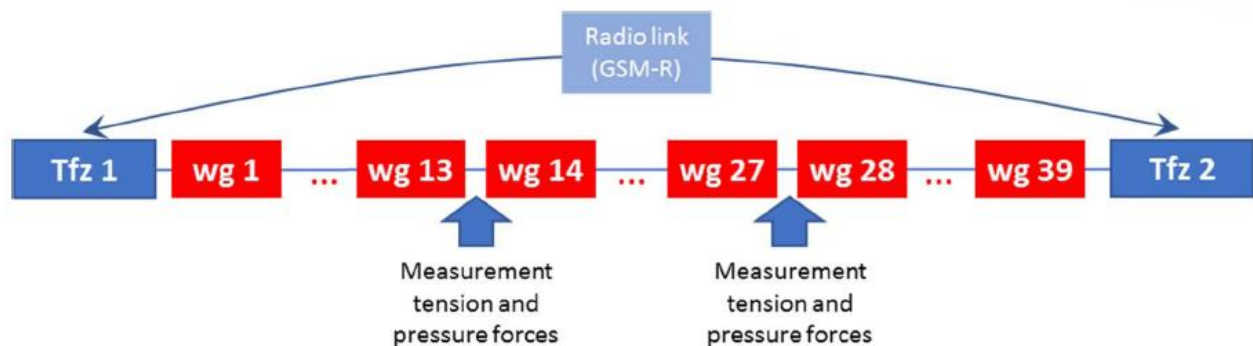
The results of these FFL4E tests were communicated to M2O with the characteristics of the Bombardier TUs (BOMBARDIER AC3 locomotives (DB-Type BR187)) utilised in these tests which will serve for the study and simulations of the various consists.

4   OBJECTIVE/AIM

The present document constitutes the Deliverable D2.1 "GSM-R or LTE Design solution" in the framework of the TD5.4, of IP5.

4.1   Train configurations to be studied

In M2O the initial objective was to use GSM-R radio communication system offering a large coverage in Europe and an acceptable safety level. At the same time the objective was to analyse consists involving up to 4 TUS and a train length up to 1500m.
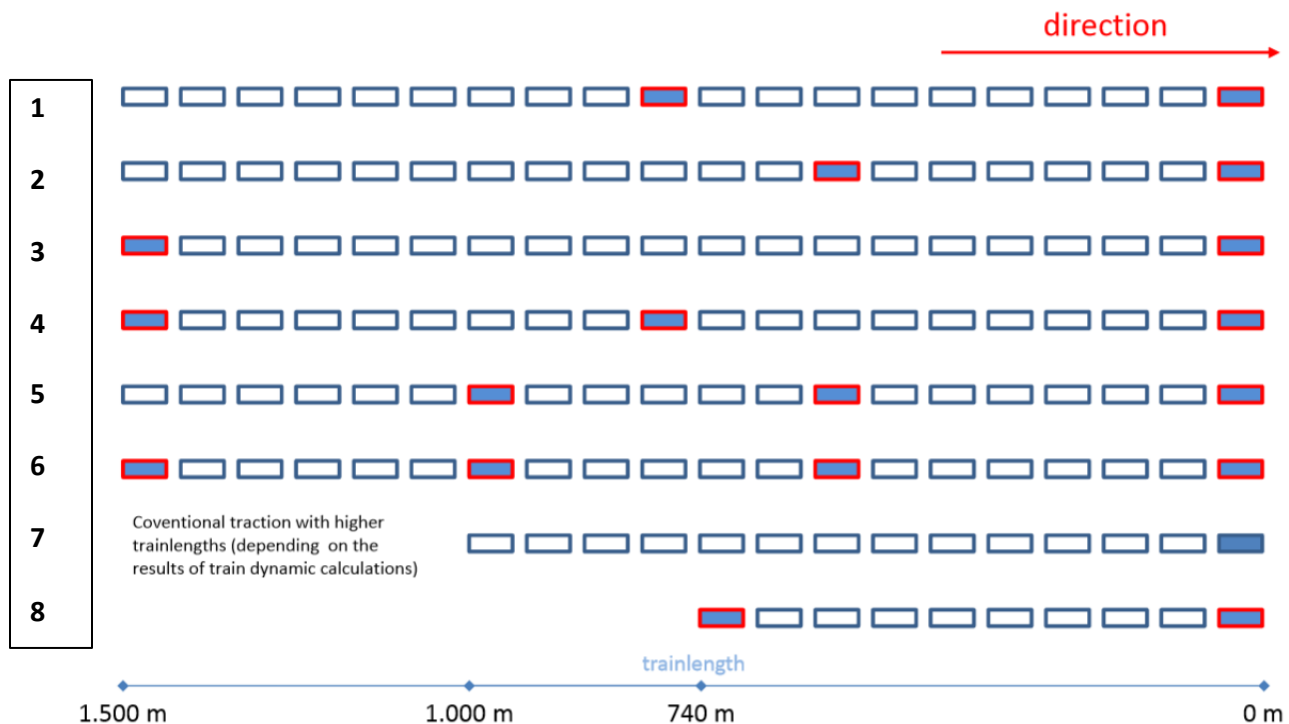
From the general market analysis several types of trains are running presently on the Network:

- Bulk trains for which the challenge is to increase the overall load which can be driven by one driver. Generally, these trains are often homogeneously loaded and the boundaries are often linked to the maximum load rather than by the overall length of the consist as the cargo transported (liquid or solid is often characterized by a high density). The corresponding type of the consist is configuration 8 for very heavy cargo, configuration 4 for a little less heavy cargo and configuration 3 for lighter cargo. The objective is to gain competitiveness and for lighter cargo to gain also capacity on the network.

- For combined transport trains carrying containers and/or swap-bodies and /or semitrailers the average load is around 3T /m including the wagon deadweight which is coherent with the

capacity of traction of recent electric or diesel locomotives for a 740m train on a classical track with slopes not exceeding 10‰. This shows the interest to couple two such trains to gain traffic while saving capacity on the network per ton carried and cost of operation. In case of steeper slopes, a pushing locomotive could be necessary. The corresponding configurations are 1;2;3; 4.

- Finally, for countries having preserved cluster of industries, single wagon load traffic is still interesting even beyond transport of dangerous goods. Sometimes coupling such short trains to create longer consists involving any type of wagon on longer trips may result in configurations like: 4;5;6;8

These types of consists are justified both for capacity reasons on the network and for economic reasons as they could produce up to 30% cost reduction by ton transported. They could offer a significant step towards the European rail freight market share defined in the last white papers.

According to the density of the products transported more than two TUs might be necessary.

These TUs must be remotely controlled by the lead locomotives and previous projects based on GSM-R have only tested consists with two TUs.

The first objective of this deliverable is to study if GSM-R radio solution is fitted for more than two TUs in such consists or if a different solution must be chosen.

If a new solution appears to be necessary its main characteristics in terms of safety, availability, transmission delay will have to be compared with GSM-R solution where applicable to employ one radio solution for one train consist. This comparison will take into account the expected evolution in radio communication for rail.

4.2   Operational situations to be encountered inducing functional requirements

These new DPS consists have to go through an initialisation phase during which two drivers have to set up the radio communication link between each guided TU and the leading TU, check if the orders sent by the lead TU are well received by the guided TU and correctly interpreted in particular the direction of the traction, the braking orders either for pneumatic braking or ED braking. They have also to check if the information when the action is executed has correctly been reported to the lead TU. These operations will have to be done successively with each guided TU.

After that initialisation phase, the train will be able to depart after classical verifications: test brake, integrity, couplings correctly screwed…

The train running the power is progressively increased to reach the cruise speed and the various situations that may occur are classical the need to reduce the speed with ED brakes, the need to operate a service braking, the need to operate an emergency braking, the need to stop the train on a siding and to restart after, the need to drop the pantograph after using the circuit braker.

These operational situations have to be analysed in the various size and weight of the consist (with a random distribution of the load) and in the various track configurations straight or curved, with a positive or negative gradient on the whole train or only positive on a part of the train and negative on the rest and vice-versa. For each of these situations the Longitudinal Forces will be simulated with TrainDy.

These analyses made in Nominal mode will have to be repeated in degraded modes. The degraded modes may result from a communication loss with a variable duration, or from emergency situations like a fire on one of the TUs.

All the hazards quoted in this deliverable are extensively analysed in the general safety analysis with the adequate mitigations to ensure the safety of the consist.

The principle followed in the project is to ensure that the consists that are studied will be as safe as trains already running on the network and for that purpose define boundaries in terms of length, loads and track characteristics. Some parameters are specifically critical as the availability of the radio communication. Such DPS trains will be able to run on tracks where this availability of the radio communication is sufficient to fulfil the requirements issued at the end of the project.

Among the parameters which are impacting the safety of the consist the latency in the transfer of orders from the leading TU to the guided TUs is important and the type of radio communication solution will be a key point.

5 FEATURES OF TU AND OF BRAKE PIPE COMMUNICATION

As far as Longitudinal Train Dynamics is concerned, train consists like those listed before are meant to be equipped by TU of the same model, on at least very similar characteristics, to avoid a complex LTD behaviour.

TU of FR8RAIL II Partners have mechanical characteristics that can affect LTD such as the maximum power and the ED brake force, the gradients of traction and ED brake application and removal; these parameters are considered in D3.1 and D3.3 of M2O. Among the features of DPS, the time interval to react to a communication loss and the behaviour of the DBCU when the communication loss is detected have an impact on LTD. Effect of these parameters on LTD is studied in D3.1 and D3.3, as well.

Differently from FFL4E, M2O Partners have suggested to FR8RAIL II Partners to use the brake pipe as an effective and reliable radio back-up, as it was in Fp7 Marathon. Therefore, the venting of brake pipe is not commanded by the time interval of radio communication loss, but by the detection of a pressure drop (fixed equal to 0.2 bar) in brake pipe. The time interval is responsible only of the traction removal. Moreover, two ways of venting the brake pipe are suggested, when the radio communication is loss:

- Stepwise reduction of pressure upon detection of 0.2 bar: first step has a target of 4.5 bar in brake pipe; if the pressure becomes equal to 4.3 bar, another brake application is commanded with target of 3.5 bar and if a further pressure drop is detected (3.8 bar in BP), the service braking with target 3.5 bar is commanded. This behaviour was already tested by FFL4E Partners in experimental tests of May 2019.

- Service braking with target of 3.5 bar in BP is commanded when the first pressure drop of 0.2 bar is detected, as in FP7 Marathon. This behaviour is safer than the stepwise reduction in case of emergency braking application from the leading TU, but not is the leading TU commands just a first-time braking (i.e. target pressure of 4.5 bar in BP). These topics are addressed by TrainDy simulations in D3.1 and D3.3 of M2O.

Lastly, it is important to mention that, when there is a radio communication loss and the DBCU detects a pressure drop of 0.2 bar, the traction force (if any) is removed.

6 THE CHOICE OF RADIO COMMUNICATION

The analysis of the GSM-R solution is based on the architecture of the communication system developed by FFL4E for their test runs of 2019. This have shown the radio part of the latency time of the end to end message transfer between the TCMS of the two TUs. This latency time is an important factor in the safety analyses developed for the DPS trains. The availability of any new proposed solution, being also an important factor in the safety analysis will have to precisely assessed on any route on which DPS trains

might run.

Starting from GSM-R communication solution, the new requirements linked to the number of TUs to be radio remote controlled by the leading TU will lead to a new proposed solution which characteristics will serve for the general analysis of the studied consists in order to define general guidelines for new longer and heavier DPS trains.

Some basic definitions are necessary during these developments on the communication system for the transmission of data records from the following system components:
1. vehicle control computer (CCUO)
2. radio controller (RCDPS)

The following transmission paths must be considered for communication:
1. local communication
2. radio transmission

For the end-to-end transmission, the following path results:
1. CCUO →   RCDPS (local communication vehicle 1)
2. RCDPS →   Radio network (radio link vehicle 1)
3. Radio network →   RCDPS (radio link vehicle 2..n)
4. RCDPS →   CCUO (local communication vehicle 2..n)

Both for local communication and for radio transmission, the data sets are specified in the following chapters and a performance analysis is executed for the entire transmission path.
The scope of this deliverable is focused on the links RDCPS (TU lead)—Radio Network—RDCPS of any guided TU) in both directions

6.1 Starting Point: GSM-R

The GSM-R radio link solution was developed during the first project phase 2018/2019 (Figure 1).
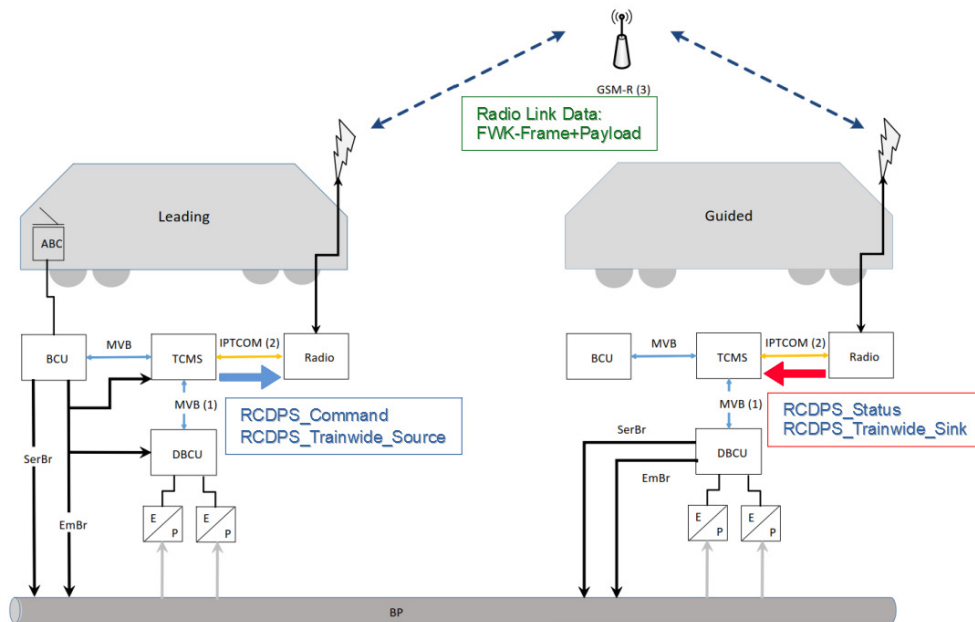

Figure 1: Overview of vehicle communication related to radio transmission based on GSM-R

In the project FFL4E, the test run concept was based on a train with two traction units (locomotives). The scalability of the technical solution was not the focus of the test setup. The performance of radio transmission was estimated (see section "Assumptions for GSM data transmission with data call (CSD)"). A laboratory test was used to validate the performance estimation (see section 6.6.2 "Results from Lab Tests with CCUO Simulators (GSM-R / Data Call)"). The resulting expected latency time was determined at the level of about 1.1 second.

During the test run with the test train, latency times of about 1.5 seconds were often measured and in exceptional cases up to 2 seconds. These latency times are due to the radio transmission in the GSM-R network in the field. The contribution to latency through radio transmission including the radio infrastructure is 0.5 to 1.5 seconds. Nevertheless, the test run with GSM-R radio transmission was successful. But – for longer trains with up to four traction units the requirement was specified that the typical latency time should not exceed 500 ms for the part of the radio transmission.

6.2 From GSM-R to LTE

6.2.1 Why GSM-R is no longer suitable for more than two TUs including the lead TU

The first approach to use GSM-R for radio communication was not feasible because of:
1. Poor performance leading to high latency times as demonstrated by the tests
2. Need of dedicated radio modules on the leading locomotive for each other (three) locomotive with own antenna path (three additional antenna on the roof of leading loco)

3. Count of permanent occupied GSM channels (6 radio modules occupy 6 channels permanently) which will not be guaranteed by GSM-R network in a cell because of other users
4. Leading loco needs more equipment as the other locos which is not applicable in practice
5. High complexity of installation and testing
6. For the identification by radio of the guided TU by the leading TU, the MSISDN (or telephone number) has to be found with some effort (on the train "inauguration")

6.2.2   LTE as bridge technology to 5G network

LTE (4G) is a bridge technology to 5G because:
1. Point to multipoint communication is possible
2. IP communication is used instead of proprietary communication protocol
3. Low latency communication is introduced by LTE network elements (see section 6.6.4 "Performance measurement in LTE network")
4. Change over to 5G is a short step
5. For the identification by radio of the guided TU by the leading TU, TUs are registered to a base station controller

In section 6.6.4 "Performance measurement in LTE network" the typical latency time (Vodafone LTE network in laboratory) is determined about 100 ms (+/- 20 ms) (including processing time of one RCDPS). The delay is an order of magnitude better than in the GSM-R network.
The requirement was specified that the typical latency time should not exceed 500 ms. This requirement cannot be fulfilled with GSM-R CSD radio communication, but with LTE network communication.

6.3   Radio Transmission concept

The progress of M2O project requires an extension of the concept and a change of the radio procedure. The concept includes more than two traction vehicles now – a multiple radio link is necessary but not feasible with GSM-R CSD data calls (multiple radio modules with antenna requirements). The concept will deal instead with LTE (4G) radio communication based on IP traffic.
The approach is:
- No direct IP routing between the traction vehicles
- Use the RCDPS as a kind of proxy (abstraction layer for radio communication)
- RCDPS manages the VPN and address resolution issues
- The radio technology used by the RCDPS is replaceable. It does not matter whether 4G or e.g. 5G radio technology is used.

6.4 Communication concept (LTE based)

6.4.1 Overview

The vehicle communication related to onboard and radio transmission is illustrated in the following figure.

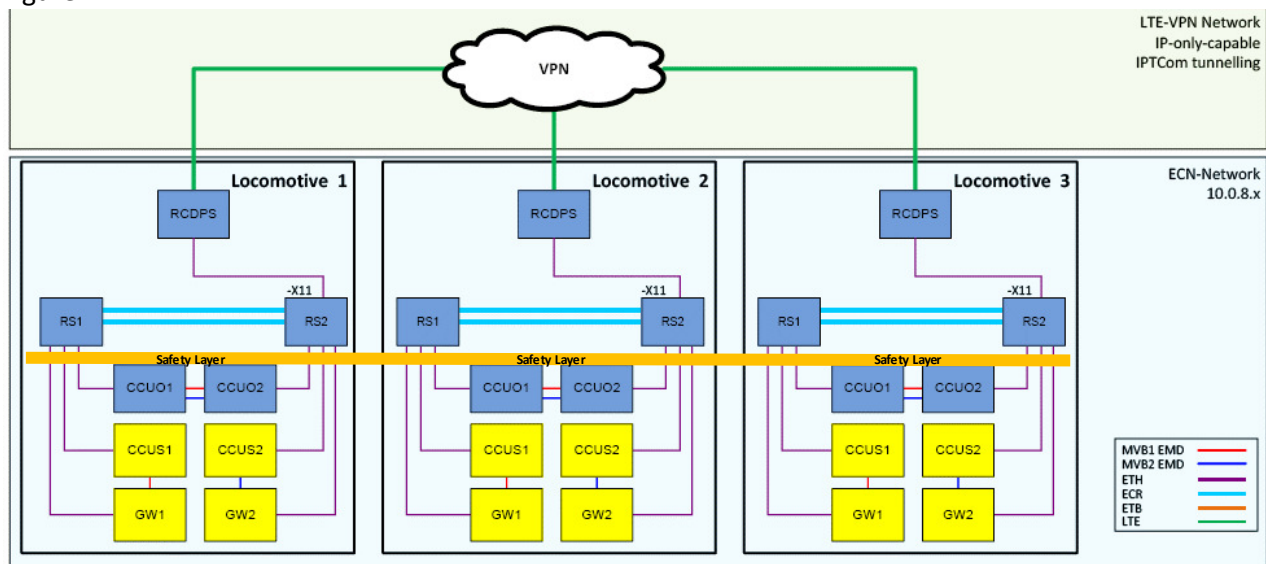**Figure 2: Overview of vehicle communication – based on LTE / IP**

The local communication has two aspects:

1. The Control and Monitoring Channel for local communication between RCDPS and TCMS within each traction vehicle
2. The Process Data Channel for communication between the traction vehicles.

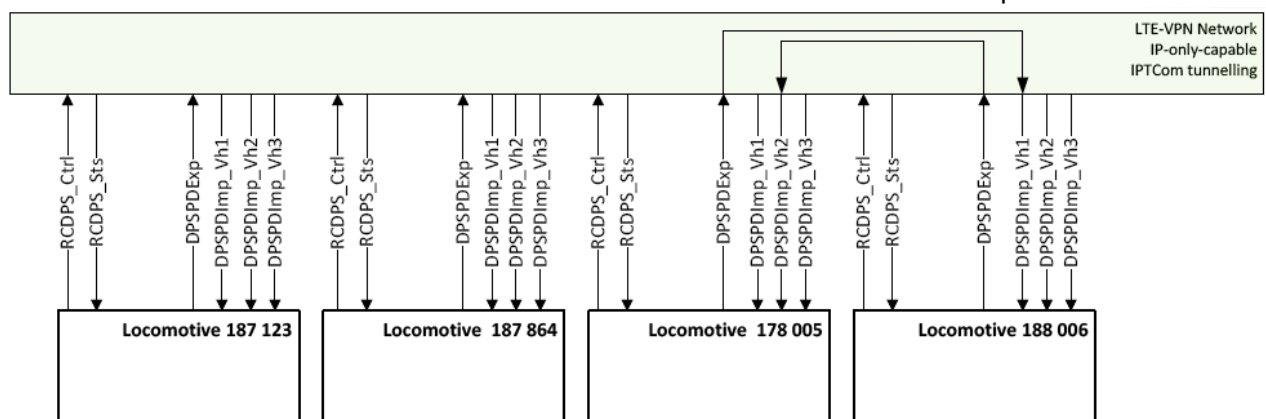The RCDPS device has one Ethernet Interface – both channels must share the same path.

Figure 3: Telegram identification

6.4.2 Interaction between CCUO and RCDPS

6.4.2.1 General

To build a logical train formation with multiple traction vehicles a unique identifier must be used to associate the traction vehicles (cars/vehicles) to the train. The GSM-R typical solution is to use the train running number supplemented with the position number (e.g. driver #1, driver #2, …). Cab Radios and other equipment operate with this data within GSM-R communication. This concept will be partly applied to the DPS as follows.

Assumptions:

1. Car/vehicle position numbers will be ignored
2. RCDPS does not know (and deal with) car positions or rules like "leading car" or "guided car"
3. A communication between the car directly is not guaranteed by the given LTE/VPN setup during prototype phase in 2020 – later on it is unknown if multicast services are available on 5G network (FRMCS solution)
4. The traction vehicles can identify themselves with their UIC vehicle numbers

6.4.2.2 Pairing Sequence

RCDPS receives the Control Command from CCUO.

1. Startup

Command data:

a. CCUO_RCDPS_Ctrl.WDPSOpSt=1
b. CCUO_RCDPS_Ctrl.WConReq=1
c. CCUO_RCDPS_Ctrl.XTnNr=FFFFFFFF
d. CCUO_RCDPS_Ctrl.XUICIDOwnVh_High=eeeeeeee
e. CCUO_RCDPS_Ctrl.XUICIDOwnVh_Low=eeeeeeee

Status data during initialization of RCDPS:

a. RCDPS_CCUO_Sts.XOpSt=0
b. RCDPS_CCUO_Sts.XConSt=0
c. RCDPS_CCUO_Sts.XRadSt=0
d. RCDPS_CCUO_Sts.XRadQual=0

Status data of RCDPS after initialization (ready for operation):

a. RCDPS_CCUO_Sts.XOpSt=1 (standby)
b. RCDPS_CCUO_Sts.XConSt=1 (disconnected)
c. RCDPS_CCUO_Sts.XRadSt=0
d. RCDPS_CCUO_Sts.XRadQual=0

2. Going to active mode and register to radio network

Command data:

a. CCUO_RCDPS_Ctrl.WDPSOpSt=2 (activate request)
b. CCUO_RCDPS_Ctrl.WConReq=1 (disconnect request)
c. CCUO_RCDPS_Ctrl.XTnNr=FFFFFFFF
d. CCUO_RCDPS_Ctrl.XUICIDOwnVh_High= eeeeeeee
e. CCUO_RCDPS_Ctrl.XUICIDOwnVh_Low=eeeeeeee

Status data of RCDPS after activating:

a. RCDPS_CCUO_Sts.XOpSt=2 (active)
b. RCDPS_CCUO_Sts.XConSt=1 (disconnected)
c. RCDPS_CCUO_Sts.XRadSt= 2 (in case of any error, like coverage, SIM, … : 1)
d. RCDPS_CCUO_Sts.XRadQual=1..3 (poor..excellent)

3. Connect to VPN and publish own vehicle ID (UIC Engine Number) and Train Number and waiting for data from remote vehicles on radio network

Command data:

a. CCUO_RCDPS_Ctrl.WDPSOpSt=2
b. CCUO_RCDPS_Ctrl.WConReq=2 (connect request)
c. CCUO_RCDPS_Ctrl.XTnNr=nnnnnnnn (must be set from this point)
d. CCUO_RCDPS_Ctrl.XUICIDOwnVh_High= eeeeeeee
e. CCUO_RCDPS_Ctrl.XUICIDOwnVh_Low=eeeeeeee

Status data of RCDPS:

a. RCDPS_CCUO_Sts.XOpSt=2
b. RCDPS_CCUO_Sts.XConSt=2..3 (connecting → connected)

c. RCDPS_CCUO_Sts.XRadSt= 2
d. RCDPS_CCUO_Sts.XRadQual=1..3

Additional Status data after receiving first remote vehicle data:

a. RCDPS_CCUO_Sts.XUICIDOwnVh1_High=eeeeeeee
b. RCDPS_CCUO_Sts.XUICIDOwnVh1_Low=eeeeeeee
c. RCDPS_CCUO_Sts.XConStVh1=2 (connected)

When this state is reached, process data communication is started.

4. Deregister own vehicle and disconnect VPN

Command data:

a. CCUO_RCDPS_Ctrl.WDPSOpSt=2
b. CCUO_RCDPS_Ctrl.WConReq=1 (disconnect request)
c. CCUO_RCDPS_Ctrl.XTnNr=FFFFFFFF
d. CCUO_RCDPS_Ctrl.XUICIDOwnVh_High= eeeeeeee
e. CCUO_RCDPS_Ctrl.XUICIDOwnVh_Low=eeeeeeee

Status data of RCDPS:

a. RCDPS_CCUO_Sts.XOpSt=2
b. RCDPS_CCUO_Sts.XConSt=1 (disconnected)
c. RCDPS_CCUO_Sts.XRadSt= 2
d. RCDPS_CCUO_Sts.XRadQual=1..3

Additional Status data after sending a disconnect request:

f. RCDPS_CCUO_Sts.XUICIDOwnVh1_High= eeeeeeee
a. RCDPS_CCUO_Sts.XUICIDOwnVh1_Low=eeeeeeee
b. RCDPS_CCUO_Sts. XConStVh1=2 (disconnected)

Additional Status data 1 second after sending a disconnect request:

g. RCDPS_CCUO_Sts.XUICIDOwnVh1_High=FFFFFFFF
a. RCDPS_CCUO_Sts.XUICIDOwnVh1_Low= FFFFFFFF
b. RCDPS_CCUO_Sts. XConStVh1=0 (unknown)

6.4.2.3   Using a Repeater, Registrar and Monitor

The prototype test run will be based on Vodafone network and VPN provided by MDEX. With this setup a direct communication between the RCDPS over radio link is not possible.
Therefor a **REPEATER** is used on land site: all RCDPS send data only to the repeater and receives data (send by other RCDPS) only from this repeater. The IP address of the repeater is well known by all RCDPS. This way the IP addressing of RCDPS is hidden / abstracted by the repeater.

To build the logical train consist and register the traction units to the train specific logical network the RCDPS send the registration data to the repeater which implements a **REGISTRAR** functionality.
All communication traffic is routed over this repeater – this can be used to **MONITOR** the state of the logical train network and record all data including performance indicators.

6.4.2.4   Life Sign Monitoring over Radio Link

If a RCDPS is gone online, it is transmitting a life sign cyclically with configurable interval time over LTE-VPN to publish own identification data. The life sign message is to be transmitted to one of the configurable targets:

- UDP address (IP and port)
- UDP broadcast address
- UDP multicast address

If a RCDPS is gone online and receives the disconnect request from local CCUO then it shall transmit a last life sign with a flag "BYE".

If a RCDPS is gone online, it is waiting for life signs transmitted by other RCDPS. If a life sign is received the RCDPS compares the Train Number with the own Train Number. If the Train Numbers are equal the RCDPS stores the transmitted UIC vehicle number at one of three slots and set the corresponding connection state to "connected".

If the life sign of the registered vehicle is missed (configurable timeout) then the connection status is set to "interrupted".

If the life sign of the registered vehicle contains a "BYE"-flag (the remote TCMS requests to disconnect) or the local TCMS requests to disconnect (CCUO_RCDPS_Ctrl.WConReq = 0 or 1) or the life sign is missed 10 times then the connection status is set to "disconnected". After one second the slot for this vehicle shall be reset to an empty engine number and status "unknown".

6.4.2.5   Life Sign Monitoring IPTCom side

After 10 seconds of missed data the RCDPS will enter the idle state: standby / disconnected.

6.4.2.6   Process Data Communication

Multicast messages from IPTCom (CCUS_RCDPS_DPSPDExp) will be transformed to messages transmitted via UDP PtP streams to a dedicated repeater, UDP broadcast or UDP multicast.

The reason for avoiding multicast communication in the radio network is that it is still unknown how large the network is and how many participants are active in the network. This is still true for a LTE/VPN network.

Received messages over radio link (beside life sign) are transmitted to IPTCom as follows:

- Registered vehicles are stored at slot #1 .. #3 of data RCDPS_CCUO_Sts:
    - Slot **#1**: XUICID**Vh1** and XSt**Vh1**, transmission ComID for received data: 5903001**10** (RCDPS_CCUO_DPSPDImp_**Vh1**)
    - Slot **#2**: XUICID**Vh2** and XSt**Vh2**, transmission ComID for received data: 5903001**20** (RCDPS_CCUO_DPSPDImp_**Vh2**)
    - Slot **#3**: XUICID**Vh3** and XSt**Vh3**, transmission ComID for received data: 5903001**30** (RCDPS_CCUO_DPSPDImp_**Vh3**)

Remark: the slot enumeration does not correspond to the vehicle position or its role within the train. The slot attribution might be different on each traction unit within the same train. It follows the rule "first come, first served", so each newly connected traction unit gets the first free slot.

6.4.3 Data Processing / Transmission Model

A model of the processing and transmission of data on the traction vehicles and between the cars is crucial for a later latency calculation. After establishing the paired state, the end-to-end calculation must cover the local processing and transmission time on Loco1 (CCUSx →   RCDPS), the LTE transmission time and the local processing and transmission time on Loco2 (RCDPS →   CCUSx).
The calculation schema includes the processing of data by RCDPS because the communication model contains a variant in which the RCDPS implements a proxy function.
Following assumptions are done:

1. Loco1:

   i. T1 (CCUxx): **processing time**
   ii. T2 (CCUxx): **transmission time** (IPTCom or other protocol) with fixed time slices (waiting delay until slice: in worst case the cycle time)
   iii. T3 (LAN/network): **transmission time** between network nodes
   iv. T4 (RCDPS): **time for receiving** data from IPTCom or other protocols with fixed time slices (polling cycle)
   v. T5 (RCDPS): **processing time** until transmission via radio interface

2. LTE:

   i. T6: Transmission time to base station (upload)
   ii. T7: Processing time in the LTE-network
   iii. T8: Receiving from the base station (download)

3. Loco2:

   iv. T9 (RCDPS): **processing time** after receiving data from radio interface
   v. T10 (RCDPS): **transmission time** (IPTCom or other protocol) with fixed time slices (waiting delay until slice: in worst case the cycle time)
   vi. T11 (LAN/network): **transmission time** between network nodes
   vii. T12 (CCUxx): **time for receiving** data from IPTCom or other protocols with fixed time slices (polling cycle)
   viii. T13 (CCUxx): **processing time**

6.4.4 Calculation

The following calculation is done with the worst-case timings on locos and an estimated average time for radio transmission time without radio disturbances. The first step is some simplification / streamlining:

1. **processing time CCUxx** (controller internal time) is the same (T1=T13) and can be set to the internal CCU cycle[4] time 128 ms – named $T_{CCUproc}$
2. **processing time RCDPS** (controller internal time) is the same (T5=T9) and can be estimated to 50 ms – named $T_{RCDPSproc}$

3. **transmission time** (worst case the cycle time) is the same (T2=T10) and can be set to 64 ms – named T_{cycle}

4. **time for receiving** (worst case the polling time) is the same (T4=T12) and can be set to 25 ms – named T_{poll}

5. **transmission time** (between network nodes) is the same (T3=T11) and is considered negligible

6. **radio communication time** (RCDPS and LTE interaction) will be summarized (T6+T7+T8) and set to 60 ms – named T_{LTE}

The resulting calculation formula for one way communication is:

1. Locomotive 1: $T_{loco1} = T_{CCUproc} + T_{RCDPSproc} + T_{cyle} + T_{poll}$
2. LTE network (radio link upload, network, radio link download): $T_{LTE} = 60\,ms$
3. Locomotive 2: $T_{loco2} = T_{loco1}$

Summarized (one way):

$T_{end-to-end} = 2 * T_{CCUproc} + 2 * T_{RCDPSproc} + 2 * T_{cyle} + 2 * T_{poll} + T_{LTE}$
$T_{end-to-end} = 2 * 128\ ms + 2 * 50\ ms + 2 * 64\ ms + 2 * 25\ ms + 60\ ms$
$T_{end-to-end} = 256\ ms + 100\ ms + 128\ ms + 50\ ms + 60\ ms$
$\mathbf{T_{end-to-end} = 594\,ms}$

An average latency is expected within average time values (estimated as the half value) for the particular transmission and processing delay times:
$T_{end-to-end} = 128\ ms + 50\ ms + 64\ ms + 25\ ms + 60\ ms$
this results in
$\mathbf{T_{end-to-end} = 327\,ms}$

6.4.5 Optimization

The main optimization variable is the cycle time of the CCU controller. If the CCU cycle time can be adjusted to 64 ms then 128 ms worst case delay can be avoided:

$T_{end-to-end} = 2 * 64\ ms + 2 * 50\ ms + 2 * 64\ ms + 2 * 25\ ms + 60\ ms$
$T_{end-to-end} = 128\ ms + 100\ ms + 128\ ms + 50\ ms + 60\ ms$
$\mathbf{T_{end-to-end} = 446\,ms}$

An average latency with adjusted cycle times is expected then:

$T_{end-to-end} = 64\ ms + 50\ ms + 64\ ms + 25\ ms + 60\ ms$

This results in :

$$\mathbf{T_{end-to-end} = 263\,ms}$$

6.5 Data for radio transmission (Radio-Link)

Data records that are exchanged between the radio controllers (RCDPS) over the air (with framing). This frame is not transmitted via IPTCom.

6.5.1 Header

Header length is 16 Byte.

Validity	Name	Offset	Data type	Description	Requirement
Long Train FwkFrame	pid	0	UINT16	Protocol ID	In diesem Fall 33474
	len	2	UINT16	Length (including header and payload)	Variable, min. value 16 (empty payload)
	tid	4	UINT16	Telegram type ID	Type of payload
	flags	6	UINT16	Telegram flags	Counter
	source	12	UINT32	Source ID	Source IP address

Telegram content Radio-Link Data Header (RCDPS - RCDPS)

6.5.2 Vehicle Status Message

Payload length is 16 Byte.
Transmission cycle time is 5 seconds.

Validity	Name	Offset	Data type	Description	Requirement
Long Train FwkFrame	Source UIC-ID High	0	UINT32	UIC ID (11 digit) Vehicle 1 High and Low Part	The engine number (UIC ID) is BCD coded. Not used parts of the engine number will filled up with binary 1111 or hexadecimal 0xF. The engine number is filled up from the left side, for example High Part: FF.FF.F9.18 and Low Part: 06.18.79.96 is equal to decimal engine number 91806187996.
	Source UIC-ID Low	4	UINT32		
	Source Train Number	8	UINT32	Train Running Number (8 digits)	The train number is BCD coded. Not used parts of the train number will filled up with binary 1111 or hexadecimal 0xF. The train number is filled up from the left side, for example FFF00123 means 00123 – a correct 5 digits EIRENE train number (with two leading zeros).
	Flags	12	UINT32	Flags	Status bits for internal use of RCDPS (e.g. BYE-Flag)

Telegram content vehicle status message (RCDPS - RCDPS)

6.5.3 Vehicle Data Message

The payload size is 216 Byte. The transmission cycle time is 64 milliseconds.

6.6 Common Radio Performance Considerations

For comparison purposes performance calculation for GSM-R / Data Call and LTE / IP is described in the following sections.

6.6.1 Assumptions for GSM data transmission with data call (CSD)

GSM data calls transmit only 24 bytes per data packet (see also GSM TDMA procedure).
For the Circuit Switch Data Call in mode 'transparent' at 9600 Baud applies:
TCH (data, 9,600 kbit/s) : 4 x 60 bits (block) with block spacing 5 ms = 240 bits / 20 ms 30 bytes / 20 ms
These 30 bytes of 'raw data' can transport a maximum of 24 bytes of application data (24 bytes * 8 * 50 per second results in 9600 baud).
For the transmission of the 30+5=35 bytes (see chapter 2 "Data for radio transmission (radio link)"), 2 time slots / data packets are required under optimum circumstances. If only part of the first data packet is used, 3 data packets are required for transmission. This corresponds to a theoretical transmission time of approx. 60 ms per radio link.
Since both vehicles are each connected to the base station(s) via a radio link, the transmission time is 120 ms assuming that the three data packets are received sequentially by the base station and only then sent (worst case scenario). This means that theoretically about 8 times per second user data can be transmitted between the vehicles.
Due to possible impairments of the performance on the radio links, a maximum number of four transmissions per second should be assumed.

6.6.2 Results from Lab Tests with CCUO Simulators (GSM-R / Data Call)

In order to determine the actual performance to be achieved, a laboratory test with simulators for the CCUO was carried out:
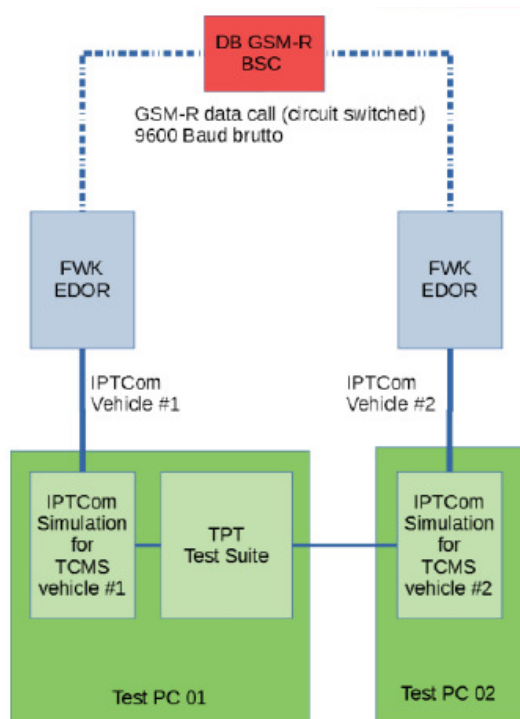

Figure 4: Schematic Test setup for GSM-R data call communication

Results of testing:

1. The measured latency time is approx. 1.1 second and is a combination of:
   a. 120 ms radio transmission duration (two radio links – theoretical minimum value without radio disturbance – see above)
   b. Up to 400 ms latency by GSM-network (network elements BSC and MSC) and radio disturbance
   c. Up to 256 ms Ethernet IP transmission duration (2x IPTCom)
   d. Up to 300 ms processing time (two CCUO -/IPTCom-simulators and applications running at each EDOR-device)

2. typical delay variations are about +/- 100 ms as a result of:
   a. 40 ms variation by GSM radio transmission (2 or 3 data packages on two radio links – see above)
   b. 20 ms variation by GSM-network (fixed station side)
   c. Max. 128 ms due to inefficient timing on IPTCom on both vehicles (per polling cycle 50 ms)

6.6.3 Results from Tests Run 2019 (2 locos with GSM-R / Data Call)

The above laboratory performance test was validated by the 2019 test run with two locomotives. The typical latency time was measured about typical between 1.1 … 1.5 seconds (in some cases up to 2 seconds) end to end (driver at leading TU → … → brake pipe valve of guided TU).

It is important to point out that 1D train simulations of previous DYNAFREIGHT project were carried out considering a deterministic time delay between the two TUs. These time delays are different in nature, since for 1D train simulator (as TrainDy) the only important value is the time interval between the first venting of brake pipe at leading TU and the first venting of brake pipe at guided TU; this time has been taken equal to 2 s by DYNAFREIGHT Project.

In M2O, for the sensitivity analysis of D2.2 in which it is needed to consider the parameters dispersion, following the initial suggestion of FWK, this time was reduced to 1.7 s +/- 30% (assuming it still on the safe side). The analysis of FFL4E experimental tests of May 2019 made in D3.1 has found that this time is around 1.6 s +/- 30%, therefore it is coherent with the assumptions done for the sensitivity analyses of D2.2. Since the expected latency of GSM-R is in the interval 1.1s (average), but the tests provided additional 0.5 s: this value will be used also for LTE, waiting for the availability of experimental data coming from FR8RAIL II full scale experimental tests.

6.6.4 Performance measurement in LTE network


```
pi@raspberrypi:~ $ ping 8.8.8.8
PING 8.8.8.8 (8.8.8.8) 56(84) bytes of data.
64 bytes from 8.8.8.8: icmp_seq=1 ttl=119 time=52.5 ms
64 bytes from 8.8.8.8: icmp_seq=2 ttl=119 time=64.1 ms
64 bytes from 8.8.8.8: icmp_seq=3 ttl=119 time=82.9 ms
64 bytes from 8.8.8.8: icmp_seq=4 ttl=119 time=51.1 ms
64 bytes from 8.8.8.8: icmp_seq=5 ttl=119 time=118 ms
64 bytes from 8.8.8.8: icmp_seq=6 ttl=119 time=32.1 ms
64 bytes from 8.8.8.8: icmp_seq=7 ttl=119 time=35.4 ms
64 bytes from 8.8.8.8: icmp_seq=8 ttl=119 time=31.5 ms
64 bytes from 8.8.8.8: icmp_seq=9 ttl=119 time=37.4 ms
64 bytes from 8.8.8.8: icmp_seq=10 ttl=119 time=33.4 ms
64 bytes from 8.8.8.8: icmp_seq=11 ttl=119 time=36.6 ms
64 bytes from 8.8.8.8: icmp_seq=12 ttl=119 time=33.3 ms
64 bytes from 8.8.8.8: icmp_seq=13 ttl=119 time=34.7 ms
64 bytes from 8.8.8.8: icmp_seq=14 ttl=119 time=36.2 ms
^C
--- 8.8.8.8 ping statistics ---
14 packets transmitted, 14 received, 0% packet loss, time 13021ms
rtt min/avg/max/mdev = 31.574/48.578/118.203/24.052 ms
```

Figure 5: LTE network – laboratory ping measurement

The figure above shows the ping time – the roundtrip time between and LTE mobile and a fixed IP-Server (internet). Typical roundtrip time is less than 40 ms (radio link upload + network + radio link download) – time to access the IP-Server is therefore less than 20 ms. The one way end-to-end average time for LTE radio network part in this project will be estimated conservatively with 60 ms until more sophisticated measurement results are available.
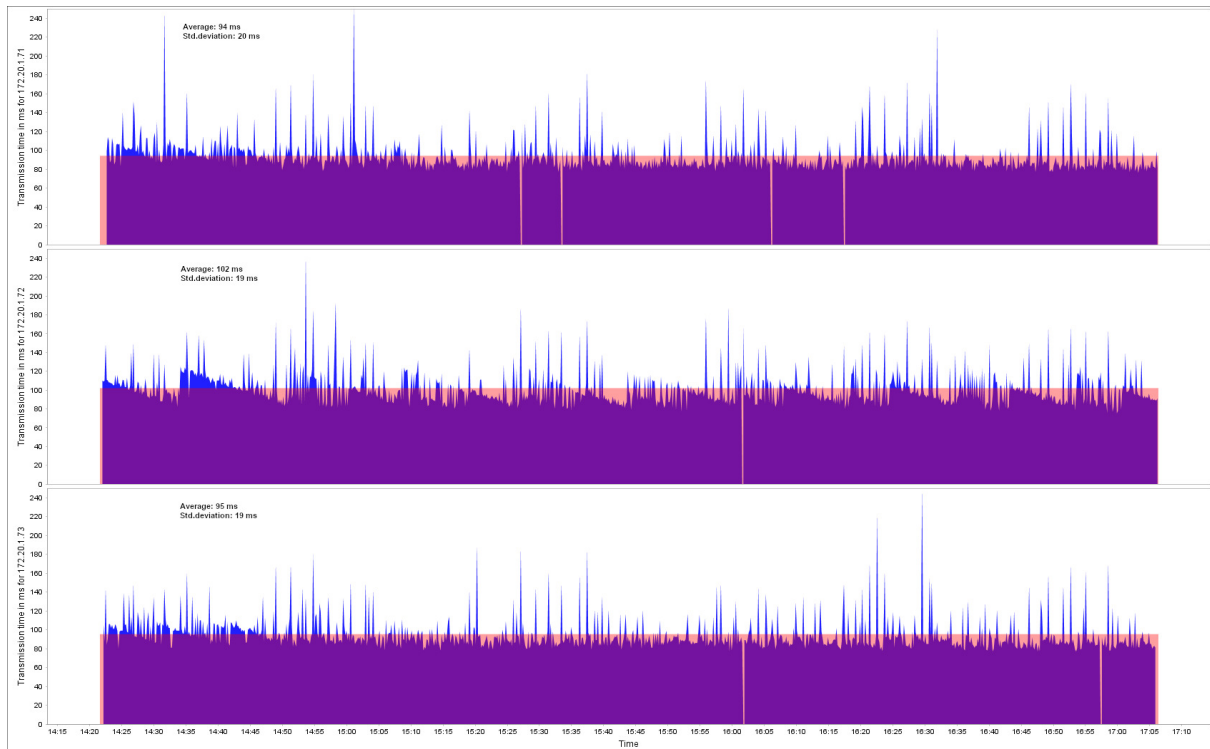
Figure 6: LTE network – laboratory performance test with 3x RCDPS

Figure 6 shows the result of a preliminary RCDPS test with the setup which will be used during test run 2021:

- 3 RCDPS (172.20.1.71..73) each connected to a PC with an IPTCom Simulation (3 traction units)
- Each RCDPS is configured to use the Vodafone MDEX APN over LTE radio link
- RCDPS executes the Release Candidate Software for the test run
- One PC is connected via Internet / VPN to MDEX APN Gateway and run the repeater / registrar / monitor Software

The data were recorded by the monitor software. The measured time is the duration between a request was sent from monitor to a dedicated RCDPS until the answer was received (two times radio link transmission). Included is the processing time on RCDPS.
The worst performance is shown in the second row (RCDPS with IP address 172.20.1.72) with:

- Average time = 102 ms
- Standard deviation = 19 ms

With the calculation derived in section 6.4.4:

Summarized (one way end to end):

$T_{end-to-end} = 2*T_{CCUproc} + 2*T_{RCDPSproc} + 2*T_{cyle} + 2*T_{poll} + T_{LTE}$

$T_{RCDPSproc} + T_{LTE} =$ 50 ms + 60 ms = 110 ms can be substituted by the measured value (average time + standard deviation) = 121 ms

Estimated : $T_{end-to-end} = 2*128$ ms $+ 2*50$ ms $+ 2*64$ ms $+ 2*25$ ms $+ 60$ ms $= \mathbf{594\ ms}$

Partly measured : $T_{end-to-end} = 2*128$ ms $+ 1*50$ ms $+ 2*64$ ms $+ 2*25$ ms $+ 121$ ms $= \mathbf{603\ ms}$

An average latency was expected within average time values (estimated as the half value) for the particular transmission and processing delay times:

$T_{end-to-end} = 128$ ms $+ 50$ ms $+ 64$ ms $+ 25$ ms $+ 60$ ms

this results in

$\mathbf{T_{end-to-end} = 327\ ms}$

With the measured part the 25 ms (1x RCDPS processing time) + 60 (LTE) = 85 ms can be substituted by the average time of all three rows of Figure 6: (94 ms +102 ms + 95 ms) / 3 ≈ 100 ms.

$T_{end-to-end} = 128$ ms $+ 25$ ms $+ 64$ ms $+ 25$ ms $+ 100$ ms

$\mathbf{T_{end-to-end} = 342\ ms}$

The expected average latency time must be correct from 327 ms to 342 ms.

Further end-to-end measurement from IPTCom simulation #1 over radio link to IPTCom simulation #2 should be performed to validate the end-to-end latency estimation.

6.6.5   Data Volume per Month and Mobile

With the defined data telegrams, transmit frequency and number of vehicles a data volume can be estimated as follows (test vehicles):

S…Size of data telegram (byte) including 16 byte RCDPS Header

F…Frequency (times per hour)

N…Number of remote vehicles H…Hour per day in permanent use

D…Days per month in use V…Volume per month

$V_{month} = S_{data} * F_{hour} * N_{remote\ vehicle} * H_{day} * D_{month}$

with

$S_{data} = 216 + 16\ byte_6$

$F_{hour} = 1000\ ms 64\ ms * 60 * 60 = 56.250$

$N_{remote\ vehicles} = 2$

$H_{day} = 12$

$D_{month} = 20$

this results in

$V_{month} = 232\ byte * 56.250 * 2 * 12 * 20$

$\mathbf{V_{month} \approx 6{,}0\ GB}$

6.6.6 Comparison among GSM-R and LTE made by using tests labs.

Table below provides a synthetic comparison between GSM-R and LTE, based on test lab measurements.

Criteria	GSM-R	LTE
1) Latency between Train Controller Unit (CCU) and Radio Controller (RCDPS) for both TU's (end-to-end without radio communication)	300..350 ms	300..350 ms
2) "Fitting" parameter to FFL4E experimental tests	500 ms (measured)	500 ms (assumed, more probably 300 ms)
3) Latency between radio module on leading TU and radio module on guided TU	750 ms (+/- 30%) (measured in FWK lab using GSM-R network with CSD call) Theoretical minimum: 120 ms without GSM-R infrastructure	70 ms (+/- 15%) (measured in FWK lab using public Vodafone LTE) Estimated minimum: 20 ms with LTE infrastructure
4) Latency between Train Controller Unit (CCU) and Radio Controller (RCDPS) for both TU's (end-to-end **with** radio communication)	1100 ms (+/- 10%) (measured in FWK lab)	390 ms (+/- 15%) (measured in FWK lab)
5) Average measured system wide latency during test run in 2019 (driver at leading TU → … → brake pipe valve of guided TU)	1600 ms Including the above values from criteria 2) and 4)	- to be measured after FR8RAIL II full scale tests
6) Prognosis for system wide latency (driver at leading TU → … → brake pipe valve of guided TU)	-	900 ms (+/- 15%) Including the above values from criteria 2) and 4) and rounded up
7) Additional equipment on leading TU	3 RCDPS + 3 GSM-antenna	1 RCDPS + 1 LTE-antenna
8) Permanent used network resources	6 CSD channels	Low bandwidth packet switched traffic

Comparison table for GSM-R and LTE based on a long train with max 4 TU's – latencies are given as average values.

From above table, it is justified the initial assumption (on the safety side) about the time interval between the brake pipe venting at leading and at guided TU with LTE radio used for TrainDy simulations of D3.1: this time interval is between 0.5 s and 1 s (with a uniform distribution), with a supposed optimized LTE implementation within TU. Average value of previous time interval comes from the rounding of (900 ms – 200 ms). The 200 ms come from the difference between 500 ms and 300 ms in row 2) of above table. The uniform distribution is used to be more conservative.

For D3.3, it could be assumed at least a different time interval 0.9 s +/- 15% based on a not optimized LTE implementation in TU (or an implementation like that of May 2019), therefore following what is written in row 6) of above table. Gaussian distribution must be used.

7 CONCLUSIONS

The first part of this deliverable developed by NEWO shows the interest of the various configurations of trains with DPS in order to support the rail freight developments expected by the EU.

The second part of this deliverable based on the essential contribution of FUNKwerk has demonstrated that GSM-R solution, efficient for consists with 2 TUs was not extendable to 3 or 4 TUs. The LTE solution representing a first step towards the development of future FRMCS is fulfilling the requirements of the radio communication system in terms of capacity which is an important parameter for the safety of such consist. The change from GSM-R to LTE is thus fully justified.

This demonstration will be completed in the analysis of the full integration of the radio communication in the train with the local communication inside the TUs depending on the TCMS of the TUs.

All these features of radio communication solutions will be used in other WP2 and WP3 Tasks.