Digital Automatic Coupling

Phase I

Test Report Data Communication

Conclusion Phase I

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Contact:

Prof. Dr.-Ing. Stefan Witte Email: Stefan.Witte@owita.com Phone: 05261/702-5763
Roland Heß, Dipl.-Ing. Email: Roland.Hess@owita.com Phone: 05261/28896-15

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Management Summary

In the subproject Data Communication of the communication systems **evaluation** Phase I, three **coupling and communication systems** were examined. The examination objective was to test the fitness of the coupling and communication systems for freight train communication in general, as well as whether the requirements for further evaluation under operating conditions in Phase II are met.

For this purpose, **physical channel measurements** were conducted over couplings and wagons as well as **performance tests** with the communication systems integrated in the freight wagons. The tests were carried out within the groups of wagons with the same coupling types in order to make a comparison between the different couplings. In the overall train, the tests were carried out with all available wagons in order to derive an estimate of stability and performance for a longer train.

As a result of the investigations, it can be stated that the **three communication systems** (Powerline PLUS, WiFi and CAN-FD) are suitable for further evaluation in **Phase II**. This also applies in interaction with the coupling systems: Although the physical communication properties differ, the criteria for communication via two-wire systems (CAN-FD) and via Powerline systems are met in principle. In summary, it is therefore recommended that all three communication systems are investigated further in **Phase II** in order to evaluate interference immunity under operating conditions.

1 Outline

In a first phase of the project DAC4EU, four coupling systems were evaluated by a consortium of RUs and freight wagon providers. For the evaluation of distinct coupling systems, mechanical tests were required in particular, but tests were also carried out regarding the electrical connection of the automatic couplings. The electric connection tests were split into tests regarding the electric power transmission in compliance with their respective standards, and tests for qualified assessment of data communication. In addition to the electrical tests, three different communication systems were evaluated for this purpose, which could be suitable for use in freight trains in terms of their physical transmission properties, but differ in terms of their technology: Powerline (on the power line), CAN (separate two-wire line) and WiFi (contactless point-to-point radio communication). The tests to assess communication were divided into three fields, which also belong to different project phases of the DAC4EU project [1]. The first two fields (acquisition of physical channel characteristics and performance measurements with different communication systems) are part of the tests in the DAC4EU Phase I. The results are presented in this document.

During the mechanical tests, one coupling type (CAF MiiRA) was removed from the test due to insufficient fulfillment of the requirements, so that only three coupling variants are included in this evaluation. In Phase II of the project, the couplings and communication systems will be evaluated under operational conditions.

In project phase I, the measurements were carried out in a stationary state (stationary train):

1. Stationary measurements to determine the physical channel properties:

   For these measurements, the communication channels over the couplings were measured in terms of their physical transmission properties using a network analyzer (Keysight Fieldfox N9915B, 30 KHz - 6 GHz) in the form of S-parameters. From this, additional channel models can be generated for later simulations. These measurements focused in particular on the qualitative evaluation of the different coupling types with respect to their physical transmission characteristics. The results of the channel measurements are presented in chapter 2.

2. Stationary performance measurements with different communication systems:

   The measurements with the three communication systems Powerline (Powerline PLUS, plc-tec), two-wire communication system (CAN-FD) and RF communication (WiFi) focused on the performance of the communication systems and their stability (in steady state). For this purpose, an investigation of the various communication systems was carried out at OSI layer 2 and layer 3 level. The results of the performance measurements are presented in chapter 3.

As a result of project phase I, it was to be shown whether the requirements for the communication properties of the coupling systems and the selected communication systems can be met for further evaluation in phase II.

2 Configuration of the wagons and wagon groups

During the equipping of the wagons, the wagon boxes with the communication systems were not mounted in the same way on all wagon groups. This results in different cable lengths between the wagon boxes in some of the wagon groups. To enable a differentiated assessment of the results, the structure of the individual wagon groups is shown here.

2.1 Voith

The wagons of the Voith group were designated with the wagon numbers 1 to 3. The wagon box (Figure 1, green element) is connected in each case to the coupling connection boxes located at the ends of the wagon (blue element). In the Voith group, there is a greater distance (approx. 35 – 40 m) between wagon 2 and 3, which had to be bridged by the communication systems.

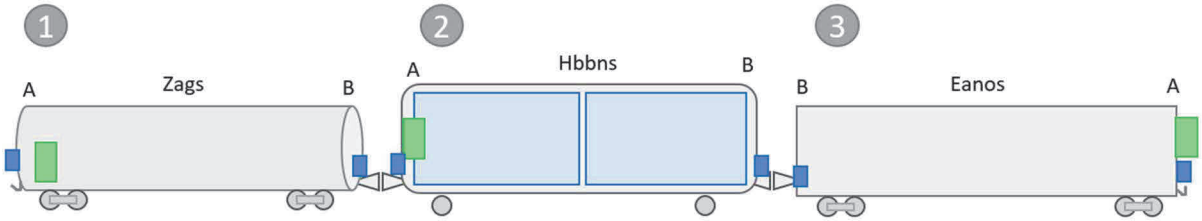


Figure 1: Wagon configuration Voith Group

2.2 Wabtec

The wagons of the Wabtec group were designated with the wagon numbers 4 to 6. In the Wabtec group, there is a greater distance (approx. 35 – 40 m) between wagon 4 and 5, which had to be bridged by the communication systems.

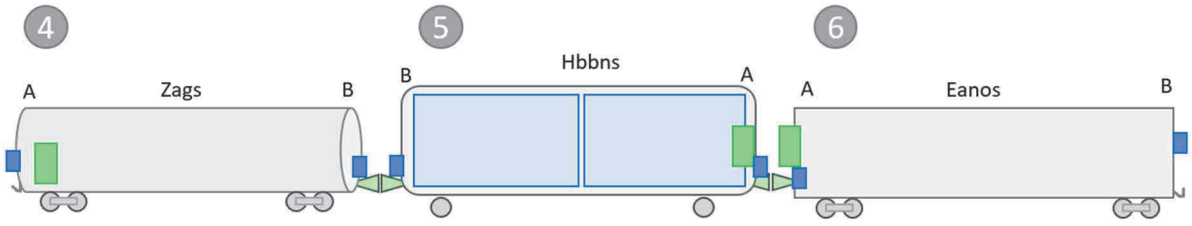


Figure 2: Wagon configuration Wabtec Group

2.3 Dellner

The wagons of the Dellner group were designated with the wagon numbers 7 to 9. The orientation of the wagons was rotated when they were equipped at the DB plant in Mannheim in comparison to the Voith and Wabtec groups.

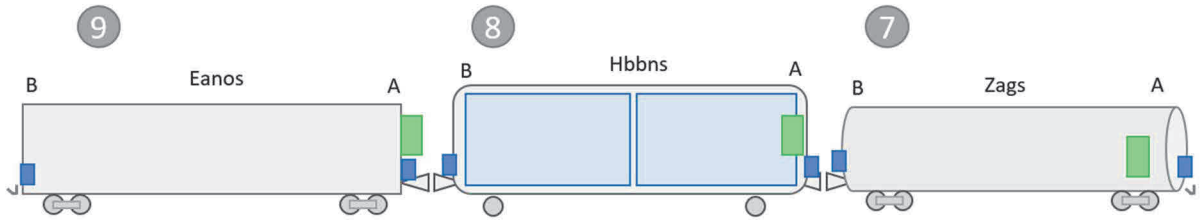


Figure 3: Wagon configuration Dellner Group

2.4 CAF

The CAF wagon group was not investigated separately in the performance tests, because the mechanical requirements for the coupling system were not met. In the investigation of the overall train measurements, the CAF wagons were used to be able to test the communication systems in the overall train on a larger number of wagons.

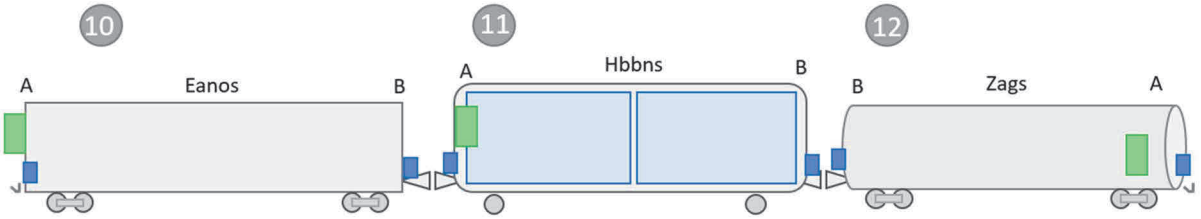


Figure 4: Wagon configuration CAF Group

3 General evaluation of the communication channels

During the general evaluation of the communication channels, the coupling-specific electrical parameters relevant for data communication were determined without discrimination. These parameters can later be used in a model of the communication channels. The model can be applied as a basis for a simulation in order to derive the communication behavior, even of arbitrary communication systems, from the measured data. Furthermore, this model can be utilized to check the plausibility of the measured data of the real communication systems.

When measuring the communication channels, a basic distinction was made between two types: Line-bound two-wire communication systems (CAN-FD), as well as Powerline (Powerline PLUS) and radio-based communication systems (WiFi).

3.1 Channel measurement of the line-bound communication channels

The purpose of measuring the line-bound communication channels was to identify differences in the coupling types. In addition, the general ability of the communication system to communicate over a 12-car train was to be estimated.

For this purpose, the following parameters were determined:

- Forward and reverse transmission factor S_{21} and S_{12}.

In the case of the coupling connections, the following parameters were also determined:

- Near-end crosstalk (NEXT) between Powerline and a two-wire line,
- Far-end crosstalk (FEXT) between Powerline and a two-wire line.

Determining the transmission factor of the near- and far-end crosstalk allows a statement to be made about the interference sensitivity of the two-wire line to interference emitted from the Powerline line.

The measurement bandwidth of the network analyzer was 50 MHz for Powerline and 10 MHz for the two-wire line to cover the bandwidths of commercially available communication systems. The influences of the test leads used were removed by means of normalization.

3.1.1 Channel properties of the coupling connections

Coupling characteristics: To determine the coupling characteristics, a channel measurement was performed using a vector network analyzer between the coupling junction boxes mounted on each end of the wagons (Figure 5). All communication links in the coupling transition (Powerline, two-

wire line 1 and two-wire line 2) were examined in this measurement. The lines from the coupling junction box to the wagon box were removed in each case.

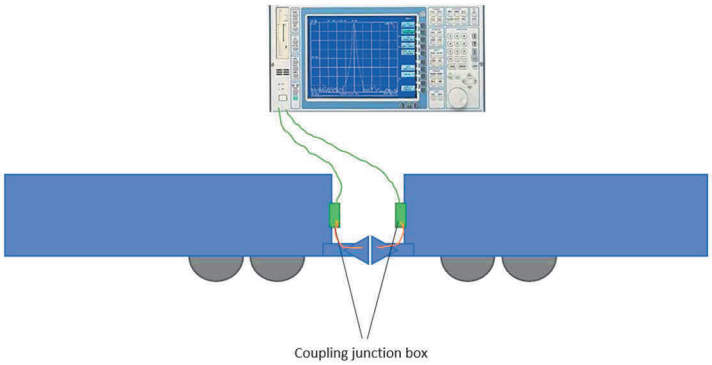
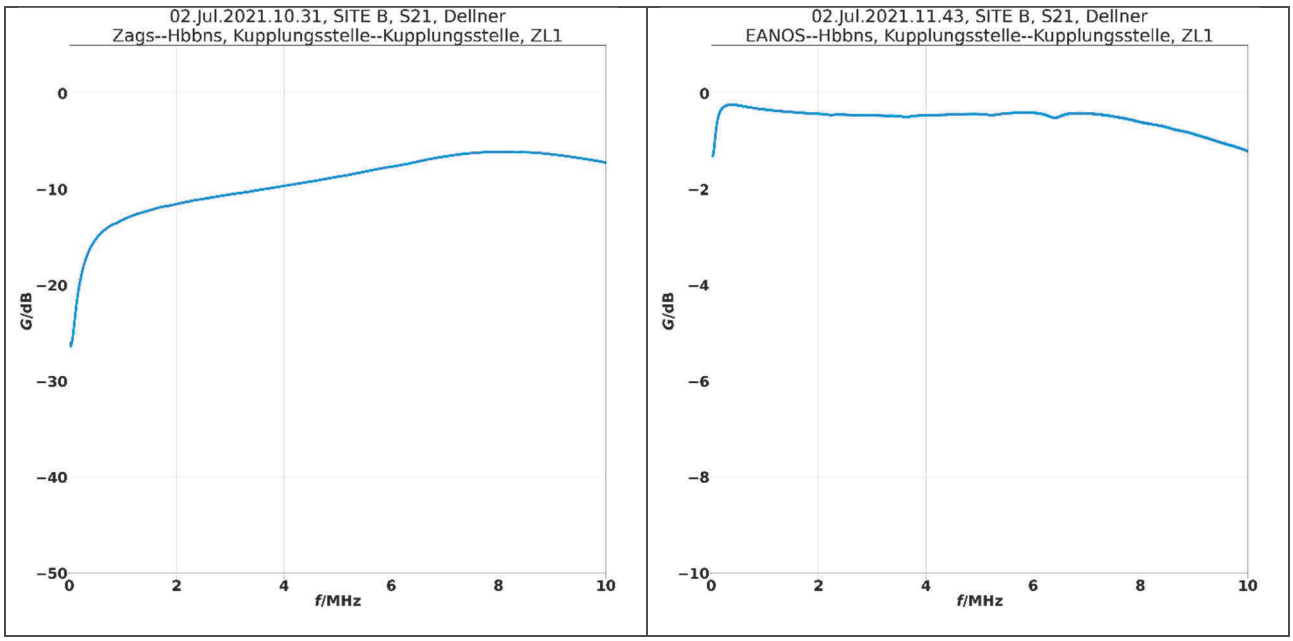
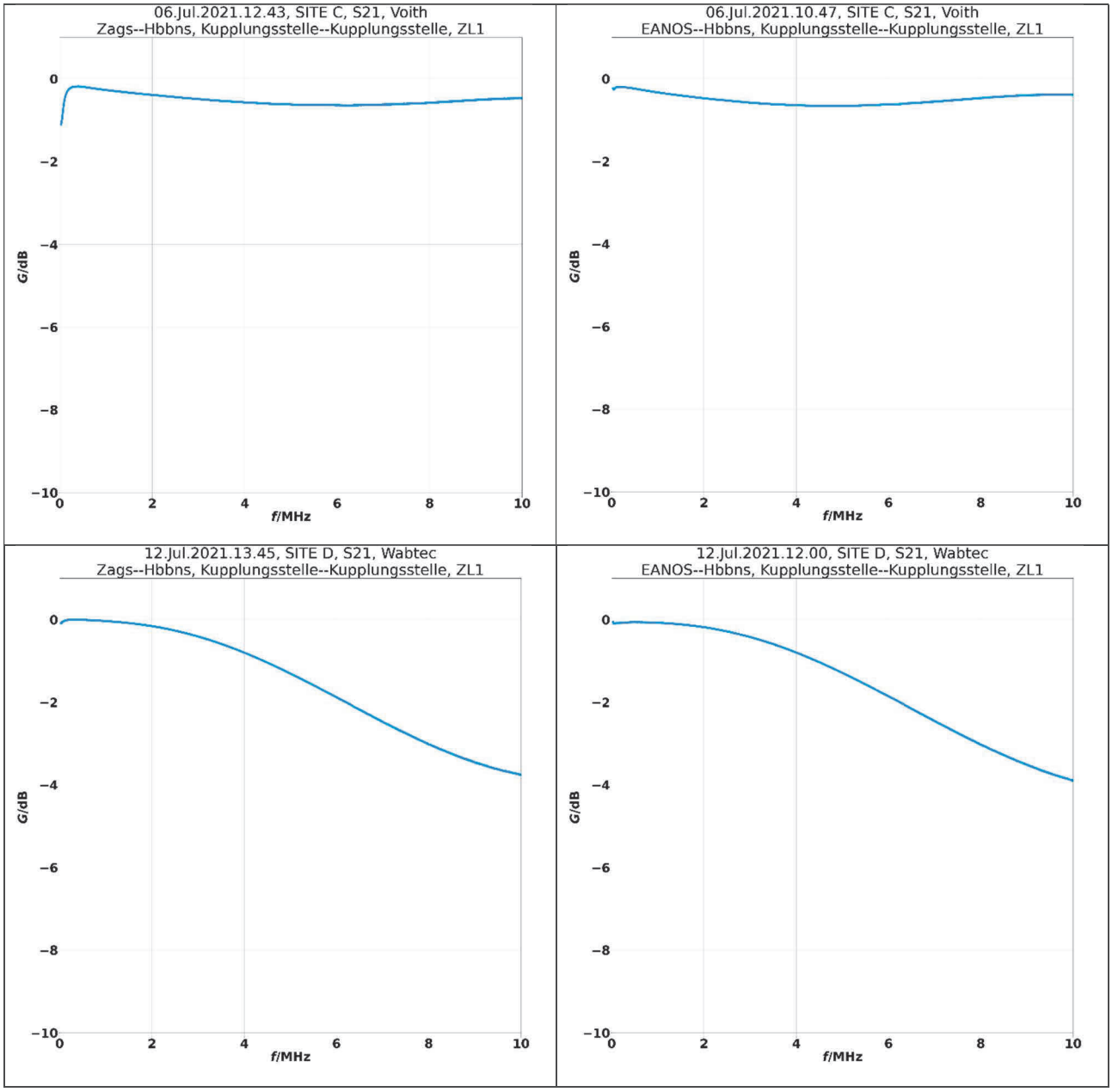


Figure 5: Channel measurement via a coupling junction

To measure the **two-wire lines**, the network analyzer was connected to the two-wire communication line in the coupling junction box of each of the first and second wagons, as well as the second and third wagons. This was done separately for two-wire line 1 and 2.

Table 1: Representative examples Dellner, Wabtec and Voith two-wire line





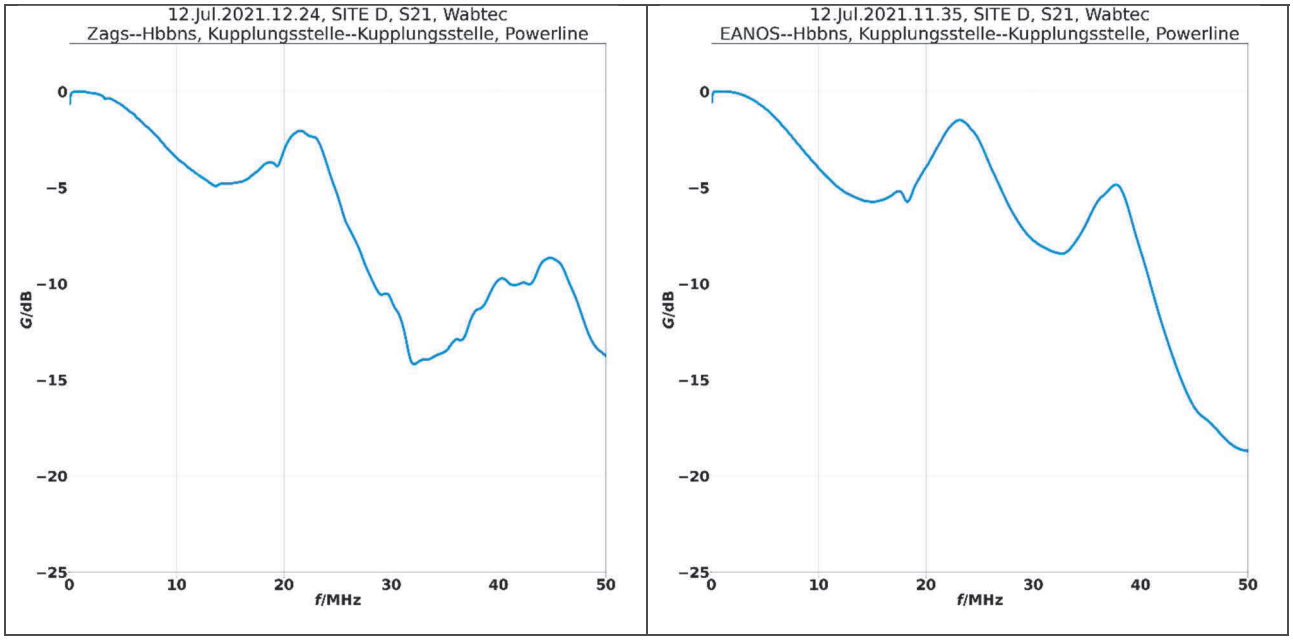
The two-wire lines and contacts of the coupling connections generally exhibited very good transmission characteristics in the range 30 kHz - 10 MHz. Only the connections "Dellner Zags-Hbbins", as well as "Wabtec Zags-Hbbins" and "Wabtec Eanos-Hbbins" were conspicuous by less optimal progressions of their transmission characteristics (Table 1).

In the case of the Dellner coupling, this is most likely due to an incomplete connection between the contact surfaces within the coupling. This would cause capacitive coupling, which can have a high-pass-like characteristic comparable to the measured transmission channel.

The low-pass-like progression of the transmission channel of the Wabtec couplings could be explained by a higher capacitance of the two-wire lines. However, this effect is negligible in view of the magnitude of the low-pass behavior.

To measure the **Powerline** lines, the network analyzer was connected to the 110 VDC supply line (without the supply voltage switched on) in the coupling junction box of each of the first and second wagons, as well as the second and third wagons.

Table 2: Representative examples Dellner, Wabtec and Voith Powerline

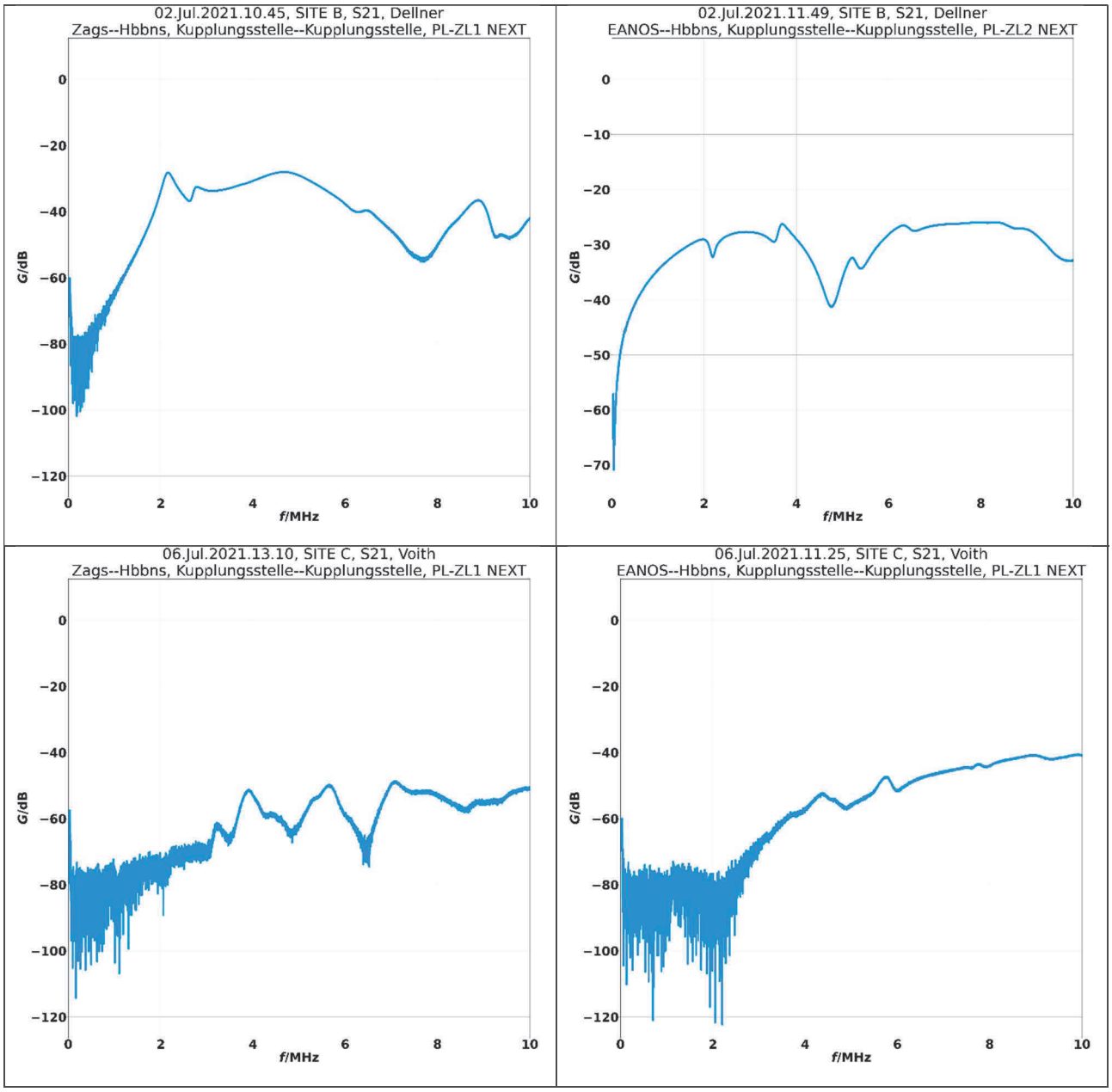


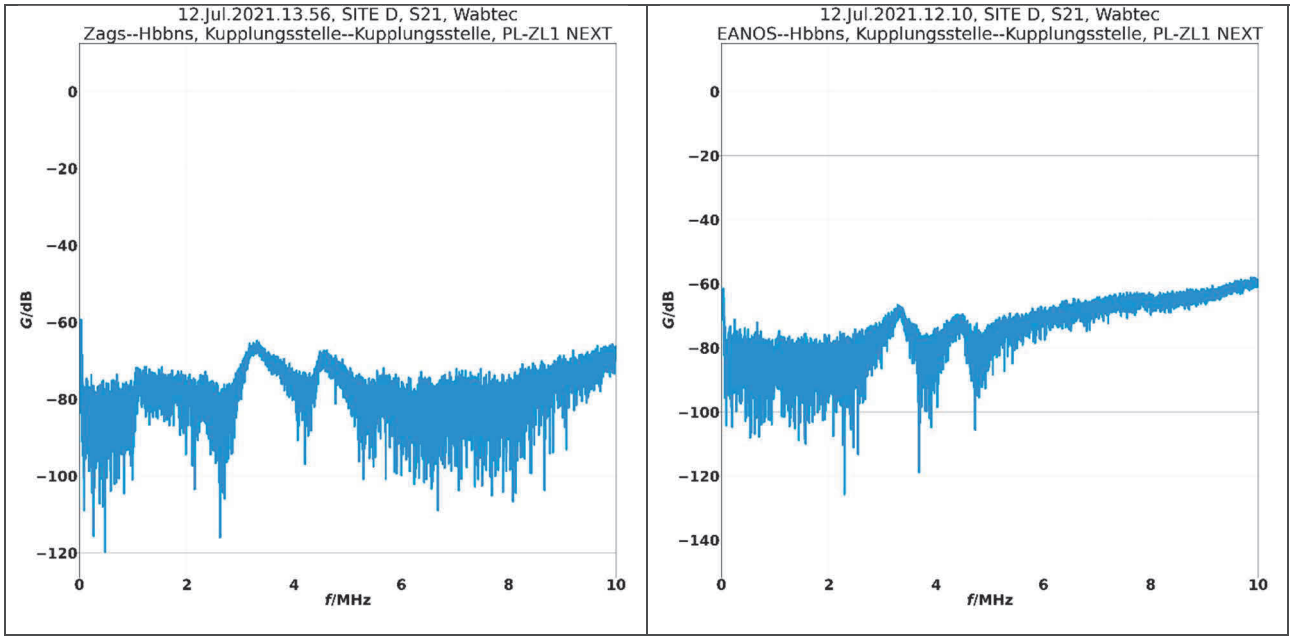
The Powerline lines and contacts of the coupling connections generally exhibited suitable transmission characteristics in the range 30 kHz - 20 MHz (Table 2). Among these, the "Dellner Zags-Hbbins" connection was notable for high attenuation at low frequencies. Analogous to the measurement of the two-wire lines, this is most likely due to an incomplete connection between the contact surfaces within the coupling. This would cause capacitive coupling, which may exhibit a high-pass-like characteristic comparable to the measured transmission channel.

Furthermore, the coupling connections from Dellner and Wabtec exhibited a much more pronounced low-pass behavior with a higher basic attenuation compared to the coupling connection from Voith.

To measure the **NEXT** (near-end crosstalk), the network analyzer was connected inside one of the two junction boxes of each of the two DAC coupling points, with one port on the 110 VDC supply line (without the supply voltage turned on) and the other port on one of the two-wire lines 1 and 2.

Table 3: Representative examples Dellner, Wabtec and Voith NEXT

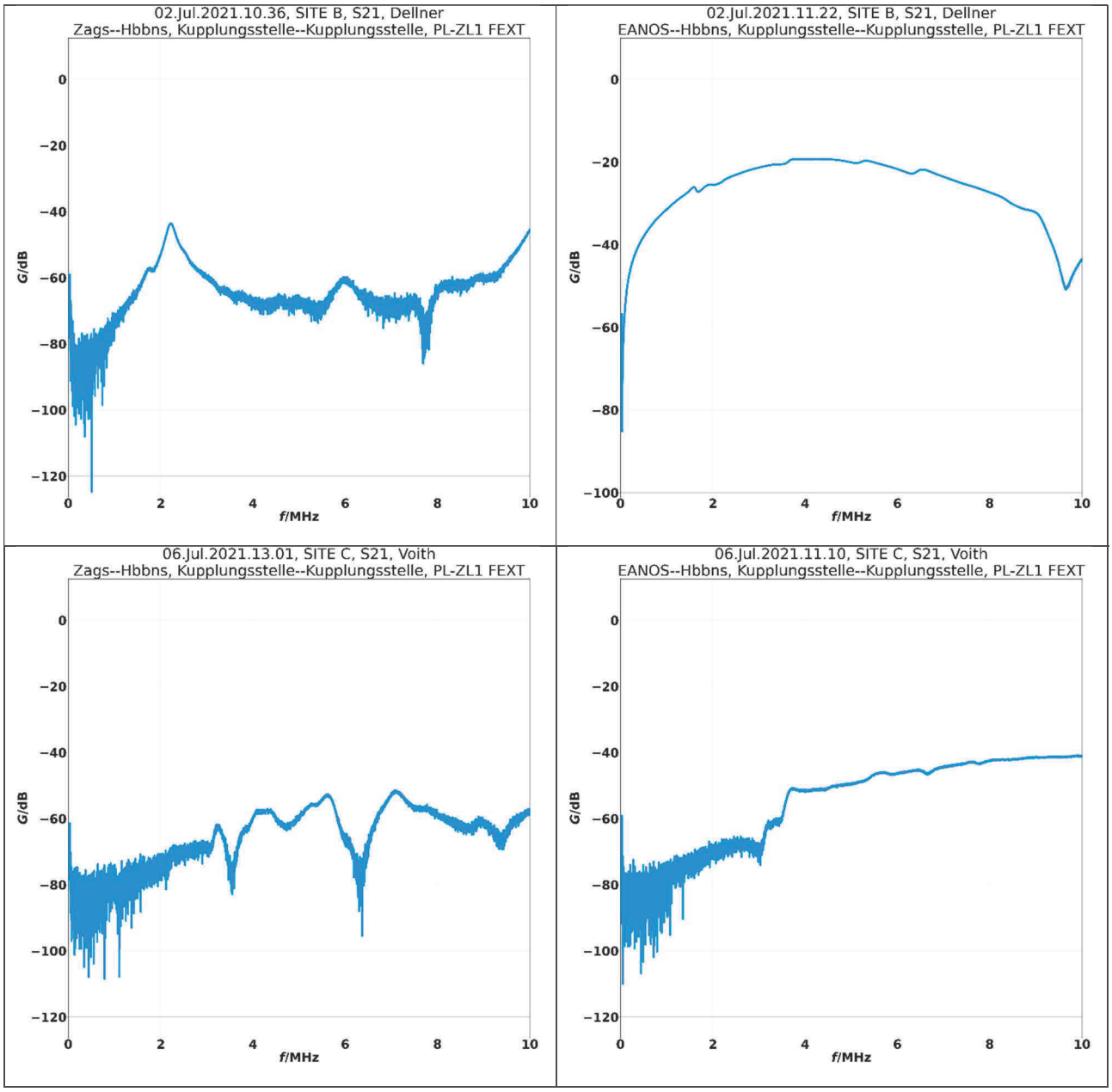


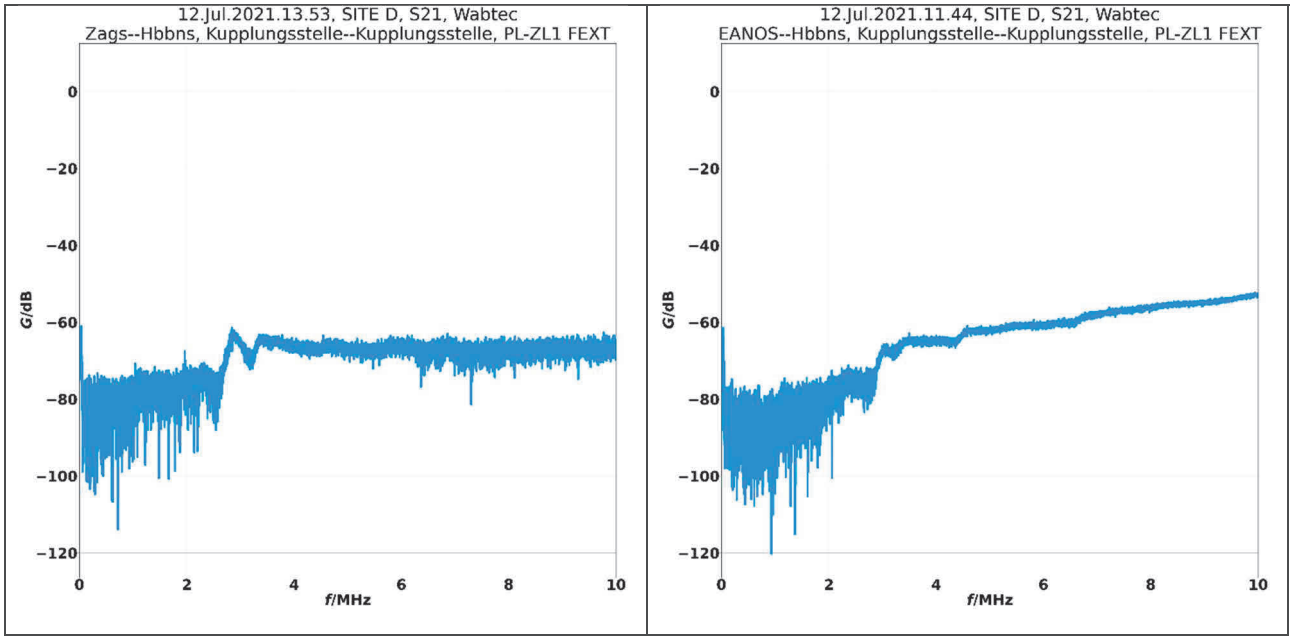


The near-end crosstalk between the Powerline line and two-wire lines of the Voith and Wabtec couplings was uniformly good with a minimum attenuation between 40 and 60 dB. Attenuation of the near-end crosstalk of the Dellner coupling was comparatively low at nearly 20 dB, making spurious crosstalk between communication channels more likely. This reduced attenuation could be due to the unshielded two-wire lines within the Dellner couplings, allowing direct capacitive coupling between the two-wire and Powerline lines.

To measure the **FEXT** (far-end crosstalk), the network analyzer was connected in each case to the 110 VDC supply line (without the supply voltage switched on) with the first measurement port in one coupling connection box of the DAC coupling points, and with the second measurement port to two-wire line 1 and then to two-wire line 2 of the other coupling connection box.

Table 4: Representative examples Dellner, Wabtec and Voith FEXT





The far-end crosstalk between Powerline and two-wire lines of the Voith and Wabtec couplings was uniformly good with attenuation between 40 and 60 dB. Attenuation of the far-end crosstalk of the Dellner coupling was comparatively low at nearly 20 dB for one coupling, making spurious crosstalk between communication channels more likely. Again, the reduced attenuation could be due to unshielded two-wire lines within the Dellner coupling, allowing direct capacitive coupling between the two two-wire lines. The prominent high-pass behavior of the Dellner couplings could be due to capacitive coupling of the contact surfaces within the coupling as described above.

3.1.2 Channel measurements over a wagon with coupling point

Channel measurement over a wagon with coupling point: The transmission parameters of the channel from one wagon box to the wagon box of the next wagon were performed. The measurement was performed over the two available coupling points for each coupling type. The lines continuing from the wagon box to the other end of the wagon were removed from the connection terminal and were thus not connected, see Figure 6.

The increased attenuation compared to the measurement of the coupling points was not caused by the actual couplings of the manufacturers, but by the additional connection lines, laid in the wagons, and the way they were installed. Furthermore, only a slight deterioration of the channel properties was to be expected, especially compared to the two-wire line measurements over one coupling point. For this reason, only one two-wire line measurement was carried out for one carriage group as an example. A significant deterioration was expected for the Powerline line measurements, and therefore these measurements were carried out for all wagon groups.

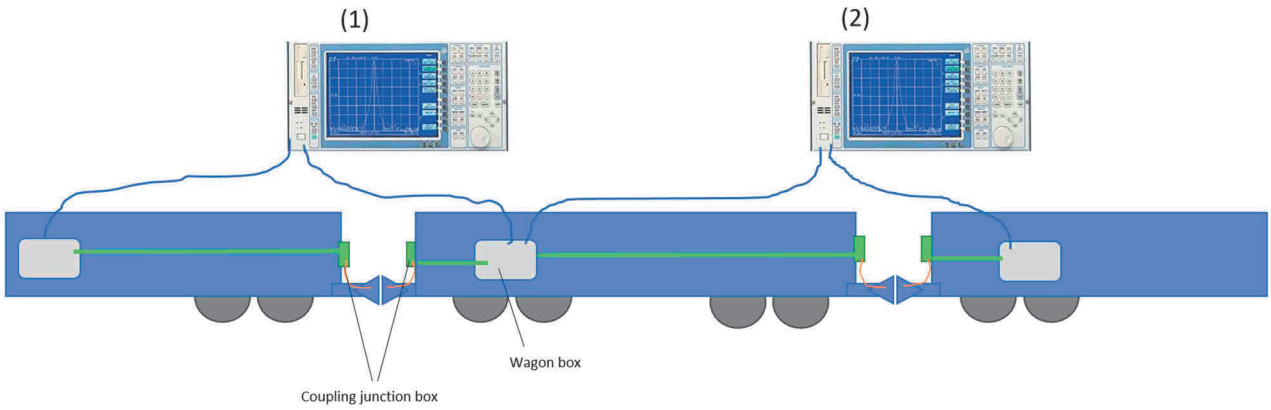
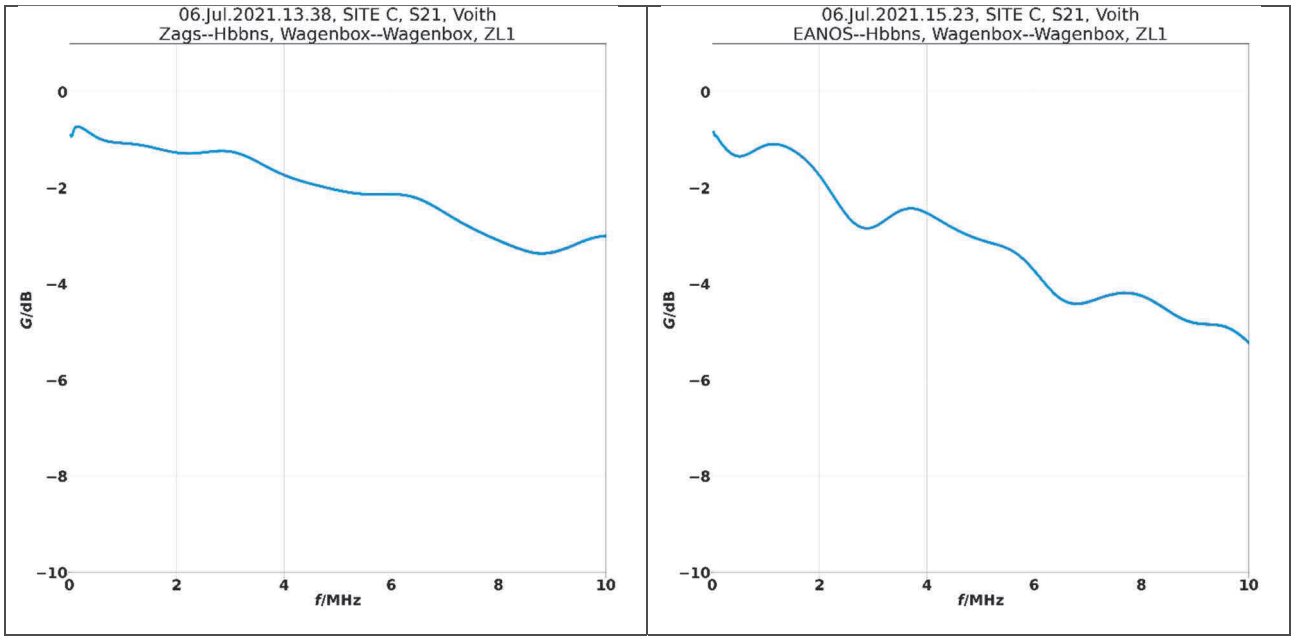


Figure 6: Channel measurement via a wagon

To measure the two-wire lines, the network analyzer was connected to the two-wire communication line in the wagon box of each of the first and second wagons, as well as the second and third wagons. This was done separately for two-wire line 1 and then two-wire line 2.

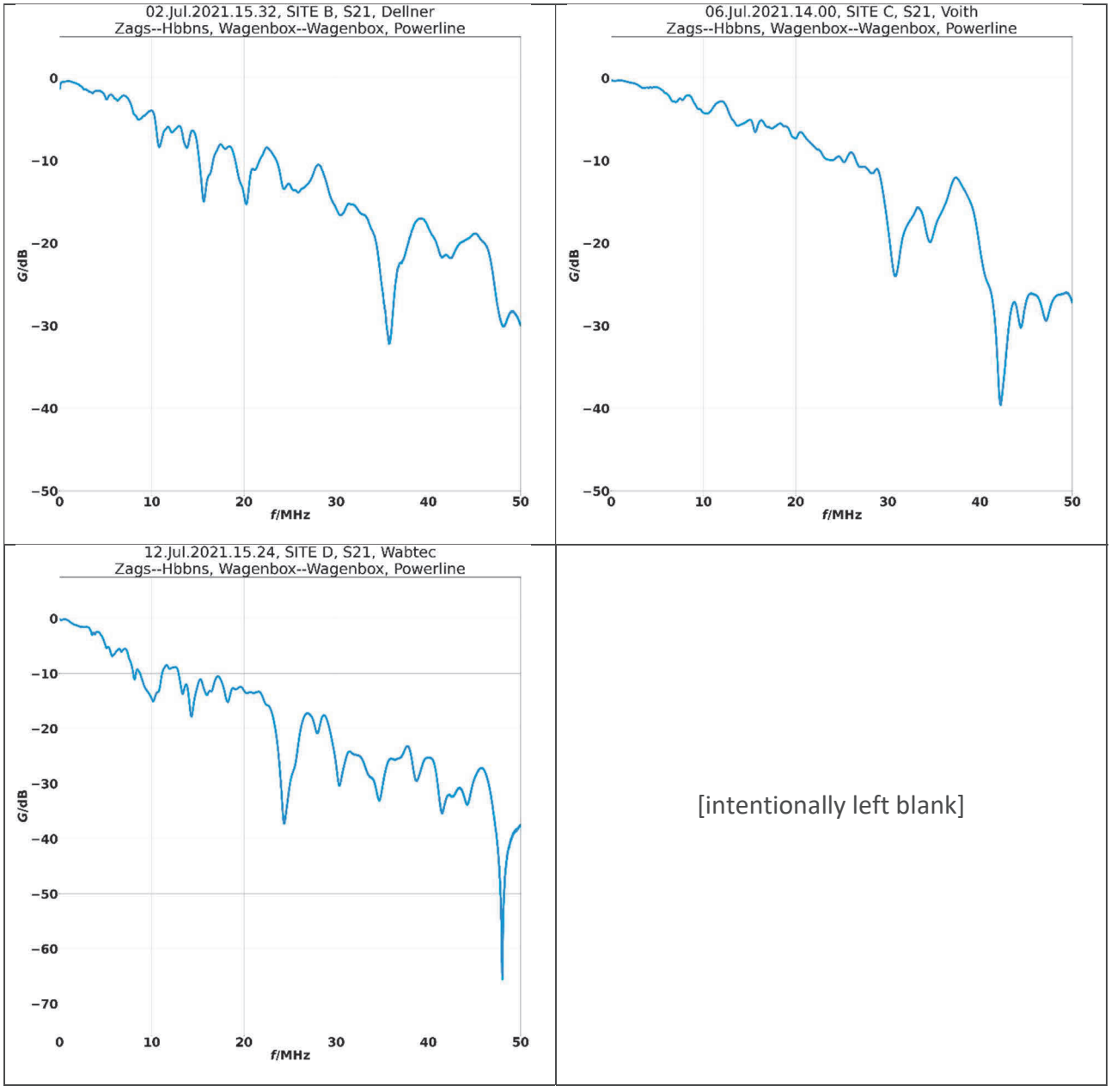
Table 5: Representative examples Voith two-wire line



As expected, the attenuation of the two-wire lines over one wagon increased compared to the direct coupling connection. The additional attenuation and the increased low-pass effect compared to the measurement of the coupling point are caused by the additional, significantly longer two-wire connection line between coupling junction boxes and wagon boxes.

To measure the **Powerline** lines, the network analyzer was connected to the 110 VDC supply line (without present supply voltage) in the wagon box of each of the first and second wagons, as well as the second and third wagons.

Table 6: Representative examples Dellner, Wabtec and Voith Powerline



As expected, the attenuation of the Powerline lines over one wagon increased compared to the direct coupling connection. The increased attenuation and the enhanced low-pass effect are due to the additional, significantly longer Powerline line between the coupling connection boxes and the wagon boxes. Thus, the response was mainly determined by the additional connecting lines and

their installation methods in the wagons. This assumption, which was also made above for the two-wire lines, is confirmed by the present measurement results.

A strong frequency-variant course of the channel attenuation is generally a challenge for communication systems. In multicarrier communications in particular, the frequency-variant attenuation can be compensated for by appropriate parameterization of the physical layer, a lower code rate and FEC (forward error correction), with losses in the data bandwidth.

3.1.3 Channel measurement over a wagon group

The characteristic formulated as a requirement for a suitable communication system was the need to compensate for the **failure of the wagon's communication system**. To describe this failure from the communication channel's point of view, measurements were taken over a wagon group with three wagons. In the middle wagon, the respective communication lines were bridged.

To measure the **two-wire lines**, the network analyzer was connected to the two-wire communication line in the wagon box of the first and third wagon respectively. This was done separately for two-wire line 1 and 2.

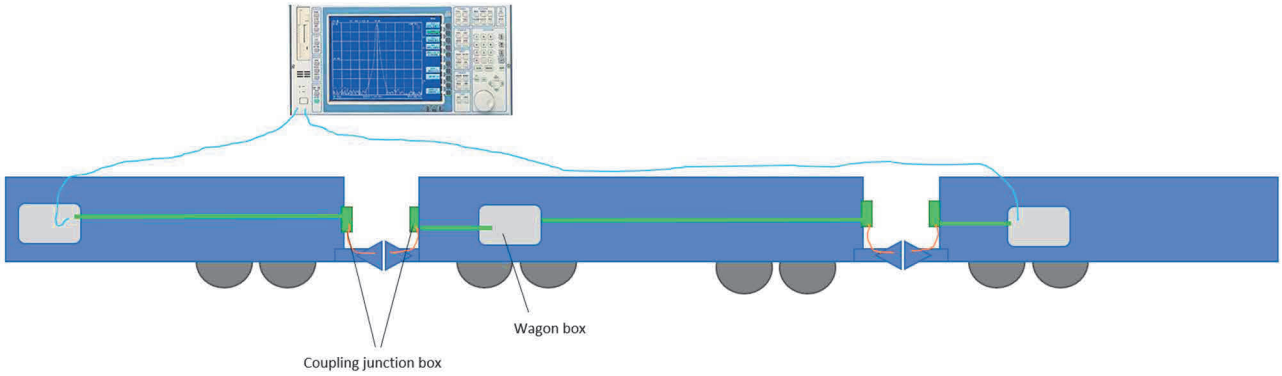
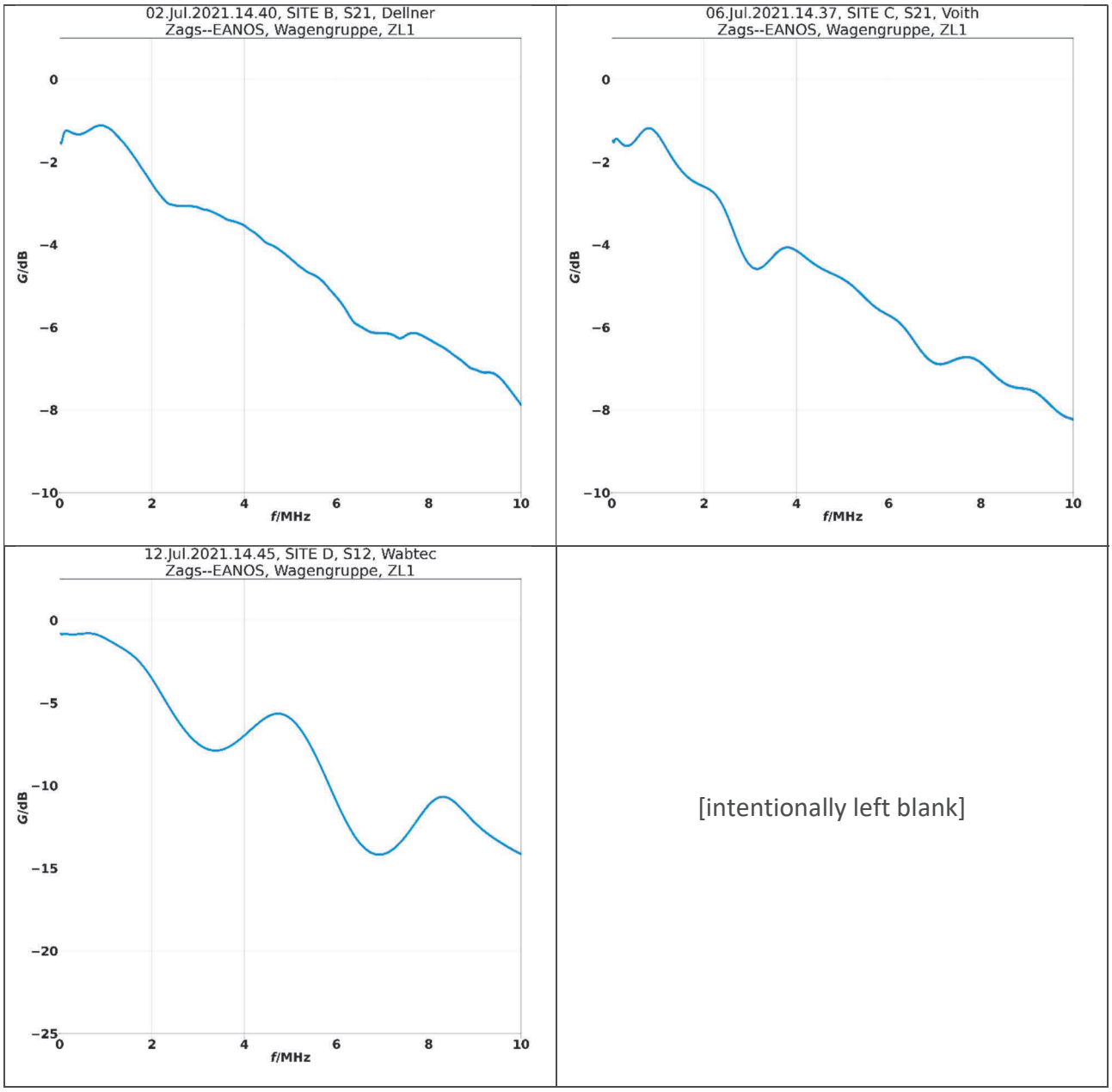


Figure 7: Measurement over a wagon group of three wagons

Table 7: Representative examples Dellner, Wabtec and Voith two-wire line



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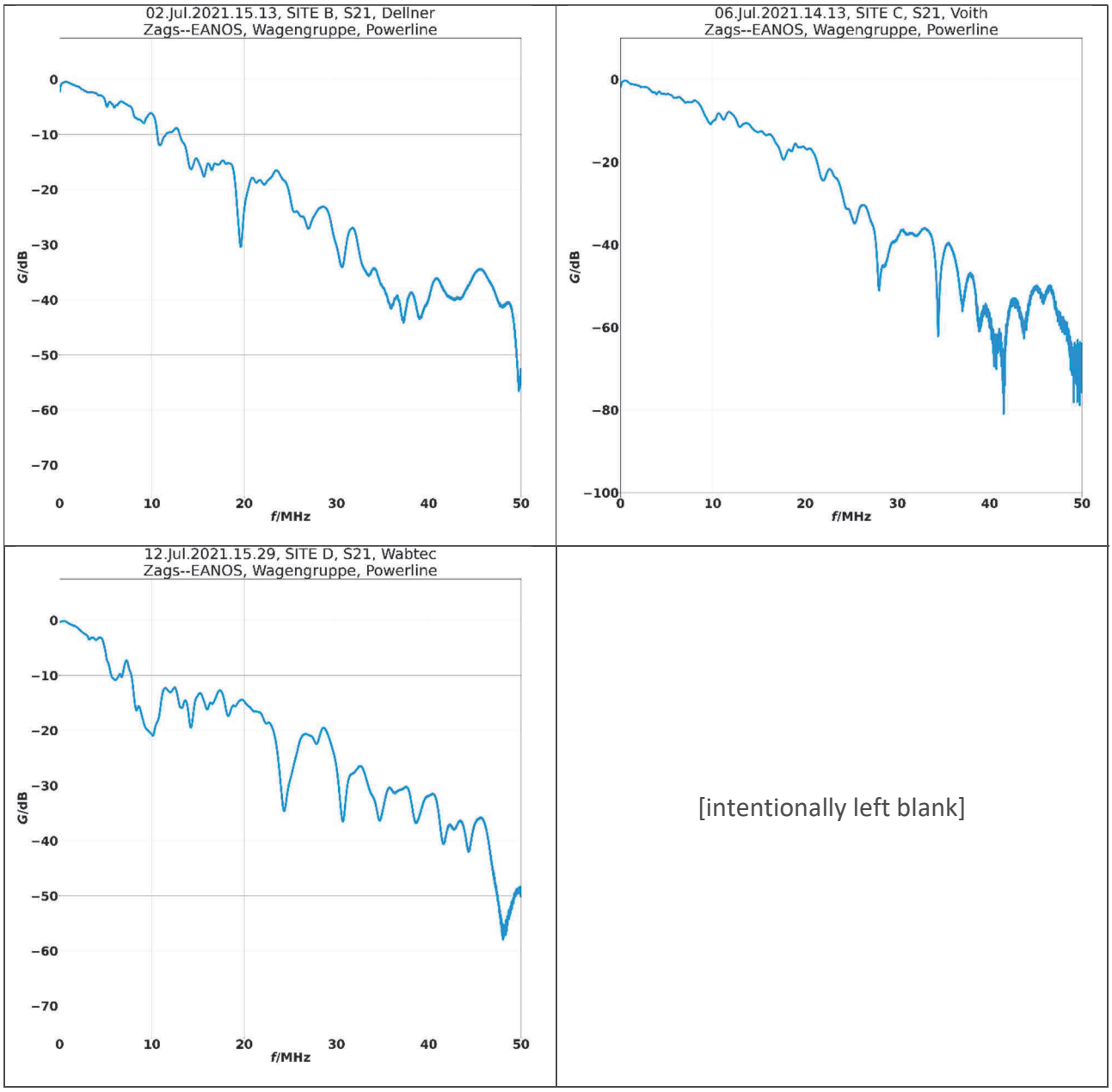
All two-wire lines exhibited a very good connection over the entire group of wagons. The expected prominent low-pass effect is due to the additional length of the connection lines within the wagons.

To measure the **Powerline** lines, the network analyzer was connected to the 110 VDC supply line (without the supply voltage switched on) in the wagon box of the first and third wagon respectively.

Table 8: Representative examples Dellner, Wabtec and Voith Powerline



All Powerline lines showed a rather average connection quality over the entire group of wagons. The expected prominent low-pass effect is caused by the additional length of the connecting lines within the wagons.

A strongly frequency-variant course of the channel attenuation is generally challenging for communication systems. The channel quality deteriorates significantly for the measured wagon groups at around 20 - 25 MHz. Depending on the technical implementation of the physical layer, this can lead to an increased packet error rate. For the Dellner group, a larger drop can already be

observed at 20 MHz. Below 20 - 25 MHz (depending on the coupling type), powerline communication is considered feasible, capable of communicating at least to the next but one car.

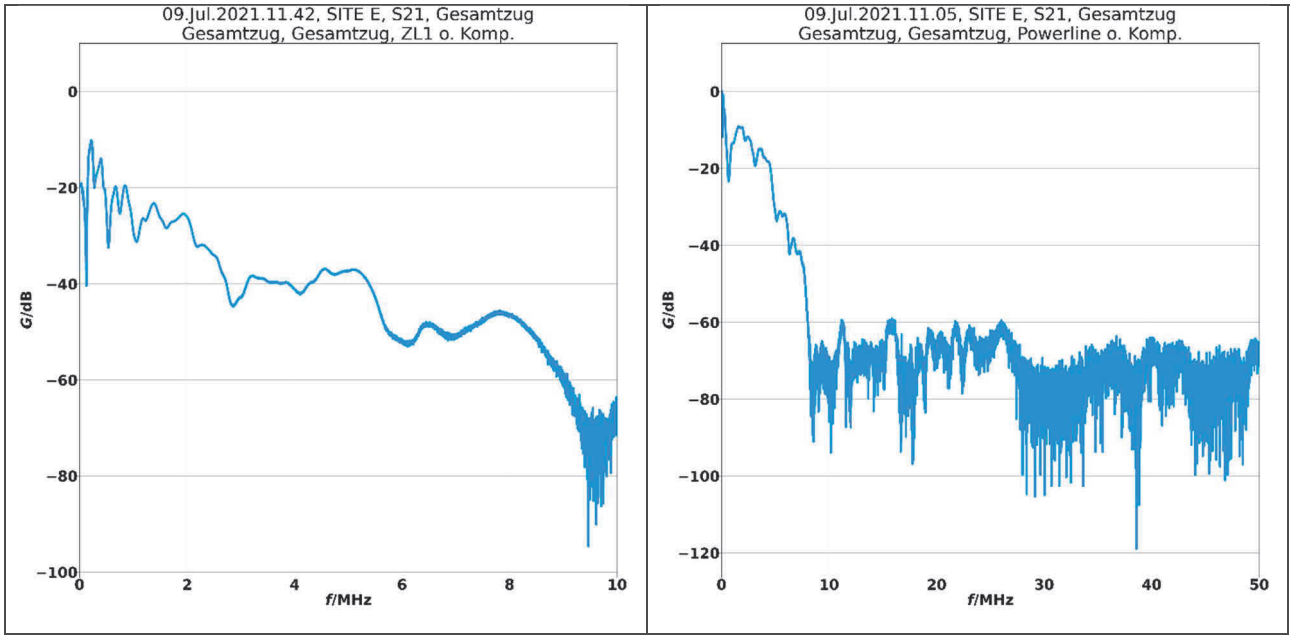
3.1.4 Overall train channel measurements

Measurement over 12 wagons: Measurements were performed across all available wagons. In particular, the communication channel for a longer distance in the train was identified. Adjacent car sides of different coupling manufacturers were connected using jumper cables that can be plugged into connectors of the coupling connection box (see Figure 19: Coupling connection box with jumper cable plugged in).

To measure the **two-wire lines**, the network analyzer was connected to a two-wire communication line in the wagon box of the first and last wagon respectively.

To measure the **Powerline** lines, the network analyzer was connected to the 110 VDC supply line (without the supply voltage switched on) in the wagon box of the first and last wagon respectively.

Table 9: Representative example two-wire line and Powerline



The two-wire line showed prominent low-pass behavior as well as significant high-pass behavior. The latter is most likely due to an incomplete connection between the contact surfaces within a coupling. This would cause capacitive coupling, which may exhibit a high-pass-like response comparable to the measured transmission channel. The low-pass response of -40 dB around 3 MHz was much more prominent than would be expected based on the combination of measurements across individual wagon groups. This also indicates an incomplete connection in a coupling.

The Powerline line exhibited a similar low-pass behavior. From about 10 MHz, it can be assumed that the detection limit of the measuring device was reached. This assumption is supported by the increased noise in the upper frequency ranges. Thus, Powerline lines are not suitable for high bandwidth communication methods (such as PTB, plc-tec AG) without segmentation across the entire train.

In the range of a few 100 kHz, a Powerline line communication in a train with 50 wagons and 750 - 835 m length could be functional (Powerline-G3).

3.2 Radio channel measurements

When measuring the radio channel, the positions of the antennas and the measuring antenna characteristics were particularly relevant for consideration. When measuring the radio channel, the measurement position already had to represent a realistic position with regard to the later application. There are currently two approaches for this:

1) The antennas are located on the front side of each wagon (on the coupling connection box).

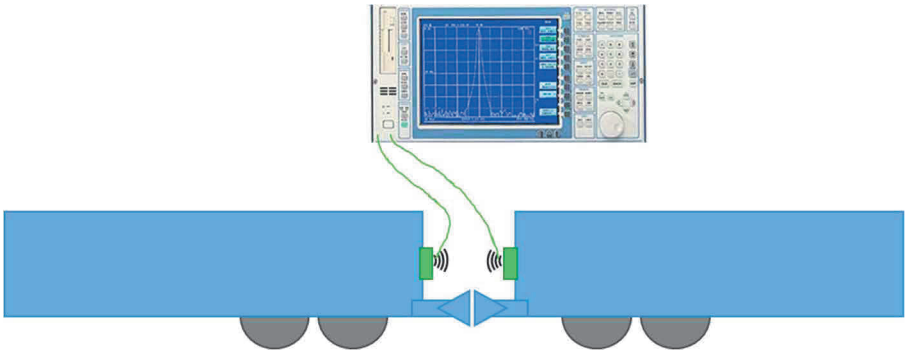


Figure 8: Measurement of the radio channel on front sides

2) The antennas are located inside the coupling (Figure 9) and are a few centimeters apart in front of each other (NFC, near field communication).

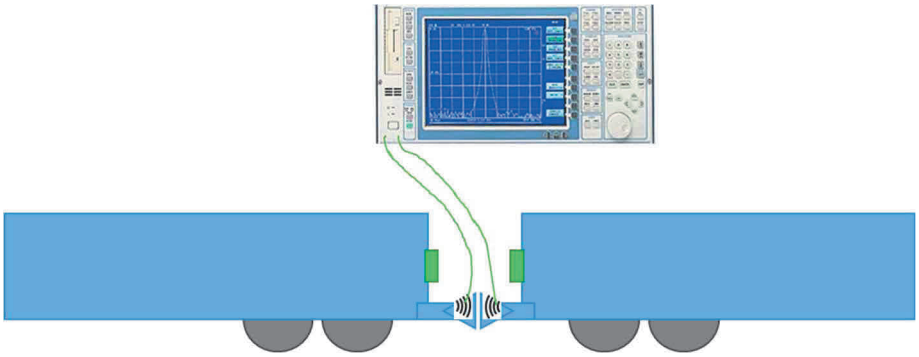


Figure 9: Measurement of the radio channel in couplings

The measurement of a channel inside the couplings could not be performed as no space for the installation of an antenna was provided in any coupling variant.

3.2.1 Measurement setup

A network analyzer was used to measure a radio channel with a comparatively short spatial extent. For this purpose, the suitable frequency channels were swept and the relevant parameters (transmission factors S21 and S12) were recorded in a time-invariant manner. The following frequency ranges were considered:

1) 2.4 GHz ISM band
2) 3.7 - 3.8 GHz band (5G campus networks)
3) 5.725 - 5.875 GHz ISM band (SRD usage) (measured: 5.70 - 5.80 GHz)

To measure the channels, antennas with a broadband characteristic [2] [3] without horizontal directivity (preferably omnidirectional characteristic) were used. When using directional antennas, a statement can be derived from these results. A reduced influence of multipath propagation compared to the use of non-directive antennas had to be assumed, which reduces the proportion of frequency-selective dips in the frequency response.

3.2.2 Measurement execution

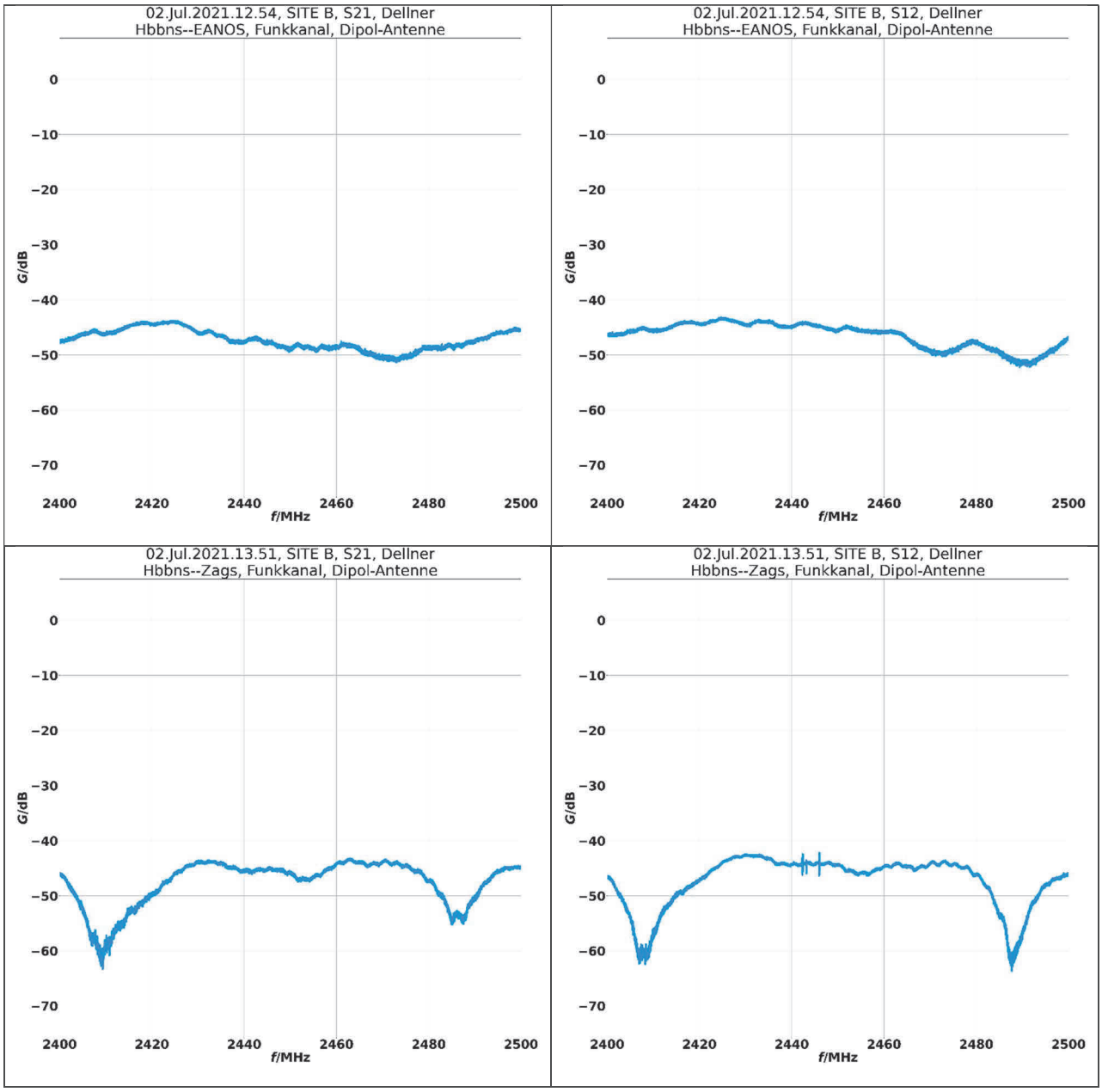
The measurement of the radio channels was only carried out on one wagon group, as any influence on the radio channel by the different couplings is negligible. In particular, there are some channel dependencies with regard to the wagon types used, as these may have different reflection characteristics.

For the radio channel measurement between the front sides of the wagons, antennas were installed at the coupling junction boxes, and the channel was measured between the antennas. The antenna position and the wagon type had a significant influence on the channel characteristics.

3.2.3 Measurement evaluation

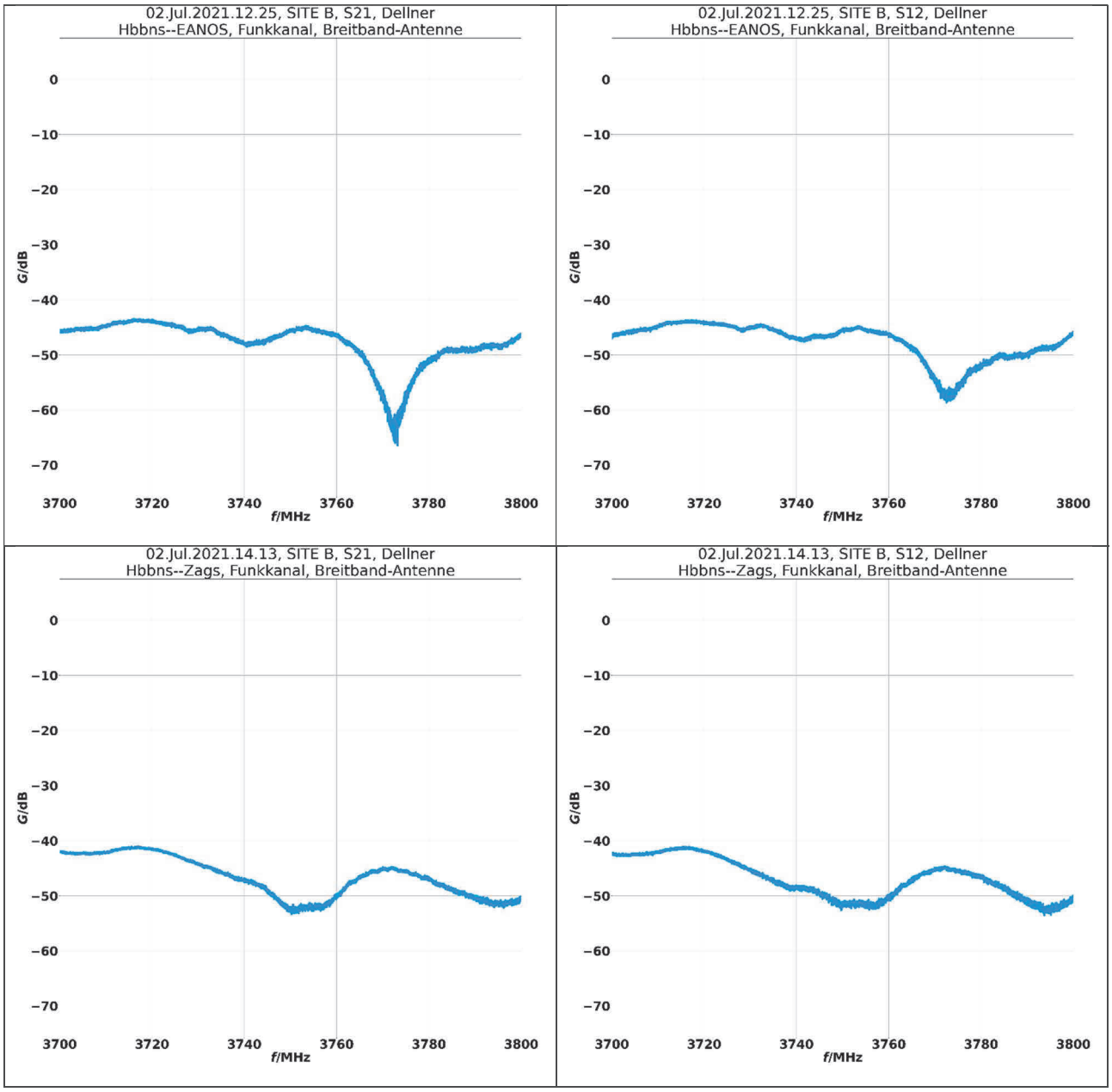
The radio channel measurements are shown below for the measured wagon connections.

Table 10: Representative examples 2.4 GHz ISM Band



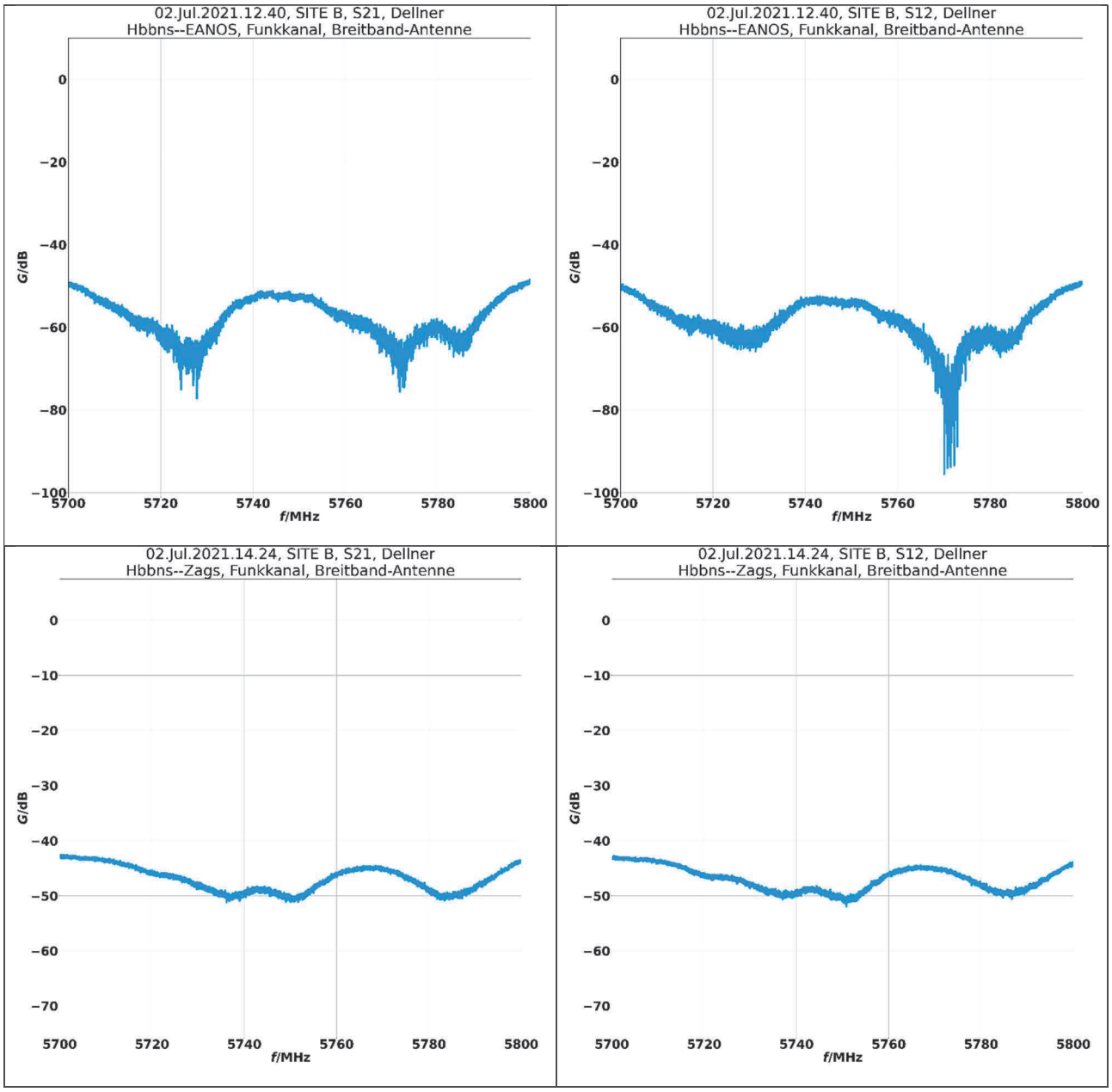
The radio channel of the 2.4 GHz band was relatively frequency flat between the Hbbins and Eanos wagons, with attenuation appropriate for the distance. Between the Hbbins and Zags wagons, the radio channel was rather variable in frequency, with two dominant dips in the course of the attenuation, as well as an overall attenuation that was also appropriate for the distance. The ripple is due to matching errors between the network analyzer and the antenna. The dips are due to multipath propagation of the radio waves in and adjacent to the "Berne rectangle".

Table 11: Representative examples 3.7 – 3.8 GHz Band



The radio channel of the 3.7 to 3.8 GHz band was not very frequency-variant between the Hbbins and Zags wagons, with an attenuation appropriate for the distance. Between the Hbbins and Eanos wagons, the radio channel was more frequency-variant, with a dominant dip in the attenuation curve and attenuation also appropriate for the distance. The dip is due to multipath propagation of the radio waves in the "Berne rectangle".

Table 12: Representative examples 5.7 – 5.8 GHz Band



The radio channel of the 5.7 to 5.8 GHz band was less frequency flat between the Hbbins and Zags wagons with attenuation appropriate for the distance. Between the Hbbins and Eanos wagons, the radio channel is more frequency-variant, with two dominant dips in the course of attenuation, as well as an overall attenuation that was also appropriate for the distance. The dips are due to multipath propagation of the radio waves in the "Berne rectangle".

For the three frequency bands 2.4 GHz, 3.7 GHz and 5.8 GHz, the reflection pattern is clearly dependent on the surrounding geometry of the wagons as well as additional structures adjacent to the "Berne rectangle". The influence of the manufacturer-specific couplings is assumed to be small.

Interference is to be expected with neighboring trains when using the same frequency bands. This cannot be ruled out even when using antennas with greater directivity due to the metallic ambient conditions.

For common wireless communication systems, these radio channels are expected to provide a good connection with a low packet loss rate. This was confirmed by the communication measurements with WiFi (Table 21: Results WiFi measurements wagon-to-wagon).

3.3 Eye diagram measurements over wagon group

The eye diagram measurement was performed only on the Wabtech group, as they showed the weakest channel measurement results. The measurements were performed with a peak-to-peak voltage of 2 V. A Hameg signal generator (HM 8030) was used as the signal source.

A square wave sequence with a duty cycle of 50% and various measurement signal rates was used as the measurement signal. To generate the eye diagram, a superposition of the time-shifted measurement signal in the oscilloscope was used. Here, long-term fluctuations in the bias voltage between individual rectangles of the measurement signal lead to a supposedly reduced opening of the eye. The mean value of the opening of the eye, which is shown as a yellow line (see Figure 10 and Figure 11), therefore represents the relevant variable for the signal at the differential receiver.

The failure scenario was chosen as the test scenario, in which the middle wagon is bypassed and thus communication has to take place across the middle wagon (Hbbins) (worst-case scenario).

The eye diagrams are evaluated regarding the planned use of CAN-FD with a data rate of 2 Mbit/s at a symbol rate of 2 MBaud due to the modulation. Here, twice the measurement signal rate was used compared to the symbol rate in order to increase the confidence against noisy channels and jitter due to less expensive communication hardware.

3.3.1 Measurement with 1 MHz measuring signal rate

The measurement with 1 MHz measurement signal rate in the baseband allows considering the CAN arbitration signal with 250 kbit/s or 500 kbit/s.

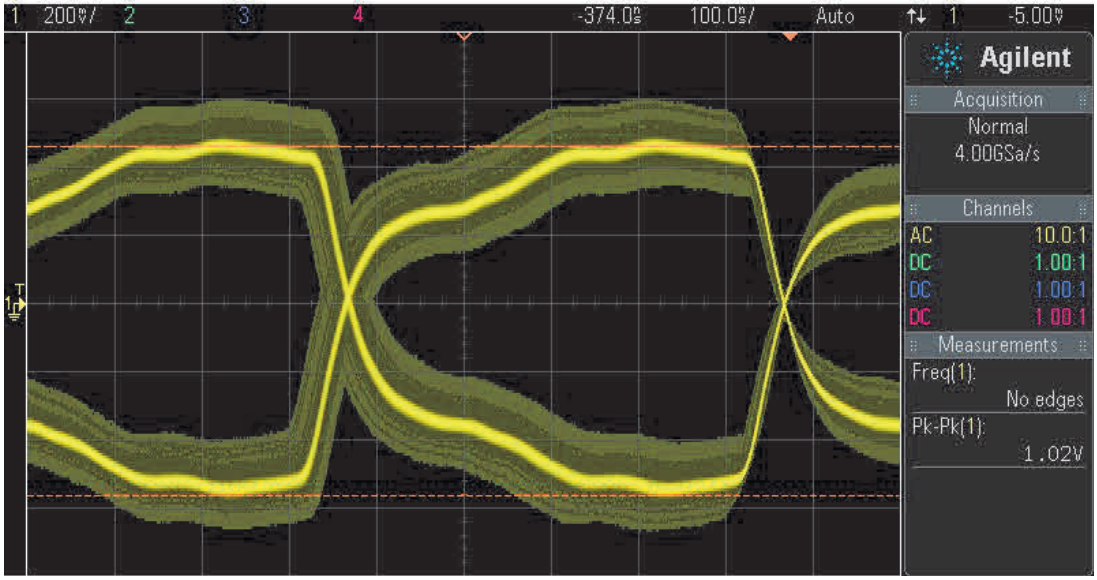


Figure 10: Eye diagram with a 1 MHz measurement signal (yellow: received signal, orange line: peak-to-peak value of the average value)

The eye diagram shows that a reliable peak-to-peak voltage of > 1 V was still achieved at the regular sampling time of the signal at approx. 75% of the period duration. A square wave signal with a typical signal level for CAN of 2 Vpp was generated with the signal generator. The voltage at the receiver should be 500 - 750 mV for the CAN bus [4]. In the present case, a robust communication between two nodes can be assumed based on the eye diagram.

The reduced opening of the eye in the dark yellow areas is due to long-term fluctuations of the bias voltage.

3.3.2 Measurement with 4 MHz measuring signal rate

CAN-FD can be operated with a 2 Mbit/s data bandwidth in the data segment. For the measurement, a peak-to-peak voltage of 2 Vpp was set similarly to the measurement with 1 MHz measurement signal rate.

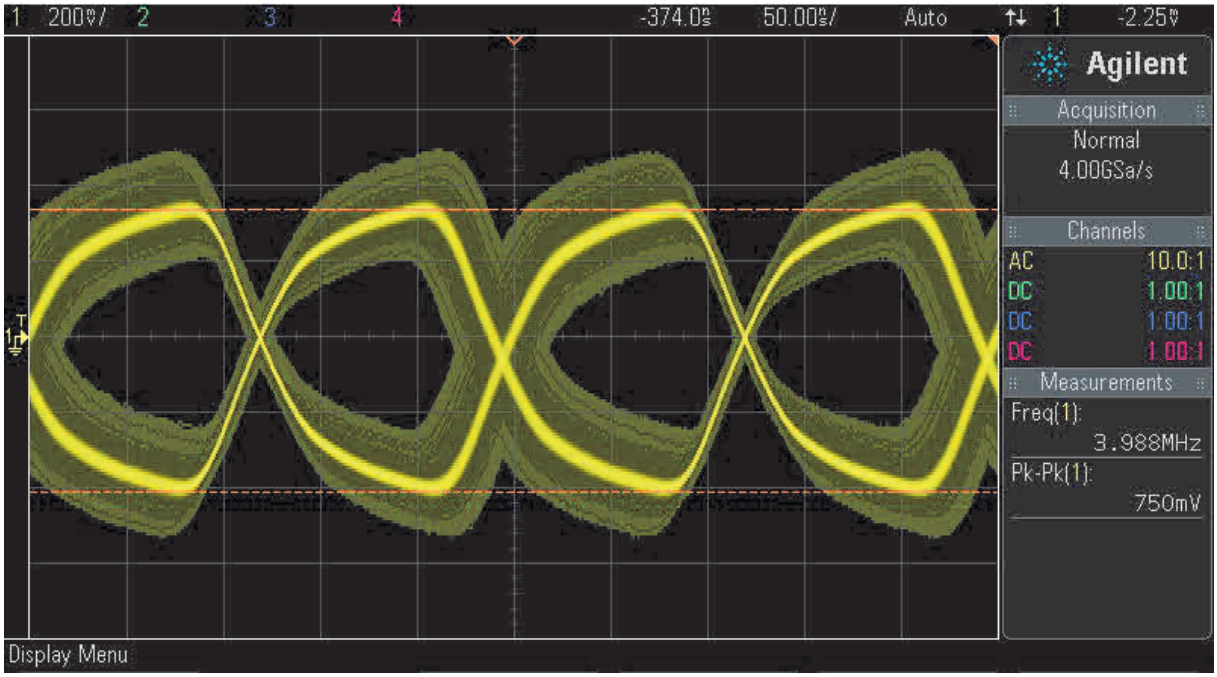


Figure 11: Eye diagram with a 4 MHz measurement signal (yellow: received signal, orange line: peak-to-peak value of the average value)

At the sampling time, 750 mV was still reached at 4 MHz measurement signal rate. This meets the requirements for maximum transmission attenuation for a CAN FD signal with a symbol rate of 2 MBaud [4]. In the present case, a robust communication between two nodes can be assumed on the basis of the eye diagram.

The reduced opening of the eye in the dark yellow areas is due to long-term fluctuations of the bias voltage.

3.4 Channel measurement summary

1. The channel measurements on the overall train with twelve wagons show that, in principle, only segmented communication systems or repeating communication systems (Powerline-PLUS) are feasible, since the channel attenuation for communication systems with a suitable communication bandwidth would become too great with the required number of 50 wagons and 750 m/835 m total train length. The measurements demonstrated that even 12 wagons have such high channel attenuation that communication would only be feasible with the aid of segmented/repeating communication systems. In addition, the signal bandwidth would have to be very low, and thus the communication bandwidth could also fail to meet the requirements.

2. Both the measurement of the transmission factors and the eye diagram representation show that transmission across a defective wagon appears unproblematic for a two-wire communication system (e.g. CAN-FD) on the two-wire line. For the Powerline system, the

applicability of the scenario depends on the used signal bandwidth as well as at the signal power injected into the system. According to the channel measurements, a reasonable limit was 20 - 30 MHz, depending on the coupling type. Above these frequencies, channel attenuation increased rapidly, which can lead to a higher packet error rate or even a connection failure.

It should be noted that during the measurements the line length over three wagons was approx. 45 m to 60 m, depending on the wagon group, and thus was shorter than the required segment lengths of 100 m - 150 m without a communications system.

3. For the Powerline system, it is recommended that the 16 mm² cables are twisted when installing the cables. This would reduce frequency-selective dips in the transfer function due to impedance fluctuations, and thus contribute to improved channel characteristics and a reduced error probability.
4. The NEXT and FEXT measurements show that the coupling between the power line and data line was low at -40 dB to -60 dB when using shielded two-wire lines. A significant advantage in terms of crosstalk with the power and data lines laid in separate corrugated tubes (Voith) compared to laying them in the same corrugated tube (Wabtec) cannot be identified. This observation is attributed to the fact that shielding at short distances allows higher crosstalk attenuation compared to a mere additional increase of the distance (1/r proportionality of the field strength of a line conductor) by plastic tubes.

4 Stationary performance measurements with communication systems

4.1 Measured variables

To determine the communication systems' performance, the following parameters were determined as measured variables:

- **Data rate** as a function of packet size: During the measurement, the data generator was given optimized packet sizes for the respective communication system in order to determine the maximum possible communication bandwidth. The packet size was based on the MTU (Maximum Transfer Unit) of the respective communication system. For the IP-based communication systems (WiFi, Powerline-PLUS), the bandwidth measurement was performed with TCP/IP, for CAN-FD with a data generator without flow control.
- **Packet rate:** Packets with minimal information (payload) were transfered on the communication systems. A minimum data content of approx. 16 bytes was assumed due to protocol overhead. The determination of packet rates had to be specified individually for each communication system. For the Ethernet-based transmission systems (WiFi, Powerline), the packet load was selected so that a slight overload of the system (with packet loss up to 5 %) was apparent in order to demonstrate the load limit. For CAN-FD, the packet rate was set by the transmitter to produce approximately 99 % bus load. The packet rate measurement was performed with UDP for the IP-based communication technologies (WiFi, Powerline-PLUS), and with a CAN-FD packet generator for CAN-FD.
- **Packet error rate/packet loss rate:** To identify the packet error rate, test loads were injected into the communication systems that did not represent a system overload after measuring the packet rate (approx. 60 % for WiFi and Powerline, approx. 60 - 80 % for CAN-FD). At the receiver, the received packets were counted and compared with the number of transmitted packets. For CAN-FD communication, error counters were also recorded. In the case of the WiFi communication system, this method can only be used to diagnose packet errors where no successful retransmit is performed (link layer of IEEE 802.11b).
- **Transmission latency:** The communication systems must comply with transmission latencies to meet the specified requirements. For the use case "integrity check", it should be possible to detect a failure after approx. 1 second. The transmission latency for a 50-wagon train should therefore be a factor of 5 - 10 lower than the limit for detecting the failure time, i.e. 100 - 200 ms. Another requirement regarding transmission latency concerns the distributed traction function. Here, the leading locomotive must transmit cyclic control parameters to a second locomotive. The latency parameters here must likewise be 100 - 200 ms. Latencies

and jitter were determined by measuring packet transmission times. Transmission latency was determined by measuring the Round Trip Time (RTT).

- **Range:** It should be possible to bridge at least one wagon without an operational communication system.
- **Initialization time:** Time from switching on the power supply until the nodes are ready for communication. Since no implementation of train inauguration for CAN and WiFi communication was carried out in project phase I, an estimation had to be made here. The estimation consisted of the following parameters:
  - Start-up time of the devices until communication readiness[1]
  - Time phase for initialization/train inauguration of the communication system: Transfer of approx. 5 - 10 messages (for CAN-FD and WiFi) between the locomotive and each wagon is considered to be a realistic number for an initialization protocol.

4.2 Stationary performance measurement results

4.2.1 Powerline

The Powerline measurements required the configuration of a node as master. In all wagon groups, the Zags wagon was configured as the master.

4.2.1.1 Powerline tests wagon to wagon connection

With the Powerline system, only the connection from the master to the slave nodes or in the opposite direction could be measured, since no cross communication between the slaves was directly possible. The measurements were carried out in a three-way network of the wagon group, in which all three Powerline modems were always active. Therefore, the performance parameters of the wagon-to-wagon connection were determined for each wagon group via only one coupling.

Table 13: Results Powerline measurements wagon-to-wagon

	Voith*	Wabtec	Dellner
Data rate Master -> Slave	6.12 Mbit/s	6.67 Mbit/s	6.67 Mbit/s
Data rate Slave -> Master	1.92 Mbit/s	1.7 Mbit/s	1.7 Mbit/s

[1] Due to the test setup using industrial components, a strong deviation compared to systems specifically adapted to the application was to be expected.

Packet rate Master -> Slave	677 fps	163 fps	164 fps
Packet rate Slave -> Master	92 fps	176 fps	171 fps
Error rate Master -> Slave	PER < 10^{-4} (0 % @ 50000 Packets)	PER < 10^{-4} (0 % @ 10931 Packets)	PER < 10^{-4} (0 % @ 12501 Packets)
Error rate Slave -> Master	PER <= 10^{-4} (0.01 % @ 10000 Packets)	PER < 10^{-4} (0 % @ 11683 Packets)	PER < 10^{-4} (0 % @12491 Packets)
RTT (min, avg, max) Master -> Slave	3.3 ms/17.3 ms/63.8 ms ** 2.8 ms/4.2 ms/5.0 ms	2.2 ms/3.7 ms/6.1 ms	2.5 ms/3.8 ms/4.7 ms

* After the performance tests of the Voith group, plc-tec reconfigured the devices with a different firmware. The measurement for packet rate and error rate was changed to the iperf3 software.

** At the Voith group, two measurement runs were performed for the latency measurement, since an unsteady behavior was identified in the first run. In the second measurement on the following day, the behavior could not be reproduced and the latency times proved to be very stable (as with the other wagon groups).

4.2.1.2 Powerline tests with wagon groups

Table 14: Results Powerline measurements wagon groups

	Voith Wg. 1 … Wg. 3 *	Wabtec Wg. 4 … Wg. 6 **	Dellner Wg. 7 … Wg. 9
Data rate Master -> Slave	6.83 Mbit/s	6.67 Mbit/s	6.67 Mbit/s
Data rate Slave -> Master	1.92 Mbit/s	1.7 Mbit/s	1.7 Mbit/s
Packet rate Master -> Slave	677 fps	142 fps	164 fps
Packet rate Slave -> Master	97 fps	161 fps	176 fps
Error rate Master -> Slave	PER < 10^{-4} (0 % @ 50000 Packets)	PER < 10^{-4} (0,09 % @ 12491 Packets)	PER < 10^{-4} (0 % @ 11204 Packets)
Error rate Slave -> Master	PER <= 10^{-4} (0 % @ 50000 Packets)	PER < 10^{-4} (0.72 % @ 12490 Packets)	PER < 10^{-4} (0 % @ 11619 Packets)

* After the performance tests of the Voith group, plc-tec reconfigured the devices, using a different firmware if necessary. The measurement for packet rate and error rate was changed to the iperf3 software.

** During the test on the Wabtec wagon group, the Powerline modems lost the connection several times. The TTD mechanism had to be started to reconnect the subscribers. The connection losses could not be directly derived from the results for the channel measurements of the Wabtec wagon group. Reconnection was possible without any problems in every case.

Failure scenario measurement:

In the following measurement, the Powerline modem in the center wagon of the wagon group was disconnected from the power supply to simulate a failure scenario after the connection was established; the communication link to the 110 VDC line remained active.

Table 15: Results of Powerline measurements wagon group (failure scenario)

	Voith Wg. 1 … Wg. 3 *	Wabtec Wg. 4 … Wg. 6 **	Dellner Wg. 7 … Wg. 9
Data rate Master -> Slave	4.09 Mbit/s	7.8 Mbit/s	4.37 Mbit/s
Data rate Slave -> Master	1.92 Mbit/s	3.75 Mbit/s	0.94 Mbit/s
Packet rate Master -> Slave	- ***	163 fps (Measurement before communication failure)	167 fps
Packet rate Slave -> Master	- ***	213 fps	160 fps
Error rate Master -> Slave	PER < 10^{-4} (0 % @ 17558 Packets)	PER < 10^{-4} (0.09 % @ 12491 Packets)	PER < 10^{-4} (0 % @ 12491 Packets)
Error rate Slave -> Master	PER <= 10^{-4} (0% @ 50000 Packets)	PER < 10^{-4} (0.72 % @ 12490 Packets)	PER < 10^{-4} (0 % @11619 Packets)

* After the performance tests of the Voith Group, plc-tec reconfigured the devices.

** After the connection of the Powerline modems was terminated, the TTD process was restarted. This resulted in the slave node in the middle wagon no longer being included in the bandwidth allocation and therefore higher data and packet rates were achieved.

*** Measurement results were not usable. It can be assumed on the basis of the data rate that the same results as for the Dellner group are present.

Irregularities:

- When a PL modem failed (Dellner group measurement), the achievable data rate was reduced due to system-related timeout times.

- In the case of the Wabtec group, it can be seen in the failure scenario that the packet rate from the slave to the master was relatively high compared to the measurement in the reverse direction. This is because the packet rate was measured after the system was reinitialized and a slave was detected in this constellation (the slave node in the middle wagon was de-energized due to the failure scenario).

4.2.1.3 Powerline tests with the overall train

The overall train for the Powerline measurements consisted of a total of twelve wagons (Figure 12). The wagon groups stood in a row on one track and were connected with a jumper cable (4 m), which was plugged into the coupling junction boxes. In addition, all electric couplings of the CAF group as well as one electric coupling of the Dellner group had to be bridged, since these had no electrical contact on the 110 VDC line.

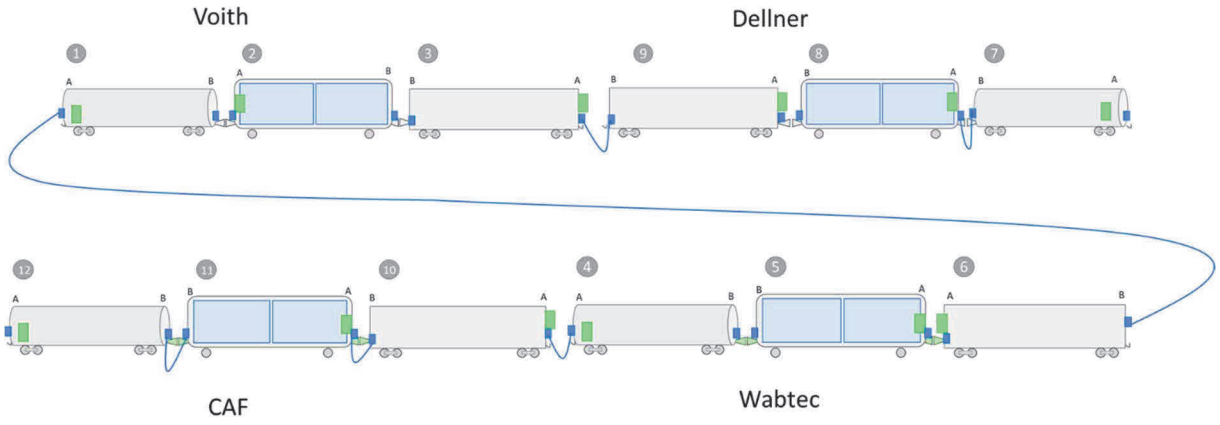


Figure 12: Configuration of the wagon groups for the overall train Powerline measurement

Table 16: Results Powerline measurements overall train

	Wg. 7 (Mst) … Wg. 12 (last Slave Node)
Data rate Master -> Slave	0.993 Mbit/s
Data rate Slave -> Master	0.17 Mbit/s
Packet rate Master -> Slave	160 fps
Packet rate Slave -> Master	16 fps
Error rate Master -> Slave	PER < 10^{-4} (0 % @ 57122 Packets)
Error rate Slave -> Master	Not performed, because packet rate for measurement at << 16 fps very low

Start-up Time*	ca. 48 seconds
Round Trip Time (min, avg, max)	8.3 ms / 42.3 ms / 100.0 ms

* Due to the test setup, the start-up time of the Powerline system was related to the start-up time of the Ethernet switch. However, the Ethernet switch already had a start-up time of approx. 45 - 50 seconds. Therefore, it can be assumed that the start-up time of the Powerline modem is significantly lower.

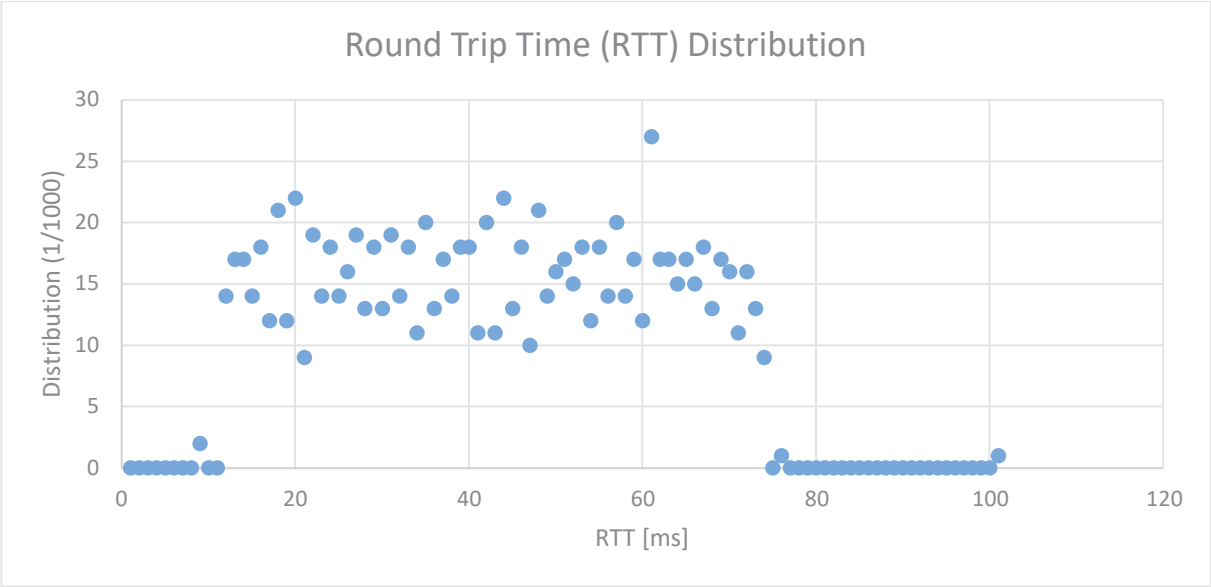


Figure 13: Distribution of latency as round-trip time in the Powerline system

When measuring the latency as round-trip time for the Powerline system, it had to be taken into account that this was a mixed calculation of latency from the master node to the slave nodes and in the opposite direction. Since the master node could transmit to the slave nodes in each communication cycle, a separate evaluation would show the latency from the master node to the slaves to be significantly lower than the average measured times. Considering the physical layer with the measured packet rate of 160 packets/second, the latency from the master node to the last node (11th slave node) would be about 6 ms. The almost uniform distribution of the RTT times is attributable to the fact that the communication system is accessed in an unsynchronized manner with the communication system cycle.

4.2.1.4 Summary measurements Powerline communication

The measurements with the Powerline communication system generally showed very stable communication behavior. Communication could be established and initialized without any problems, even in the "overall train" test configuration. Here, in the tested wagon configuration, the sequence determination also worked without errors. During the measurement of the Wabtec group, three connection interruptions were observed, after which the connection could be restored

by restarting the TTD mechanism. This behavior could not be observed in the tests of the overall train.

An advantage of the system is the relatively constant latency between master node and slave nodes as well as between slave nodes and master node due to the cyclic communication. To gain an advantage from this for an overall system, the application layer must be synchronized with the communication system.

4.2.2 Two-wire communication system (CAN-FD)

For measuring the CAN-FD communication system as two-wire communication, two different data rates were defined in the test plan. It was first tested with the higher data rate, which showed no problems. Therefore, extensive tests with a lower data rate were not performed. Thus, only the results with the higher data rate (250 kBit/s for CAN-FD arbitration, 2 Mbit/s for CAN-FD data) are presented here.

The utilized CAN-FD gateway from IXXAT/HMS (CAN@NET NT 420) supports CAN-FD in principle, but the bit rate switch between arbitration and data part was not accepted by the gateway. The manufacturer could not find a reason for this or has not offered a solution so far. Therefore, the measurements had to be performed with CAN gateways without a bitrate switch. This resulted in comparatively lower packet and data rates compared to the communication between the CAN analyzers.

4.2.2.1 CAN-FD tests wagon-to-wagon connection

With CAN-FD communication, the connections were measured in one direction only. For the CAN-FD communication system, it can be assumed that the results also apply to the reverse direction, since the system is not based on a master-slave principle, but rather with participants always transmitting on an equal basis.

For the wagon-to-wagon measurement, the connection with the CAN analyzers was tested without the involvement of the CAN gateways.

Table 17: Results CAN-FD measurements wagon-to-wagon (250 kBit/s, 2 MBit/s)

	Voith	Wabtec	Dellner
Data rate Zagns -> Hbbins	1.04 Mbit/s	1.04 Mbit/s	1.04 Mbit/s
Data rate Hbbins -> Eanos	1.04 Mbit/s	1.04 Mbit/s	1.04 Mbit/s
Packet rate Zags -> Hbbins	4508 fps	4509 fps	4508 fps
Packet rate Hbbins -> Eanos	4508 fps	4508 fps	4508 fps

Error rate Zagns -> Hbbins	PER < 10^{-6} (0 % @ 510030 Frames)	PER < 10^{-6} (0 % @ 588730 Frames)	PER < 10^{-6} (0 % @ 521770 Frames)
Error rate Hbbins -> Eanos	PER < 10^{-6} (0 % @ 518817 Frames)	PER < 10^{-6} (0 % @ 525906 Frames)	PER < 10^{-6} (0 % @ 517923 Frames)

4.2.2.2 CAN-FD tests with wagon groups

For the wagon group measurements (Table 18), the CAN analyzers were connected to the coupling junction boxes of the outer wagons of the wagon groups. Thus, the measurements were performed with three CAN gateways.

Table 18: Results CAN-FD measurements wagon groups (250kBit/s 2 MBit/s)

	Voith Wg. 1 … Wg. 3	Wabtec Wg. 4 … Wg. 6	Dellner Wg. 7 … Wg. 9
Data rate Zags -> Eanos	0.19 Mbit/s	0.19 Mbit/s	0.19 Mbit/s
Packet rate Zags -> Eanos	1000 fps	1000 fps	1000 fps
RTT Zags -> Eanos	4.37 ms	4.37 ms	4.37 ms

When testing the failure scenario (Table 19), the two-wire line in the wagon box of the middle wagon was bridged. The CAN gateway was no longer connected to the two-wire line here. The measurement was performed with two CAN analyzers (Vector VN1610). The CAN gateways in the Zags and Eanos wagons were active on the two-wire line, but without actively sending CAN FD frames.

Table 19: Results CAN-FD measurements wagon groups in the failure scenario (250kBit/s, 2 MBit/s)

	Voith Wg. 1 … Wg. 3	Wabtec Wg. 4 … Wg. 6	Dellner Wg. 7 … Wg. 9
Data rate Zags -> Eanos	1.04 Mbit/s	1.04 Mbit/s	1.04 Mbit/s
Packet rate Zags -> Eanos	4508 fps	4508 fps	4508 fps
Error rate	PER < 10^{-5} (0 % @ 553326 Frames)	PER < 10^{-5} (0 % @ 546084 Frames)	PER < 10^{-5} (0 % @ 501862 Frames)

4.2.2.3 CAN-FD tests with the overall train

For the measurements of the overall train (Table 20), the CAN analyzers were connected to the coupling junction boxes of the outer wagons of the overall train (Figure 14). Thus, the measurements were performed with twelve CAN gateways. For operational reasons, two wagon groups were on parallel tracks at a time. The tests were performed without bridging the CAF-DAC.

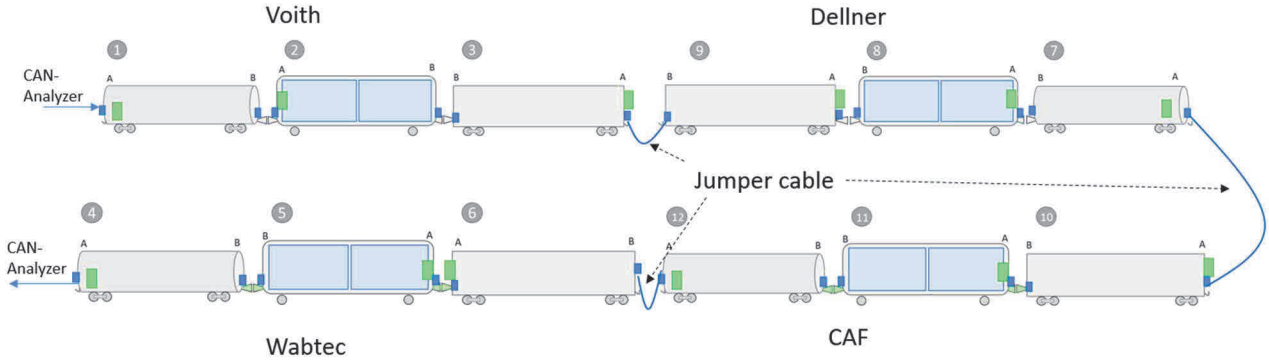


Figure 14: Test configuration overall train for CAN FD measurements

Table 20: Results CAN-FD measurements with the overall train (250kBit/s 2 MBit/s)

	Wg. 1 … Wg. 4
Data rate Zags -> Eanos*	0.19 Mbit/s
Packet rate Zags -> Eanos	1000 fps
RTT Zags -> Eanos	18.38 ms
Start-up Time	ca. 2 seconds
Error rate*	PER < 10^{-4} (0 % @ 104937 Frames)

* The data rate achieved is far below the theoretically achievable value and below the measurement with the CAN-Analyzer (see Table 19). This is due to an error in the CAN FD devices used. The devices do not perform a bit rate switch at the set arbitration data rate of 250 kbps. The achievable data rate is estimated here to be 1.04 Mbit/s, following the measurement with the CAN-Analyzer, since almost the maximum bus load could be achieved with the devices at higher data rates.

** The error rate measurement for CAN-FD in the overall train is not specified in the measurement concept and was performed as an addition. The measurement has only a very limited informative value, since with CAN frames a retransmit of the frames is always performed if no acknowledgement is received from the receiver. In the present segmented system, errors can therefore only be forced

by choosing packet load and measurement period in such a way that the retransmit leads to buffer overflow in the devices due to the high bus load and the absence of packets at the receiver became detectable. Errors could not be forced with this setup. This indicates a very low error rate.

4.2.3 WiFi

The WiFi system is implemented with two WiFi access points each (IEEE 802.11bg), which are routed to the ends of the wagons with antenna cables. In the RF communication concept, it was initially planned to integrate the antennas for RF coupling into the electrical couplings. The necessary installation space and corresponding means for laying an antenna cable were not provided by the coupling manufacturers, so that RF transmission had to be implemented with antennas on the coupling connection boxes. Therefore, there is no direct dependency between the coupling system and the WiFi communication. For this reason, the assignment to the coupler type of the respective wagon group has been omitted in the following illustrations. However, the measurements have been carried out at each coupling point of each wagon connection.

4.2.3.1 WiFi tests wagon-to-wagon connection

Table 21: Results WiFi measurements wagon-to-wagon

	Group 1	Group 2	Group 3
Data rate Zags -> Hbbins Hbbins -> Zags	32.1 Mbit/s 35.9 Mbit/s	28.5 Mbit/s 34.9 Mbit/s	34.6 Mbit/s 36.4 Mbit/s
Data rate Hbbins -> Eanos Eanos -> Hbbins	36.3 Mbit/s 31.2 Mbit/s	32.5 Mbit/s 30.4 Mbit/s	33.4 Mbit/s 32.1 Mbit/s
Packet rate Zags -> Hbbins Hbbins -> Zags	12542 fps 16255 fps	> 12302 fps 5872 fps	5705 fps 12073 fps
Packet rate Hbbins -> Eanos Eanos -> Hbbins	12894 fps > 12465 fps	16042 fps 12572 fps	12073 fps 5534 fps
Error rate Zags <-> Hbbins *	PER < 10^{-6} (0%@1505112 Frames)	PER < 10^{-6} (0%@1403339 Frames)	PER < 10^{-3} (0,02%@441389 Frames)
Error rate Hbbins <-> Eanos *	PER < 10^{-6} (0%@1495887 Frames)	PER < 10^{-6} (0%@1050538 Frames)	PER < 10^{-6} (0%@961271 Frames)
RTT (min, avg, max)	2.2 ms/3.6 ms/37.8 ms	2.2 ms/5.2 ms/66.9 ms	2.2 ms/4.0 ms/58.2 ms

* The error rate was measured in both directions. In the table, the worse value was included in each case.

4.2.3.2 WiFi tests with wagon groups

A significant drop in the data rate can already be observed in the WiFi tests of the wagon groups. This behavior is reinforced in the overall train measurements.

Table 22: Results WiFi measurements wagon group

	Group 1	Group 2	Group 3
Data rate Zags <-> Eanos	15.7 Mbit/s 15.7 Mbit/s	14.6 Mbit/s 17.7 Mbit/s	14.1 Mbit/s 17.8 Mbit/s
Packet rate Zags <-> Eanos	11234 fps 5512 fps	12592 fps 14630 fps	12528 fps 15155 fps
Error rate Zags <-> Eanos	PER < 10^{-4} (0.001%@1495887 Frames)	PER < 10^{-5} (0.0002%@1004454 Frames)	PER < 10^{-6} (0%@1489868 Frames)
RTT (min, avg, max)	4.0 ms/6.1 ms/42.7 ms	4.0 ms/6.2 ms/68.2 ms	4.4 ms/6.5 ms/67.1 ms

4.2.3.3 WiFi tests with the overall train

The wagon configuration for the overall train measurement for the WiFi configuration was identical to the wagon configuration for the Powerline measurements (see Figure 12). The connection was established in a stable manner.

Table 23: Results WiFi measurements overall train

	Wg. 7 … Wg. 12	Wg. 12 … Wg. 7
Data rate	5.38 Mbit/s	2.0 Mbit/s
Packet rate	2972 fps	2332 fps
Error rate	PER < 10^{-5} (0%@214114 Frames)	PER < 10^{-3} (0.064%@142893 Frames)
Start-up Time	ca. 114 seconds	
RTT (min, avg, max)	22.2 ms / 34.6 ms / 193.9 ms	

When measuring the data rate, it should be noted that in one direction the data rate was significantly higher than in the reverse direction. The measurement was repeated and the results were reproducible. The direction-dependent difference cannot be explained.

The significantly reduced data rate compared to the measurement of the wagon groups may also be explained by the increased latency, since the test was performed with TCP packets and the confirmation of the incoming data in combination with the TCP window size can cause such effects. With a UDP measurement, it is assumed that higher data rates are achievable.

The start-up time is very long for the WiFi access point. This may be due to the MOXA-specific mode, in which the access points automatically negotiate the access point/and client mode (ACC - Auto Carriage Connection).

When plotting the RTT, it can be seen that an almost uniform distribution is formed around the mean value. The minimum round-trip time for eleven WiFi transitions is 22.2 ms, from which a minimum latency per transition of about 1 ms can be derived. Since media access is not coordinated in the WiFi system, the temporal distribution of the measurements is plausible. Notable are isolated outliers of more than 100 ms assuming that no test packets were lost during the measurement. This is due to the acknowledge and retransmit mechanism of 802.11b/g.

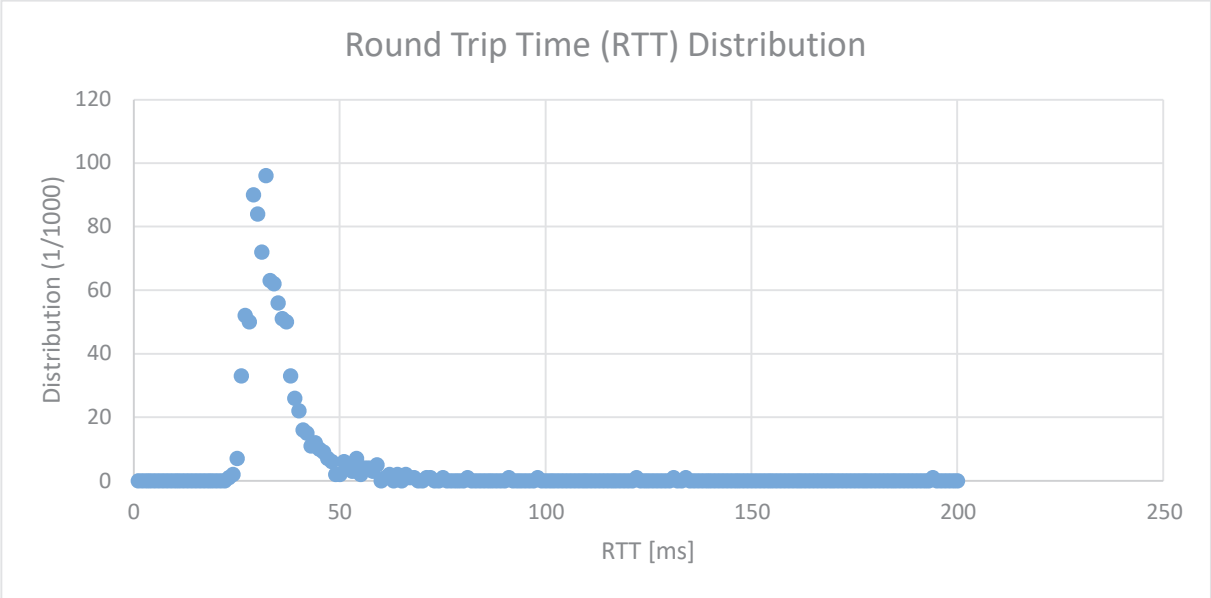


Figure 15: Distribution of RTT in WiFi overall train measurement

4.3 Summary and measurement interpretation

Stable communication was demonstrated for the three communication systems tested, both in the wagon groups and in the overall train. No dependency on the type of coupler could be detected. According to the measurement results in the steady state, all communication systems are therefore suitable for further consideration in Phase II(a).

Table 24: Comparison of the relevant communication system parameters (12 wagons)

	Powerline *End-to-end Session Layer Performance (L5)*	CAN-FD *End-to-End Network Layer Performance (L2/L3)*	WiFi *End-to-end Session Layer Performance (L5)*
Data rate	0.993 Mbit/s (Mst->Slave) 0.17 Mbit/s (Slave->Mst) Total: 2.86 Mbit/s (0.993 Mbit/s + 11*0.17 Mbit/s)	1.04 Mbit/s (Extrapolated from point-to-point measurements *)	2.0 – 5.8 Mbit/s
Packet rate	160 fps (Mst->Slave) 16 fps (Slave->Mst) Total: 336 fps	2600 fps (Extrapolated from point-to-point measurements *)	2332 fps
Error rate	PER < 10^{-4} (0 % @57122 Packets)	PER < 10^{-4} (0 % @104937 Frames)	PER < 10^{-3} (0,064 % @142893 Frames)
Latency (RTT)	min: 6.3 ms avg: 42.2 ms max: 98.0 ms	18.38 ms	min: 22.2 ms avg: 34.6 ms max: 194 ms

* The value from the measurement of the wagon group was used here (see Table 19), since the value measured for the entire train is based on a device error of the CAN FD devices used.

Due to the different structure of the physical layer and the data link layer of the three communication systems, a direct comparison of the measurements with regard to the achievable data rate is not completely permissible. In particular, when comparing CAN-FD and Powerline, it must be taken into account that the Powerline system integrates a TDD (Time Division Duplex) method in which fixed time slots are assigned to the bus nodes. In the CAN FD system, arbitration between the nodes is already solved at the bit transmission layer.

From the measured data of the overall train, approximate performance parameters can be estimated for a train consisting of 50 wagons and one locomotive.

Table 25: Estimation for a train with 50 wagons

	Powerline *End-to-end Session Layer Performance (L5)*	CAN-FD *End-to-End Network Layer Performance (L2/L3)*	WiFi *End-to-end Session Layer Performance (L5)*
Cycle time (50 Wagen)	ca. 25 ms	-	-
Data rate	< 480 kbit/s (UDP, Mst->Slave) < 24 kBit/s (UDP, Slave->Mst) Total: ca. 1.7 Mbit/s	ca. 500 kBit/s*	Inestimable
Packet rate	40 fps (Mst -> Slave) 2 fps (Slave -> Mst)	1300 fps*	Inestimable
Latency (RTT)	25 ms – 300 ms**	75 ms	100 ms – 170 ms**

* Considering a bus load of 50 % on the CAN-FD bus.

** 90th percentile

One advantage of **Powerline communication** is the relatively low latency in the context of a 50 wagon train. The total data rate (master and slave nodes combined) is significantly higher than for the CAN FD system. The communication priority is in the communication direction from the master (traction unit) to the slaves (wagons, locomotive in distributed traction), which is also plausible due to the functional requirements (brake control, traction control if necessary). On the other hand, the packet rate from the slave nodes to the master is very low, but sufficient for status queries every second.

No well-founded estimation is possible for **WiFi communicati**on in terms of data and packet rate, since no linear relationship has emerged from the measured data of the various configurations. The latency/round trip time is high in relation to the other technologies, but is still within the requirements (<< 1 second to reliably fulfill an integrity check).

CAN-FD communication shows a very stable latency with the tested FPGA-based industrial components. Furthermore, the latency of the CAN-FD system could be reduced further if the segmentation is not interrupted at each wagon, but comprises e.g. three wagons. Another advantage is the high packet rate, which is constant and available independent from the system size. Disadvantages of the CAN-FD system consist in the limited data segment, which can transport a maximum of 64 bytes. This makes it difficult to use existing IP-based protocols in the rail sector (ETB, Ethernet train backbone).

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Appendix

Figure 16: Wagon box with components

Figure 17: Wagon box mounted on Zags wagon

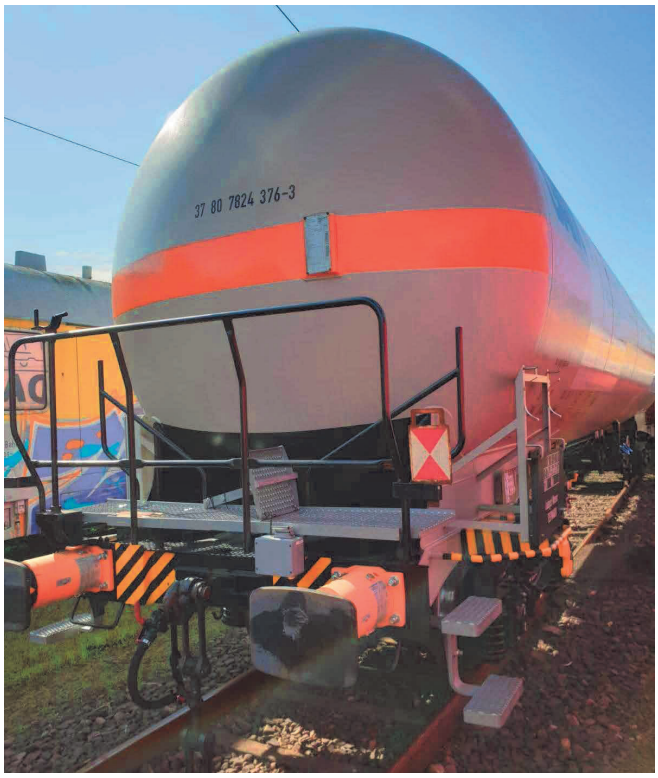

Figure 18: Coupling connection box on Zags wagon screw coupling side

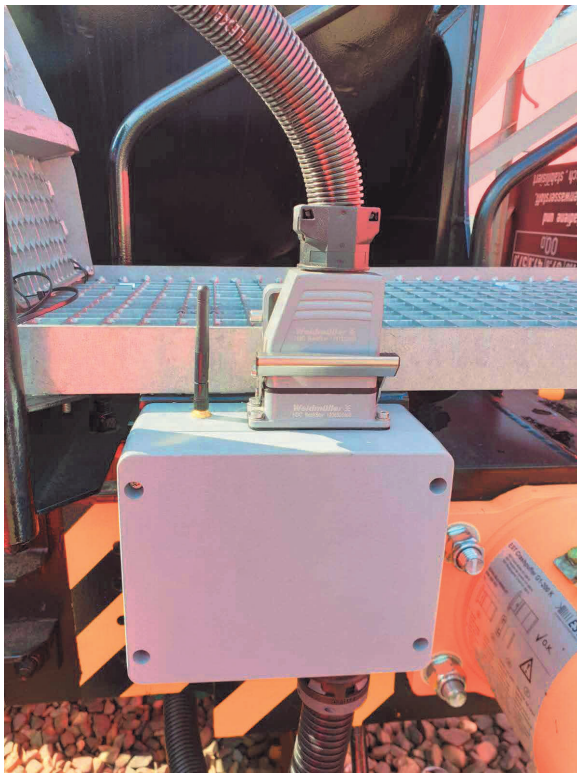

Figure 19: Coupling connection box with jumper cable plugged in