Test: Digital Automatic Coupling

Phase II
Test report on data communication
Final project report

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Document acceptance

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List of abbreviations

ACC	Auto carriage connection
AC	Automatic coupler (without electric coupler)
CAN	Controller area network
DAC	Digital automatic coupler
EDDP	European Dac Delivery Programme
FEC	Forward error correction
FPS	Frames per second
ICMP	Internet control message protocol
IPC	Industrial PC
OFDM	Orthogonal frequency division multiplex
OPC UA	Open platform communication/unified architecture
PLC	Powerline communication
RTT	Round trip time
RFT	Rail freight transport
SNR	Signal-to-noise ratio
SPE	Single-pair Ethernet (IEEE 802.3cg/10Baste-T1L)
TCP	Transmission control protocol
TRDP	Train realtime data protocol
TTD	Train topology detection (Powerline-PLUS)
TTDP	Train topology discovery protocol
UDP	User datagram protocol
UPS	Uninterruptible power supply
VLAN	Virtual local area network

1 Data communication measuring instruments

Phase II of the project focused on evaluating the communication systems in operational scenarios. For this purpose, the following groups of tests were carried out:

- Proof of operational functions via the communication systems
- Measurements of the availability of the communication systems

According to interim results, problems with the communication systems could be traced back to isolated contact breaks in the electric couplers. In order to be able to investigate the reliability of contacts, additional measuring instruments were set up:

- Measurement of contact losses by means of a logic analyser
- Measurement of contact losses and disturbances on the cable by means of an oscilloscope.

1.1 Cables and components of the test system

The design of the test system was partially changed compared to the system in Phase I (measurements under static conditions).

1) Following the decision of the EDDP group[1], to place the single-pair-Ethernet (SPE) on the short list as a two-wire communication system, the replacement of the existing CAN-FD communication systems with SPE was undertaken for Phase II in the DAC4EU project. The cable installation was not changed.
2) It was also decided to initially evaluate three communication systems (Powerline-PLUS, WiFi and SPE) in parallel in line runs in Phase IIa (until June 2022). Since two Ethernet-based technologies were to be operated in parallel with WiFi and SPE, the Ethernet switch had to be replaced by a VLAN-capable switch (IEEE 802.1Q) to separate the networks. WiFi was not tested further in Phase IIb.
3) Additional communication system equipment was installed in a measurement coach. This is used to simulate the locomotive during testing. The essential components of the communication system structure are identical to the systems installed on the wagons. In contrast to the freight wagons, the measurement coach's system does not require a UPS or a battery.

[1] EDDP (European Dac Delivery Programme) WP1 SG3 (Communication Technology)

1.1.1 Hardware set-up in the test system

The structure of the wagons was not fundamentally changed for Phase II. The installations of the cables, wagon box and terminal box were retained. For the wagons in Phase IIb, the two two-wire cables were laid as a combined cable (2x2x0.5mm²) due to the availability of the previously used cable type. The shield of the communication cables is not connected to the wagon potential on any wagon. The position of the wagon box varies depending on the wagon type. Basically, the wagon box was mounted as a control box at one end of the wagon. On the container wagons (Sgmmns) and the modular wagons (m² wagons, Uas), the wagon boxes were mounted approximately in the middle of the wagon. The coupler cables were led into a coupler connection box and connected to corresponding terminals. This was necessary in order to be able to connect any type of coupler to the wagon in the same way. In principle, there should be a defined (and standardised) plug connection between the coupler and the wagon in the future.

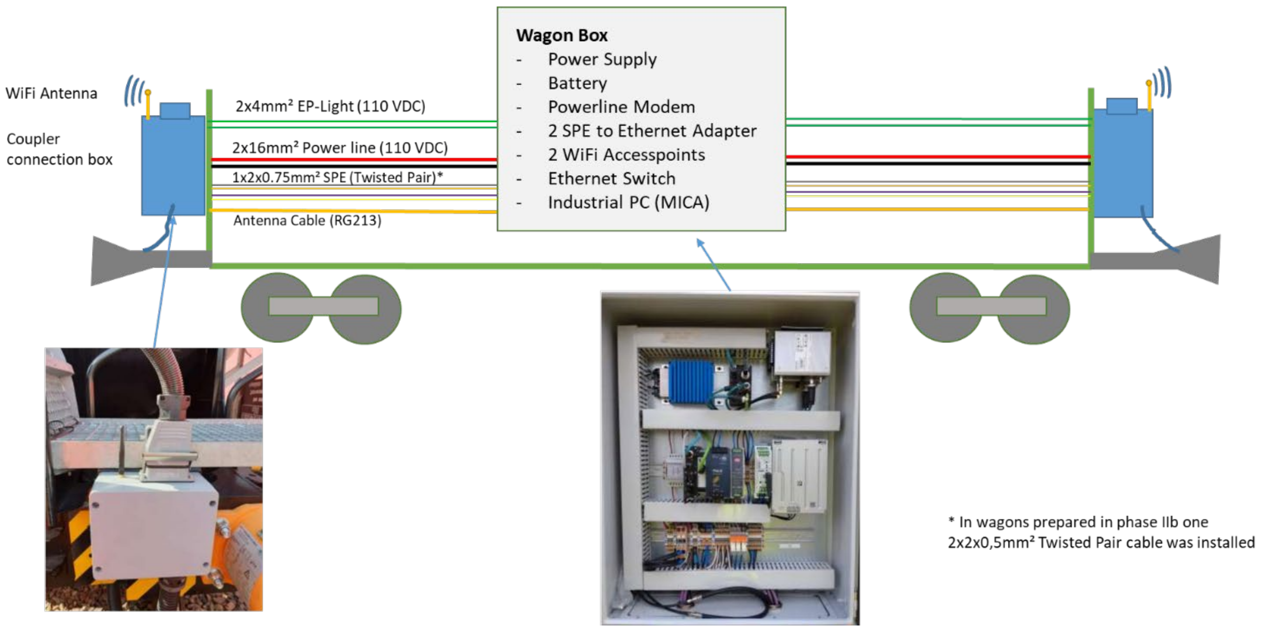

Figure 1: Installations in the wagons

In addition to the communication and power cables (110 V_{DC} and ep brake), an antenna cable (cable type RG213) was also laid from the wagon box to each coupler connection box in order to implement a radio link across the Berne rectangle. In practice, it has been found that the RF connections need to be checked regularly, as vibrations have led to loose connections in some cases. Producing practical RF cable connections for freight transport is costly and should therefore be avoided.

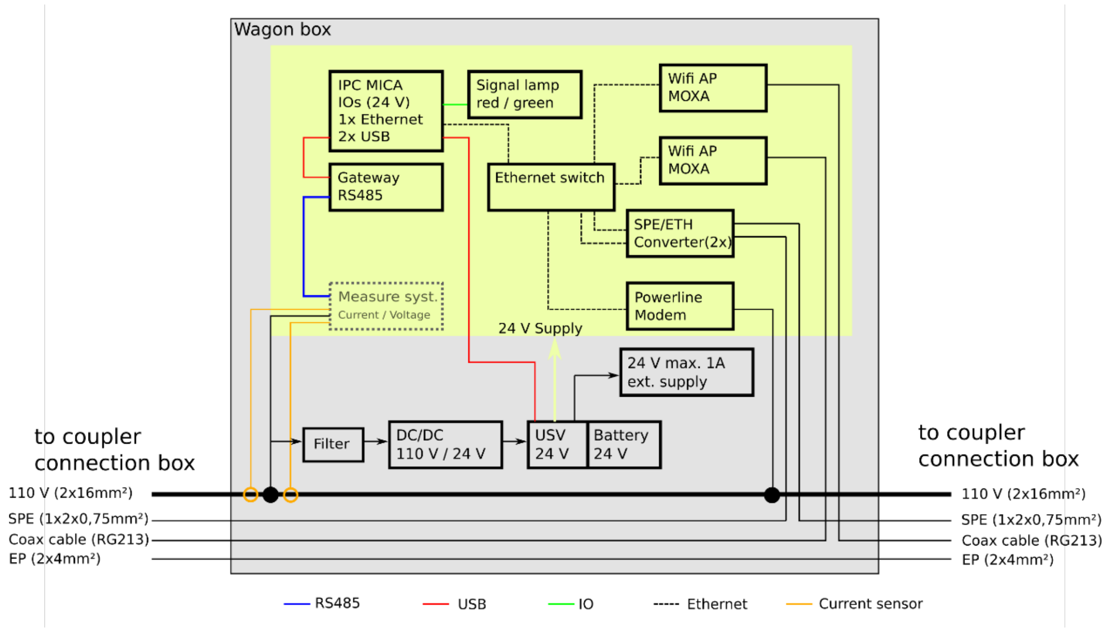

Figure 2: Structural design of the test system in the wagon box

Three communication systems are integrated in the DAC4EU Phase IIa test system (see **Figure** 2). The control of the communication systems and the management of wagon-specific parameters are carried out on the industrial PC (IPC, MIC). All communication components are connected internally via Ethernet through a managed Ethernet switch. On the one hand, the Ethernet switch establishes the connectivity of the wagon components, and on the other hand, with the SPE and WiFi communication system, it also transmits train communication. For wagons involved in Phase IIa, the Ethernet switch was replaced by a managed switch with VLAN functionality (model FL Switch 2608, Phoenix Contact).

A media converter was used to connect SPE (functional sample from OWITA GmbH). This converts the 10 Mbit/s SPE physical layer to 10Base-T Ethernet. The SPE signal cables (SPE+ and SPE-) were connected to two-wire cable 1 in all wagons.

The Powerline-PLUS modem was connected directly to the 110 V_{DC} power cable. This connection is only used for communication, as the power supply of the modem is provided by the 24 V_{DC} connection via the 24 V board network. In addition, there is an Ethernet connection to the managed Ethernet switch.

A MOXA access point (model AWK-3131A) was used for WiFi communication. This device has a special ACC mode, which automatically negotiates AP/client roles between carriages. At the end of Phase IIa, the WiFi communication system was not tested further and the WiFi access points were therefore switched off.

Furthermore, a filter was installed in each wagon between the DC/DC converter (110 V_{DC} to 24 V_{DC}) and the 110 V_{DC} power cable. The filter was provided by plc-tec AG to filter the disturbances in the Powerline-PLUS communication caused by the switching power supplies. A UPS with a lithium battery was installed between the power supply unit and the 24 V_{DC} board network (models QUINT

UPS 24DC/24DC/20 and UPS-BAT/LION/24DC/120WH, Phoenix Contact). The UPS is used to supply the measuring instruments in the event of a failure of the 110 V_{DC} power supply during the runs.

Furthermore, a signal lamp was fitted to the wagon box, which indicates the switch-on status of the 110-V_{DC} supply. The signal lamp lights up red when the supply voltage is switched on.

The design of the system in the measurement coach is similar to the design in the other wagons. The difference is mainly in the power supply (230 V_{AC} instead of 110 V_{DC}) and the fact that no UPS is needed in the measurement coach. Furthermore, the measurement coach is equipped with fuse devices for the power supply. These consist of a circuit breaker for the 110 V_{DC} supply of the wagons and an insulation monitor (model IsoRw425, Bender), which monitors the insulation value of the IT network (110 V_{DC}).

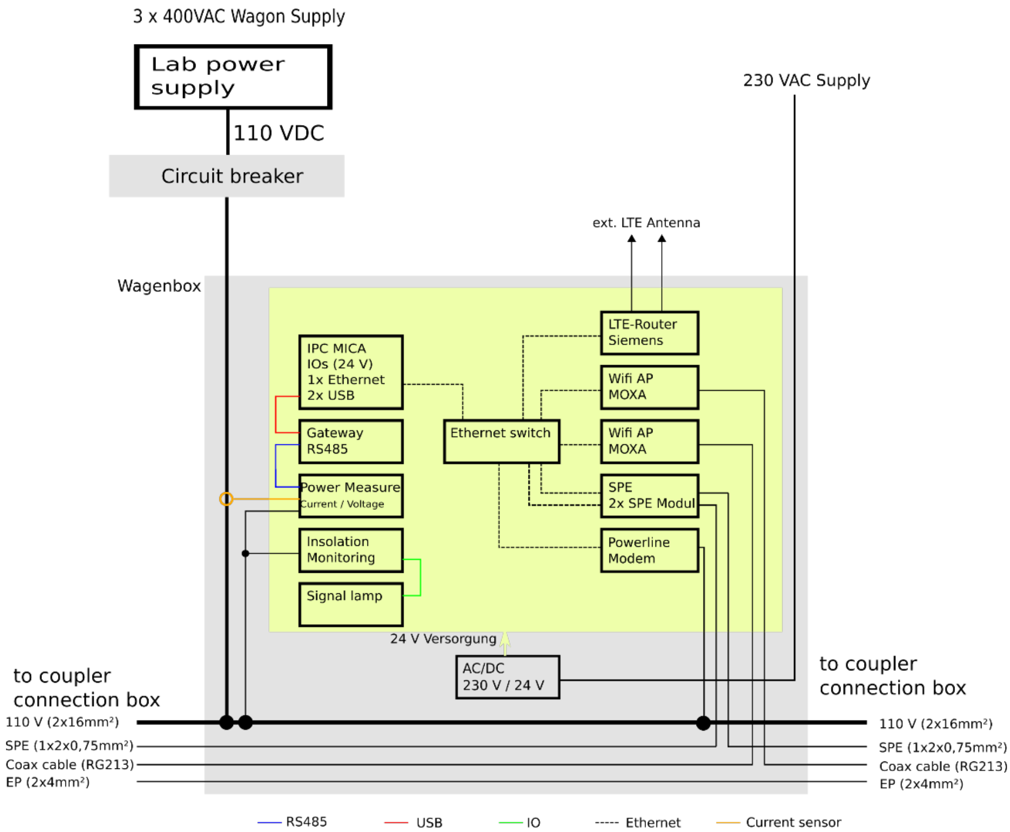

Figure 3: Structural design of the power supply and communication system in the measurement coach

The insulation monitor measures the insulation resistance of the train supply system against the earthed wagon body and signals the non-critical state via a signal output by means of a green indicator lamp. The signal threshold is 40 kohm. If the insulation value of a conductor of the power cable is lower than the wagon earth or the rail potential, the green light is automatically switched off.

The 110 V_{DC} supply voltage, which is fed into the train at the measurement coach in order to supply the wagons, was provided by a laboratory power supply unit from Elektro Automatik, which can provide the required 30 A to achieve the 3 kW. The maximum output current was set to 32 A for the laboratory power supply unit, as it has already been shown when switching on the train with 19 wagons that the switching power supplies in the wagons cause a high current due to being switched on simultaneously. In contrast to an industrial power supply, the laboratory power supply limits the current to the set value and does not allow any short-term overcurrent.

1.1.2 Structure of the various communication networks

In each wagon, the communication components are connected via a managed Ethernet switch. The separation of the individual communication systems (WiFi, SPE) is done via a VLAN configuration and is only necessary for parallel operation of the communication systems without mutual interference (**Figure** 4).

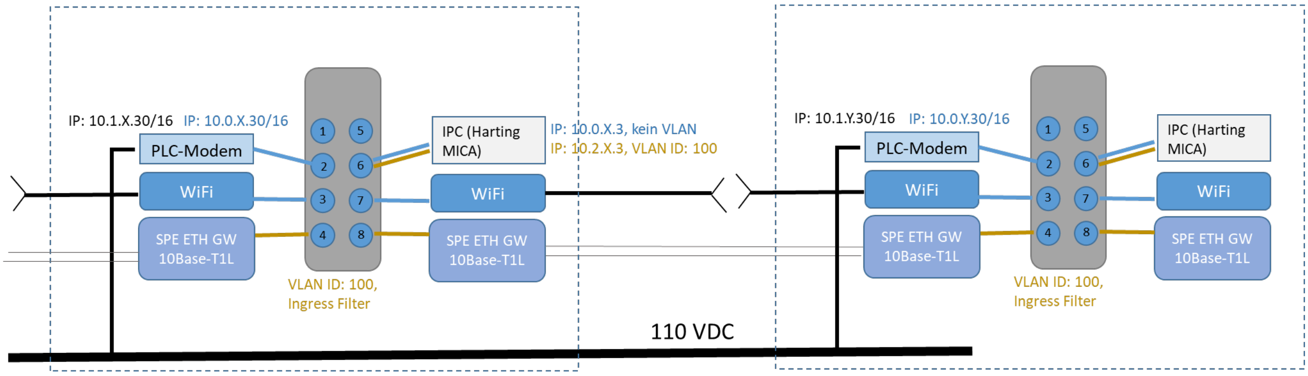

Figure 4: Network structure/configuration within the wagons

For separation, ports 3 and 7 of the Ethernet switch are reserved for the WiFi system, and ports 4 and 8 for the SPE system. The SPE ports are configured in the Ethernet switches so that communication works exclusively with VLAN ID 100 (activation of the ingress filter). The VLAN group 100 also contains port 6, to which the MICA is connected. This allows the MICA to access ports 4 and 8 using VLAN ID 100. For this purpose, two IP addresses are configured in the MICA, the IP addresses *10.0.<Wagon number>.3/16* and the IP address *10.2.<Wagon number>.3/16* with VLAN ID 100. If communication is established from the measurement coach to another wagon, the communication system can be determined by selecting the IP address. This applies to WiFi and SPE. Communication via Powerline-PLUS runs separately from this. The initialisation and availability data are determined by the Powerline PLUS modem and transmitted to the MICA only for display and storage. To separate the Powerline PLUS network from the other networks, a separate subnet is defined in the Powerline PLUS modems for the network interface. Routing between the wagon's internal network and the Powerline PLUS network is switched off in the Powerline PLUS modem.

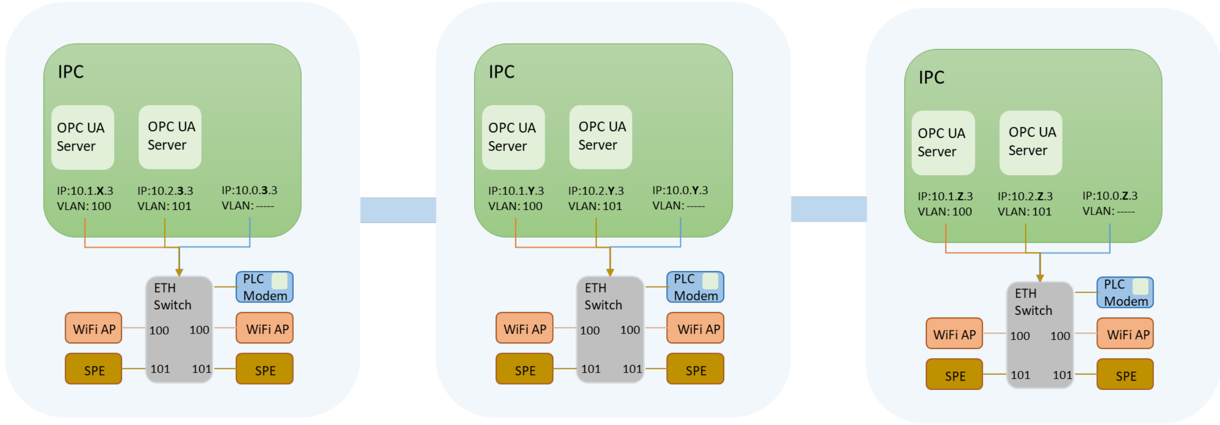

Figure 5: Separation of networks through IP subnets and VLANs

1.1.3 Structure of the test software

The implementation of the test functions is partly dependent on the communication systems. For this purpose, a concept for communication was created in a preliminary study [1]. The implemented functions for testing the operating functions are based on the communication model (**Figure** 6). Basically, there are three levels: A hardware-related component (modem/GW), a technology adapter and an application level for connecting services.

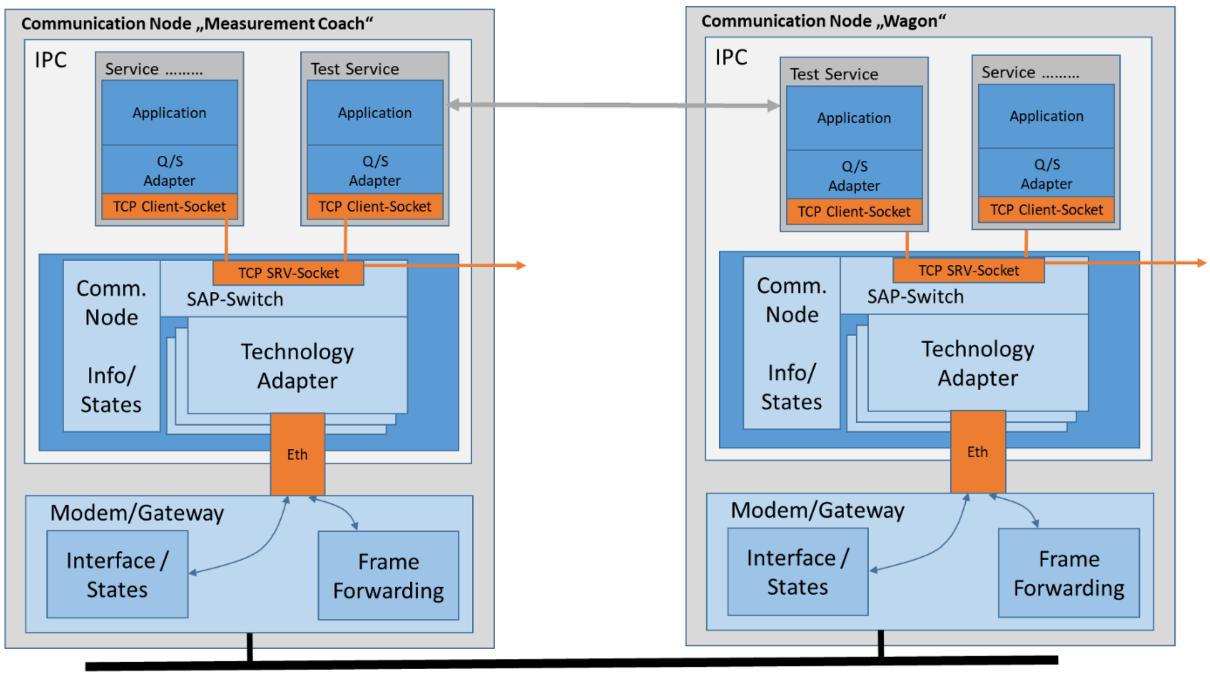

Figure 6: Structural organisation of communication

The lowest layer as a connection to the specific communication system in the form of modems and gateways/converters is specified by the corresponding hardware components.

The technology adapter serves as an intermediary layer that understands the respective communication system and organises the initialisation of the communication system and the train initialisation. This includes a service access point switch (SAP switch), which provides a uniform interface for services that want to exchange data via the communication system. The basic technology selected for this is OPC UA [2]. TRDP (train real time data protocol, IEC 61375-2-3) will probably be used as the future technology here.

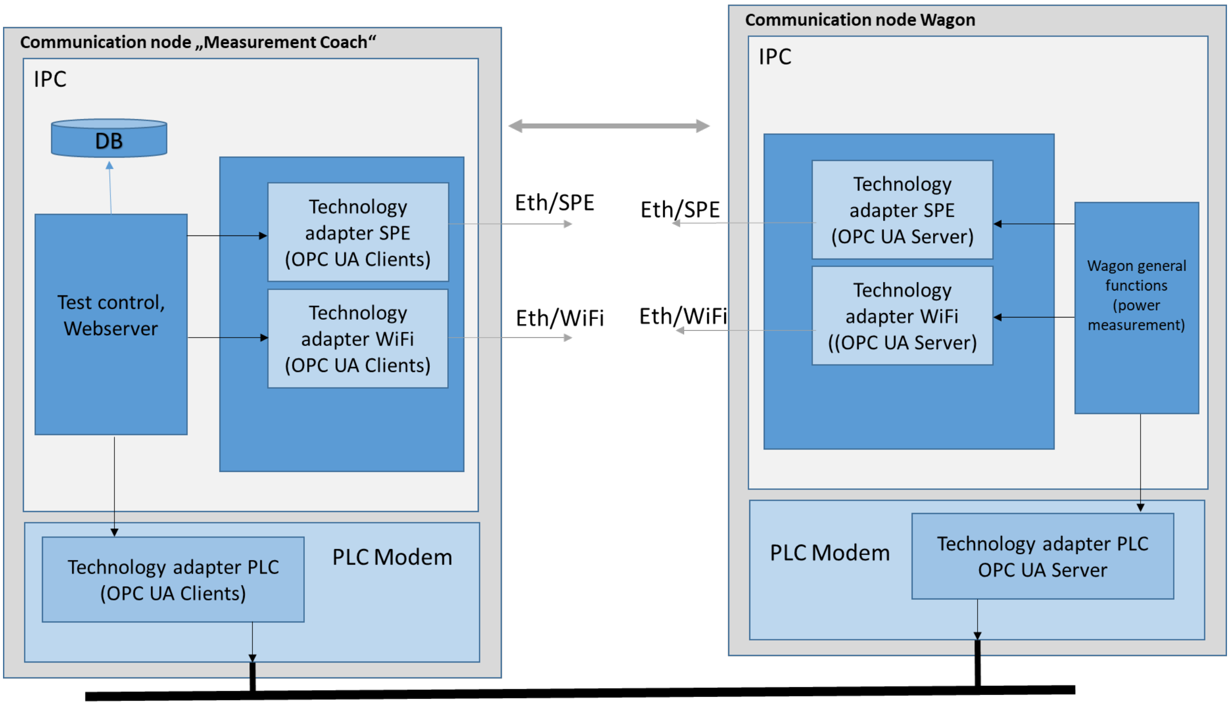

Figure 7: Communication model in the test set-up

The technology adapter for WiFi and SPE is located entirely in the IPC (MICA). The technology adapter for the Powerline PLUS system was integrated into the Powerline PLUS modem. To implement the technology adapter, an OPC UA server was installed in the wagon. Corresponding OPC UA nodes were created in the OPC UA server, which map the wagon status. In the measurement coach, the technology adapter was implemented using OPC UA clients. For each identified wagon, a client instance was created for direct communication with the wagon.

1.1.4 Communication test and availability test

The sequence is detected when the train is initialised. Once the sequence has been determined, an ICMP ping request packet (ping) is sent to the IPC of the last wagon or, in the case of Powerline-PLUS, to the last Powerline-PLUS modem in the wagon network via a cyclical mechanism at intervals of 100 ms to determine availability. The measurement of the availability of the communication systems is simultaneously used as an integrity check function. The sent ICMP packet is automatically answered by the TCP/IP stack with a reply. The reception of the response is registered in the measurement coach. Each ICMP ping request packet also receives a unique ID so that a duplicate response packet can be detected. The following parameters are recorded at intervals of 1000 ms:

- Sent ICMP packets,
- Received ICMP packets,
- Lost packets,
- Measurement of the Round Trip Time (RTT): Maximum and mean RTT in the measurement period,
- Error counter if no response was received for longer than 1000 ms.

The generation of the ICMP packet is part of the technology adapter in the measurement coach.

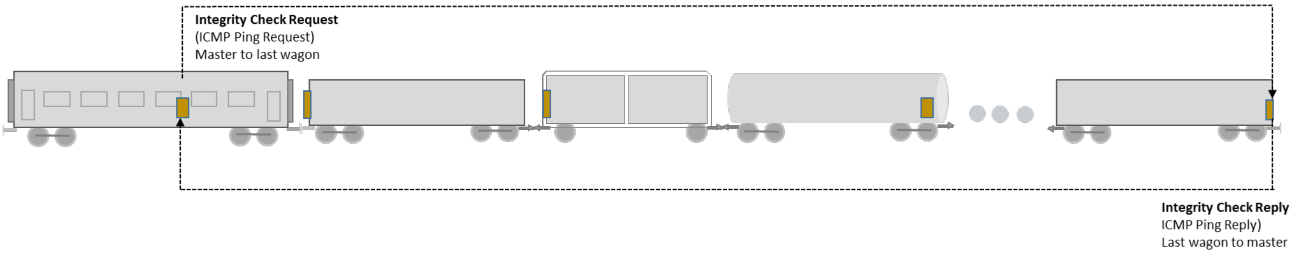

Figure 8: Measuring the availability/train integrity using ICMP packets

After an increasingly higher number of packet errors were identified in the SPE communication system during the measurement runs, the test system had to be expanded. In the expansion, a separate ICMP ping communication took place from the measurement coach to every single following wagon, as well as an ICMP ping communication from the last wagon to every single wagon up to the measurement coach. Through this mechanism, up to two simultaneous interruptions in communication (contacts/cable) can be identified and localised.

In the Powerline-PLUS system, two mechanisms were used to identify the availability of communication. On the one hand, a layer-2-based integrated function of the system was used. In the Powerline-PLUS system, messages initiated by the master ("ping") are mirrored back to the master by the last wagon ("pong"). The absence of the "pong" messages causes an integrity event to be displayed after a defined time of a few 100 ms.

On the other hand, the function described above was operated in parallel using ICMP ping packets, which was also used for SPE and WiFi.

1.1.5 Determination of the number, sequence and alignment of the wagons

With Powerline-PLUS, the sequence of the wagons is determined on the basis of the signal runtimes. After successful execution of the TTD process (Train Topology Detection), the detected topology can be read out from the system by means of a script. The result of the detection was recorded to verify the result.

Both WiFi and SPE are segmented Ethernet systems. In each wagon node, the Ethernet switch either switches the Ethernet packets to the wagon itself or forwards them to the next wagon. Thus, the conditions for detecting the number of wagons and the sequence are identical. To detect the number of wagons, a scan of the wagons is carried out, i.e. the addresses of the known wagons are specifically searched for. This procedure can only be used here in the known test environment. For a later solution during operation, an alternative approach must be developed in which the wagons are assigned their IP addresses dynamically or in which the wagons set them independently through a defined scheme (see TTDP - Train Topology Discovery Protocol, IEC 61375-2-5).

To determine the sequence, a system was implemented that relied on the power measurement of the power cable within each wagon. In this approach, the power is measured on the 110 V_{DC} power supply cable in each wagon. After the initialisation process, the existing wagons are known through a scanning process. Now the performance data of the wagons on the 110 V_{DC}- power supply cable are queried using OPC UA. For this purpose, two current sensors are installed in each wagon, one sensor on the input and one on the output side of the 110 V_{DC} power supply cable. The power is determined via the voltage and current measurement and made available as an average value calculated from the two sensor values. If a sensor does not provide any measured values, only one sensor value is used.

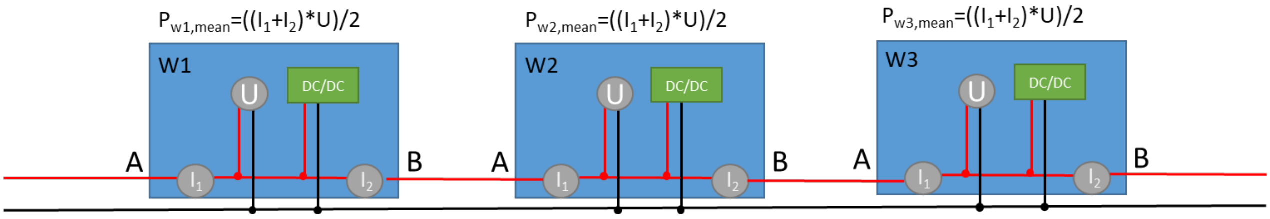

Figure 9: Sorting the sequence based on the power measurement

After all the powers are known in the technology adapter of the master (measurement coach), the wagons are sorted in descending power order (the wagon with the lowest measured power in the power cable is at the end of the convoy). The orientation of the wagon is determined by the direction of the current flow. Wagons with a positive current reading travel in the direction of the A side, while wagons with a negative current reading travel in the B direction.

This procedure differs from that defined in the Ethernet Train Backbone (ETB), [3]), which is based on neighbourhood detection at the network level. An alternative procedure and the necessary boundary conditions must be evaluated here.

1.2 Test set-up for measuring the availability of the communication systems

1.2.1 SPE and WiFi

The measurement of the availability of the communication systems is simultaneously used as a functional approach for integrity checking. For this purpose, an ICMP ping packet is generated by the measurement coach, which is sent to the last wagon. The IP address of the last wagon is obtained from the result of the train initialisation. The ICMP packets are generated with a cycle of 100 ms. The ICMP packets received from the last wagon are sent back to the measurement coach as ICMP ping reply packets. The RTT (round trip time) can be generated as information from the received reply messages. Both the maximum and minimum RTT and the number of packets sent and received are registered for each communication system. Furthermore, if the response packets are missing for more than 900 ms, an integrity counter is incremented.

2 Description of wagons and wagon-sets

The structure of the wagons and wagon-sets can be found in the interim report's master document. Here, the specific characteristics of the wagons are provided as supplementary information.

Each wagon was assigned a wagon number (**Table** 1). The number of the wagon was derived from the communication plate, which was installed in the wagon (wagon box). The systems with the numbers 12 and 13 were used for experiments in the laboratory.

Table 1: Assignment of wagon numbers to wagon-sets

Wagon no. (Communication)	Couplings	Wagon type	UIC number
Measurement coach (0)			
1	Voith SC, DAC	Z	37 80 7824 377-1
2	Voith DAK	H	21 80 2470 520-2
3	Voith AC, SC	E	31 80 5375 261-0
4	Voith AC	Z	37 80 7824 376-3
5	Voith AC	H	21 80 2470 787-7
6	Voith DAC, AC	E	31 80 5375 306-3
7	Dellner DAC, SC	Z	37 80 7824 375-5
8	Dellner DAC	H	21 80 2470 687-9
9	Dellner SC, DAC	E	31 80 5375 131-5
10	Voith DAC	S	37 80 4505 281-8
11	Voith DAC	Z	37 80 7824 940-6
14	Voith AC	H	21 80 2470 570-7
15	Dellner DAC	S	37 80 4505 277-6
16*	Dellner DAC	U	31 80 9300 017-8
17*	Dellner DAC	Z	37 80 7824 939-8
18*	Voith DAC	S	37 80 4505 278-4
19*	Voith DAC	U	31 80 9300 018-6
20*	Voith DAC	F	33 87 6771 791-5
21*	Dellner DAC	S	37 80 4505 268-5
22*	Dellner DAC	F	33 87 6771 699-0

** Wagons were not upgraded until Phase IIb; wagons with AC were equipped with an electric coupler in Phase IIb*

Table 1 shows the wagon numbers and their association with the corresponding wagon-set. In Phase IIa, the wagons can be divided into three groups:

- Wagon with Dellner DAC,
- Wagon with Voith DAC. There was an electrical uncoupling mechanism on four couplers. This has no relevance for the investigation of the communication systems.
- Wagons with Voith AC: These wagons did not have an electric coupler. These wagons were bridged for train movements with a bypass cable between the coupler connection boxes of the two wagon sides. The bypass cables have a length of 3 or 4 metres and connect the power cable, both two-wire cables and the ep control cable.

In Phase IIb, the wagons with Voith AC were equipped with a modified version of the electric coupler. This meant that only bypass cables were needed between the wagon-sets.

3 Post-testing and stress testing at a standstill

In Phase II, further tests were conducted to supplement Phase I. CAN-FD was replaced by SPE (single-pair Ethernet) in Phase II. Corresponding performance measurements, such as those for the WiFi and Powerline-PLUS communication systems, were carried out analogously to Phase I for SPE.

Following the EDDP's decision to continue to consider only SPE and Powerline-PLUS as preferred communication systems, additional stress tests were conducted. These concerned in particular the communication distance of the communication systems as well as special cases of communication.

3.1 Single-pair Ethernet

3.1.1 Performance measurements

Analogous to the measurements for the WiFi and the Powerline-PLUS system, performance measurements were also carried out for the SPE. The measurements were taken after the line runs in Austria.

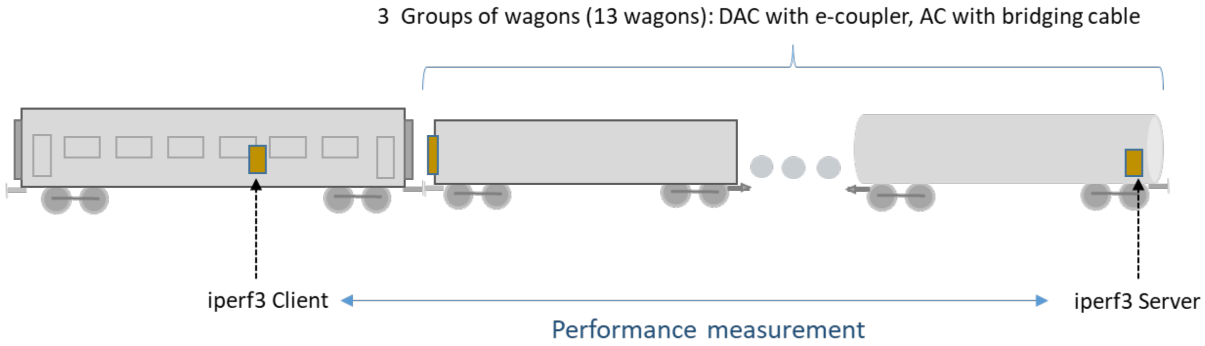

Figure 10: Performance measurements with SPE

The performance measurements were carried out analogously to the measurements in Phase I [4]. In contrast to the wagon-sets in Phase I, the measurements were carried out with 14 participants in the network (13 freight wagons and one measurement coach).

Table 2: Performance measurements for SPE

Data rate (TCP transmission)	Frames per second (UDP transmission)	Error rate	Latency (RTT)
7.5 MBit/s	6669 FPS	PER < 10^4 (0% @ 213293 frames)	Min: 3.47 ms Avg: 3.65 ms Max: 4.12 ms

The performance measurements show that SPE clearly meets the requirements for the communication system. SPE has very good values, especially for latency (measurement of RTT - round trip time).

3.1.2 Measuring the communication distance without repeaters

A wagon-set consisting of six wagons with couplers from one manufacturer was ready to measure the communication distance without repeaters. On each of the outer wagons, a laptop was connected to the Ethernet switch in the wagon to measure the data communication (**Figure** 11). On the middle wagons, the SPE adapters were removed from the two-wire cables and a bridge was installed. This created a continuous line between the two SPE adapters of the outer wagons. The segment length without repeaters was about 105 metres. This measurement serves to verify the EDDP criterion of being able to bridge a segment length of at least 100 m without repeaters.

Figure 11: SPE communication test via a continuous line

Result: Communication over the segment was possible without communication problems.

3.1.3 Bridging an intact coupler

A potentially critical application could be the bridging of an intact coupler. In this case, the signals from the coupler connection overlap with the signals through the bypass cable. Due to the different signal propagation time, long bypass cables could cause transmission problems.

Test case: An SPE link between two wagons is established. The bypass cable is plugged in and the communication capability is checked.

Result: Communication after plugging in the bypass cable was functional. However, the link between the two connection partners broke down briefly and immediately re-established itself. It is suspected that the channel change led to a new channel estimation on the part of the SPE-PHYs and the link had to be rebuilt for this reason.

3.1.4 Inserting a stub line

A special challenge for communication systems is posed by stub lines, which are not terminated with the characteristic impedance of the line. Reflections then occur at the ends of these lines, which can lead to signal faults and symbol errors. This case could occur on the train if cabling is faulty or a device is defective, for example.

Result: The exhibited behaviour is similar to that when adding the bypass cable. Communication after adding the stub line was functional. During this time, the link was dismantled and rebuilt. It is suspected that the channel change led to a new channel estimation on the part of the SPE-PHYs and the link had to be rebuilt for this reason.

This behaviour can become critical if a change in resistance of the coupling contacts changes the channel so much that a new channel estimation becomes necessary. The resulting link break of a few hundred milliseconds (approx. 700–900 ms) leads to an interruption in communication and can disrupt safety functions.

3.2 Powerline communication distance

The Powerline-PLUS communication system communicates via the 110 V_{DC} power supply cable. For this purpose, the signal (packet) is repeated after a defined number of Powerline-PLUS slaves (forward distance). The maximum communication distance can thus be determined by increasing the forward distance. The forward distance was determined in various configurations in the tested wagon-set, consisting of seven wagons, with DAC electric couplers.

The forward distance setting has an influence on the performance of the Powerline-PLUS communication system. The aim is to achieve stable communication with as large a forward distance as possible, i.e. as few repeater slaves as possible. Each additional repeater in the communication system leads to higher latency or less data bandwidth. Furthermore, the requirement of approx. 100 m should be achieved without a repeater.

Test sequence

After switching on the supply voltage, the forward distance (between two and four) was set in the master and the connection was established. After the connection was established, an attempt was made to reach the furthest wagon by means of ping. If the wagon could not be reached or an unstable ping connection was demonstrated, the test was rated as failed.

Figure 12: Test of the Powerline-PLUS forward distance in a wagon-set

With forward distance 2[2], the Powerline-PLUS could be operated in every wagon configuration. Forward distance 3 worked in one configuration, but in another test configuration with the master on the other side of the wagon-set, a stable connection could not be achieved. The ICMP ping communication to the last slave was only answered sporadically; the integrity check indicated an integrity error. However, the wagons in the wagon-set were correctly detected in this constellation.

Regarding the results, it must be noted that the cabling used is not optimal for use as a communication cable. In the DAC4EU wagons, two separate 16 mm² cables were used, which are routed through a corrugated tube.

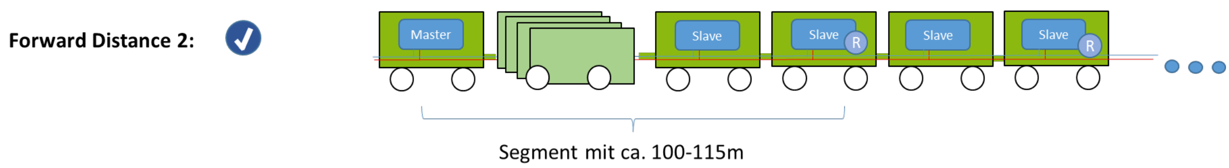

Figure 13: Test with dummy wagon

In a later test, dummy wagons were equipped with a cable consisting of 2x10 mm² in twisted-pair design (recommended cable of the EDDP). A segment length from the master to the first repeater of approx. 100–115 m was achieved. Using a suitable cable, the 100 m bridging criterion was achieved. It can be assumed that a correspondingly greater forward distance would also be achieved when using the twisted-pair cable.

[2] During the field tests (line runs), the Powerline-PLUS was always operated with the forward distance 2.

3.3 Investigating WiFi communication problems

The line runs in Austria and Switzerland showed a very unstable WiFi communication system. Connections to the last wagon were interrupted for periods of a few seconds to a few hours. During the tests in Austria and Switzerland, a more detailed analysis of the problems was not possible due to the tight time frame. Therefore, some tests were undertaken after the line runs to identify the problems.

Figure 14: Reception power at the WiFi access point (measured with WiFi access point)

First, different wagon connections were examined with regard to WiFi reception performance (**Figure** 14). Values of -58 dBm to -48 dBm at a transmitter power output of 18 dBm were demonstrated. The values were determined by reading out the device status at the WiFi access point. The measurement of the direct attenuation of the transmission in the Berne rectangle with the antennas used was carried out in Phase I and showed an attenuation of about 45–50 dB, measured in the 2.4 GHz ISM band. The coaxial cables from the wagon box to the coupler connection box and the RF connectors must be added to the attenuation. The cables have an attenuation of about 0.42 dB/m at 2.4 GHz. Thus, in a wagon connection where a wagon box is on the opposite side of the bridged coupler, there is an additional attenuation of approx. 10 dB due to the cables. Thus, the measured reception powers are considered to be valid.

In the next part of the test, it was investigated whether wagon sides of a wagon can connect to each other and whether a connection across a passive wagon is possible. For this purpose, access points were deactivated in several tests and then examined to see which connections are possible (**Figure** 15).

In a first measurement, the connection to the coupler (2) was interrupted. A connection from coupler (1) to coupler (3) was established with a received power of -70 dBm. A similar value could be measured for the connection of coupler 3 to coupler 5. This is an unexpectedly high received power overall, as the antennas are shielded by the massive wagons, which are earthed via the rail potential. An influence due to reflections from adjacent vehicles is considered probable. Another test resulted in a received power from coupler 3 to coupler 6 of -92 dBm. This means that this connection must be classified as poor. Therefore, the data rate was set to 1 Mbit/s by the access point in order to achieve a better SNR.

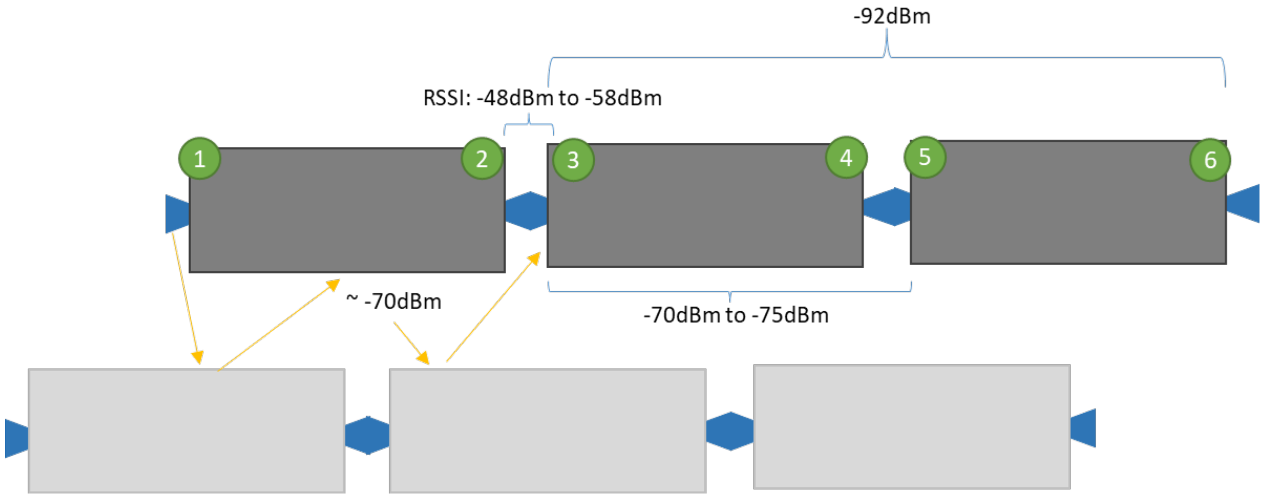

Figure 15: Measuring WiFi received power over different coupling connections

ACC mode was set at the access points. In this mode, the access points automatically negotiate the role of the access point and the client. Before this, the access points are in search mode to find devices within range with which a connection can be established. The access point remains in this mode for several minutes. An access point with the highest RSSI is then selected from the list of possible devices. This mechanism had basic functionality during the line runs, as the connection via the coupling point has the best RSSI value. However, the access point returns to search mode when a defined threshold (-60 dBm) is undershot. This probably led to a connection failure for connections that are close to the -60 dBm threshold. During the line runs, the attenuation can even increase due to the movement of the RF cables and plug connections as well as due to the weather.

Note: In the WiFi system discussed in the EDDP, which was on the short list of possible communication systems for SGV (rail freight transport), the antennas and WiFi transceivers are integrated in the electric coupler. However, this could not be tested because it was not possible to integrate antennas/transceivers into the electric couplers.

4 Communication tests and field tests in line runs

The following table shows the measurement runs that were carried out in Phase II. In the first measurement runs (1–3), the test system was put into operation. The measurement runs with evaluations of the data communication took place from measurement run (4). From measurement run (9) onwards, communication failures were increasingly registered in the SPE communication system. In order to analyse these failures more closely, the test system was adapted with regard to the localisation of the communication errors.

Table 3: Measurement runs for data communication and evaluation of contact interruptions

No.	Coun-try	Date	Locations	Comment
1	DE	18 October 2021	Minden - Ludwigshafen	Communications technology facility
2	DE	15 November 2021	Mannheim - Ingolstadt	Communications technology facility
3	DE	2 February 2022	Mannheim - Bruch Hall	Communications technology facility
4	AU	11 February 2022	Rankweil - Langen am Arlberg	Communication measurement (installation/commissioning SPE)
5	AU	14 February 2022	Langen am Arlberg - Selzthal	Communication measurement
6	AU	16/17 February 2022	Selzthal - Eisenerz - Gstatterboden	Communication measurement
7	AU	22 February 2022	Selzthal - Niklasdorf	Communication measurement
8	AU	25 February 2022	Niklasdorf - Vienna	Communication measurement
9	CH	11 March 2022	Goldau - Biasca (via (Gotthard Base Tunnel) - Goldau (via (Gotthard Base Tunnel) - Limmattal	Communication measurement
10	CH	21 March 2022	Limmattal - Biasca (via Gotthard mountain route) - Basel (via Gotthard mountain route)	Communication measurement
11	CH/DE	31 March 2022	Basel - Minden	Communication measurement
12	DE	28 April 2022	Nuremberg - Minden	Communication measurement
13	CZ	26 July 2022	Brno - Budweis	Logic analyser measurements
14	CZ	27 July 2022	Budweis - Pilsen	Logic analyser measurements
15	CZ	29 July 2022	Pilsen (round trip)	Logic analyser measurements
16	CZ	1 August 2022	Pilsen - Most	Logic analyser measurements
17	CZ	2 August 2022	Most - Pilsen	Logic analyser measurements
18	DE	16 August 2022	Kassel - Bebra	Oscilloscope measurements
19	DE	16./17 October 2022	Minden - Saarbrücken	Oscilloscope measurements
20	DE	9 November 2022	Minden - Heessen - Minden	Oscilloscope measurements

21	DE	10 November 2022	Minden - Heessen - Minden	Oscilloscope measurements
22	DE	14 November 2022	Minden - Bebra	Oscilloscope measurements
23	DE	15 November 2022	Bebra - Lichtenfels	Oscilloscope measurements
24	DE	16 November 2022	Lichtenfels - Probstzella - Lichtenfels	Oscilloscope measurements
25	DE	17 November 2022	Lichtenfels - Mannheim	Oscilloscope measurements

After locating a point of failure, the cause was determined by the process of elimination. As a result of this investigation, the focus in the following measurement runs was placed on monitoring the contacts and their behaviour during the line runs. For this purpose, a measuring set-up with a logic analyser (13–17) was installed first. This set-up exhibited many disruptions, so that for the next measurements (18–25), various measurements were performed with an oscilloscope.

4.1 Measurement runs for communication

4.1.1 Measurement run: Rankweil - Langen am Arlberg

Before the measurement run from Rankweil to Langen am Arlberg, the SPE adapters were installed for the first time for communication with single-pair Ethernet via the two-wire cables. During the measurement run, all three communication systems (Powerline-PLUS, SPE and WiFi) were tested.

Table 4: Train configuration: Rankweil - Langen am Arlberg

WG 0 (MC)	WG1	WG10	WG11	WG2	WG6	WG14	WG4	WG5	WG3	WG9	WG8	WG15	WG7

Table 5: Results: Rankweil - Langen am Arlberg

	WiFi	SPE	Powerline-PLUS
Detection of the number of wagons	OK	OK	OK
Sequence correct	OK	OK	OK
Alignment detection	OK	OK	Does not exist
Integrity events (failure > 1000 ms) Integrity check ICMP (interval 100 ms)	1* (failure for 448 seconds)	0	0

Sent/received Packets	57465/52632	58220/58215	58386/58386
Packet loss	8.4%	< 0.001%	0%
Integrated integrity check	-	-	OK
Comment	Initially, the sequence was not correctly detected. After eliminating a sensor error, the detection was correct.		

4.1.2 Measurement run: Langen am Arlberg - Selzthal

Table 6: Train configuration: Langen am Arlberg - Selzthal

WG 0 (MC)	WG1	WG10	WG11	WG2	WG6	WG14	WG4	WG5	WG3	WG9	WG8	WG15	WG7

Table 7: Results: Langen am Arlberg - Selzthal

	WiFi	SPE	Powerline-PLUS
Detection of the number of wagons	OK	OK	OK
Sequence correct	NO	NO	OK
Alignment detection	OK	OK	Does not exist
Integrity events (failure > 1000 ms) Integrity check ICMP (interval 100 ms)	5	0	0
Sent/received Packets	273301/209239	275133/275025	294796/294793
Packet loss	23.4%	< 0.001%	~0%
Integrated integrity check	-	-	OK
Comment			

During this measurement run, as with the other measurement runs, a very high number of packet errors were identified in the WiFi communication system. The packet errors at SPE were also analysed. Four events were identified here that showed an accumulation of 7–8 burst errors. The downtime with 700–800 ms therefore did not trigger an integrity event.

4.1.3 Measurement run: Selzthal - Eisenerz - Gstatterboden

The measurement run was only carried out with 12 freight wagons, as wagon 8 was removed due to a defect.

Table 8: Train configuration: Selzthal - Gstatterboden

WG 0 (MC)	WG7	WG15	WG9	WG3	WG5	WG4	WG14	WG6	WG2	WG11	WG10	WG1

Table 9: Results: Selzthal - Gstatterboden (outward run)

	WiFi	SPE	Powerline-PLUS
Detection of the number of wagons	OK	OK	OK
Sequence correct	OK	OK	OK
Alignment detection	OK	OK	Does not exist
Integrity events (failure > 1000 ms) Integrity check ICMP (interval 100 ms)	0 (until communication failure)	0*	0
Sent/received Packets	20994/20994 (until communication failure)	108759/108729	108858/108855
Packet loss	Not determinable	< 0.001	~0%
Integrated integrity check	-	-	OK

On the outward run, the WiFi system identified a communication failure to the last wagon after about 35 minutes. The WiFi system did not re-establish communication until the end of the outward run.

On the return run, the Powerline-PLUS communication system could not be successfully put into operation. Not all wagons were identified and communication to the last wagon was not possible. The reason for this was identified as follows: Only a "warm start" of the Powerline-PLUS master was carried out between the outward and return runs. This led to initialisation errors with the tested software variant in some cases. The problem did not occur with a cold start (reset of the supply voltage).

No packet errors were identified during the test of the SPE communication system.

4.1.4 Measurement run: Selzthal - Niklasdorf

Table 10: Train configuration: Selzthal - Niklasdorf

WG 0 (MC)	WG3	WG5	WG4	WG14	WG6	WG2	WG11	WG10	WG1	WG7	WG15	WG8	WG9

Table 11: Results Selzthal - Niklasdorf

	WiFi	SPE	Powerline-PLUS
Detection of the number of wagons	OK	OK	OK
Sequence correct	OK	OK	OK
Alignment detection	OK	OK	Does not exist
Integrity events (failure > 1000 ms) Integrity check ICMP (interval 100 ms)	Integrity until 12:53 Failure WG11-WG10 Later: Failure WG2-WG11	0	0
Sent/received Packets	53933/19444	44263/44248	44794/44793
Packet loss	Not determinable	< 0.001	~0%
Integrated integrity check	-	-	OK

The analysis of packet errors in the SPE system showed that, as in the measurements before, individual burst errors with a length of approx. 700 ms occurred. These errors therefore did not lead to an integrity event.

4.1.5 Measurement run: Niklasdorf - Vienna

The measurement run from Niklasdorf to Vienna was only carried out with nine wagons due to a defective wagon in one wagon-set.

The measurements were extended to include the identification of round trip times (RTT).

Table 12: Train configuration: Niklasdorf - Vienna

WG 0 (MC)	WG3	WG5	WG4	WG14	WG6	WG2	WG11	WG10	WG1

Table 13: Results: Niklasdorf - Vienna

	WiFi	SPE	Powerline-PLUS
Detection of the number of wagons	OK	OK	OK
Sequence correct	OK	OK	OK
Alignment detection	OK	OK	Does not exist
Integrity events (failure > 1000 ms) Integrity check ICMP (interval 100 ms)	27 events 1 event > 3 min 6 events 10–26 s 20 events < 10 s	0	0
Sent/received Packets	109733/102412	110686/110669	111022/111021
Packet loss	6.7%	< 0.001	~0%
Round trip time (max., avg.)	998 ms*, 46.5 ms	21.5 ms, 2.58 ms	34.6 ms, 20.1 ms
Integrated integrity check	-	-	OK
Comment		Start-up problem of some SPE adapters	

** Values of 1000 ms and higher are discarded, as they no longer arrive within the valid interval*

The analysis of packet errors in the SPE system showed that, as in the measurements before, individual burst errors with a length of approx. 800 ms occurred. These errors therefore did not lead to an integrity event. A maximum downtime of 209 seconds was identified for the WiFi system.

4.1.6 Measurement run: Goldau - Biasca - Limmattal

Table 14: Train configuration: Goldau - Biasca

WG 0 (MC)	WG1	WG10	WG11	WG2	WG6	WG14	WG4	WG5	WG3	WG7	WG15	WG8	WG9

Table 15: Results: Godau - Biasca

	WiFi	SPE	Powerline-PLUS
Detection of the number of wagons	OK	OK	OK
Sequence correct	OK	OK	OK
Alignment detection	OK	OK	Does not exist
Integrity events (failure > 1000 ms) Integrity check ICMP (interval 100 ms)	129	1 Failure of 14 following packets (approx. 1.4 seconds)	0
Sent/received Packets	64680/56035	65666/65396	67449/67448
Packet loss	6.7%	0.41%	~0%
Round trip time (max., avg.)	999 ms*/64.7 ms	16.3 ms/ 3.75 ms	187.8 ms/50.82 ms
Integrated integrity check	-	-	OK

** Values of 1000 ms and higher are discarded, as they no longer arrive within the valid interval*

As per the analysis of the SPE packet errors, single errors also occurred during the ride, in contrast to the previous rides. This trip was the first time that a downtime > 1 second was detected, which would lead to faulty integrity detection.

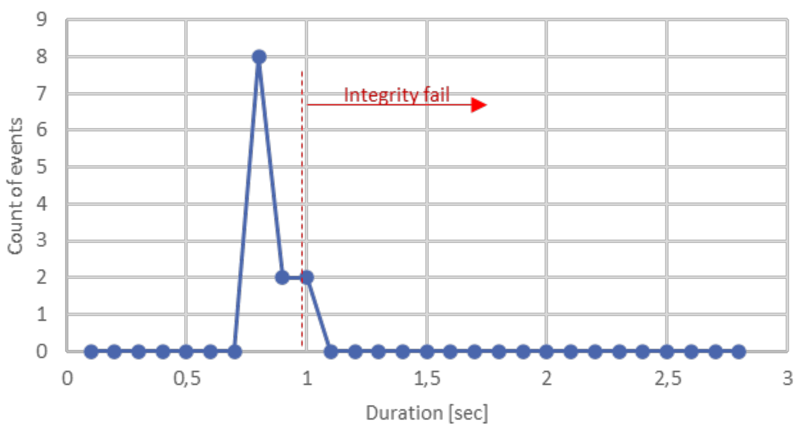

Figure 16: Occurrence of communication interruptions from Golda to Biasca

On the return run, the measurement coach was moved to the other side of the train. This meant that the position of the measurement coach was between the locomotive and wagon 9. Furthermore, the return run was carried out with the ep brake activated. Some emergency brake applications were carried out with the ep brake.

Table 16: Results: Biasca - Limmattal

	WiFi	SPE	Powerline-PLUS
Detection of the number of wagons	OK	OK	OK
Sequence correct	NO	NO	OK
Alignment detection	OK	OK	Does not exist
Integrity events (failure > 1000 ms) Integrity check ICMP (interval 100 ms)	213	83	0
Sent/received Packets	109733/102412	93297 / 90720	93423 / 93398
Packet loss	6.8%	2.6%	< 0.1%
Round trip time (max., avg.)	998 ms*/126 ms	28.9 ms, 4.48 ms	629 ms/51.9 ms
Integrated integrity check	-	-	OK

** Values of 1000 ms and higher are discarded, as they no longer arrive within the valid interval*

When initialising the SPE and WiFi systems, the order of the last two wagons was reversed. The measured performance data from current and voltage of the 110 V_{DC} power cable, on which the sorting of the sequence is based, was then analysed. The performances are fairly close together, especially at the end of the train. The second-to-last wagon measured about 2 watts less power than the last wagon. This is probably due to power fluctuations on the power cable as well as due to the unsynchronised measurement of the power data on the wagons.

The analysis of the SPE communication showed that failures of up to 4 seconds occurred. In contrast to the previous runs, significant packet losses occurred in the SPE communication system.

<u>Analysis of possible causes for the packet errors:</u>

- The examination of the timing of the packet errors with the SPE and Powerline-PLUS revealed no association with the tunnel run and the emergency braking.

- Communication data was recorded during the standstill in Biasca. Within the recording period (approx. one hour), no packet error was detected for the SPE and Powerline-PLUS.

⇨ It is suspected that at least one electric coupler has poorer electrical connection properties compared to the previous runs.

The error rates for the Powerline-PLUS communication system also increased compared to the runs in Austria. However, the packet errors did not lead to a train integrity failure.

4.1.7 Measurement run: Limmattal - Biasca - Basel

Due to the problems with the SPE communication system with comparatively high packet error rates and failures during the journey from Biasca to Limmattal, monitoring was set up of all connections from the measurement coach to the following wagons and from the last wagon to the measurement coach. This allows two simultaneously occurring connection faults to be detected and their position to be localised. In order not to overload the communication system, the subsequent connection test was carried out with a lower cycle time (250 ms).

Table 17: Train configuration: Limmattal - Biasca

WG 0 (MC)	WG1	WG10	WG11	WG2	WG6	WG14	WG4	WG5	WG3	WG7	WG15	WG8	WG9

Table 18: Results: Limmattal - Biasca

	WiFi	SPE	Powerline-PLUS
Detection of the number of wagons	OK	OK	OK
Sequence correct	OK	OK	OK
Alignment detection	OK	OK	Does not exist
Integrity events (failure > 1000 ms) Integrity check ICMP (interval 100 ms)	135	16	0
Sent/received Packets	130846/86299	132091/130417	132155 / 132132
Packet loss	34.1%	1.27%	< 0.1%
Round trip time (max., avg.)	999 ms*/74.7 ms	56.8 ms/3.9 ms	168.8 ms/51.1 ms
Integrated integrity check	-	-	OK

** Values of 1000 ms and higher are discarded, as they no longer arrive within the valid interval*

As can be seen in **Table** 18, the packet losses of the SPE communication occur less than in the preceding measurement run. However, their performance in terms of integrity events is still in an unacceptable range.

In the WiFi communication system, failures with longer times were registered, which led to a very high overall packet loss.

Table 19: Directional SPE packet losses: Limmattal - Biasca

Transmitter	Receiver	Packet error direction Train end*		Transmitter	Receiver	Packet error direction Measurement coach*
Measurement coach	WG1	0		WG9	WG8	0
Measurement coach	WG10	3		WG9	WG15	0
Measurement coach	WG11	3		WG9	WG7	0
Measurement coach	WG2	3		WG9	WG3	0
Measurement coach	WG6	596		WG9	WG5	0
Measurement coach	WG14	596		WG9	WG4	0
Measurement coach	WG4	595**		WG9	WG14	0
Measurement coach	WG5	596		WG9	WG6	0
Measurement coach	WG3	596		WG9	WG2	668
Measurement coach	WG7	597		WG9	WG11	668
Measurement coach	WG15	596		WG9	WG10	665**
Measurement coach	WG8	598		WG9	WG1	672
Measurement coach	WG9	598		WG9	Measurement coach	672

** The direction-dependent packet losses of different magnitudes are associated with the later switch-on time of the function*

*** The packet streams for measuring packet loss are independent of each other. Therefore, slightly better loss values can also occur among worse values.*

The measurement of the direction-dependent packet losses for the SPE communication system shows a clear weak point between wagon 2 and wagon 6. In both directions, the majority of the packet losses occur here.

Before the return run, the measurement coach was moved to the other side of the train. This meant that the position of the measurement coach was between the locomotive and wagon 9.

Table 20: Return run: Biasca - Basel

	WiFi	SPE	Powerline-PLUS
Detection of the number of wagons	Only 11 wagons detected	OK	OK
Sequence correct	Only 11 wagons detected	OK	OK
Alignment detection	OK	OK	Does not exist
Integrity events (failure > 1000 ms) Integrity check ICMP (interval 100 ms)	111	86	0
Sent/received Packets	136101/126753 (only up to wagon 11)	137528/134308	137585/137568
Packet loss	6.68%	2.34%	< 0.1%
Round trip time (max., avg.)	999 ms*/53.2 ms	433.6 ms/3.9 ms	225.6 ms/51.9 ms
Integrated integrity check	-	-	OK

** Values of 1000 ms and higher are discarded, as they no longer arrive within the valid interval*

With the WiFi communication system, only eleven wagons were detected at departure. The connection to the last two cars was interrupted. Therefore, the integrity check was only carried out up to wagon 11.

Table 21: Directional SPE packet losses: Biasca - Basel

Transmitter	Receiver	Packet error direction Train end*		Transmitter	Receiver	Packet error direction Measurement coach*
Measurement coach	WG9	0		WG1	WG10	7
Measurement coach	WG8	0		WG1	WG11	7
Measurement coach	WG15	0		WG1	WG2	7
Measurement coach	WG7	0		WG1	WG6	1241
Measurement coach	WG3	0		WG1	WG14	1247
Measurement coach	WG5	0		WG1	WG4	1243
Measurement coach	WG4	0		WG1	WG5	1244
Measurement coach	WG14	0		WG1	WG3	1240
Measurement coach	WG6	0		WG1	WG7	1241
Measurement coach	WG2	1292		WG1	WG15	1253
Measurement coach	WG11	1294		WG1	WG8	1247

Measurement coach	WG10	1294		WG1	WG9	1238**
Measurement coach	WG1	1295		WG1	Measurement coach	1254

** The direction-dependent packet losses of different magnitudes are associated with the later switch-on time of the function*

*** The packet streams for measuring packet loss are independent of each other. Therefore, slightly better loss values can also occur among worse values.*

The measurement of the direction-dependent packet losses with the SPE system showed a picture similar to the outward run (Limmattal - Biasca). In both directions, most of the packet losses were registered between wagon 6 and wagon 2. An analysis of the possible causes was carried out. With the observations of the packet losses made in Austria that many burst errors occurred in the range of 7–8 packets, it was reasonable to suspect that an interrupted connection or a changed communication channel leads to a link break, which results in a downtime of 0.8–1.5 seconds and can thus lead to loss of integrity.

The following failure modes were identified:

- Possibility of a faulty SPE adapter: Defective adapter with loose contact or defective cable.
- Connections of the communication cables in the terminals are faulty (wagon box and coupler connection box).
- Contacts in the coupler or electric coupler are defective.

Corresponding measures to evaluate the fault location were taken in the subsequent measurement runs (measurement runs Basel - Minden, Nuremberg - Minden).

4.1.8 Measurement run: Basel - Minden

In the following measurement runs, the focus was placed on investigating the communication problems with the SPE communication system.

Before the measurement run Basel - Minden, the following measures were taken to evaluate the fault at the coupling point between wagon 2 and wagon 6, which had been identified as problematic in the preceding measurement runs:

- The terminal connections of the cables in the wagon and coupler connection boxes were re-plugged.
- The SPE adapters of the connection in question were exchanged for adapters from other wagons to rule out a hardware fault in the adapters.

Table 22: Wagon sequence measurement run: Basel - Minden

WG 0 (MC)	WG3	WG5	WG4	WG14	WG6	WG2	WG11	WG10	WG1	WG9	WG8	WG15	WG7

Table 23: Directional SPE packet losses: Basel - Minden

Transmitter	Receiver	Packet error direction Train end*		Transmitter	Receiver	Packet error direction Measurement coach*
Measurement coach	WG3	0		WG7	WG15	0
Measurement coach	WG5	0		WG1	WG8	0
Measurement coach	WG4	0		WG7	WG9	0
Measurement coach	WG14	0		WG7	WG1	0
Measurement coach	WG6	0		WG7	WG10	9
Measurement coach	WG2	476		WG7	WG11	9
Measurement coach	WG11	475		WG7	WG2	10
Measurement coach	WG10	476		WG7	WG6	499
Measurement coach	WG1	480		WG7	WG14	489
Measurement coach	WG9	479		WG7	WG4	496
Measurement coach	WG8	478		WG7	WG5	499
Measurement coach	WG15	478		WG7	WG3	499
Measurement coach	WG7	480		WG7	Measurement coach	613

The table shows the results of one section of the measurement run (Basel - Raststatt). Comparable results were obtained in other sections. The packet error rate was about 0.6% in both directions (at the coupling point between wagon 6 and wagon 2).

As can be seen in **Table** 24, the measures taken to check the cable connections and replace the SPE adapters were unsuccessful. As before, there was a significant packet loss between wagon 6 and wagon 2. Compared to the Biasca - Basel measurement run, the error rate was only a quarter as large. However, this could also be due to the different line topology.

4.1.9 Measurement run: Nuremberg - Minden

After the cable connections and SPE adapters could be ruled out as the cause in the measurement run from Basel to Minden, the SPE communication was changed from two-wire cable 1 to two-wire cable 2 in the connection in question between wagon 2 and wagon 6.

In contrast to the previous measurement runs, the train consisted of only one wagon-set with a total of nine wagons.

Table 24: Wagon sequence measurement run: Nuremberg - Minden

WG 0 (MC)	WG1	WG10	WG11	WG2	WG6	WG14	WG4	WG5	WG3

Table 25: Directional SPE packet losses: Limmattal - Biasca

	Receiver	Packet error direction Train end*		Transmitter	Receiver	Packet error direction Measurement coach*
Measurement coach	WG1	0		WG3	WG5	0
Measurement coach	WG10	0		WG3	WG4	0
Measurement coach	WG11	0		WG3	WG14	0
Measurement coach	WG2	0		WG3	WG6	0
Measurement coach	WG6	25		WG3	WG2	26
Measurement coach	WG14	25		WG3	WG11	25
Measurement coach	WG4	25		WG3	WG10	25
Measurement coach	WG5	25		WG3	WG1	26
Measurement coach	WG3	26		WG3	Measurement coach	26

The packet error rate was about 0.05% in both directions (at the coupling point between wagon 6 and wagon 2).

As in the previous measurement runs, the fault location between wagon 2 and wagon 6 is clearly visible. In contrast to the previous measurements, the error rate is significantly lower. The following conclusion was drawn from the evaluation of the communication problems:

- No problems of the connections and the SPE adapters have been proven.
- The change of the two-wire cables, on the other hand, resulted in a significantly lower error rate. This suggests that the SPE communication errors are due to problems with the pressure-spring contacts in the coupling point. The contacts of the two-wire cable 2 also seem to be affected, but less pronounced. A visual assessment of the contacts did not reveal any obvious faults.

4.2 Summary of the measurement runs to test the data communication

4.2.1 WiFi communication

The test of WiFi communication in the field test showed insufficient reliability. The WiFi communication system in the structure used is not suitable as a communication system for freight transport. The communication faults were characterised by two different error patterns:

- Communication failure ranging from a few packets to a few seconds,

- Communication failure for dozens of seconds up to complete loss of communication.

The error patterns are attributed to two different causes: The "short" interruptions, which in themselves are already a problem for the integrity function, can be explained by interference with other communication systems or by interference with radio links of other wagon connections via reflection. In the device in use, a specific channel is selected in "ACC - Auto carriage connection" mode. Reflections from passing trains or in tunnels can cause such interference. Prolonged disturbances are due to limits of the ACC function, as indicated by the examination of the WiFi communication. If the reception level falls below thresholds, the device searches for new connection partners. During this time, the connection to the other side of the wagon is interrupted. A new set-up can take place after approx. 30 seconds, provided that the reception level of the opposite WiFi adapter is then within the permissible range. Lowering the threshold, on the other hand, causes the adapters to no longer reliably connect to the opposite side of the wagon, but to any other wagon within range. This means that continuous communication is no longer possible.

In terms of installation, the tested WiFi communication is not the variant discussed in the EDDP. For the WiFi communication discussed in the EDDP, the antenna should be installed in the electric coupler. It is believed that this would have meant a significantly better result in terms of communication availability. Also striking in comparison to the stationary tests of Phase I were the high latency times. These are also due to the communication problems in radio transmission. The WiFi standard defines a repeat mechanism if the receiver of the packet does not send an acknowledge back to the transmitter. Packets are repeated several times before the transmission is discarded with a packet loss. In the case of a radio link affected by interference, WiFi can therefore have several times the latency for successful transmission of a packet compared to interference-free transmission.

4.2.2 Powerline-PLUS

The Powerline-PLUS communication system performs best compared to the other communication systems. No communication failures (loss of train integrity) were identified in the line runs. Nevertheless, individual packet losses were registered. Packet losses increased at the end of the line runs in Switzerland, but no burst packet errors could be identified as with the other communication systems, which ensured that train integrity could be established.

The current and voltage measurements by DB Systemtechnik (see report 60226-05-DAC Phase II - Electrical part) showed that voltage drops were recorded in one wagon-set. These drops indicate brief interruptions of the contact points of the electric coupler. Provided that the capacitive coupling of the contact points is low, the interruption of the contacts in the Powerline-PLUS communication system leads to a packet loss if Powerline symbols are transmitted at the moment of contact interruption[3].

4.2.3 Single-pair Ethernet

The SPE communication showed an increasingly higher error rate in the line runs (**Table** 26). At this point, individual packet losses are not problematic, as these must be compensated for by higher protocol layers. Critical are failures that lead to a downtime of several 100 ms. The implementation of safety-relevant communication, for which a reliable transmission of information is necessary in terms of the timeliness of the safety application (e.g. train integrity, control of the brake), thus becomes impossible in the range of less than one second.

Table 26: Overview of the SPE packet losses on the line runs (4–12)

Test run (for assignment, see **Table 3**)	Loss of integrity	Packet losses	Packet loss rate
No. 4	0	5	0.008%
No. 5	0	95	0.1%
No. 6	0	30	0.03%
No. 7	0	15	0.03%
No. 8	0	17	0.02%
No. 9/1	1	270	0.4%
No. 9/2	83	2577	2.7%
No. 10/1	16	1674	1.3%
No. 10/2	86	3220	2.3%
No. 11	19	1192	0.6%
No. 12	1	97	0.05%

As with the WiFi communication system, the packet losses here must be divided into two classes:

[3] An indication of this behaviour is shown in **Figure** 36.

a) Single packet errors: These can be caused by faults on the communication cable. The loss of a symbol with a symbol duration of 13.33 ns is already sufficient for this, as there is no error correction.

b) Burst error/prolonged communication failure: If there is an interruption of several 100 ms, it can be assumed that a link break has taken place (link break and renewed link building). To cause a link break in SPE, a change of the channel may also be all it takes (see 3.1.4).

The investigation into the interruptions in SPE communication revealed that packet losses essentially occurred at one coupling point. Visual inspection of the coupling point in question did not show any obvious damage to the contacts. Furthermore, communication at a standstill and during train initialisation worked without any problems in all cases, so that causal effects due to mechanical load or vibrations must be assumed here. A video recording of the run at the coupling point in question showed that movement can be detected in the Scharfenberg coupler as well as in the electric coupler. It cannot be ruled out that the combination of wagon types and their loading may cause an interruption of the communication contacts in certain route scenarios. The contacts to the power supply (16 mm² power cable) are probably less affected by this due to the larger contact surfaces. Furthermore, the rubbing of contact surfaces itself could lead to a sufficient change in the channel and thus to link breaks. However, this could not be demonstrated.

Since the transmission of communication via the electric couplers was identified as a weak point, a more detailed evaluation of the contacts during the line runs should be carried out in the further tests.

5 Evaluation of contact interruptions in line runs

In order to get a more precise picture of the problems of interruptions, four coupling points were first examined by means of a logic analyser with regard to contact interruptions. Although contact interruptions could be detected on a line run, the test set-up in general led to a high level of interference pulses being recorded. In the further investigations, the test system was modified and measurements were carried out at coupling points using an oscilloscope.

5.1 Evaluation of contact interruptions with logic analyser (measurement runs in the Czech Republic)

During the measurement runs in the Czech Republic, the communication contacts in various coupling points were examined with a logic analyser (Saleae Logic-8). A sampling frequency of 2 MHz was set for all measurements.

For the measurement, the set-up outlined in **Figure** 17 was installed in wagon 2 and wagon 8. From each of the two wagons, the neighbouring coupling points were monitored (wagon 8: Wg. 2 and Wg. 6, wagon 8: Wg. 9 and Wg. 15). First, a separate earth line was laid from the logic analyser to the neighbouring wagons and connected to the communication contacts. In the wagon with the measuring instruments, the contacts were each connected to an input of the logic analyser. Each contact was separately connected to the earth potential of the logic analyser via a pull-down resistor (6.8 kohm). Thus, in the normal state, i.e. when the coupling contacts are in order, the result is a high state.

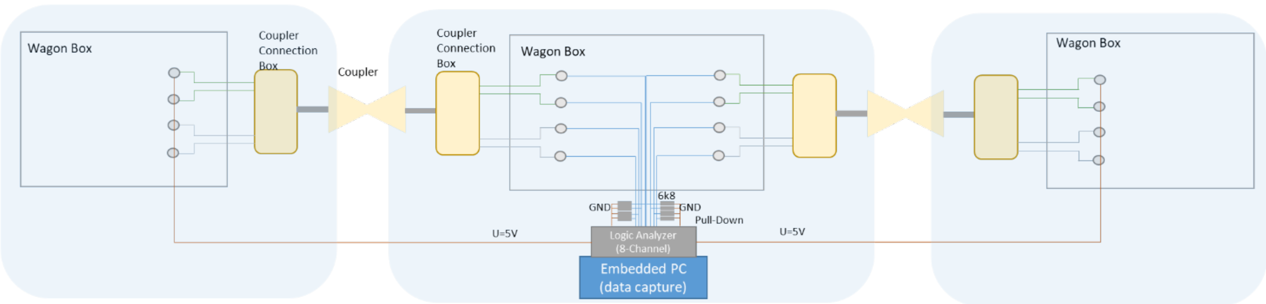

Figure 17: Monitoring contacts with a logic analyser (1)

The set-up shown in **Figure** 17 was put into operation for the first time in the measurement run from Brno to Budweis. The evaluation after the measurement run showed a high number of level changes. Since the change times of the pulses were very short, the assumption was that these were not contact interruptions, but disturbances on the line. These disturbances trigger a change of state in the logic analyser and are in the range of the sample rate (one to two sample times, 500 ns – 1 µs). Burst errors occurred frequently (**Figure** 18, **Figure** 19). The errors were identifiable on all coupling points and all cables.

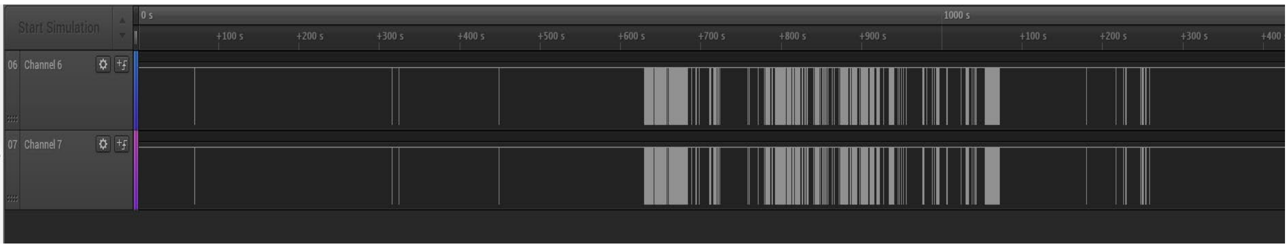

Figure 18: Disturbances with burst pulses

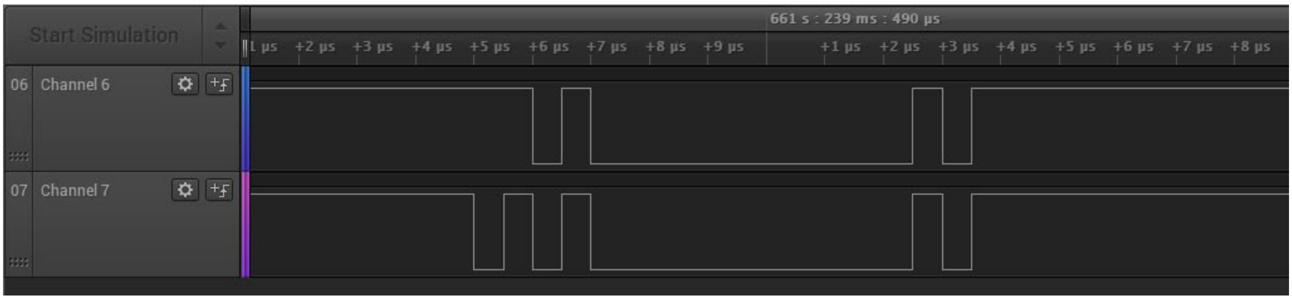

Figure 19: Disturbances with burst pulses (zoom)

In addition to the disturbances shown, longer dips in the pulses could also be measured (see **Figure** 20). However, this could only be observed on one pair of cables during one measurement run. The cable pair is the two-wire cable 1 from wagon 2 to wagon 6. Interruptions with a duration of 3 ms to 19 ms were detected. The number of interruptions was 11, with a measurement duration of approx. 3 hours.

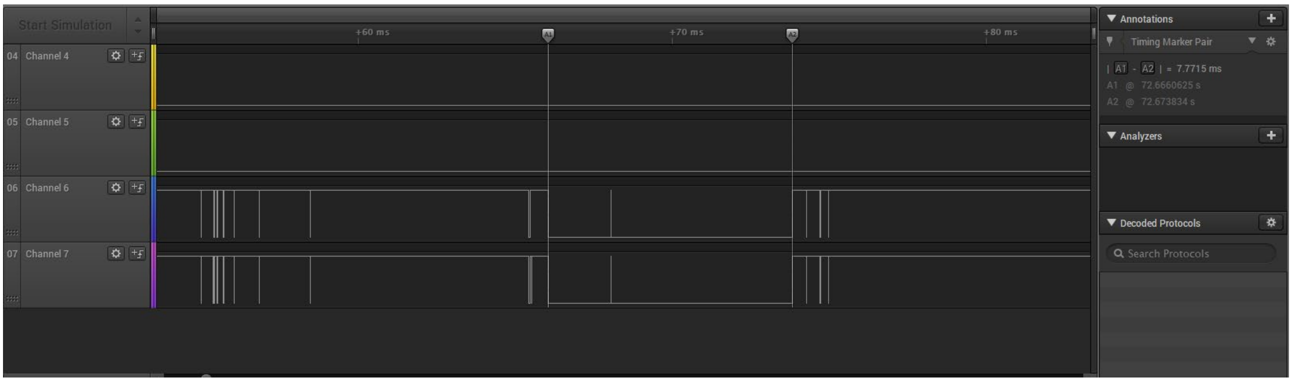

Figure 20: Section of a contact interruption (two-wire cable 1, Wg. 2 to Wg. 6)

During further runs in the Czech Republic, attempts were made to determine the cause of the disturbance pulses. The following causes were considered:

- Coupling of disturbances through the contact wire: Disturbances were also observed in the same way during runs with diesel locomotives on routes without contact wire.

- Standstill: Disturbances were also measured at a standstill, but a significantly lower number compared to while moving.

Since the additional cables for supplying the contacts with the 5 V measuring voltage create a large conductor cable loop with the two-wire cables to be measured, interference may also have been coupled in through this. Therefore, the design was changed in that individual monitoring of the contacts was dispensed with and the two-wire cables were used as forward and return conductors of the measuring voltage.

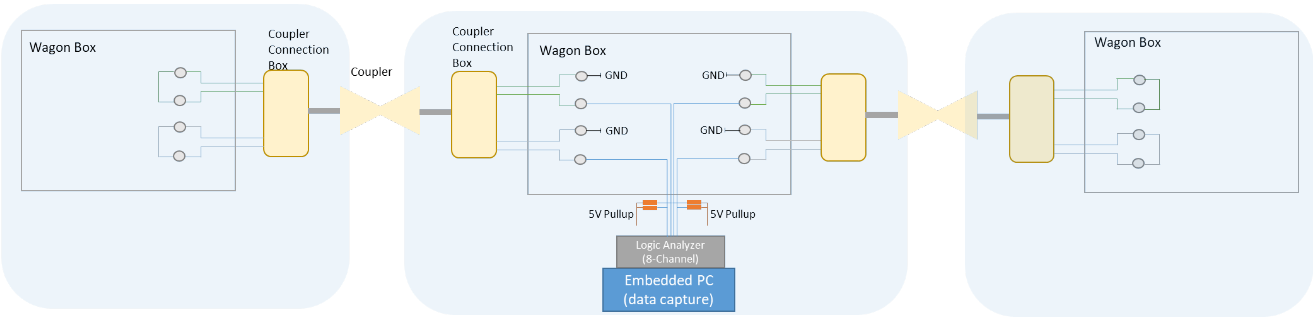

Figure 21: Monitoring contacts with a logic analyser (2)

The adjusted set-up did not result in any measurable change in the disturbances in the subsequent measurement runs. Therefore, the source of the disturbance was suspected to be coupling directly into the communication cables.

5.2 Evaluation of contact interruptions with an oscilloscope

5.2.1 Measurement run: Kassel - Bebra

During the Kassel - Bebra measurement run, a laboratory oscilloscope (LeCroy) was installed in wagon 2 (measuring set-up analogous to **Figure** 22). Attempts were made to record interruptions of the two-wire cables. No relevant findings could be obtained with the measuring instruments, possibly due to the insufficient duty cycle between measurement and storage of the measurement data.

5.2.2 Minden - Saarbrücken

Two coupling points were monitored during the measurement run from Minden to Saarbrücken. For this purpose, a USB oscilloscope (Picoscope 4444) with differential probes was used to monitor a total of three two-wire connections and the Powerline-PLUS connection (**Figure** 22). Two-wire cable 1 was connected to the 24 V battery in each of the two adjacent wagons with a 4.7 kohm resistor. The internal resistances of the SPE adapters (2 kohm each) form a voltage divider at which measurements are taken in the middle wagon. The voltage in the voltage divider (1:9.4) thus forms an offset voltage which is superimposed on the SPE signal. This means that both SPEs and contacts can be monitored.

Two-wire cable 2 between wagon 6 and wagon 2 is also connected to 24 V_{DC}. The parasitic resistance of the SPE modems cannot be used here, so a resistor of 1 kohm has been installed as a measuring resistor.

The cable inductance must be considered in each case: The cable inductance continues to drive the current through the cable even after an interruption due to the energy stored in the inductance. Likewise, the cable capacitance leads to current peaks when switching on (contact closed again). These effects should not play a role due to the relatively short cables with lengths of approx. 5–20 m and the associated low cable inductance and capacitance in relation to the expected interruption in the low millisecond range to the high microsecond range.

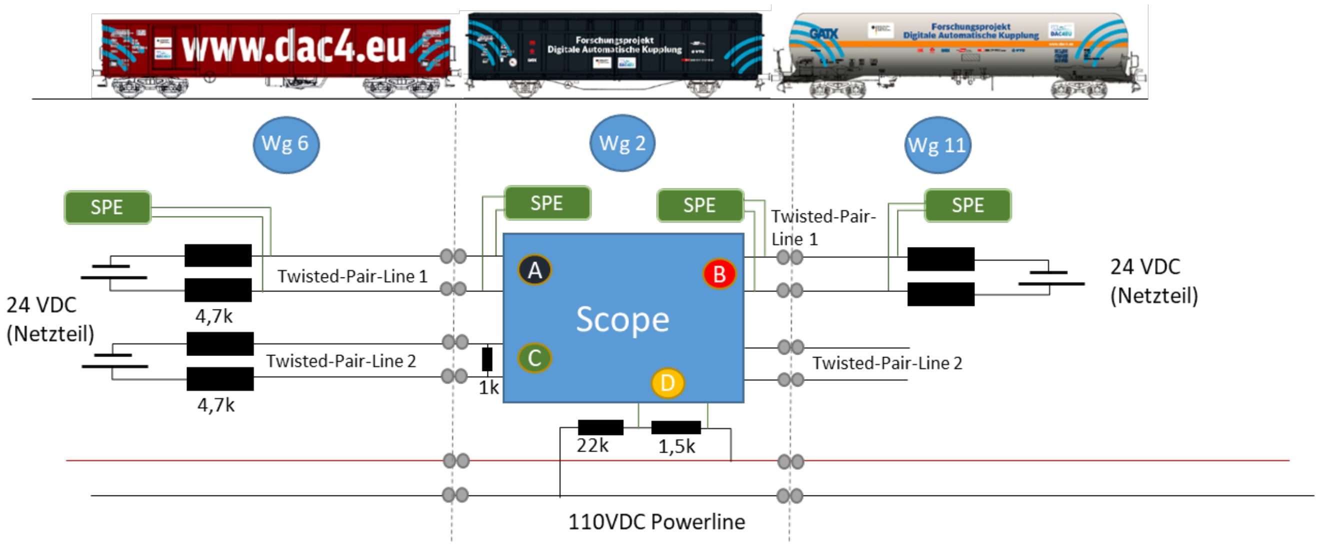

Figure 22: Test set-up for the measurement run: Minden - Saarbrücken

Sample rate: 12.5 MSamples/s,

Results:

- No interruptions in the communication cables were identified.
- Distinct disturbances can be seen on the power cable (**Figure** 23).
- No significant disturbances are seen on the communication cables.
- The disturbances on the power cable did not cause a link break in the SPE communication system.

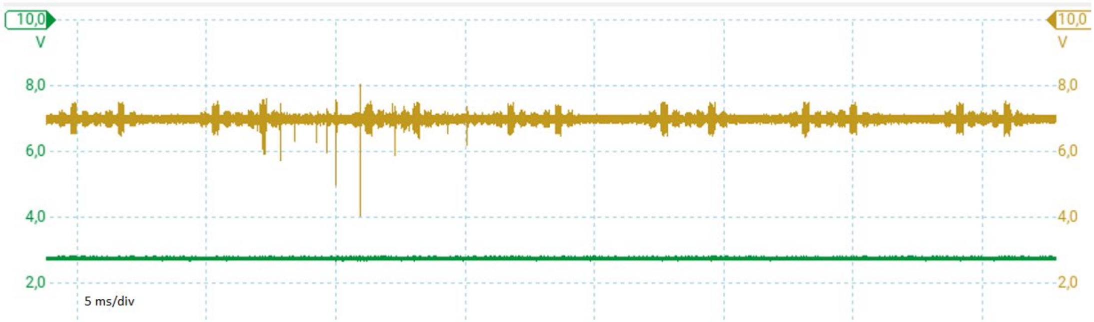

Figure 23: Recording disturbances on the power cable

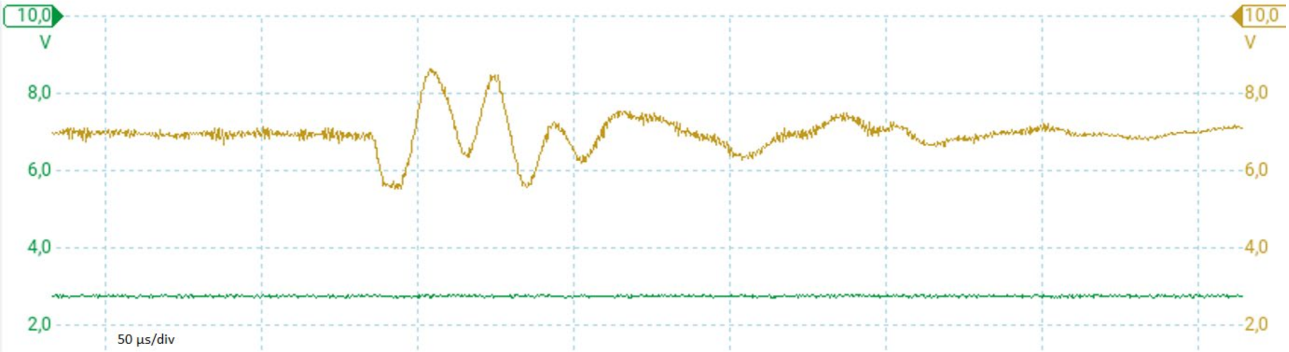

Figure 24: Zoom of the disturbances on the power cable

5.2.3 Measurement runs: Minden - Heessen - Minden

In the Minden - Heessen and Minden - Bebra measurement runs, the set-up for measuring interruptions was changed. Since no interruptions could be detected at the two monitored contact points during the measurement run Minden - Saarbrücken, all contact points of one of the two two-wire cables should be monitored in the following measurement run if possible. For this purpose, a continuous line was made by bridging the segments in the wagon boxes. A 3.3 kohm resistor was also installed in each wagon box (17 wagons). By measuring the current at a measuring shunt (with 100 ohm resistor) in the measurement coach, it should be possible to determine every interruption in the cable, as well as the position of the interruption via the reduced current.

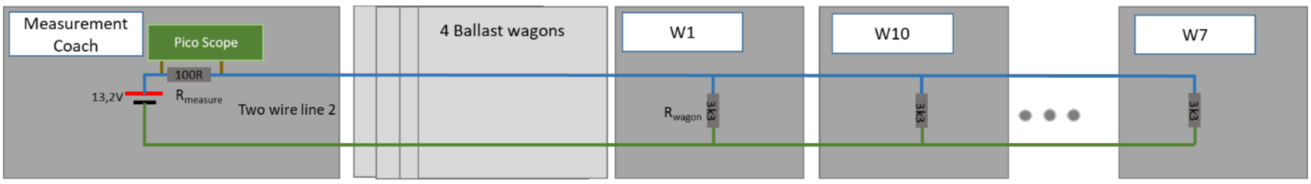

Figure 25: Measuring system with resistor network

The functionality of the measurement system could be observed at the start of the first Minden - Heessen measurement run. The connection to the last wagon (wagon 7) had a defective electric coupler from previous tests, which was known before (**Figure** 26).

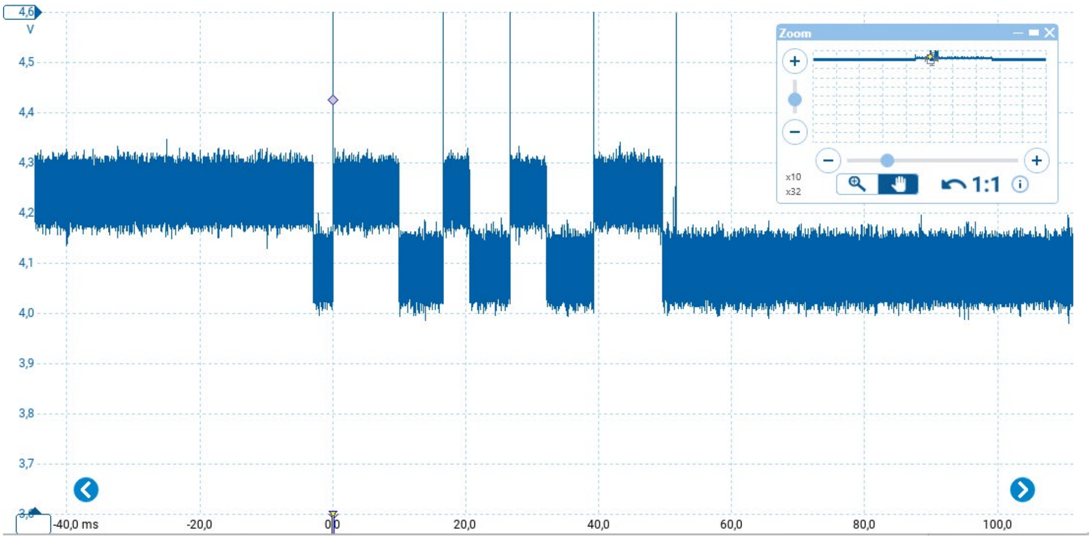

Figure 26: Measurement of a contact interruption of a known defective coupling point

When the train started moving, a mechanical vibration occurred at the coupler, which led to a bouncing effect at the contacts.

Contrary to expectations, no other current drops could be identified at the measuring shunt that would indicate contact interruptions at other points. Disturbances on the cable were also measured, which could be due to coupling from the other two-wire cable or the power cable.

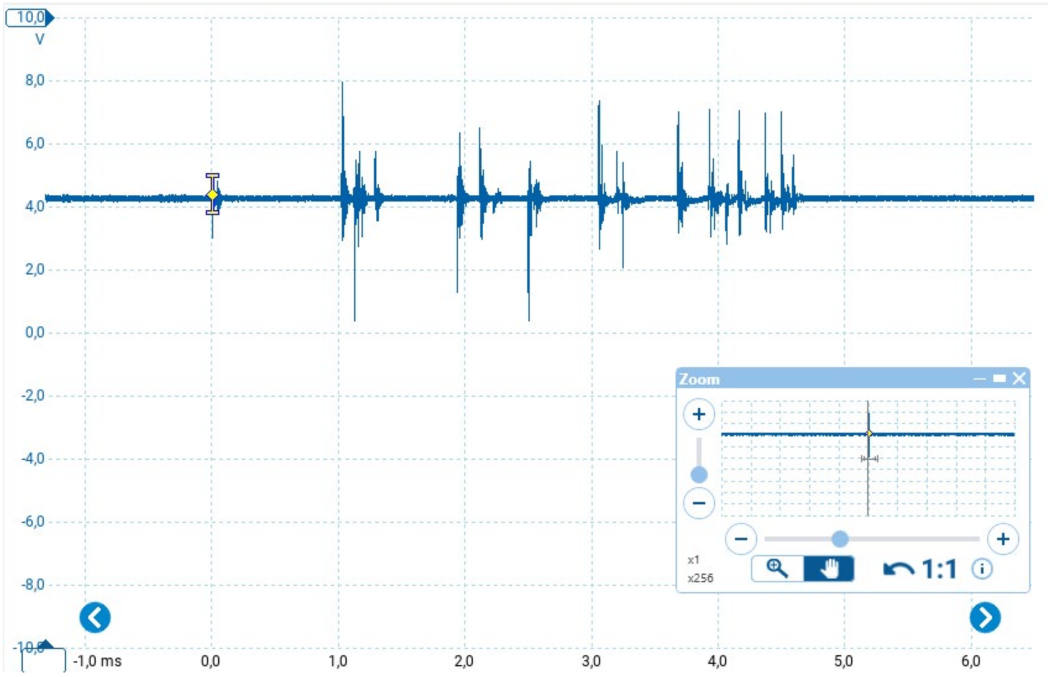

Figure 27: Interference on the continuous two-wire cable

The disturbances were often detected during movement (e.g. **Figure** 27), especially after vibrations or longitudinal forces caused by braking. However, disturbances were also observed at a standstill.

In contrast, these occurred with a significantly smaller amplitude compared to the disturbances during the run.

In addition to the measurements on the second two-wire cable for contact interruptions, the Powerline-PLUS communication system was also tested. The test case was of particular importance due to the additional ballast wagons between the measurement coach and the first DAC wagon. This increased the cable length to the first Powerline PLUS repeater slave to approx. 100–115 m. The cable installed on the ballast wagons differed from the cables installed on the other DAC wires: here, a twisted-pair power cable with a conductor cross-section of 10 mm² was used. A cable with this structure is currently favoured as a future power cable design by the EDDP committee[4], which dealt with the power supply in the SGV. Compared to the individual cables laid loosely in the corrugated tube, it has a more constant characteristic impedance and is therefore much more suitable for communication transmission.

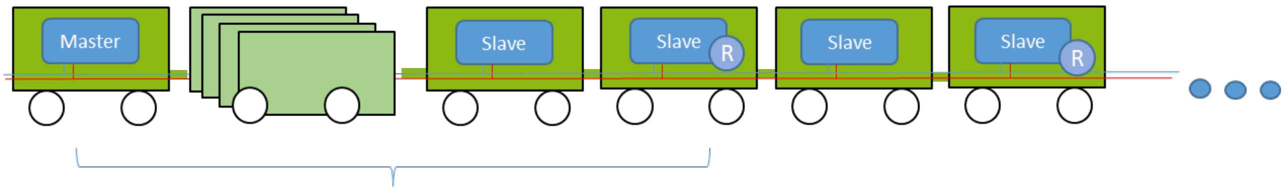

Figure 28: Powerline-PLUS with a long segment between the master and repeater slave

Result:

- All wagons in the train set were correctly detected. The sequence determined by the Powerline-PLUS communication system matched the real wagon sequence.
- No integrity detection failures were observed during the run.

5.2.4 Measurement run: Minden - Bebra

In the Minden - Bebra measurement run, the measurement coach was located between the locomotive and wagon 7. Since the connection from wagon 7 to wagon 15 was disturbed or permanently interrupted, a bypass cable was installed here. In all other respects, the same measuring set-up was used as for the previous measurement runs.

As was the case during the previous measurement runs, no direct connection interruptions could be detected. Furthermore, disturbances of the same magnitude were measured on the two-wire cable.

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[4] EDDP WP1 SG2

5.2.5 Measurement run: Bebra - Lichtenfels

In order to gain an impression of the cause of the disturbances, the measuring set-up was first measured on only one wagon-set. The two-wire connection between the wagon-sets was disconnected at the point between wagon 9 and wagon 3. Thus, the measurement loop was only measured with five wagons. A bypass cable was installed between wagon 7 and wagon 15 due to a defective electric coupler.

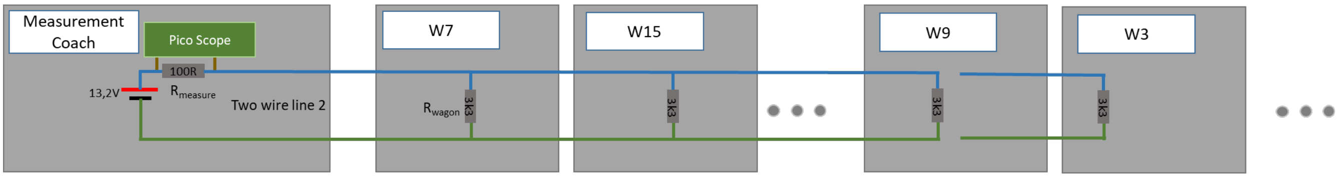

Figure 29: Structure of the measurement through a wagon-set

<u>Result:</u>

- The measurements showed no interruptions in the connection.
- Disturbances were visible on the cable, but fewer disturbances with lower amplitude compared to the measurements over the whole train.

The reason for a better result regarding the disturbances may be the shorter cable of the measured cable system, as measurements were taken over fewer wagons. Another reason could be a source of interference or coupling point outside this group of wagons, via which interference is coupled into the two-wire cable.

5.2.6 Round trip run: Lichtenfels - Probstzella - Lichtenfels

To further limit the source of interference, the measuring system with the oscilloscope was installed in the second wagon-set. The larger second wagon-set (12 wagons in total) was divided into two groups of 7 wagons and 4 wagons.

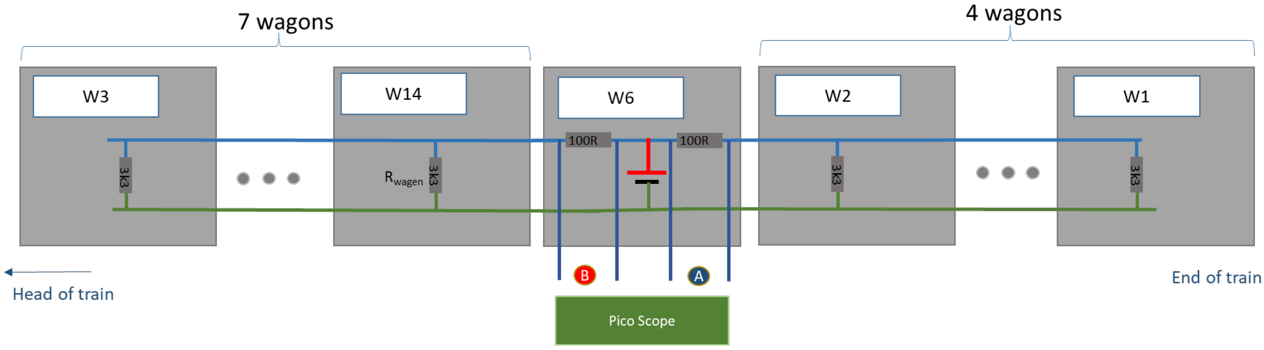

Figure 30: Structure of the measurements in the measurement run: Lichtenfels - Probstzella - Lichtenfels

<u>Result:</u>

- No interruptions of the contacts could be detected,
- Crosstalk was clearly identified on the connection side (A) towards the end of the train. The Powerline-PLUS packets transmitted on the power cable stand out on the signal of the two-wire cable 2.
- Strong disturbances are detectable on both strands. Compared to the measurement of the first wagon-set (Bebra - Lichtenfels measurement run), the disturbances have a significantly larger amplitude.

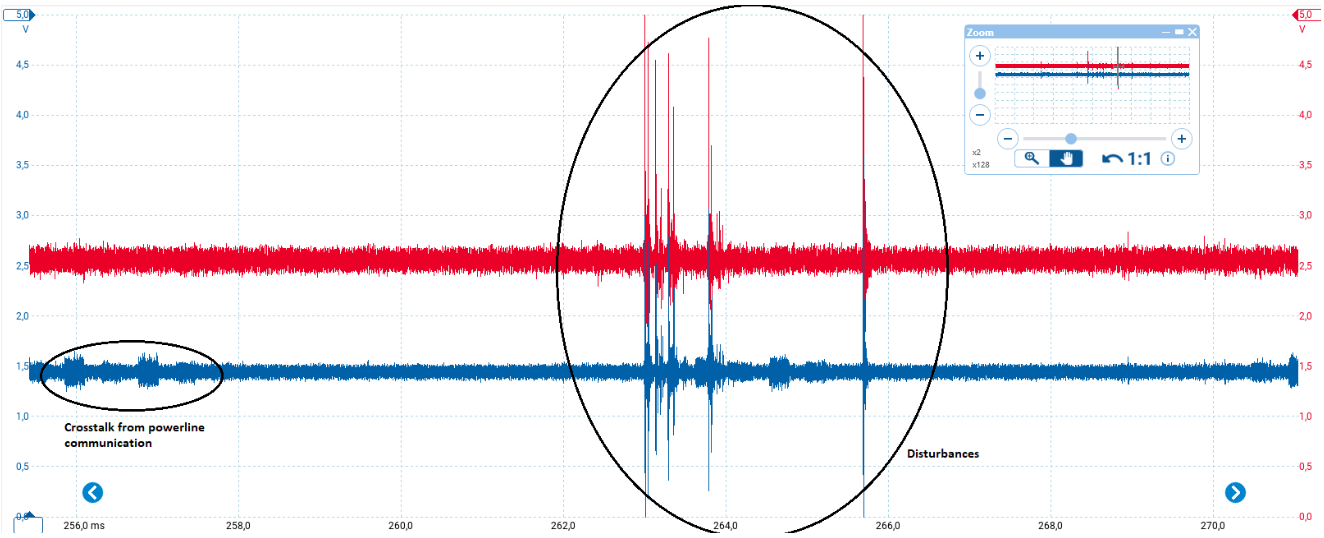

Figure 31: Measurement result of the second wagon-set

After analysing the disturbances, it was assumed that coupling of the interference by the power cable into the two-wire cables was the cause of the disturbances on the two-wire cable. On the two-wire cable towards the end of the train (**Figure** 31, blue signal), the coupling seems to be stronger. The crosstalk of the Powerline-PLUS communication can also be observed here. However, one must take into account that the Powerline-PLUS signal is only slightly above the noise and the noise in the other direction is greater (red signal). Furthermore, it must be taken into account that there is a coupling of the two cable strands, as the current for the measurement was taken from the same battery.

5.2.7 Measurement run: Lichtenfels - Mannheim

During the Lichtenfels - Mannheim measurement run, the measurement coach was at the end of the train. Fourteen loaded ballast wagons were inserted between the locomotive and the first DAC wagon. This train configuration led to very strong longitudinal forces, which were visible in the results of the measurements.

Table 27: Train composition: Lichtenfels - Mannheim

14*ballast wagons Faps											
Wg.1	Wg.10	Wg.11	Wg.2	Wg.6	Wg.14	Wg.4	Wg.5	Wg.18	Wg.19	Wg.20	Wg.3
						Wg.9	Wg.16	Wg.8	Wg.15	Wg.7	Wg.0 (MC)

During the measurement run, the set-up of the measurements was changed. The two-wire cables were now each connected directly to a measuring channel and the voltage on the power cable was monitored with a voltage divider. For this purpose, the measurement of one direction of the measuring loop along the two-wire cable 2 was dispensed with.

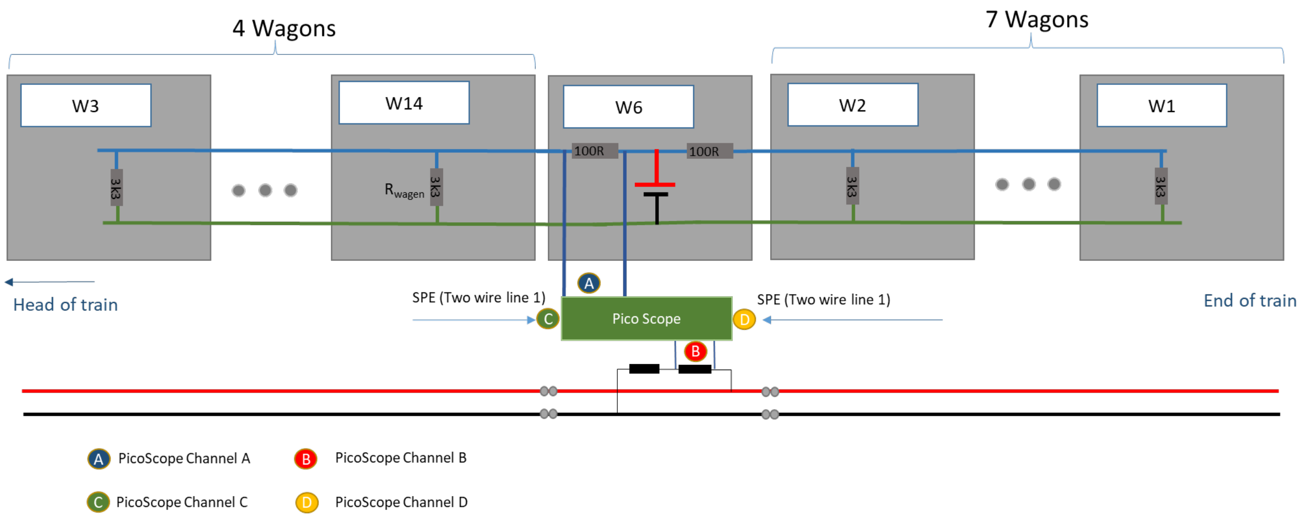

Figure 32: Structure of the measurements in the measurement run: Lichtenfels - Mannheim

<u>Result:</u>

- No interruption of the coupling contacts in the measuring loop (wagon 14 to wagon 3) of the two-wire cable 2 could be detected.
- The measurements of the power cable showed interruptions (**Figure** 33). The interruptions only occurred at the beginning of the measurement run; gentler starting and braking on the part of the driver led to lower force effects. A total of six interruptions could be recorded, with a duration of approx. 1.2 ms to approx. 6 ms. The majority of the interruptions were in the range of 1.2–2.5 ms.

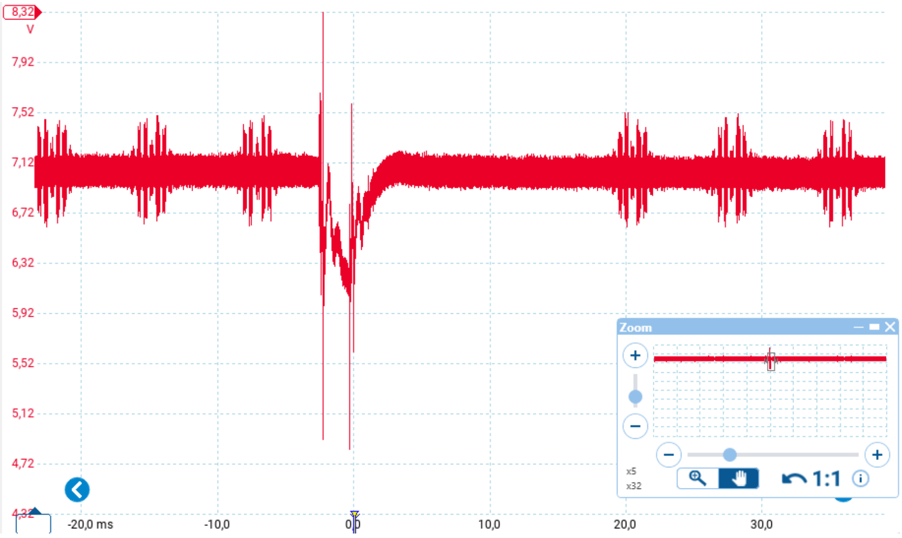

Figure 33: Voltage drop on the power cable due to contact interruption

- Significant disturbances on the two-wire cable can also be observed when the power cables are interrupted (**Figure** 34). These effects are probably not due to an interruption of the contacts of the two-wire cable. In this case, an interruption in the range of one millisecond should result in a distinct drop in the measuring current. The interference probably results from the crosstalk of the power cable onto the two-wire cable. The voltage and current peaks caused by the interruption of the power cable lead to a disturbance with a large amplitude on the two-wire cable.

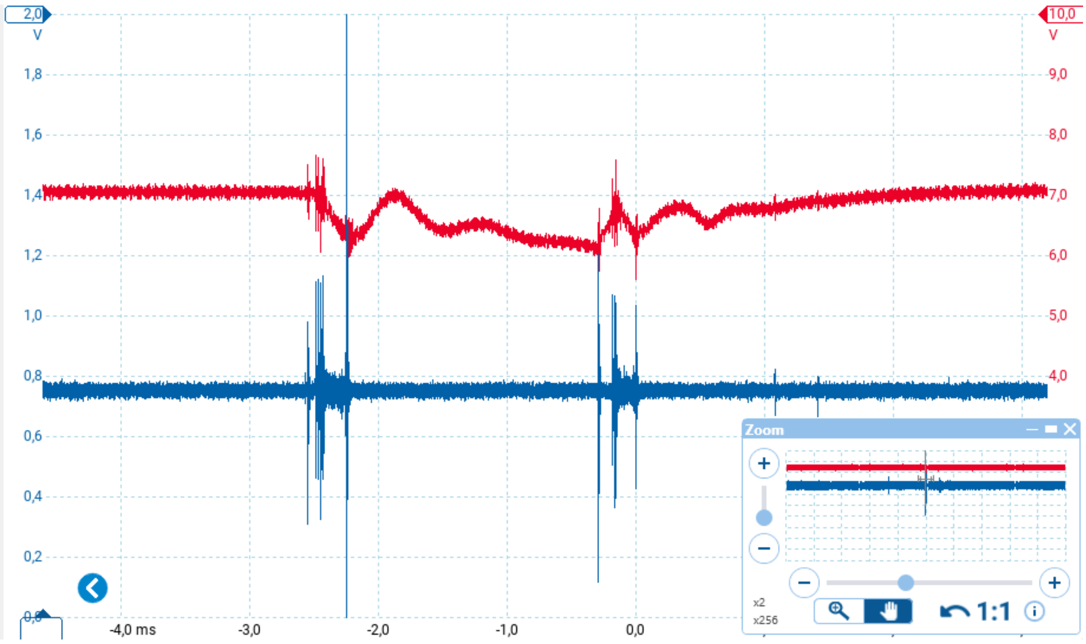

Figure 34: Disturbances on the two-wire cable at the time of the Powerline-PLUS interruption

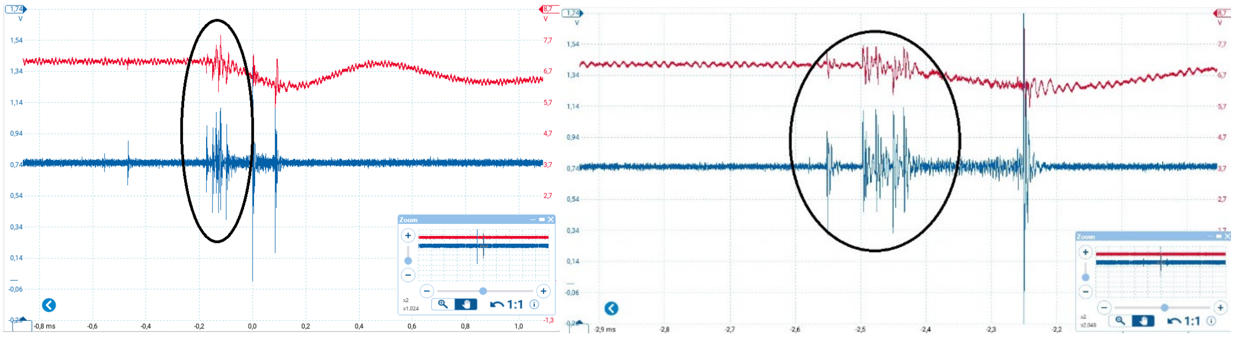

Figure 35: Disturbances before contact interruption

- The disturbances that can be observed on the power cable and the two-wire cable before the obvious contact break and the associated voltage drop are of interest: This type of disturbance is more frequently observed, even without a voltage drop. Accordingly, some of these disturbances could be a preliminary stage to contact interruption. These "near interruptions" could then cause interference with the SPE communication due to crosstalk.
- There are also effects of the contact interruptions on the Powerline-PLUS communication system. In some of the contact interruptions that occurred during the transmission of a Powerline-PLUS packet, the cyclic communication was suspended for approx. 20 ms after the contact interruption. This is probably due to timeouts that add up when a packet fails. A contact interruption therefore leads to a packet loss, but this would not have any relevant influence on safety communication protocols in which resilience against simple packet losses is achieved by implementations in higher protocol layers.

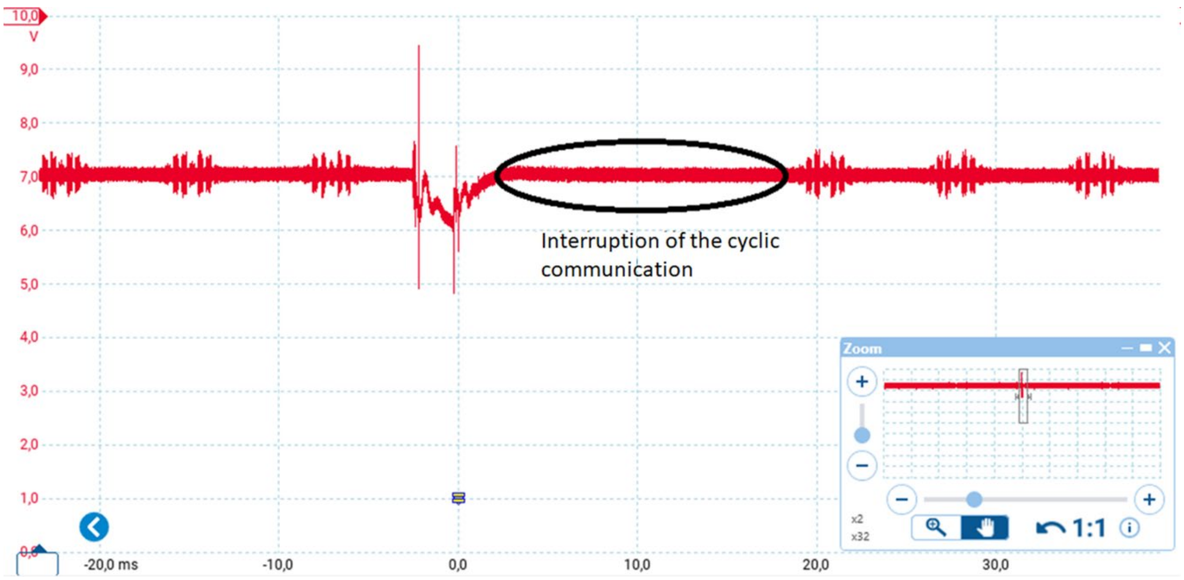

Figure 36: Influence of contact interruption on cyclic communication with the Powerline-PLUS

5.3 Summary and forecast

During the measurement runs, it was shown that communication via the couplers is possible with both Powerline-PLUS and SPE. There were no fundamental problems while the communication systems were initialised. A continuous communication link was possible at every commissioning. During the run, differences between the communication systems became apparent. The WiFi communication system was assessed as unsuitable in its installed form (WiFi components, radio link via the Berne rectangle).

Measurements of the power cable showed that contact interruptions of a few milliseconds occur due to mechanical forces in at least one of the two wagon-sets. Furthermore, the measurements suggest that there are micro-interruptions in the range of 100 µs or smaller that lead to disturbances on the cables. It cannot be conclusively assessed whether these effects are a complete interruption of contact or merely a short-term change in resistance. For the power supply via the power cable, this effect is basically irrelevant as long as no sparking occurs at the contact points, leading to long-term damage of the contacts. This cannot be completely ruled out at present, as the disturbance pulses on the two-wire cable can also result from very brief sparking in the power cable contacts.

The effects on the Powerline-PLUS communication are minor: There may be a few sporadic packet losses, as shown by both the availability measurements and the measurements with the oscilloscope. Train integrity monitoring via the Powerline-PLUS communication system was not affected by the interruptions. The resilience of the Powerline-PLUS communication system compared to the SPE communication system can be described as greater with regard to disturbances on the cable as well as to interruptions.

- OFDM modulation (orthogonal frequency division multiplex) and coding methods that allow FEC (forward error correction) can partially compensate for or correct short-term errors.
- Due to link-free communication, a short interruption does not lead to a renewed link building (in contrast to the SPE communication system).

With SPE communication, on the other hand, there were sporadic packet losses as well as longer interruptions in communication of several seconds. The packet losses increased in the course of the measurement runs (see **Table** 26). Sporadic packet losses were probably caused by coupled interference. On the measured loop through several wagons (Section 5.2.5), coupling of the power cable into the two-wire cable could be demonstrated. Both the signals of the Powerline-PLUS communication and interruptions of the power cables could also be measured on the two-wire cable. As no such coupling was visible in the other wagon-set, the reasons for the coupling in the wagon-set in question is suspected to be either the type of electric coupler or a faulty cable installation. It should also be taken into account that a simple installation of the communication cables was performed, in which the shield of the communication cable is not connected to earth (wagon body or rail potential). An optimisation of the immunity of the cable routing to improve SPE robustness must be investigated.

Interruptions of the SPE communication of a few 100 ms up to a few seconds are probably due to a link break of the SPE connection. There are two effects that can lead to a link break in the SPE:

- Contact interruptions in the connection technology or the coupling contacts,
- Change of the communication channel, which leads to faulty echo suppression.

Later investigations with a logic analyser were able to detect interruptions in a measurement run. Further measurements with an oscilloscope and monitoring of all contact points of a two-wire cable, on the other hand, showed no interruption of the two-wire cable. Interruptions with a longer duration (> 700 ms) could be traced back to a specific coupling point (Wg.2 to Wg.6). Damage to the electric coupler was not obvious, but cannot be ruled out as a cause. If the faults at the supposedly defective coupling point were disregarded, then one would arrive at very good results for the SPE communication system. However, this does not solve the problem of resilience to such errors.

Further tests in a laboratory set-up showed that interruptions and disturbances of up to 500 µs do not result in a link break. This concerns both complete interruptions and significant channel changes. Interruptions in a time range from 500 µs to approx. 10 ms lead to a link break and thus an interruption in communication of 0.8 to 1.2 seconds. Interruptions of coupling contacts in this time range are considered likely. Interruptions in the range of 10 ms to 200 ms, on the other hand, do not lead to renewed link building. Within this time range, the two SPE PHYs synchronise again and communication continues. According to the definition of state machines in the SPE standard [5], the communication would have to recover up to an interruption of 200 ms. This would mean that the SPE-PHY used in the SPE adapter would not behave in a standard-compliant manner. However, this only applies under the condition that the transmission parameters of the communication channel are comparable before and after the interruption. Otherwise, the channel would have to be re-estimated by establishing a new connection. According to [6], rubbing of the contacts leads to a change in electrical behaviour. It is assumed to be unlikely that this would lead to a link break at the SPE.

In further investigations regarding communications technology, the focus should therefore be on the following aspects:

- As part of the conversion of the power supply from 110 V_{DC} to 400 V_{AC} (two-phase), the effects on the communication systems (Powerline-PLUS and SPE) must be investigated.
- The noticeably high crosstalk between the power cable and the communication cables must be investigated. Here it makes sense to find the point where the coupling is particularly large and to initiate appropriate measures. The impact on the SPE communication system in terms of error rate must be investigated.

- Interference on the two-wire cable in general must be investigated. It can be reduced by suitable measures, such as connecting the cable shield at defined points to the wagon potential.
- Only the physical layer chip of one manufacturer (Texas Instruments) was used in the SPE adapter. The behaviour in the presence of contact interruptions and tolerance of a comparable physical layer chip (analogue device) must be investigated and compared with the results of the other device.

6 Literature

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[6] S. El Mossouess, E. Carvou, R. El Abdi, N. Benjemâa, H. Obame, L. Doublet, and T. Rodari, "Analysis of temporal and spatial contact voltage fluctuation during fretting in automotive connectors," 27th International Conference on Electrical Contacts, *2014*.