“Development of a concept for the EU-wide migration of a digital automatic coupling system (DAC) for rail freight transportation”

Technical report
“Identification of standards for electrical power/data supply”

for the
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Disclaimer

This technical report uses the generic masculine form to aid readability. Female and other gender identities are expressly included in this context, insofar as this is necessary for the statement.
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Summary

The digital automatic coupling (DAC), in combination with an electrical power and communication system (EaC), provides the foundation for the automation of further functions in rail freight traffic (RFT). The core functions to be implemented are: coupling and decoupling, train setup, the (electro-pneumatic) brake, automatic brake test, train integrity testing, provision of interfaces to telematics systems, integration sensors and actuators (e.g. tail light), and the connection of wagons to mobile radio systems (5G) for the future expansion of communication functionalities. Systems and electronics must be developed to facilitate the introduction of the DAC in the RFT sector. The functions and systems described above must themselves be standardised. This includes the selection and standardisation of technologies, communication protocols and information exchanges for interoperability – as well as the design and standardisation of the electrical power and communication systems, which provide the basis for all other functions. The train’s overall electronic system and its automation functions are conceived as a distributed electronic system. For the individual functions, there are central components in the lead locomotive (master components) and decentralised components in the individual wagons (slave components).

As a limiting condition for the migration, it was decided in consultation with representatives of the RFT sector, that the freight train should retain its indirect pneumatic brake with the main brake pipe as a fallback, and that the system design should be for a train length of 750 m with a maximum of 50 wagons. Longer trains can then be formed by segments which must have a (supplementary) communication channel. The performance parameters of the electrical power and communication systems are geared to the essential core functions and thus based on minimum requirements with low reserves. These parameters are used to derive a basic concept for the electrical power and communication systems. For the locomotives, the system should be designed as an “add on”.

The performance analysis used for designing the power supply system showed that each wagon should be provided with min. 30 W of electrical power. It was also suggested that the power requirements should be specified in relation to the length of the wagons (2.5 W per metre of wagon length). The power supply concept is based on a line running through the train, fed by the locomotive at a voltage of 110 V<sub>DC</sub>. Battery-buffered converters, which provide 24 V<sub>DC</sub> and limit power consumption, are installed in the wagons. A rough preliminary specification was developed to provide a basis for approaching the implementation. Using a power line with a 16 mm<sup>2</sup> cable cross-section and contact resistances of 2x7 mΩ per coupling interface, the system can supply a minimum power output of 2.7 W per metre of wagon length. This is sufficient for system requirements. The power supply is 110 V<sub>DC</sub> with a typical rated current of 25 A. The battery capacity should be 65 Wh to 100 Wh depending on the length of the wagon. This permits two hours of emergency operation (without power supply) if the battery is approx. 30 percent charged. The protection concept (no grounding, voltage-free coupling/decoupling) requires centralised energy management in addition to short-circuit detection.

A net data rate (information rate) of approx. 30 kbit/s is required for the communication system. In addition, there is a technology-dependent overhead, which is a factor of 3 to 20. Latency times should be less than one second. Modern railway communication systems from passenger transport cannot be used without modifications. However, many basic technologies from other industries are well-suited to the task, e.g. from production and process automation.

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1 Workshop events with companies of the Technical Innovation Circle for Rail Freight Transport (TIS), including Deutsche Bahn, Ermewa, GATX, Rail Cargo Austria, SBB Cargo, VTG, Wascosa.
Promising and possible technologies include: a powerline solution that does not require additional communication lines, a short-range radio solution (WiFi) at the coupling point that does not require an electrical contact, and a two-wire communication line (CAN, Ethernet) that creates an separate, additional electrical contact point in the DAC. However, no reliable decisions can be made regarding systems and technology without measurements on the train (availability). A decision was therefore made to evaluate three systems (powerline, radio, CAN) during the test phase.

Rough preliminary specifications were developed to facilitate testing. The approach is based on the creation of a transparent communication system throughout the train (train bus), offering service access points (SAPs) as interfaces to the automation functions. This encapsulates the train bus communication as a system. If the SAPs are defined as the interfaces, the automation functions have transparent access and the functions and their protocols can be developed almost independently. For the train bus, proposals were developed for logical internal addressing, agreements on orientation and the basic approaches for the states of the train bus system. The design approaches are shown for the Powerline PLUS system with a latency of approx. 600 ms and a bit rate > 1 Mbit/s, for a system based on CAN-FD with a latency of approx. 200 ms at a bit rate of approx. 800 kBit/s, and for a WiFi-based radio system in the 2.4 GHz ISM band with a latency of approx. 800 ms at a bit rate of approx. 10 Mbit/s. This creates communication nodes in each wagon which are initialised via the train setup and permit the individual technologies to exchange data in the train, as well as providing SAPs for automation functions in the freight train. The development prototype of the Powerline PLUS system is largely completed, the other systems still have to be implemented.

For the current development and decision-making process, the electrical interface in the DAC will therefore have electrical contact points for the power line as well as a two-wire communication line. It must also be possible to integrate antennas. In this case, the electrical wire pairs are coupled, as no grounding is provided in the freight train. In addition to these contact points, the coupling should also be provided with an EP line (analogous to the “Innovative Freight Wagon” project\(^2\)) for an EP-Light brake system, which integrates individual EP valves into the freight wagons and allows indirect control of the brake via the EP line available in the locomotives.

Meaningful standardisation of both the electrical power and communication systems is only possible once a technology has been defined and its main features validated through testing. Key parameters for the definition of a system and technologies are high system availability (these requirements have not yet been clearly quantified) and the availability of technologies to enable system development to begin immediately. The selection criteria and decision-making processes must be clearly defined. It is recommended that a (European) technology working group be set up to supervise the process, enable decisions to be made and then, if possible, drive the final development of systems and protocols through to standardisation and approval.

Taking this into account, a three-step approach is proposed to define a standard for the electrical power and communication system. Firstly, the DAC and EaC systems must be selected. This decision should also be based on measurements in a test train and take place as part of a coordinated decision-making process. A demonstrator train can then be set up for the selected overall system. This will be equipped with a DAC type and functional models integrated for the EaC system, based on industrially available hardware that incorporates the

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\(^2\) cf. BMVI research project “Construction and Testing of Innovative Freight Wagons” at www.innovativer-gueterwagen.de.
necessary implementations. The result will effectively be a demonstrator and development system for the EaC systems (and the DAC). The objectives of the demonstrator train are firstly to obtain approval for the DAC and, secondly, the development and initial validation of design standards for the EaC systems. This can be achieved with parallel support from the technology working groups. In the third phase, the special components for the EaC systems will be developed by various hardware and software manufacturers – optimised for rail freight transport and ready for approval. These systems should be integrated and tested in a European demonstrator train to ensure interoperability. The standards will be fixed and validated, and the electrical power and communication systems can be approved. Parallel to the draft standard, the automation functions in the train can be developed, tested and approved, once the standard is available.

The standardisation, development and implementation phases will require intensive (European) support with adequate human and financial resources. An interdisciplinary project team of experts (railways, industry, universities, licensing bodies, authorities, etc.) could accelerate this process, help to ensure successful development of the system, and thus lay the foundations for strengthening rail freight transport throughout Europe.
1 Introduction

The study “Development of a concept for the EU-wide migration of a digital automatic coupling system (DAC) for rail freight transportation”, commissioned by the Federal Ministry of Transport and Digital Infrastructure, includes an examination of “energy and data communication systems” for freight trains. This aims to bring together known technologies from the railway and other industrial sectors in order to develop requirements for automation functions in RFT, with particular regard to an electrical power and communication system (EaC) in freight trains, and involves analysis and evaluation of existing technologies and standards. Its objective is to determine the basis for the development of a standard for EaC systems in RFT. The necessary approaches and limiting technological conditions must be compiled and pre-specified, at least to the extent that they can provide the basis for an initial implementation.
2 Basic functions

Chapter 1 describes the functions that are to be implemented in the freight train using the DAC, an electrical power supply in the wagons and data communication throughout the train.

The power supply system is assumed to provide sufficient electrical power in the train’s individual wagons, thus permitting the use of basic electronic systems in the freight wagons. Data communication requires a train communication system (train bus), comprising communication nodes in the individual train vehicles. This communication system enables the electronic systems in the vehicles to exchange data through the train. These two elements lay the foundation for automation functions that are based on electronic systems in the individual wagons and generate efficiency gains in RFT.

The functions – including applications – were discussed and evaluated with representatives from the railway sector during the project. These discussions were based on preliminary work carried out by the TIS within the framework of the study “Energy and data transmission in freight trains; consideration of basic conditions for automation in rail freight traffic, University of Applied Sciences OWL, December 2019” [1].

The applications focus on the core functionalities required for the automation of train formation and separation processes. They also consider technologies for the digitisation of RFT (integrity check for ETCS) and for safety and maintenance functions (diagnostics for wagon condition and loads). These functions form the basis of the EaC system requirements and are explained and presented together with the development constraints in this report.

**Note:** The limiting conditions for the development of individual functions (as here) are highlighted in grey and essentially document the questions that arose during the study and must be considered for the implementation of corresponding system developments.

The following diagram Fig. 1 provides an overview of the core functions described below. The functions presented here are fundamental to the automation of RFT and require interoperable

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3 During the project, the functions were discussed and pre-evaluated in two workshops on 12.09.2019 and 15.10.2019. Further details can be found in Annex 3.
4 TIS (Technical Innovation Circle for Rail Freight Transport; www.tis.ag)
5 To operate on certain lines, ETCS systems from Level 3 and above will have to incorporate train integrity testing devices on board the train in future.
solutions that are standardised throughout Europe and implemented in new system developments. The DAC as a coupling point is an important stepping stone, but not sufficient in itself.

Figure 1: Core functions for the design of the electrical power and communication system

2.1 Train setup

The train setup refers to the initialisation of the communication system of a newly formed train [2]. It establishes the functionality of the communication system for the train’s electronic systems. The train setup is a basic task of the communication system and essentially comprises the logical addressing of the communication nodes in the individual vehicles. It also includes the determination of variable train-specific parameters (wagon sequence, orientation of the wagons, last wagon). This is understood as the creation of an assignment table in which the wagon numbers (globally unique vehicle identification numbers) and the wagon orientations are assigned to the logical addresses in the communication system.

The train setup process is initialised by the leading vehicle (locomotive). At the end of the process, the position of each (intelligent) wagon and its orientation are known, and the logical addressing scheme for the communication system is established. This provides the basis for communication between electronic systems in all the vehicles in the train and enables further cross-system or system-specific initialisation functions to be performed. After the train has been set up, a cyclical exchange of messages ensures that the system is continuously operational. The duration of the train setup process should not exceed a maximum of 120 seconds and must be implemented together with development of the communication system.
Consequence:
The implementation of the communication system will be highly dependent on the technology used. However, to ensure system interoperability, it must first be standardised – similar to other systems (e.g. UIC train bus, ECP).

Limiting conditions for implementation:
The following aspects must be considered for subsequent specifications:

- The wagons require electrical power to perform the train setup, as the communication nodes in the vehicles must be supplied with electricity. Consequently, the power supply must be switched on before the train setup is completed if the power buffers in the wagons themselves are insufficient for the task.
- The vehicle’s communication node must provide access to the wagon number. It must also be simple (and safe) to set the system parameters during installation of the system in the wagons.
- The installation or system properties must make it possible to detect the orientation.
- De-initialisation must be defined to permit detection of failures.

2.2 Automatic brake test

The automatic brake test consists of the initialisation of the brake system and the testing of its functionality for a newly formed train [3]. This process currently consumes considerable time and human resources in train formation facilities or sidings. After the train setup, the automatic brake test can be performed from the leading vehicle. The aim is to ensure that the required braking characteristics are available for the newly formed train. The specifications for controlling the brake are set via the controls operated by the train driver and thus typically via the driver brake valve [4]. It is assumed that the brakes in freight transport will continue to be indirect brakes operated using compressed air. The specific tasks of the brake test include:

- Ensuring that the control variables for the brakes are transmitted to all wagons and lead to the required actions:
  - If the control variable for applying the brake is the lowering of the main brake pipe (MBP) through the driver's brake valve, the brake test must check that the pressure in the MBP is lowered in all vehicles.
  - If the control variable for applying the brake is a communication command or electrical signal, the brake test must check that the control command triggers the correct actuating variables for braking and that the pressure in the MBP is lowered accordingly in all the wagons [3]. This may be specific to the braking system.
  - For a control variable for releasing the brake, the brake test must check that the MBP is filled by increasing the pressure in the MBP up to the given setpoint and within the given time.

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6 ECP (Electronically controlled pneumatic brakes): An electronically controlled braking system for freight trains, mainly used in the USA, based on powerline communication with LON technology.
Ensuring that the mechanical brakes are working (e.g. applying and releasing the brake pads):

- If the pressure in the MBP is lowered, the brake test must check that the mechanical brakes are effective. To do this, sensors inside the wagon are used to diagnose the application of the brake blocks and check whether the conditions are sufficiently fulfilled (e.g. pressure in the brake reservoir).
- When the MBP is filled, sensors check that the mechanical brakes can be released.

**Limiting conditions for implementation:**

- The braking system must have information on the composition of the train (it must be able to address the vehicles). It must be able to “request” this information from the communication system.
- The communication system must be initialised and functional.
- For this functionality, the braking system requires a power supply in the wagons.

### 2.3 Determination of the braking weight

This task is a function of the braking system and determines the braking characteristics of the train. These are currently described by its braking weight, which affects the permissible speed of the train [3]. This function requires information regarding the braking characteristics of the vehicles and their total weight, which may have to be gathered by sensors.

### 2.4 Electrical control of the handbrake

The electrical adjustment of the handbrake is either performed manually on the wagon, by the wagon itself when the operating pressure in the brake reservoir reaches a critical level, or by an external electronic controller. The aim is that the wagon should be braked when in the depressurised state (e.g. during parking).

**Limiting conditions for implementation:**

- Applying and releasing the handbrake requires energy. This could be a serious problem if the electrical power stored in the wagon is not sufficient to apply and release the handbrake. Manual intervention may be required.
- If the brake test involves checking the mechanical operation of the brake pads, it must be possible to release the handbrake before the brake test takes place. If this is not to be carried out for vehicles with applied handbrakes, due to the brake test process, then the handbrake can also be released before the train departs. However, in this case, it is essential to perform an additional check to ensure that the handbrakes of these individual wagons have been released.

### 2.5 Coupling the wagons

Freight wagons are coupled mechanically by rolling or pushing them together with a specified pressure. The DAC includes a mechanical coupling, the MBP coupling and the couplings for the electrical power and communication lines. The coupling status must be visible from the outside and it must be possible to record this status electronically. This is a function of the train integrity system. However, the communication system must also be able to access the coupling status in order to identify the last wagon. During the migration to the DAC, it must be able to
detect whether vehicles without electronic equipment are present in the train. The following coupling status information must be detectable: mechanically coupled, mechanically locked, electrically coupled. The system responsible for collecting and providing this information must be specified.

**Consequence:**

It is proposed that the coupling information should be collected and integrated by the communication system, as this is incorporated into each wagon as a basic system.

### 2.6 Decoupling the wagons (from AC 5)

An electrical power supply is required to automatically decouple the wagons. It must be possible to provide a decoupling signal. Before decoupling, the power supply from the locomotive must be deactivated/disconnected in order to prevent sparking when the contact points are pulled apart. An adequately charged battery is therefore required in the vehicle to enable decoupling.

**Limiting conditions for implementation:**

This function has not yet been implemented but requires a very clear description of the decoupling process. Electronic decoupling must be performed before mechanical decoupling (e.g. at the hump). To do this, the electrical coupling must be disconnected by a motor, which requires an electrical power supply in the wagon. Once the electrical coupling has been disconnected, it must be assumed that no further communication within the train is possible. The train has been disbanded.

### 2.7 Integrity check

Ensuring train integrity is an essential function of the system. The train integrity check ensures that no wagons are missing and no new wagons have been added, the train length is unchanged and the train is coupled.

To enable the train to determine its integrity autonomously in future, a cyclical integrity signal must be exchanged between the last wagon and the leading vehicle [5]. This function requires the following features:

- The last wagon detected during the train setup is used to continuously check that no new wagon has been added. The communication system can provide the information "last wagon" to the leading vehicle.
- The last wagon ensures a cyclical exchange of signals with the locomotive and the authenticity and accuracy of the transmitted signals is secured. The signal itself consists of information suitable for confirming the integrity of the train,
- This signal includes status messages from the last wagon. The cyclical presence of the signal is checked in the leading locomotive.

**Consequence:**

The train integrity must be ensured using a cyclical process in order to run ETCS Level 3 in future. The requirements (cycle times) for the internal integrity check must meet the requirements of ETCS Level 3 [6]. However, this will also result in new requirements regarding the availability of the communication system.
Limiting conditions for implementation:

The system must be based on a continuous medium that can reliably detect a mechanical separation. Possible approaches include:

- **Power line/EP line**
  - An electrical voltage at the end of the train indicates a continuous connection. This information must be communicated.
  - The feed point can be identified by modulating the current flow at the end of the train. The line is continuous.
  - Measuring the transit time of pulses in the line offers a method for continuously checking its length and continuity.

- **Main brake pipe (MBP)**
  - Measuring the transit time of pressure pulses in the MBP offers another method for continuously checking continuity and line length.
  - Cyclical transmission of MBP status data (pressure) can be used to detect continuity.

- **Communication line**
  - This check is carried out via the cyclical transmission of a message containing integrity information (e.g. voltage, MBP pressure at the last wagon, the communication signal itself) between the first and last wagons.
  - To verify functional system safety, it may be necessary to implement a special independent system which has the sole task of cyclically exchanging a secured and authenticatable message with the respective information via the communication system. This independent system should be as simple as possible. The communication system itself would then be used as a “non-secure” transmission channel. The failure of the message or the evaluation of the transmitted information would indicate a loss of train integrity. This means that the communication channel itself does not have to be secure. Security and authentication are achieved by appropriate coding in the transmitted message, similar to communication on the Internet. However, the channel must be extremely reliable in order to achieve high system availability.

2.8 **Tail light**

It should be possible to switch on the light on the last wagon from the leading vehicle [5]. This requires the communication system to provide the orientation and the status “last wagon”. The train integrity system uses this information to switch the train tail light on and off. The train tail light is switched off after de-initialisation of the train or upon the loss of the status “last wagon” due to a new train setup. A separation of the train, a system failure in the communication system, or a system failure in the power supply does not switch off the tail light.

Limiting conditions for implementation:

The situation causing the failure must be clearly defined. In principle, the tail light should remain illuminated as long as the wagon is on the track. However, this drains the battery and may prevent the light from being initialised later, or first require the battery be adequately recharged.
via the power line. The following consequences of this must be considered in the development of the system:

- The tail light must be as energy-efficient as possible.
- If necessary, a separate rechargeable battery system must be integrated for the train tail light.
- It should be possible to implement an emergency lighting mode with lower power consumption.

2.9 Sensors

Depending on their type, the wagons may be equipped with special sensors (e.g. hot box detection, load monitoring). The amount of electrical power available for these tasks depends on the wagon design and other components. The sensor information can be used as the basis for a train diagnostics system and must be transmittable throughout the train.

2.10 Telematics data

Many freight wagons already have separate telematics units. These are completely self-sufficient and therefore only considered in the concept in terms of power consumption. The telematics boxes are only powered if they are supplied by the train's power supply system, otherwise they supply their energy needs via their own batteries.

**Limiting conditions for implementation:**

It is conceivable that an “interface adapter” could be implemented between the wagon and the telematics box. This would make it possible to provide data from the wagon systems via the telematics system or to feed data from the telematics system into the train.

2.11 Other actuators

The category “Other actuators” includes electric drives for opening and closing flaps as well as electrically controlled valves in pneumatically operated final control elements. Electric drives may require high levels of power for a short time. This must be buffered by an on-board battery. It is therefore necessary to select a suitably dimensioned battery, which can provide the required power – even with a small total power supply – without affecting the service life of the battery.

The lighting system also represents a special type of actuator. It is assumed that there will be (manually operated) lighting on some wagons, e.g. on flaps, loading and unloading equipment. This function will need to offer battery powered operation for a limited time (e.g. two hours).
2.12 Connecting the wagon to external communication systems

The wagon must provide an option for establishing a connection to an external communication system.

Figure 2: Connecting the wagons via external communication systems (5G)

Examples considered here include a WLAN-connection to a local infrastructure or a 5G connection between the wagon and a mobile phone network, enabling cloud services to provide in-train communication with a high data rates for special applications (e.g. image transmission) (see Fig. 2). This is important for the energy analysis. In the long term, this system could then be added as a further element to form a basic internal communication system for the train and open up the potential for new, specific and customised functions.
3 System limiting requirements

To derive the energy and communication system requirements from the functions, it is essential to ascertain the limiting conditions for the system. These limiting conditions were also derived and documented in discussions with sector representatives.\(^7\)

3.1 Train length and number of wagons

The train length for the system is limited to 750 m including one locomotive. The number of wagons is limited to a maximum of 50. This allows an EaC system to be introduced for trains up to 750 m in length without having to change the brake controls (no safety function for the brake).\(^9\)

If longer trains are to be operated under these limiting conditions, it is essential to ensure that the pneumatic brake system is capable of braking the train safely. In this case, the system would require a second locomotive which can be controlled via a secure communication channel (not primarily the train bus system). One such second control path could be an approved radio remote control. This topic is not considered in the current project.

As a result, trains longer than 750 m always require a second locomotive in the system to supply power to the wagons and with its own secure communication link to the leading locomotive (see Fig. 3).

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\(^7\) During the project, the limiting conditions were discussed and pre-evaluated in two workshops on 12.09.2019 and 15.10.2019. Further details can be found in Annex 3.

\(^9\) It should be noted that these considerations apply to freight trains with screw couplings and buffers. Additional studies may be required to assess how the DAC alters train dynamics.

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The following explains the limiting conditions in the train regarding the design of the electrical power and communication systems. The freight train will retain the indirect pneumatic brake with the main brake pipe as a fallback. The design limit is therefore set at a train length of 750 m and 50 wagons.

The performance parameters of the EaC are geared towards the core functions (tending to the minimum requirements).

The electrical interface in the DAC includes the coupling for the power line, a two-wire communication line and the EP control line. All coupling points require the coupling of wire pairs (no grounding provided in the freight wagon).

It is important that the EaC offers high system availability (the requirements have not yet been defined) and technology availability to allow immediate development of the system with as few interventions in the locomotive systems as possible.

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Figure 3: Operation of longer trains with multiple traction

Source: Owita GmbH

If a second locomotive is used in the train, it is vital to ensure that the segments between two locomotives are not longer than 750 m and consist of no more than 50 wagons.\(^9\)
This approach provides the basis for the system considerations. Within the scope of this maximum system length in the train, the power supply and communication should at least be sufficient for the defined core functionality. In addition, it should offer a system reserve of at least 30 percent for energy consumption and communication bandwidth.

3.2 Minimum wagon equipment

The EaC system is defined and specified for a minimum level of equipment. The minimum wagon equipment should permit automatic train formation (coupling) and automatic brake testing. Furthermore, the train integrity test should be integrated in each wagon and an EP brake should be possible.

All wagons must therefore be equipped with at least the following functionalities after the migration\textsuperscript{10}:

- Automatic coupling (AC Type 4, AC Type 5).
- Transmission of energy through the train and provision of electrical power\textsuperscript{11} for the wagon.
- Communication through the train (train bus) with:
  - Train setup;
  - Communication functionalities
    - Repeater/routing function for information packets with assurance of data rate and latency requirements.
    - Exchange of data with systems inside the wagon (vehicle bus, system interfaces, ...). Interfaces must be defined for this purpose.
    - Implementation of specified protocols.
- EP brake;
- Automatic brake test;
- Train integrity test.

\textsuperscript{10} The functionalities could all be implemented in electronic hardware or accommodated in electronic systems distributed in the wagon. To aid subsequent standardisation of systems and structural clarity, it is assumed that the functionalities are also separated as electronic systems in the hardware. This makes the view of the interfaces somewhat clearer, although these can also be implemented differently later (via system-internal interfaces in the electronics).

\textsuperscript{11} Other concepts without energy transmission (without power lines, e.g. only using batteries in the wagons) were also considered. These have proven to be impracticable, as will be further explained in Chapter 3.
3.3 **Migration and failure scenarios**

The functionalities of a DAC cannot be fully used in a migration scenario where old and new wagons are connected in the same train, e.g. by coupler wagons or hybrid couplings. If the wagon group directly behind the locomotive has been converted, the functionalities – apart from the integrity check – will be available for this segment of the train. For this, the operating processes and procedures (especially for brake testing) must be redefined.

In addition, the following system failure scenarios must be considered:

**Communication failure**

The loss of communication, either within the whole train or within a segment, must be detected by the locomotive. In case of communication failure:

- The train integrity test may no longer be available,
- The train must remain operational and be able to stop safely.

**Power supply failure**

In the event of a power failure, the overall electrical system with some core functions should remain functional for a minimum period. Current discussions indicate this time will be set at several hours. In this scenario, the functioning of the communication system and the train integrity test should primarily be ensured by on-board batteries. Further functionalities are not planned in this scenario. The indirect braking system via the pneumatic main brake pipe (MBP) is retained as the fallback level for braking the train.

**Braking/Stopping safely**

The indirect pneumatic brake with the MBP as a control line remains available as a fallback level. A functioning MBP is critical for ensuring that wagons without an EaC system can be coupled during the migration period. A later braking system can then be controlled via the communication system, an EP line and also the traditional method of the MBP. The functionality of the braking system must be defined during standardisation.

**Conversion of the locomotives**

During the conversion of locomotives, interventions in safety-relevant system areas should be avoided whenever possible. System designs should be produced for implementation as “AddOn” functions for existing locomotives.

3.4 **Limiting conditions for the electrical systems**

**Grounding of vehicles**

Please note that grounding of the vehicles cannot be guaranteed. This would require very extensive modifications to the wheelsets. Consequently, two contacts are mandatory for a power line.
Communication line

The number of contact points for the communication system should be minimised in the DAC (reliability and complexity of the contact points). For this reason, only a two-wire solution is useful as a line-based communication system.

The minimum segment length, in which the communication system must function safely without repeaters, is set at 100 m. This aspect is relevant for a wired system. The aim of this requirement is to be able to bridge an electronic failure of the communication system in one or more wagons. The longest wagons have a length of approx. 34 m. If the communication nodes are mounted at the end of the wagons, even in the worst case, it will still be possible to bridge one wagon. For typical freight wagons with lengths of 15 m to 25 m, it may be technically possible to bridge as many as two or three wagons in this way.

EP brake

The EP brake has been successfully implemented and tested as an EP-Light solution\(^\text{12}\) in the project “Construction and Testing of Innovative Freight Wagons”. To enable further validation of this in the system, an electrical contact point must be provided for an EP line.

Contact points in the coupling

The maximum number of electrical contact points in the coupling is limited to six – two contacts for electrical power, EP brake and communication respectively. Redundancy or coupling symmetry requirements may, in reality, require more electrical contact points. The number of contact points actually used will depend on the overall system that has been implemented.

3.5 System and technology availability

System availability

The specifications for system availability have not yet been quantified. Digitisation and automation in RFT is generally aimed at increasing system capacity. New system elements should not reduce the availability of the current system. However, new systems also increase the probability of additional failures in the overall system. The issue of availability will require more detailed consideration.

Consequence:

These system availability requirements must be calculated during initial tests (subsequent step) and specified as limiting conditions for series development. Coordination with the railways is required.

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\(^{12}\) The EP-Light solution was developed as part of the project “Construction and Testing of Innovative Freight Wagons”. Its operating principle is based on the installation of EP valves for pressure reduction in the main brake pipe in the individual wagons. These are controlled directly via the EP line.
Technology availability

In addition to system availability, technology availability is a decisive factor in the design process. The aim is not to develop new basic technologies for the EaC system specifically for the railways, but to build on existing and, if possible, proven technologies available on the market. This should enable companies to complete the necessary system developments by ensuring that technologies are accessible from multiple sources (second source).

Consequence:
The focus is on existing standard technologies (no new chips), which can also ensure that the DAC is introduced and the migration completed in the next few years. Nevertheless, communication systems using basic technologies must be developed specifically for applications in the railway sector (e.g. train setup).

3.6 Standardisation

The EaC system must permit the development of systems by various manufacturers. Standardisation of the system is therefore essential. These standardisation requirements address very different facets of the system, as shown in the following Fig. 4:

Figure 4: Fields of activity for standardisation

<table>
<thead>
<tr>
<th>Mechanical (physics)</th>
<th>Structures / Tasks / Operation (Processes / Information)</th>
<th>Model / Structure (Information)</th>
<th>Electrical, mechanical (Physics)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard DAC</td>
<td>Standard functionalities</td>
<td>Standard power and data transmission</td>
<td></td>
</tr>
</tbody>
</table>

Source: Owita GmbH

The coupling mechanism itself must be standardised. The standard must specify the functionalities to be implemented and how the system should be integrated into operational processes and structures. The functionalities to be standardised (braking system, train integrity, ...) are based on an EaC system. Here too, the electrical and mechanical properties must be defined (physical layer), in addition to access and routing procedures in the network. Furthermore, the communication system itself is a functionality, for which information, protocols and interfaces (as for all other functionalities) must be defined.

Consequence:
Standardisation aspects must be addressed as a subsequent step in order to create an interoperable system with open access to technology. An EU-wide standardisation group should be established for this purpose.
4 Basic requirements and basic concept

The estimates for the necessary performance of the energy and communication system are derived from the functional requirements and limiting conditions in the train.

4.1 Power supply specifications

For the power supply system design, the first step is to define the minimum system specifications required to fulfil the core functions. Reserve capacity must also be specified. Functionalities beyond the core functions must either be supplied from the reserve capacity or require another wagon-specific power source (e.g. axle generator, specific battery). Applications that require significantly more power, such as refrigerated containers, must be supplied by other means (e.g. separate lines and connectors). This approach is proposed in order to avoid equipping all types of freight wagons with a possibly over-dimensioned power supply system, which would be more expensive. For example, bulk wagons used to transport coal will certainly not have the same power requirements as freight wagons for the transportation of frozen products. These would require special solutions.

4.1.1 Power requirements

Table 1 shows the estimated power requirements for the individual functions and the necessary implementation elements.

The requirements and a basic concept for the electrical power and communication systems are derived from the core functions and the limiting conditions for their implementation in the train.

The performance analysis showed that each wagon requires at least 30 W of electrical power. Here, it is helpful to specify the power in relation to the length of the wagons (2.5 W per metre of wagon length). The concept is based on a line (16 mm²) running through the train, fed by the locomotive at a voltage of 110 V DC. Battery-buffered converters are installed in the wagons, which provide 24 VDC and limit power consumption.

A net data rate (information rate) of approx. 30 kbit/s is required for the communication system. In addition, there is a technology-dependent overhead, which is a factor of 3 to 20 times higher. Latency times should be less than one second. Today’s railway communication systems cannot be used without modifications. However, many basic technologies from other industries can be considered.

In principle, a powerline solution, a radio solution (WiFi) at the coupling point and a two-wire communication line (CAN, Ethernet) are promising and possible approaches.

No decisions can be made regarding systems and technology without measurements on the train (availability). All three system approaches should therefore be pursued.

The selection criteria for this must be clearly agreed and a (European) technology group set up to supervise the process and drive forward the development of the final system and protocols.
### Table 1: Applications and power requirements per wagon

<table>
<thead>
<tr>
<th>Category</th>
<th>Output</th>
<th>Use profile</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication nodes</td>
<td>2 W active,</td>
<td>Permanent</td>
<td>Train network, Battery</td>
</tr>
<tr>
<td></td>
<td>0.05 W standby</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication interface</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRD radio (optimised)</td>
<td>500 mW</td>
<td>Permanently from train setup,</td>
<td>Train network, Battery</td>
</tr>
<tr>
<td>CAN interface</td>
<td>1 W</td>
<td>Battery operated in case of power</td>
<td></td>
</tr>
<tr>
<td>Powerline PLUS (prototype)</td>
<td>2x12 W</td>
<td>failure</td>
<td></td>
</tr>
<tr>
<td>(HS Luzern, plc-tec AG)</td>
<td>2x4 W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EP-Light brake valve</td>
<td>8 W</td>
<td>Sporadic</td>
<td>Train network, Battery</td>
</tr>
<tr>
<td>Decoupling (mechanical, electrical)</td>
<td>240 W for 5s</td>
<td></td>
<td>Battery</td>
</tr>
<tr>
<td>Diagnostics</td>
<td>8 W</td>
<td>Permanent</td>
<td>Train network</td>
</tr>
<tr>
<td>Telemetry power supply</td>
<td>2 W</td>
<td>Permanent</td>
<td>Train network</td>
</tr>
<tr>
<td>Battery charging</td>
<td>Acc. to design</td>
<td>Mixed</td>
<td>Train network</td>
</tr>
<tr>
<td>Tail light</td>
<td>16 W</td>
<td>Once on the last wagon</td>
<td>Train network, Battery</td>
</tr>
<tr>
<td>Lighting</td>
<td>4 W</td>
<td>Sporadic</td>
<td>Battery</td>
</tr>
</tbody>
</table>

Source: Owita GmbH

The estimates presented in Table 1 are relatively conservative. If the hardware is specifically designed for the application, the power requirements will be slightly lower. The total permanent power requirement per wagon is thus a minimum of approx. 13 W (with CAN interface, without battery charging), although this can increase up to 35 W sporadically, and peak at approx. 280 W for periods of up to five seconds. This peak power must be drawn from the battery and not from the train network.

When designing the power supply and the battery, it must be remembered that charging capacity for the battery must also be provided and this depends on the capacity of the power supply. Charging usually takes place at a rate of ten percent of the battery capacity per hour.\(^\text{13}\) A power supply unit is also required to convert the train network voltage to the wagon network voltage [4]. It can be assumed that the voltage is converted with an efficiency of 90 percent.

In summary, a continuous power output of approx. 20 W should be expected in a minimum scenario. In addition to a reserve of 30 percent and losses during voltage conversion, at least 30 W of continuous power should be provided for each wagon.

---

\(^{13}\) The charging capacity of the battery can vary greatly and is dependent on the technology. With lithium-ion technology, significantly higher charging rates are possible.
Insert: Battery-based power supply system in the wagon:

Another conceivable approach (see electromobility) is to use a power supply based exclusively on batteries. In this case, each freight wagon is supplied autonomously by its own battery. The advantage is that there is no need to over-dimension the entire energy system to supply individual (special) wagons. Furthermore, the rechargeable battery replaces the backup battery during standby. The resulting value related to the energy content of the battery is relevant for this system approach. The limiting conditions must first be defined:

- Energy consumption in standby mode: 100 mW
- Energy consumption during operation: 20 W
- Times of use: 30 percent operation / 70 percent standby
- 500 to 1000 charging cycles over the entire service life with cost-effective utilisation
- The use of LiFePO energy storage technology is assumed.

The designs, costs and weights required for this are estimated for various charging intervals in Table 2. The longer the charging intervals, i.e. the less frequently the battery is charged, the greater the capacity that the battery must provide for operational use. This increases the cost and weight of the battery.

Table 2: General conditions for a pure battery solution as the power supply

<table>
<thead>
<tr>
<th>Charging interval / weeks</th>
<th>Costs / Euro</th>
<th>Weight / kg</th>
<th>Capacity / kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>407,9</td>
<td>10,5</td>
<td>1,0</td>
</tr>
<tr>
<td>4</td>
<td>1631,6</td>
<td>40,8</td>
<td>4,1</td>
</tr>
<tr>
<td>8</td>
<td>3263,2</td>
<td>81,6</td>
<td>8,2</td>
</tr>
<tr>
<td>24</td>
<td>9789,7</td>
<td>244,7</td>
<td>24,5</td>
</tr>
<tr>
<td>52</td>
<td>21211,0</td>
<td>530,3</td>
<td>53,0</td>
</tr>
</tbody>
</table>

Source: Owita GmbH

This table shows that the system costs per wagon and battery weights, quite apart from the additional trackside infrastructure required for battery charging stations, are not appropriate.

4.1.2 System voltage

The selected system voltage must take several aspects and influencing factors into account. These are not only of a technical nature, but also consider the operating process.

Power per wagon

Physically, a high system voltage makes sense because it minimises transmission losses over the long cable in the train. A smaller cable cross-section is also required for transmission due to the lower current at higher voltage. Fig. 5 shows calculations for the possible maximum power consumption of a wagon in the train at different supply voltages and for different numbers of wagons in the train (due to different wagon lengths). The maximum power that can be drawn by each wagon depends on other system parameters, such as the cable cross-section, the contact resistances at the coupling point and the minimum voltage required by each wagon.
This calculation shows that the required 30 W per wagon at a voltage of 110 V\textsuperscript{DC}[7] (and of course also for higher voltages) can be fulfilled even in critical cases (only short wagons in the train) under the conditions of a 750 m train length and a maximum of 50 wagons in the train.

With an input voltage of 110 V\textsuperscript{DC}, the possible power per wagon increases with increasing cable cross-sections. It also becomes larger as the permissible voltage drop to the end of the cable increases, as Table 3 shows.

**Table 3: Available power as a function of the cable cross-section and the voltage at the last wagon at an input voltage of 110 V\textsuperscript{DC}**

<table>
<thead>
<tr>
<th>Cable cross-section</th>
<th>77 V\textsubscript{min,750m}</th>
<th>70 V\textsubscript{min,750m}</th>
<th>66 V\textsubscript{min,750m}</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 mm\textsuperscript{2}</td>
<td>40.7 W</td>
<td>45.7 W</td>
<td>48.0 W</td>
</tr>
<tr>
<td>25 mm\textsuperscript{2}</td>
<td>55.5 W</td>
<td>62.4 W</td>
<td>65.5 W</td>
</tr>
</tbody>
</table>

Source: Owita GmbH
Necessary protection measures

From a technical standpoint, a voltage greater than 120 V\textsubscript{DC} or 60 V\textsubscript{AC}\textsuperscript{14} requires a PE conductor (grounding) in order to implement protective measures. It is not possible to provide grounding as part of the wagon construction, as this is not secured in the wagons (wheelsets). Alternatively, a PE conductor could be routed through the entire train to each wagon. However, this would require at least one additional contact in the coupling and thus a greater probability of failure of the electrical power supply system. Additional technical measures are required to monitor the PE conductor, and these also generate additional costs.

Another important consideration for voltages below 120 V\textsubscript{DC} and 60 V\textsubscript{AC} is that they are not life threatening\textsuperscript{[8]}. Qualified personnel may work on the system even when the voltage is switched on. This could be useful for identifying errors during operation. Work on the systems, regardless of the system voltage, must only be carried out by qualified personnel or by persons trained in electrical engineering. However, the danger to persons if these regulations are disregarded is significantly lower at voltages below 120 V\textsubscript{DC}.

**Consequence:**

In summary, a system voltage of 110 V\textsubscript{DC} is preferred\textsuperscript{15}. This is already an established voltage in railway systems and standards [7] (EN 50155).

The following preliminary specifications/system design will clarify the basic conditions required for the use of this system voltage.

4.1.3 Basic concept for electrical power supply in trains

The electrical power supply is the basis for all the electronic functionalities in the vehicles. Fig. 6 provides an initial overview of the basic concept for the electrical power supply system.

**Figure 6: Basic concept of the electrical power supply**

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\textsuperscript{14} AC would be better for disconnecting plug contacts under load because this reduces sparking.

\textsuperscript{15} The voltage level and power supply design were critically discussed, i.e. some railways envisage a higher power requirement, which could “easily” be achieved by a higher system voltage. The specification of 110 V\textsubscript{DC} is therefore a compromise at this point, which allows a system to be introduced. Technologically, it could be possible to work with higher voltages and thus higher power ratings on the same line (given suitable insulation clearances).
supply available in the respective locomotive, e.g. via the train busbar or an existing generator. The feed system must be designed as an add-on for existing locomotives, as it should not interfere with technical equipment in the locomotive that is relevant for approval processes. The generator system is controlled by an energy manager that can modify parameters (e.g. maximum currents), switch the supply on and off or provide current actual values (current, voltages). For this purpose, the system must be provided with a standardised interface that can then be addressed, e.g. via a control unit.

On the consumption side, every vehicle has a converter with a storage battery and local energy management [9]. This system provides a buffered electrical power supply of 24 V\text{DC} in the vehicle. The system is connected to the power line. Communication between the local energy management units and the energy management on the locomotive is essential for overall energy management in the train. The functionalities and protocols for the power supply system (e.g. individual performance specifications) must also be developed and standardised.

**Consequence:**
The power supply is designed as a minimum system with a voltage of 110 V\text{DC} and a cable cross-section of 16 mm\textsuperscript{2} [1]. Optional installation of cables with a 25 mm\textsuperscript{2} cross-section should be provided for the DAC in order to create additional reserves.

### 4.2 Communication system specifications

The communication system specifications are based on the core functions. It should be noted that – like the power supply system already described – not all applications need to be in continuous operation. A further limitation when calculating the communication requirements is that different communication systems also require different protocol designs and protocol overheads. For example, if IP-specific protocols were used with an Ethernet-based communication system, the overheads would be quite large.

For this reason, this study first determines the net requirement necessary to transfer the information. A protocol-specific overhead that is dependent on the communication system must then be added. To estimate the data rates that must be provided by the communication system, signal assumptions are made for the core functions regarding the information to be exchanged. These signals are only exchanged in an initialisation phase and not considered in the estimates because they do not contribute to the system load during operation. They only affect the duration of the initialisation process. These assumptions are summarised below:

**Communication system:**
The communication system itself will also exchange information as part of its own processes. However, the train setup that determines the order and orientation of the wagons, and the allocation of logical addresses for the vehicles in the train with the transmission of identification data (wagon number), only takes place in the initialisation phase. The operative, cyclical data exchange consists of status data, control information and, if necessary, the coupling status. The estimate for this is shown in Table 4.
Table 4: Information exchange for the communication system

<table>
<thead>
<tr>
<th>Communication system</th>
<th>Bytes</th>
<th>Vehicles (transmitter)</th>
<th>Frequency [1/ s]</th>
<th>Net bit rate [Bit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status / Error message</td>
<td>4</td>
<td>50</td>
<td>1</td>
<td>1600</td>
</tr>
<tr>
<td>Train setup, wagon</td>
<td>40</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Communication node control</td>
<td>8</td>
<td>1</td>
<td>5</td>
<td>320</td>
</tr>
<tr>
<td>Coupling status (both sides)</td>
<td>4</td>
<td>50</td>
<td>1</td>
<td>1600</td>
</tr>
</tbody>
</table>

Source: Owita GmbH

**Power supply system:**

A cyclical exchange of information is required for the implementation of energy management functions and monitoring the power supply system (voltages, currents, etc.). The estimate for this is shown in Table 5.

Table 5: Information exchange for the power supply system

<table>
<thead>
<tr>
<th>Power supply system</th>
<th>Bytes</th>
<th>Vehicles (transmitter)</th>
<th>Frequency [1/ s]</th>
<th>Net bit rate [Bit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage on 110 V&lt;sub&gt;DC&lt;/sub&gt; line</td>
<td>1</td>
<td>50</td>
<td>1</td>
<td>400</td>
</tr>
<tr>
<td>Current measurement for power line</td>
<td>1</td>
<td>50</td>
<td>0,5</td>
<td>200</td>
</tr>
<tr>
<td>Power consumption from the train network</td>
<td>1</td>
<td>50</td>
<td>0,5</td>
<td>200</td>
</tr>
<tr>
<td>Charging capacity of the battery</td>
<td>1</td>
<td>50</td>
<td>0,2</td>
<td>80</td>
</tr>
<tr>
<td>Charge state of the battery</td>
<td>1</td>
<td>50</td>
<td>0,2</td>
<td>80</td>
</tr>
<tr>
<td>Power consumption in the wagon</td>
<td>1</td>
<td>50</td>
<td>0,5</td>
<td>200</td>
</tr>
<tr>
<td>Power system status message</td>
<td>2</td>
<td>50</td>
<td>0,5</td>
<td>400</td>
</tr>
<tr>
<td>Control of energy management</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>32</td>
</tr>
</tbody>
</table>

Source: Owita GmbH

**Braking system:**

As a new function, a communication-based braking system (with automatic brake testing [3]) requires data for controlling the brakes, but also status, diagnostic and sensor data which must be exchanged cyclically (see Table 6).

Table 6: Information exchange for the braking system

<table>
<thead>
<tr>
<th>Braking system</th>
<th>Bytes</th>
<th>Vehicles (transmitter)</th>
<th>Frequency [1/ s]</th>
<th>Net bit rate [Bit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual values MBP pressure</td>
<td>2</td>
<td>50</td>
<td>1</td>
<td>800</td>
</tr>
<tr>
<td>Reservoir pressure</td>
<td>1</td>
<td>50</td>
<td>1</td>
<td>400</td>
</tr>
<tr>
<td>Cylinder pressure</td>
<td>1</td>
<td>50</td>
<td>1</td>
<td>400</td>
</tr>
<tr>
<td>Position / Force of brake linkage</td>
<td>2</td>
<td>50</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Controls (hand brake, brake position, ...)</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td>Sensors for brake discs / brake pads</td>
<td>8</td>
<td>50</td>
<td>1</td>
<td>3200</td>
</tr>
<tr>
<td>Status bits for brake system / error bits</td>
<td>4</td>
<td>50</td>
<td>1</td>
<td>1600</td>
</tr>
<tr>
<td>Target value for brake</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>40</td>
</tr>
</tbody>
</table>

Source: Owita GmbH
Train integrity:

To ensure train integrity, it is assumed that there is a secure, cyclical exchange of information between the last vehicle and the leading locomotive (see Table 7).

Table 7: Information exchange for train integrity

<table>
<thead>
<tr>
<th>Train integrity</th>
<th>Bytes</th>
<th>Vehicles (transmitter)</th>
<th>Frequency [1/s]</th>
<th>Net bit rate [Bit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status data</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>320</td>
</tr>
<tr>
<td>Sensor information</td>
<td>2</td>
<td>2</td>
<td>10</td>
<td>320</td>
</tr>
<tr>
<td>Authentication</td>
<td>6</td>
<td>2</td>
<td>10</td>
<td>960</td>
</tr>
<tr>
<td>Protection</td>
<td>4</td>
<td>2</td>
<td>10</td>
<td>640</td>
</tr>
</tbody>
</table>

Source: Owita GmbH

Wagon diagnostics:

To connect wagon diagnostics or special actuators in the train, it is necessary to exchange sensor data via the train bus. Even if event-based communication is conceivable here later in the realisation, a cyclical exchange is assumed for the purposes of this estimate. Further typical sensor systems are conceivable here (see Table 8):

Table 8: Information exchange for wagon diagnostics

<table>
<thead>
<tr>
<th>Wagon diagnostics / Actuators</th>
<th>Bytes</th>
<th>Vehicles (transmitter)</th>
<th>Frequency [1/s]</th>
<th>Net bit rate [Bit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derailment sensor</td>
<td>2</td>
<td>50</td>
<td>1</td>
<td>800</td>
</tr>
<tr>
<td>Hot box detection</td>
<td>2</td>
<td>50</td>
<td>1</td>
<td>800</td>
</tr>
<tr>
<td>Flat spot detection</td>
<td>2</td>
<td>50</td>
<td>1</td>
<td>800</td>
</tr>
<tr>
<td>Telematic signals (transmission)</td>
<td>3</td>
<td>50</td>
<td>0.5</td>
<td>600</td>
</tr>
<tr>
<td>Switch-on signals</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>Status signals</td>
<td>2</td>
<td>50</td>
<td>1</td>
<td>800</td>
</tr>
</tbody>
</table>

Source: Owita GmbH

Load monitoring

In addition to vehicle data, load monitoring sensors are also conceivable. These are represented here by some typical signals (see Table 9).

Table 9: Information exchange for load monitoring

<table>
<thead>
<tr>
<th>Load monitoring</th>
<th>Bytes</th>
<th>Vehicles (transmitter)</th>
<th>Frequency [1/s]</th>
<th>Net bit rate [Bit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>1</td>
<td>50</td>
<td>1</td>
<td>400</td>
</tr>
<tr>
<td>Gases (EX-protected wagons)</td>
<td>2</td>
<td>50</td>
<td>1</td>
<td>800</td>
</tr>
<tr>
<td>Humidity</td>
<td>2</td>
<td>50</td>
<td>1</td>
<td>800</td>
</tr>
<tr>
<td>Status signals (flaps, lights, ...)</td>
<td>2</td>
<td>50</td>
<td>1</td>
<td>800</td>
</tr>
<tr>
<td>Vibrations</td>
<td>3</td>
<td>50</td>
<td>1</td>
<td>1200</td>
</tr>
</tbody>
</table>

Source: Owita GmbH
Multiple unit operation:
The use of multiple traction units – even if not explicitly stated as a core function – requires the exchange of information between the locomotives involved. A train using four locomotives is considered for the purposes of this estimate (see Table 10).

Table 10: Information exchange for multiple unit operation

<table>
<thead>
<tr>
<th>Multiple unit operation</th>
<th>Bytes</th>
<th>Vehicles (transmitter)</th>
<th>Frequency [1/ s]</th>
<th>Net bit rate [Bit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status / Error message</td>
<td>12</td>
<td>4</td>
<td>5</td>
<td>1920</td>
</tr>
<tr>
<td>Traction control</td>
<td>8</td>
<td>1</td>
<td>5</td>
<td>320</td>
</tr>
<tr>
<td>Security, authentication</td>
<td>12</td>
<td>1</td>
<td>5</td>
<td>480</td>
</tr>
</tbody>
</table>

Source: Owita GmbH

Additional functions:
In addition to these core functions, applications such as live remote control based on video transmissions and many other features are conceivable in the future. However, these functions require a very high level of data exchange. Another communication channel must be provided for this purpose (e.g. mobile 5G communication). These requirements are deliberately not considered here for the communication system (train bus).

Summary – Estimate of required data rate
The consideration of signal requirements for these functions can be used to estimate the minimum data rate per second. A value of 24.4 kbit/s is estimated. With the addition of a reserve capacity of approx. 30 percent – as not all aspects were considered in the estimate – a net data rate of approx. 30 kbit/s appears realistic for the core functionalities.

Furthermore, system-specific overheads due to protocol structures and reserves must be taken into account in order to convert this figure to the physical bit rate actually required on the train bus. Using a CAN system, for example, experience suggests that the bit rate in the communication line may be a factor of three to four times higher than the information rate [10]. A bit rate of 125 kbit/s would thus be sufficient for a CAN system. For IP-based systems, the bit rate may be 10 to 20 times greater than the information rate, since the overhead in the protocol structures is significantly higher in relation to the information. Consequently, a bit rate of 300 kbit/s to 600 Kbit/s should be the goal for IP-based communication systems. These rates are easy to achieve using current technologies.

In addition to the net data rate, latency is also an important factor – especially in the implementation of real time systems. The latency is the time that elapses between the initiation/alteration of a piece of information on the transmitter side and it being received by the receiver. For the core functions considered here, this latency should be less than one second.
4.3 Existing standards for communication systems in the railway sector

The following section provides a brief review of existing standards that are widely used in the railway sector and compares these with the requirements presented above.

- **WTB with RS485 IEC 61375-2-1 (part of the TCN)** [11]: The “classic” Wire Train Bus (WTB) has a data rate of 1 Mbit/s via the UIC cable up to a distance of 860 m (this would be sufficient), but is only designed for up to 32 bus participants. As a result, this would require the modification of a technology that is not used in any other industry.

- **WTB with CAN IEC 61375-3-3 (part of the TCN)** [12]: CAN is already used as a physical layer in railway applications for communication between locomotives and passenger rolling stock. In addition, CAN is established as a communication system within vehicles. IEC 61375-3-3 uses CAN with the CANopen protocol and a corresponding definition for a CAN object dictionary. This maps functionalities that have already been defined and are tailored to passenger traffic. Therefore, only a small part of this standard could be used for these messaging structures. Furthermore, the CAN bus system for the TCN is specified as a continuous line with a total length of 450 m (data rate 125 kbit/s). For a train length of 750 m, a different system design would be required because 125 kbit/s cannot be implemented on a line length of 750 m. Therefore, both a new approach to the system topology and the definition of protocols for a new standard would be required for a CAN system.

- **WTB with Ethernet (part of the TCN)** [13]: The WTB based on 100 Mbit/s Fast Ethernet communication uses redundant lines, i.e. it requires at least eight communication lines and thus eight contact points at each coupling point.

- **ECP system (Powerline)**: This system is primarily used in the USA and operates at 10 kbit/s via a powerline (LON technology). It is designed for an electronic braking system in trains. In its present constellation, it does not meet the requirements.

This means that the technologies available today in the railway sector are not suitable in their current forms. It therefore makes sense to consider new technological approaches that are available and used in other industrial sectors. These can provide the robust, low cost and high availability solutions required for RFT, while creating the best conditions for open access to technology.

4.4 Systems approaches to communication

Fig. 7 classifies the qualities of various communication technologies as a basis for the requirements described above. The technologies under consideration aim to minimise the number of contact points at the interconnection point. The diagram classifies the achievable data rates (x-axis) and the latencies (y-axis) to be expected in the system for various communication technologies. The sizes of the circles represent the system costs.

---

16 TCN: Train Communication Network in IEC61375-1
To be suitable, a future technology must primarily fulfill the technical requirements. Secondary considerations include properties such as robustness, availability and system costs. Essentially, there are many technological approaches that are potentially suitable for the train bus system.

In addition to possible technologies, this study considers three different topological approaches for the communication system. These are briefly explained below.

### 4.4.1 Segmented bus system

A segmented bus system is a system that communicates from wagon to wagon via a line. The messages are forwarded from a communication node in the wagon to the next wagon. The short distances between the wagons mean that this approach can achieve significantly higher data rates than continuous lines through the entire train (see Fig. 8).
Examples of suitable technologies include CAN (Controller Area Network) or CAN-FD (Controller Area Network with Flexible Datarate) and SPE (Single Pair Ethernet) in the 10 Mbit/s variant (IEEE 802.3cg) – both of which operate via a two-wire connection, are well-established in industrial applications and widely available.

A key limiting condition (but also an open question regarding the system) for the realisation of a cable-based, segmented communication system is the reliability of the contacts for data transmission in the coupling. If a communication node (electronics) fails, it may be possible to implement a bridging line so that communication does not fail throughout the entire train.

4.4.2 Segmented system with technology change (radio)

In the segmented system approach with technology change, a separate transmission method is used at the coupling point (preferably a short-range radio system) in order to completely dispense with electrical contacts for communication in the coupling point (see Fig. 9).

The limiting condition for implementation here is the integration of an antenna in the coupling. This is to enable contactless transmission while ensuring sufficient immunity to interference by means of short transmission ranges and, if possible, shielding by the coupling. Suitable wireless technologies include WiFi (IEEE 802.11), Zigbee (IEEE 802.15.4) and Bluetooth (IEEE 802.15.1) or NFC\(^\text{17}\) technology, as the objective is to use available standards. 5G technology is not seen here as the basis for communication within the train, but rather as a future expansion option for connecting individual wagons to a cloud, as described in Chapter 2.

\(^{17}\) NFC: Near field communication
The implementation offers two possibilities:

- The first is to transmit the radio signals from a communication node in the wagon where the radio systems are installed via an antenna cable through the wagon to the antennas in the couplings.

- The second is to install radio systems with antennas directly on the wagon's two couplings. Both these systems at the ends of the wagons then communicate within the wagon via an internal communication line using a suitable technology, such as CAN or Ethernet. This is shown in Fig. 8 above.

The selection of the most suitable approach is primarily based on the cost and robustness of the system. Based on the initial assessment, Option 2 is recommended.

The extent to which the radio interface is subject to interference from external influences remains an open question. In this constellation, it must be noted that the failure of a contact point is accompanied by the failure of the electronics or antennas. The availability provided by this approach must be at least as good as with an electrical contact point. Reliable data on this issue is not currently available.

### 4.4.3 Continuous line (Powerline)

A continuous line is a system in which the line is not interrupted by connections between communication nodes. This can be a communication line, or even the power line. This study examined the Powerline PLUS system, which was developed by the Lucerne University of Applied Sciences and Arts (HSLU) for use in aircraft and is now being adapted for railway applications (see Fig. 10).

**Figure 10: Communication system with a continuous line**

The reliability of contacts in the coupling is the limiting condition for the realisation of the Powerline system. System requirements here pay particular attention to the energy consumption of the communication nodes and the availability of the key technology components (transceivers) on the market.
4.4.4 Basic approaches to train setup

Possible mechanisms for train setup (determining the order and orientation) must be considered with reference to the basic approaches discussed above. Table 11 summarises the known mechanisms.

Table 11: Methods for the implementation of train setup

<table>
<thead>
<tr>
<th>Principle</th>
<th>Powerline</th>
<th>Segmented line</th>
<th>Continuous data line</th>
<th>Radio segmentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance and current measurement (e.g. ECP)</td>
<td>x</td>
<td>(x)</td>
<td>(x)</td>
<td>(x)</td>
</tr>
<tr>
<td>Line separation by relay (e.g. WTB)</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Daisy chain (e.g. Ethernet)</td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Transit time measurement (MBP) (implementation not known)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Transit time measurement, electrical line</td>
<td>x</td>
<td>(x)</td>
<td>(x)</td>
<td>(x)</td>
</tr>
</tbody>
</table>

Source: Owita GmbH

The table clearly shows that not every communication approach is suitable for every train setup procedure. In other words, the development of the system is significantly affected by the technology chosen for the communication system. This will require the development of a specific system for freight trains based on existing communication technology.

4.4.5 Access of functionalities to the communication system

The functionalities (applications) are understood as a distributed system in the train. Functional elements on the leading vehicle (with interfaces to the locomotive) and functional elements on the wagons are necessary to provide the functionality. The functional elements on the leading vehicle are understood as function masters, the elements on the vehicles as function slaves. These functional elements must be able to communicate with each other (distributed over the train). Protocols must be defined for this communication and for each functionality to be implemented in the train.

The exchange of information using protocols between the various elements of a functionality takes place via the communication system (see Fig. 11).
To do this, the functions must be able to access services of the communication system via an interface (a Service Access Point, SAP [14]). To do this, the SAP must be defined as hardware (physical layer) and as an interface (structuring of data transfers). However, the functionalities do not then need to know how the information exchange is implemented via the communication system, and conversely, the communication system does not need to know how the information for the functionality is structured. Overall, the approach can be seen as an SOA (Service Oriented Architecture) approach, which enables transparent communication [15].

4.5 Evaluation and selection of technology

This initial consideration and the required properties did not result in the clear preliminary selection of a specific communication technology. Parameters must therefore be defined in order for this selection to be made. Several core parameters must be fulfilled for the communication technology. In addition, there are secondary parameters that must be considered in the decision. The following section proposes and explains these technical and non-technical criteria in order to assess the electrical power and communication systems. These criteria will be used as a basis for decision-making, especially for the selection of a communication system. The railway sector must therefore achieve a consensus regarding the parameters and quantification.

Consequence:

In a subsequent step, it is necessary to agree the criteria and decision-making metrics for the definition of precisely one communication system with experts from the railway sector.

4.5.1 Parameters for technology assessment

The following parameters should be considered in the decision-making process:

Communication performance:

The following parameters are relevant as performance parameters:

- Bandwidth of the communication system: The bandwidth should at least fulfil the requirements for the application scenarios and include a reserve for future functions. The critical value calculated for the bandwidth was a net data rate of approx. 30 kbit/s without encryption and authentication of the data. Depending on the communication system and the protocols, data rates of 0.6 Mbit/s may well be required.

- Achievable cycle times and latency: The cycle time requirements are not a major challenge for modern communication systems. It should be possible to query the status
of all wagons within ten seconds and transmit events that affect all wagons (brake) to the last wagon within one second.

- **MTU (Maximum Transfer Unit):** This denotes the maximum packet sizes that can be transmitted. The larger the MTU, the greater the flexibility available when designing communication protocols.

- **Time to establish the connection:** Establishing the communication connections in the train is part of the process time included in the train setup. The train setup must be completed within 120 seconds, including the exchange of status information and the registration of wagon order and direction.

**Reliability of communication:**

Apart from the performance criteria, the reliability of the technologies is the most important property of the system. If the performance and reliability criteria are not met, it is not possible to use the communication technology in a meaningful way. The reliability assessment aims to highlight system-specific limitations for the individual communication system variants. These include:

- Stability of the technology,
- External interference,
- Options/costs for redundancy.

**Availability and future viability of the technology:**

On the one hand, the availability of the technology is an expression of the number of manufacturers from whom it can be purchased today. On the other, it reflects the expected time required for the delivery of the technology. If the technology is only available in consumer products, it is assumed to offer a shorter service life. With some technologies, this does not matter since transceivers can also be emulated from passive components (e.g. CAN, RS485) or implementations are freely available as codes.

**Dissemination of technology:**

The dissemination of the technology is both a measure of the duration of its availability and a measure of the available know-how base. The more widespread the technology, the easier it is to find experts and tools for development, maintenance and testing.

**Costs:**

Cost is a decisive factor in the choice of technology. In addition to the initial system installation costs, the expected maintenance costs during the lifetime of the wagons must also be considered.

**Energy requirements:**

Communication systems with a higher energy requirement are generally disadvantageous, as they reduce the reserves available for other systems and charging the batteries.
4.5.2 Assessment procedure

The following core parameters must be fulfilled in the selection of a communication technology system and a system approach:

- The specified data rate and reliability must be achieved.
- Transmission capacity must provide sufficient reserves.
- The technology should be available and not developed specifically for the railways.
- The coupling point should incorporate the minimum possible number of contacts.

Three basic system approaches for a communication system were pre-evaluated and considered expedient based on the criteria: Powerline, a segmented CAN system and a short-range radio system. A two-wire Ethernet solution is also a good option but availability of the technology is currently still critical.

To create an evaluation metric, the criteria are rated according to the degree that they fulfil the requirements (1: very poor, 10: very good). If each criterion is weighted according to its importance, an overall evaluation of the systems can be achieved by multiplying the degree of fulfilment by the importance and then adding the marks (see Fig. 12).

Figure 12: Evaluation of communication systems with initial criteria

Source: Owita GmbH

A final evaluation for the selection of a communication system is not possible at present. There are a number of open questions, especially regarding the reliability of the systems and technologies. These can only be answered by practical testing of the communication systems in combination with the DAC. It is not yet possible to provide meaningful, detailed specifications
for the communication system because a decision regarding the technology is required beforehand.

Consequence:
Specifications for the communication system and protocols will contain technology dependent elements. Until a decision regarding the technology has been made, it is not possible to produce meaningful system specifications and fully implement the communication system. A (European) standardisation group should therefore be set up to supervise the development of systems and technologies. It may be expedient to establish an expert and development group consisting of representatives from industry, railways, universities, licensing bodies and others as an interdisciplinary European team.

Consequence:
Before a final decision is made on the technology and the system concept for the communication system, three communication technology approaches will be pursued and their metrics evaluated. These are explained and detailed below (preliminary specifications).
5 Overview of the overall system

A complete system for automation functions in RFT requires the train to be equipped with a power supply and communication lines. Distributed electronic systems in the train are essential for the automation functions. These require components in the leading locomotive and the wagons. The system outlined in this overview should contain the components relevant for the overall system.

5.1 System components in the locomotive

As the leading vehicle in the train, the locomotive feeds in the power supply and controls communications. The same applies to the control and visualisation of the automation functions, especially when an interface with the driver is needed. This requires the installation of additional components in the locomotive. No modification of safety-relevant systems should take place in the locomotive. This is important for limiting conversion costs and minimising issues relating to approval as far as possible at this stage. The components are presented in Figure 13 and explained below.

Figure 13: System components in the locomotive

The train uses a distributed electronic system. For the individual functions, there are central components on the lead locomotive (master components) and decentralised components in the individual wagons (slave components). Structurally, these can be connected to an internal vehicle bus in the vehicles.

For the locomotives, the system should be designed, as far as possible, as an “add-on”.

Components with different functions can also be implemented as software components on a hardware platform.

Train Communication Master:

This module controls the train bus communication as necessary (train setup, checks, etc.) and provides the link between the locomotive’s internal communication system (which links the additional new system components) and the train communication system. To avoid influencing existing systems, the locomotive’s internal communication system is a vehicle bus system which is separate from the locomotive’s existing communication system.
Train Driver UI (HMI):
This component is the train driver's interface to the new freight train functionalities. It displays the status of the automation systems and allows the train driver to operate them. The primary control options in the first step are as follows:
- Initiation and visualisation of the train setup.
- Disconnection of the train from the power supply.
- Preparation for decoupling.
Control options for further automation functions will be added here at a later date, e.g. the automatic brake test, EP brake controls. Information from the new train diagnostics systems or even train integrity data will also be displayed here.

Internal Communication Bus:
An internal communication bus (vehicle bus) should be provided to connect the individual new system modules in the locomotive. This can be the same communication bus used by the train, or a different technology to ensure a clear separation of the systems. For connecting the visualisation systems, it makes sense to use a technology familiar from automation engineering that can use standard components. The interface between the vehicle bus and the train bus is located in the communication node (Train Communication Master).

Control & Diagnosis:
This module provides the central diagnostics for the entire system. It combines the monitoring and status messages from the individual systems and derives the necessary, higher level consequences of these messages, such as switching the power on or off. It can generate control commands for the individual functionalities and issue warnings to the train driver.

Power Supply & Control:
This module converts the voltage of the power source available in the locomotive (e.g. 1500 V$_{AC}$) to 110 V$_{DC}$ and implements the safety systems for feeding power into the train. The module has a corresponding communication connection to the train bus, which permits the integration of energy management functionalities for the entire train. However, it is also intended that requirements can be passed on here by the Control & Diagnosis module or the operating unit (train driver).

Brake System & Diagnosis:
This module is the master function of the brake system. The first step is always to receive the brake commands via the driver brake valve (DBV) and transfer this information as a control variable to the train bus (if a communication-based indirect EP brake is implemented). In addition, this unit checks the train’s braking system and provides the necessary initialisation and verification. For visualisations and interactions with the train driver, the module accesses the control unit via the vehicle bus. The module is required for two applications:
- Automated brake test: During the automated brake test, the application and release of the brake is monitored and compared with the diagnostic parameters of the wagons.
- Replacement of the EP line: If no separate EP line is installed in the train, the control variable from the driver brake valve must be detected and transmitted to the wagons via the communication system.
To connect a Brake System & Diagnosis module to the locomotive, a conversion to a $110 \text{ V}_\text{DC}$ control signal for an EP-Light system should already be available. In this case, a connection without intervention in safety-relevant systems is conceivable.

**Train Integrity Control:**

This module implements the integrity test functionality (train integrity detection) in the leading locomotive. The system must have the SIL required for ETCS applications [16]. A connection to the locomotive’s ETCS system will be necessary in the future [5].

### 5.2 System components in the wagon

Fig. 14 shows the basic system components required in the wagon. The components can also be fully or partially integrated as software functionalities in individual hardware solutions.

**Power supply system:**

The power supply system is a core component in the wagon and consists of a DC/DC converter, a management unit and a battery. It provides a $24 \text{ V}_\text{DC}$ supply in the wagon and is connected to the central power supply and control unit via the train communication system.

The DC/DC converter converts the $110 \text{ V}_\text{DC}$ power supply in the train network to the internal wagon voltage of $24 \text{ V}_\text{DC}$. The battery comprises the battery storage system including a battery management system (BMS).

**Wagon Communication Node:**

This component provides the physical link to the train’s communication system. This is where the overall communication functionality is implemented. The wagon communication node communicates with the central communication unit in the locomotive.

**Figure 14: System components in the wagon**

Source: Owita GmbH

**Train Integrity:**

This component is responsible for verifying train integrity. During the train setup, it is activated by the information “Last wagon”. It makes sense to construct the component separately from
other parts in order to simplify the approval process (SIL\textsuperscript{18} according to ETCS requirements). The communication system in the wagon and in the train is then used only as an 'non-secure communication channel' to transmit a secured and authenticatable message to the integrity components in the locomotive.

**Tail light:**

A train tail light is located on each side of the wagon and can be switched on from the central control unit in the wagon via a control unit in the locomotive. It is thus a simple further application.

**EP brake light:**

This component contains the functions required by the electrical controls for the brake valve or an automated brake test (sensor technology). Even if the EP brake is controlled by a separate EP brake line, it must still be possible to communicate the information from the required sensors to the locomotive. It must therefore be connected to the communication node.

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\textsuperscript{18} SIL: The safety integrity level describes the level of safety required for a system.
6 Power supply system concept

The previous chapters derived the requirements for the electrical power and communication system. They concluded that preliminary investigations are necessary before a system can be selected (also for the DAC). To do this, corresponding systems must at least be set up as functional models. The following section provides a further elaboration of the general requirements for the power supply system.

6.1 Requirements

The requirements for the power supply resulting from the automation functions for RFT were derived in Chapter 3. Using specially adapted hardware that has been optimised for the specific applications, it is anticipated that the average power requirement will be 30 W per wagon including reserves. The system is buffered by batteries.

The question of the required battery capacity is still open. This battery capacity is determined on the basis of a minimum “bridging time” in which power must be supplied by the battery. In addition, it is necessary to know the average power drawn from the battery. This also includes the frequency of automatic decoupling processes, which require electrical power.

Three different scenarios are relevant for the power supply and the specific system design:

1. A wagon is in the moving train and supplied via the power line. This is the state in which the highest average power consumption from the power line is expected, since the battery is also being recharged in addition to the requirements of electrical consumers.

2. A wagon is in a moving train without a power supply via the power line (power supply fault). The train must be able to continue moving for a defined period in power-saving mode using battery power. As a minimum requirement, the communication system and the train integrity test must be supplied with power. (Duration: several hours)

3. The wagon has no power supply and is standing in a siding or being loaded/unloaded. The wagon must have sufficient power available for decoupling, the handbrake function and supplying relevant systems (e.g. “wake-up” function for the communication system, communication to infrastructure). (Duration: two to three weeks and e.g. ten coupling operations).

6.2 System specifications for the power supply system

The wagon’s on-board power network is designed in such a way that it can only extract power from the train’s power network. The wagons cannot feed power back in. Although batteries could feed power back into the train’s power network to supply important systems for an
extended period in the event of a power failure, it is not considered to be cost-effective in the overall system.

The power supply system should include a power management system with central and decentralised components for the fixed definition of power consumption. The train’s power management is centralised on the leading locomotive and determines how much additional power a wagon is permitted to draw (e.g. to charge batteries faster). This requires a decentralised power management component in the wagon, e.g. as a parameterisable power supply unit. The decentralised power management in the wagon must also be able to switch off individual consumers (or groups of consumers).

To quantify the power available, the train’s power supply requirements are defined below. This affects the cable cross-section, the contact points in the electrical coupler in the couplings, and the transition between the coupling and the wagon. The aim is to define feasible maxima (worst case estimates) over the life cycle.

**Note:** A tool has been developed for the calculation and design of the power supply system. This is explained and presented in Annex 2.

**Electrical properties of the coupling point:**

The electrical resistance must be determined to take account of losses at the coupling point. For this purpose, a structure of the type shown in Figure 15 is considered.

The contact points in the electrical coupler of the coupling are exposed to environmental influences and mechanical loads during the coupling and decoupling processes. The electrical resistance for typical connectors used in railway technology\(^{19}\) over their life cycle (10,000 plugging operations) is given as approximately 4 mΩ. A significantly lower resistance can be assumed for the connection points from the wagon to the coupling. From a technical point of view, it is not essential to use a connector here. A screw connection with a ring shoe could also be used. Consequently, a resistance of 0.8 mΩ per contact point is assumed. The resistances were stated with a safety margin of 20 percent. This means that a maximum resistance of 7 mΩ per wagon and cable direction is expected overall due to connector and screw contacts.

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\(^{19}\) e.g. Harting.
Figure 15: Electrical contact points in the wagon

Source: Owita GmbH

Cable requirements and loss resistance:

A 16 mm² copper cable is provided for the power line in the wagon [1]. This results in a resistance of 1.13 mΩ/m of cable length. Allowing for an additional 20 percent of cable length (for laying the cable), this results in a value of 1.35 mΩ/m of wagon length.

In total, a wagon must therefore fall below the following electrical impedance:

\[ R_{\text{wagon}} = \text{Wagon length} \times 1.35 \text{ mΩ} + 7 \text{ mΩ} \]

System voltage:

The voltage is set at a nominal value of 110 V\text{DC}. The following voltage ranges apply on the supply side (locomotive):

\[ U_{\text{min}} = 110 \text{ V}_{\text{DC}} \]
\[ U_{\text{max}} = 116 \text{ V}_{\text{DC}} \text{ (} U_{\text{min}} + 5\% \) \]

The calculation of the upper voltage limit does not follow the standard EN 50155 with a factor of 1.2 of the nominal voltage – a voltage above 120 V\text{DC} must be avoided at all costs due to the associated need for protective measures [8].

In addition to the defined supply voltage, there is also a voltage drop along the cable in the train. The calculation of the voltage drop is based on the definition of the line impedance and the lower voltage threshold of 77 V\text{DC} in accordance with EN 50155 [7] (factor 0.7 of the nominal voltage) (see Figure 16).
Figure 16: Voltage curve in a train with 50 wagons and a length of 750 m at a maximum possible power consumption of 41 W/wagon

Source: Owita GmbH

**System performance:**

The specifications can be used to calculate the maximum available power for each wagon. If there is no power management system, each wagon is guaranteed this calculated level of power. The power available is standardised according to the length of the wagon. Longer wagons are therefore permitted to draw more power than shorter ones. The maximum power consumption for the wagon is calculated using the LoB\(^{20}\) dimensions: \(P_{\text{max, wagon}} = 2.7\) W/m.

A maximum of 34.1 W may thus be drawn from the power line by the shortest wagon (12.5 m) used in this system design. It therefore meets the requirements.

**Protection concept:**

Grounding of the wagons cannot be provided by changes in the wagon design. In order to ensure equipotential bonding for the wagons despite this restriction, the coupling is electrically connected to the wagon body with low resistance. This connection is independent and electrically isolated from the power transmission. An electrical contact must be made on the couplings when the mechanical part is connected; this can be provided by the mechanical coupling or may require an additional plug contact in the coupling.

**Network design and protective measures in the train network:**

The protective measures required depend on the network standard that is implemented. A safety extra-low voltage network (SELV) is provided with safe separation from the feed network (feed point in the locomotive) (DIN-VDE 0100-7). This system removes the need to ground the wagons. For implementation, however, it is essential to guarantee the upper limit of max. 120 V\(_{\text{DC}}\) in the train network.

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\(^{20}\) LoB = length over buffer
Protective measures at the feed point (locomotive):

In addition to ensuring compliance with the maximum system voltage, equipment for the protection of the line and connectors (fire protection) must also be provided at the feed point. This is particularly relevant to the detection of short circuits in the train network. The resulting short-circuit currents can vary greatly depending on the distance from the feed point. Note the high total resistance for long trains. This means that the maximum currents occurring in the system are low in relation to the operating current. Consequently, it may take a long time before a thermal fuse trips. This makes short-circuit protection particularly difficult, as the magnetic quick trip circuit breaker will not trip if a short circuit occurs at the far end of the power line. Short-circuit currents occurring at the feed point (locomotive) were determined to be 4350 A at the front of the train and 29 A at the end of the train.

If necessary, a short-circuit occurring at the end of the train may be acceptable due to the harmless current level (dimensioning of the plug contacts 70 A, power cable approx. 80 A at 16 mm²) if it is detected and reported by the power system (wagon diagnostics).

6.3 Preliminary specifications for system components

The system design in the wagon and the implementation of the system may vary depending on the coupling and the communication system. Furthermore, the wagon keepers/wagon builders should be given freedom in terms of the technical implementation. For this reason, only mandatory components and their properties are pre-specified in this sub-chapter in order to implement them for required tests.

6.3.1 Preliminary specifications for cables

A power cable is required to connect the couplings. This must be independent of the communication system. The cable with a nominal voltage of 110 V\(_{DC}\) must meet the following requirements:

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire protection</td>
<td>EN 50355:2013 [17]</td>
<td></td>
</tr>
<tr>
<td>Dielectric strength</td>
<td>EN 50155 [7]</td>
<td>1,500 V</td>
</tr>
<tr>
<td>Rules for installation of cabling</td>
<td>DIN EN 50343:2014 [18]</td>
<td></td>
</tr>
</tbody>
</table>

Source: Owita GmbH

All cables must be tested in accordance with EN 50355 [17]. Further standard requirements may apply to wagons with EX protection and when transporting hazardous goods.
6.3.2 Feed system on the leading vehicle

The feed system on the leading vehicle must provide a reliable electrical power supply for all the following vehicles. For this purpose, an appropriate DC chopper must be retrofitted, avoiding changes to the locomotive that may be relevant to the approval process. Modifications should always be made in close consultation with the relevant locomotive manufacturers.

An operator (driver) must be able to control the feed point via an operator interface (HMI). During the coupling and decoupling process, the power supply must be switched off (de-energised coupling and decoupling). Design measures must be implemented to prevent an unintentional restart. System failures should be monitored by diagnostics and shown in a display. Possible detectable faults are:

- Idle, no power;
- Overcurrent, short circuit;
- Implausible current, oscillating, periodic, jumping, interruptions.

All statuses must be clearly and unambiguously displayed on the HMI. A remote call function may be useful (for DAC Type 4) to enable personnel to check the status at any time when operating the coupling manually. Table 13 summarises the electrical pre-specifications for the feed system:

Table 13: Parameters for monitoring the power feed (without power management)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>110 V&lt;sub&gt;DC&lt;/sub&gt; +5%/-0%</td>
</tr>
<tr>
<td>Rated current</td>
<td>&lt; 25 A&lt;sup&gt;21&lt;/sup&gt;</td>
</tr>
<tr>
<td>Timing:</td>
<td></td>
</tr>
<tr>
<td>Switch-off time (rated current ≤10 mA)</td>
<td>1 s</td>
</tr>
<tr>
<td>Switch-on time (≤10 mA → rated current)</td>
<td>1 s</td>
</tr>
<tr>
<td>Maximum current (&lt;5 s)</td>
<td>&lt;sub&gt;IRATED&lt;/sub&gt; x 1.2</td>
</tr>
<tr>
<td>Inrush current</td>
<td>&lt;sub&gt;IRATED&lt;/sub&gt; x 5</td>
</tr>
<tr>
<td>Diagnostic limit values:</td>
<td></td>
</tr>
<tr>
<td>Minimum current</td>
<td>0.1 A</td>
</tr>
<tr>
<td>Maximum current (16 mm&lt;sup&gt;2&lt;/sup&gt; cable)</td>
<td>80 A (5 A/mm&lt;sup&gt;2&lt;/sup&gt;)</td>
</tr>
<tr>
<td>Current carrying capacity of plug contacts at 16 mm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>70 A</td>
</tr>
</tbody>
</table>

Source: Owita GmbH

6.3.3 Energy management

The maximum electrical power that a wagon can draw from the power line has been standardised as a power per metre. If performance monitoring (power monitoring) is implemented for the individual wagons, then a central energy management system in the locomotive can also be used to allocate higher power consumption to individual wagons. Especially in shorter trains, the wagons could be supplied with considerably more power than in a 750 m train. This approach is also illustrated by Figure 5 in Chapter 3. The additional power can be used, e.g. to charge the batteries more quickly or as a short-term power supply to actuators for loading and unloading wagons. Thus, if all wagons are switched to an economy mode, a large consumer could be provided with power in the lower kilowatt range for a short

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<sup>21</sup> The nominal current was calculated with the Excel energy tool (see annex) using the parameters 50 wagons and 750 m train length.
period, e.g. for opening doors and flaps. For this function, it should be noted that the DC/DC converters in the wagons must be designed to handle the higher power.

Monitoring and anomaly detection are required for the implementation of an energy management system. Table 14 presents the variables that must be recorded in the wagon for the power supply diagnostics.

**Table 14: Energy management parameters in the wagon**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage on 110 V&lt;sub&gt;DC&lt;/sub&gt; line</td>
<td>V</td>
<td>10 mV</td>
</tr>
<tr>
<td>Current on 110 V&lt;sub&gt;DC&lt;/sub&gt; line</td>
<td>A</td>
<td>10 mA</td>
</tr>
<tr>
<td>Input current for 110 V&lt;sub&gt;DC&lt;/sub&gt; to 24 V&lt;sub&gt;DC&lt;/sub&gt; power supply</td>
<td>A</td>
<td>1 mA</td>
</tr>
<tr>
<td>Battery capacity</td>
<td>Wh</td>
<td>0.1 Wh</td>
</tr>
<tr>
<td>Charge state of the battery</td>
<td>%</td>
<td>1 %</td>
</tr>
<tr>
<td>Temperature of voltage converter</td>
<td>°C</td>
<td>0.5°C</td>
</tr>
</tbody>
</table>

Source: Owita GmbH

### 6.3.4 System concept and design for the wagon

**DC/DC converter (power supply unit)**

In each wagon, DC/DC voltage converters (power supply units) are used to transform the 110 V<sub>DC</sub> voltage (according to definition 77 V<sub>DC</sub> - 115 V<sub>DC</sub>[7]) in order to supply the wagon systems. It may be possible to use standard technology with railway approval for this purpose (EN 50155). The following general conditions must be taken into account:

- **Inrush current/soft start:** Due to the long cable length and filters in the DC/DC voltage converters, high inrush currents and possible overvoltages will result if the supply voltage is switched on in an uncontrolled manner. A soft start is thus required in the feed module, which allows the voltage to rise slowly and thus prevents current and voltage peaks in the power line. When designing the power-up characteristics, care must be taken to ensure that the current carrying capacity of the plug contacts in the event of a short circuit is maintained.

- **Output power:** The output power of the power supply unit must be parameterisable in order to implement an intelligent energy management system.

- **Interface:** The power supply unit must provide a communication interface for wagon controls, diagnostics and output power control.

- **Power-up procedure:** Before switching on the supply voltage, it must be ensured that the train is fully assembled and the supply voltage may be switched on. The communication system can be included in this process. The exact procedure depends on the design of the coupling and the coupling process.

- **Separation from the train network:** Depending on the design of the coupling, it may be necessary to provide a means of actively separating the power supply unit from the train network. If a mechanical separation of the coupling is detected by the coupling contacts, an immediate separation of the electrical systems from the train network may be useful in order to protect the coupling contacts (prevent arcing with DC currents).
Battery and battery management

DB Systemtechnik has already investigated suitable batteries. The following battery technologies may be suitable, depending on the operating conditions:

- Lead accumulator (already widely used in railway applications);
- Possible alternatives could be provided by some lithium cells (lithium titanate), which allow operating temperatures from -40°C to +70°C.

The use of other battery types may be useful for special temperature ranges (temperatures below -25°C, Class T2 and TX according to EN50155) (extended temperature range for vehicles used in Sweden and Finland).

Battery capacity: A (usable) battery capacity of **60 Wh to 100 Wh** is considered reasonable depending on the length of the wagon. This can vary depending on the characteristics of the systems to be supplied and the basic energy requirements. The recommendation is based on the following limiting conditions:

- A total of 6 W to 10 W are available in a short wagon for charging the battery: As a rule, a battery should be charged at 10 percent of its capacity per hour.
- A wagon with a remaining battery charge of 30 percent should be able to run safely for one to two hours on battery power. For this (emergency) mode, a power consumption of 10 W is assumed. This results in a necessary (usable) capacity of approx. 65 Wh.

Battery management: There must be a battery management system that records the status of the cells in terms of their maximum capacity and current charge state [9]. This system should detect faulty cells. It must be possible to control the charging capacity of the cells.

Interface: A communication interface must be provided to transmit relevant parameters to the wagon control system (cell status, charging status, voltage and current). The charging power must be configurable via the communication interface.

Consequence:

Existing industrial components and technologies may be used for the implementation of the energy system in a functional prototype. However, specific, optimised system developments will be required for an implementation which is approved for the railways. This must be based on the definition of a functional protocol, the validation of the limiting conditions and the pre-specification/final standardisation of the power supply system as the basis for an interoperable system with components from different manufacturers.

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7 Communication system concept

7.1 Basic approach

The communication system in the train can basically be divided into a train bus and a vehicle bus. The approach of structurally separating these systems is already familiar from railway applications in passenger transport under the term TCN (Train Communication Network). To do this, the TCN specifies a number of communication systems for the train bus in different physical layers (IEC 61375) [14] [19].

The aim of the communication system pre-specified here is to define the essential aspects of the train bus and enable the implementation of functional models, especially for essential testing in freight trains with DAC. This requires a communication node in each vehicle as a functional system component of the train bus system.

The automation functions in the freight wagon require functional components to be installed in the wagon and these must be connected to the train bus.

This can be seen in Figure 17. The functional components can be connected to the communication nodes via a separate bus system (vehicle bus) (1). For this purpose, a gateway function (vehicle bus - train bus) must be implemented in the communication node [20]. Alternatively, the connection of the functional components can be completely or partially integrated in the communication node (software module in the communication node) or have an individual interface (2).

For the communication system, three different approaches (powerline, CAN, radio) require further study. These are implemented here as a basic concept and roughly pre-configured for a design. The approach is based on the creation of a transparent train bus communication system, offering service access points (SAPs) as interfaces to the automation functions. This encapsulates the train bus communication as a system. The development of the functions and their protocols can be carried out independently. The various train bus technologies should offer the same interfaces.

For this purpose, proposals are made for logical internal addressing, agreements on orientation and the basic approaches for the states of the train bus system.

The design approaches are shown for the Powerline PLUS system with a latency of approx. 600 ms at a bit rate > 1 Mbit/s, for a system based on CAN-FD with a latency of approx. 200 ms at a bit rate of approx. 800 kbit/s, and for a WiFi-based radio system in the 2.4 GHz ISM band with a latency of approx. 800 ms at a bit rate of approx. 10 Mbit/s.
Investigations into possible physical layers for a communication system have identified three or four different approaches for a train bus. However, a conclusive assessment of these approaches can only be made once they have been evaluated in practice with the new automatic couplings. The communication concept described in this chapter has thus been kept very general as a preliminary specification. It maps the principle of transparent train bus communication to all technology variants, thus keeping it open for future system expansions.

As shown in the description of the core functions, the information exchange will be applicationspecific and have its own data exchange and function protocols. The communication system must transmit the contents of these function protocols transparently through the train. For this purpose, the interface from a functionality to the communication system is implemented as a service access point (SAP) [14]. Each function accesses the train bus system via its own service access point. These access and exchange mechanisms (interfaces) must be defined for the functionalities.

### 7.2 Terms and designations

Each train has a leading vehicle (typically the locomotive) and following vehicles (typically wagons). For train formation and diagnosis, individual (logical) addressing and determination of the main direction of travel for the vehicles are essential. First of all, this requires the following definition for a numbering scheme and the direction of the vehicles in the train.

**Logical addressing**

Logical addressing describes the allocation of sequential addresses for vehicles in a train. The allocation of logical addresses for the vehicles takes place during the train setup [2]. The leading vehicle (forward direction) is allocated the logical address “1”. The logical addresses of the following vehicles continue in sequence starting from the leading vehicle, as shown in Figure 18.
In addition to the logical address, each vehicle has a globally unique identification number – the wagon number (or locomotive number). The wagon number is assigned to the logical address during the train setup. With the help of information provided by this allocation table, the wagons can also be addressed using the unique wagon number.

The logical addresses remain valid for as long as no new vehicles are added to the train or existing vehicles separated from it. If a change is detected (e.g. if additional vehicles are attached), all the allocated addresses become invalid and a new address allocation takes place.

**Orientation**

Each vehicle has an orientation in the train, or a left and right side. The *front* is defined as the end facing the leading vehicle, the *rear* as the end facing away from the leading vehicle. The right and left sides are defined by the direction of view from the *rear* towards the leading vehicle (see Fig. 19, view from above).

**Last wagon**

The logical address (N) of the last wagon corresponds to the number of wagons in the train (if all wagons have a communication node). The last wagon is addressed using the number “N”. In addition to this number, a further logical address (128) is allocated to the last wagon. This makes it easy to establish, e.g. a service for monitoring train integrity.

**Other addressing features**

Broadcast addressing is the term used to describe the simultaneous addressing of all vehicles in the train. For this, a logical broadcast address must be provided. However, it should also be possible to address specific vehicle groups (e.g. all locomotives in the train) together at the same time. This is called multicast addressing and specific multicast addresses must be provided.

**7.3 Logical system states**

Different states and phases can be described for the communication system. Figure 20 shows an initial, rough status structure, which must be implemented for a communication node.
7.3.1 “Off”
This state occurs when there is no electrical power supply in the wagon, i.e. the battery charge level is too low. In this state, all systems in the wagon are switched off and can only be reactivated by switching on the power supply (110 V\text{DC}), which means that the wagon has electrical power again.

7.3.2 “Start up”
“Power on”, a special wake-up event or a special reset event puts the communication node into the “Start up” state. This wake-up event or reset event (e.g. timeout of messages by the communication master) is technology dependent. When the system goes into this state, the communication node is restarted and initialised.

- The communication node assumes the state “not set up”. Its logical address is not initialised.
- The communication node operates in basic mode and reacts only to broadcast addresses. An important function in a segmented communication system is the activation of forwarding for all packets on the train bus. This must be ensured even in this state so that all communication nodes can be reached by the master.
- After a timeout period, the communication node returns to standby mode.
- SAPs are not served in this phase (only the communication system is in operation).

7.3.3 “Train initialisation”
In this phase, it is assumed that all participants on the train bus can be reached. Each wagon is brought from the “Start up” state into the “Initialisation” state by a command from the communication master. The “train initialisation” state provides forwarding of broadcast messages, as in the “start-up” state. The master performs an initialisation (train setup [2]), which requires technology-dependent implementation. After this step, the following states are reached:

- The communication master (in the locomotive) recognises all the vehicles in the train (number, sequence, wagon number, type).
Vehicles have been allocated their logical addresses and know their orientation.

The last wagon in the train – in the communication system – has been determined and it is known whether this is the last wagon in the train.

Vehicles have initialised their SAPs and the communication master knows the services that are supported by the wagons.

After all the wagons have been initialised correctly (successful train setup), the communication master sets the status to “Operation”.

If communication with the communication master fails during this phase, the system will return to the start-up state after a timeout period.

If an initialisation fails for the umpteenth time, the communication node will enter the “Fault” state.

7.3.4 “Operation”

The “Operation” state is reached after successful initialisation (train setup). In this state, the train’s communication system is initialised and can be used by the functionalities:

- The communication master cyclically checks the system’s ability to communicate within the train and performs a self-diagnosis (if necessary, internal forwarding by line switching).
- The communication nodes offer transparent communication via the train bus and serve the SAPs accordingly. They perform their routing tasks for message packets.
- Automation functions in the train (functionalities) can use the communication system.

The following status changes are possible:

- The system changes from the “Operation” state to the “Fault” state when a serious fault occurs, e.g. when packets can no longer be forwarded. The specific implementations and effects are dependent on the technology used. However, important conditions include:
  - Timeout communication: No telegrams are received on the train bus for a period of 15 minutes.
  - Serious (communication) errors.
- The change from the “Operation” state to the “Standby” state takes place in the wagon under the following conditions:
  - The master (on the locomotive) puts the wagons into the “Standby” state.
  - There is a signal that decoupling is imminent (train to be broken up).
  - Possibly due to a combination of timeouts by the electrical power supply and communication monitoring: The power supply via the train network (110 V<sub>DC</sub>) is interrupted for a time and communication is interrupted (locomotive experienced a hard disconnect from the train). For this purpose, the power supply system in the wagon must give a signal that can be read by the communication node.

7.3.5 “Standby”/“Power Save”

In the “Standby” state, the train bus system is not active. However, other systems may continue to be supplied with power in this state, depending on their type and requirements.
7.3.6 “Fault” state

The effect of entering the “Fault” state must be highly dependent on the technology. Key aspects are:

- The communication master on the leading locomotive must be informed of the situation as far as possible.
- If possible, the integrity system at the end of the train must be informed about the situation.
- If possible, a second communication channel must be used (bridging the faulty wagon).
- The systems in the wagon can no longer communicate.

7.4 Communication architecture

An SOA (Service Oriented Architecture [15]) is used as the communication architecture in order to decouple the applications from each other and from the underlying communication system. It provides a way to avoid monolithic hardware and program structures, thus promoting an open architecture and creating the basis for long-term compatibility.

Figure 21: Connection of the SAPs via a physical channel

Source: Owita GmbH

Fig. 21 illustrates this basic approach for one application (distributed function): the application is connected to the communication system via an SAP. Every vehicle that includes components for this function makes this corresponding SAP available via the communication system node.

The communication system provides the application with containers that have a specific data width (MTU: maximal data unit or payload) for the exchange of data packets, which are then forwarded in the network. The application can fill the containers with data content as required – and thus implement specific function protocols. The content of the application data is not relevant for the communication system. The necessary structuring elements for the communication system are shown in Figure 22.
Further explanations and requirements for these elements are provided below.

### 7.4.1 Physical layer and MAC layer

The physical layer determines how a data signal carrying information is physically implemented and transmitted. It also defines the transmission medium (e.g. cable) and the connection to the medium (e.g. connector). In this context, the physical layer, together with the MAC layer, can be considered the lowest layer of the communication system. The MAC layer describes the structuring of the data signal as a frame and defines the addressing and access procedures to the medium. These two elements are defined for each communication technology (CAN, Ethernet, WLAN, ...) and they are different. The following aspects must be considered as a consequence of the physical layer of a technology for the train bus:

- **Transmission of addressed data packets**: A packet with data and a destination address is transferred to the technology. The destination address is a hardware address in the technology that need not be identical with the logically assigned address (see Chapter 7.2, Logical addressing).

- **Transmission of broadcast data packets**: A packet with data and a destination address is transferred to the technology. The destination address is a hardware broadcast address that need not be identical with the logical address.

- **Receipt of addressed packets**: Packets with their own hardware address are received and forwarded to the higher layers. This includes packets with a hardware broadcast address.

### 7.4.2 Network layer

The network layer forwards data packets in a network. The network layer decides how to handle packets. Packets arriving on the communication line are either forwarded or, if addressed to themselves, only forwarded internally to the components in the vehicle.

*Note: IP technologies (or switch\textsuperscript{23} technologies) can be used with radio communication using WIFI, Powerline PLUS or a two-wire Ethernet solution. A specific train bus solution must be implemented for CAN-FD.*

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\textsuperscript{23} Switches are used in Ethernet-based networks to enable data frames to be forwarded within a network (one address range). On the network level, there are actually routers (IP) that forward packets between networks. Here, for technical reasons, it is
7.4.3 Fragmentation layer

The fragmentation layer is an optional layer and does not have to be implemented by every communication system. The task of the fragmentation layer is to separate data packets from the application into sub-packets, send them individually and merge them again on the receiving side, if the maximum transfer unit (MTU) of the communication system is smaller than the packet sizes guaranteed for the functions.

*Note: For radio communication with WiFi, with Powerline PLUS or a two-wire Ethernet solution, it is assumed that the MTU of 1500 bytes is sufficient for the functions to communicate. A fragmentation layer may be necessary for CAN-FD communication due to the MTU of 64 bytes.*

7.4.4 Transport and authentication layer

The transport layer enables data to be exchanged between applications belonging to different communication participants – as a quasi point-to-point connection in the network. It is the intermediary for the transmission of packets to the service access point (SAP) layer in the direction of the application and to the network layer or fragmentation layer, if applicable, in the direction of the transmission system.

An important aspect of this layer is its capacity for integrating data authentication and encryption. The authentication of data, in particular, could play an important role in ensuring operational safety (e.g. train integrity) and should be considered. The intended approach for data authentication is a PKI (Public Key Infrastructure) solution. However, appropriate mechanisms for this purpose still need to be worked out.

*Note: If the network layer uses IP-based communication technologies, this layer would be secured by TCP or UDP protocols. There is also an optional protocol for ensuring the authenticity of the data (TLS). For CAN or CAN-FD, a separate protocol must be specified or adapted for this purpose. Figure 23 shows one such approach.*

![Figure 23: Protocol-specific frame structure for CAN-FD with authentication](image)

Source: Owita GmbH

When using CAN-FD, the application layer is provided a maximum payload (MTU) of 38 bytes, which can be transmitted in one frame. Larger quantities of data can be transmitted in several frames by implementing fragmentation.

7.4.5 Service access point layer

In the service access point layer, a separate SAP is defined for each service (each functionality that is used by the communication system). Depending on the service identity, incoming packets are forwarded from the train bus to the responsible SAP. The SAP can also handle the packet in different ways for different functionalities. The packet can be fed directly to an application in the service application layer (internal data exchange if the application is implemented as a software module in the communication node), it can be routed to a special interface (e.g. serial interface), or it can be prepared for a vehicle bus system if the application

assumed that exactly one such network exists within a train and that switch technologies can therefore be used for packet forwarding.
is implemented in an external component. In the latter case, the SAP functions as a gateway to the wagon's internal vehicle bus.

### 7.4.6 Service application layer

The service application layer maps the functionalities (the individual automation applications in the freight train). One of these functionalities is the communication system itself, which fulfills certain tasks such as the train setup or the provision of status information to the communication system, etc.

### 7.4.7 Logical addresses

During the train setup, the communication system allocates the addresses of the communication nodes (one in each vehicle) in ascending order starting from the front of the train [2]. The allocation process is controlled by SAP "Communication" and the logical address is forwarded to the network layer. Table 15 shows a proposal for this. The leading vehicle usually allocates the addresses and gives itself the address “1”. The address “0” is not allocated and represents the “non-initialised state”. The last vehicle in the train is also allocated the address 128. The vehicles are addressed via this logical address in the train. In addition, all vehicles can be addressed via the broadcast address 255. Multicast addresses are also assigned for special groups. Address 251 is used to address all wagons, and 252 to address all powered vehicles. Vehicles that have not been initialised can be addressed via the address 253.

**Table 15: Logical addresses in the train**

<table>
<thead>
<tr>
<th>Address</th>
<th>Target vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Leading vehicle</td>
</tr>
<tr>
<td>2 - 120</td>
<td>Regular vehicles</td>
</tr>
<tr>
<td>121-127</td>
<td>Free</td>
</tr>
<tr>
<td>128</td>
<td>Last vehicle</td>
</tr>
<tr>
<td>129-250</td>
<td>Free</td>
</tr>
<tr>
<td>251 (multicast)</td>
<td>All wagons</td>
</tr>
<tr>
<td>252 (multicast)</td>
<td>All powered vehicles</td>
</tr>
<tr>
<td>253 (multicast)</td>
<td>Non-initialised vehicles</td>
</tr>
<tr>
<td>254</td>
<td>Free</td>
</tr>
<tr>
<td>255</td>
<td>Broadcast: All vehicles</td>
</tr>
</tbody>
</table>

Source: Owita GmbH

### 7.4.8 Function addresses for SAPs

A dedicated service number is assigned to each SAP (service access point). However, the implementation of the service number in the protocol may differ depending on the communication system. For the CAN-based system, a byte is provided for addressing the SAP. Table 16 shows a proposal for this.
### Table 16: Addressing SAPs

<table>
<thead>
<tr>
<th>SAP Index</th>
<th>Function / System</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Communication</td>
</tr>
<tr>
<td>2</td>
<td>Energy</td>
</tr>
<tr>
<td>3</td>
<td>Coupling</td>
</tr>
<tr>
<td>4</td>
<td>Brakes</td>
</tr>
<tr>
<td>5</td>
<td>Train integrity</td>
</tr>
<tr>
<td>6</td>
<td>Drive</td>
</tr>
<tr>
<td>7</td>
<td>Diagnostics</td>
</tr>
<tr>
<td>8</td>
<td>End of train</td>
</tr>
<tr>
<td>9-99</td>
<td>Reserved</td>
</tr>
<tr>
<td>100-199</td>
<td>Wagon-specific sensors/actuators</td>
</tr>
<tr>
<td>255</td>
<td>Test system</td>
</tr>
</tbody>
</table>

Source: Owita GmbH

### 7.5 Power line system concept

The power line system is based on communication via the continuous power line. The Powerline PLUS system, currently under development, was selected as the system for this purpose. In power line transmission, the data packets to be transmitted are modulated onto the power line. This bandpass transmission requires a certain frequency range, which is characterised by a bandwidth and a centre frequency. The high-frequency signals are attenuated in the line, so repeaters (devices to refresh the signal) must be provided on long lines.

#### 7.5.1 Detailing the system structure and topology

In this system, the communication node on the locomotive is known as the communication master (M). The communication nodes in the wagons are the communication slaves (S). To bridge a train length of 750 m (including the locomotive), some slaves are assigned the function of repeaters (relay slaves/relay nodes) during the initialisation process. These then forward the frames (packets on the physical layer). Data packets for the corresponding wagon are forwarded to the wagon-internal communication systems (Figure 24, grey boxes).

To determine the direction of the wagon, two communication nodes are required – each in the vicinity of the coupling (Figure 24). The powerline modems, as interfaces between the communication nodes and the power line, are capacitively coupled to the power line. To avoid additional reflections on the line, it is recommended not to let the spur line in a wagon junction box – used to connect the 110 V_{DC} power supply and the powerline modem – become too long.

The modem can either use a separate power supply unit or the 24 V_{DC} supply in the vehicles.
Bus access itself is controlled by the master in the locomotive. Thus a master-slave communication control is provided, which is used as Time Division Duplex process (TDD [21]). This is shown in Figure 25: The master sends a message (ping message), which spreads over the train’s entire power supply system. Due to the signal attenuation in the train, the message’s range is limited and must be repeated by relay slaves in the same frequency range. At the end of the train, the last slave then reflects the message back to the master (pong message). After receiving the message from the master, the addressed participant (slave) replies with the corresponding response data. Here, the communication can be divided into communication cycles. In one cycle, the master queries all the slaves at least once. A different order or prioritisation of certain slaves would also be possible. Consequently, the time for a communication cycle has a linear relationship with the number of slaves, and thus the number of wagons, in the train. The Lucerne University of Applied Sciences and Arts (HSLU) specifies a time (cycle time/round duration) of 700 milliseconds for 50 wagons and 100 slaves (nodes). The master, on the other hand, has the option of sending information, e.g. a command to all slaves, with each ping message. Thus, the latency in this case is only approx. 15 milliseconds with the same number of wagons or slaves.

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24 The Powerline PLUS system is being developed by plc-tec AG in cooperation with Lucerne University of Applied Sciences and Arts, SBB Cargo and German system suppliers.
Figure 26: Latency for communication from slaves to the master

Source: plc-tec AG / HS Lucerne

Figure 27: Latency for communication from the master to slaves

Source: plc-tec AG / HS Lucerne
7.6 Segmented CAN system concept

The communication node for a segmented CAN network is located directly in the communication line (CAN-H, CAN-L) between the two couplings. A single-shielded twisted pair cable with a 0.75 mm² wire cross-section should be used as the cable type.

Note regarding CAN bus cable: According to DIN 61375-2-1, cables with a cross-section of 0.75 mm² (AWG 18) should be used for CAN communication [11]. For cable transitions (D-Sub connectors), cross-sections smaller than 0.56 mm² should be used.

The basic structure of a communication node (not a redundant design) is shown in Figure 28. The communication node is connected to its neighbouring wagons in each direction via a CAN line. Message forwarding, the connection to the SAPs and the functionalities of the communication node must be implemented as software. Each system can transmit independently, cyclically or on demand. If a communication node fails, the line in the wagon can be bridged by a relay so the following wagons remain connected to the train bus system. To do this, it is also necessary to be able to switch off the terminating resistors. In its default state, the system should operate as a segmented bus system.

Figure 28: Internal structure of a CAN communication gateway

7.6.1 Technology parameters and system definitions

CAN-FD technology should be used to permit the transportation of a larger number of application and protocol-specific data in one frame.

The bit rate between two vehicles is set at 500 kbit/s. At this bit rate, CAN is capable of bridging a distance of 125 m [20] [22]. This allows it to bridge a long wagon without reducing the data rate even in Fault mode or during the migration process.
7.6.2 Functional description of communication nodes

7.6.2.1 “Start up” state

In the “Start up” state, the CAN system actively interrupts the transmission between the lines and the terminating resistors are switched on. All CAN frames, regardless of the direction of reception, are transmitted/reflected back in the other direction (hub method). Similarly, broadcast packets (protocol-specific addressing) are forwarded to the internal communication layers.

7.6.2.2 “Initialisation” state

In the “Initialisation” state, the communication master (locomotive) uses the protocol agreements for the “communication system” application to address the wagons in the train via the communication SAP, together with the exchange of the necessary initialisation information (wagon number). After being successfully addressed, the wagon can be reached via the allocated logical address. Only when the addressing procedure has been completed does the communication master switch the communication into “Operation” mode.

Specific information for the other systems can also be queried within the wagon via the SAP of the communication system. This consists of:

- Logical addresses in the train;
- Orientation in the train;
- Own wagon number;
- Communication system status.

This query mechanism (protocol structure) must be defined in detail. In addition, further information can also be requested from the communication system master. This is particularly important for the masters of the other automation functions in freight traffic, which are also found on the locomotive:

- Wagon number list / Logical addresses
- Number of wagons.

7.6.2.3 “Operation” state

In the “Operation” state, the network layer of the communication system works as intended and forwards messages according to their addresses. This means that logical/physical addresses of the wagons are stored based on the direction, and frames are only forwarded in the direction of the destination addresses. This is necessary to relieve the bus and send the data in a targeted manner.

7.6.2.4 “Fault” state

The “Fault” state is reached when the communication node in the wagon does not receive any frames for a defined period of time. If, on the other hand, a large number of CAN errors are detected, the system should switch to an emergency mode in which only high priority frames are transmitted (integrity check).
7.6.3 Performance parameters

When using CAN-FD, the data field in the CAN frame is transmitted at approx. 5 Mbit/s [23]. Thus, with a nominal bit rate of 500 kbit/s in the CAN bus, a net-user data rate of up to approx. 1 Mbit/s is possible. Due to the segmented system, frames must be completely received and retransmitted by each wagon. The latency per wagon is assumed to be a maximum of 2 ms. Assuming a train of 50 wagons, this results in a round trip time (RTT) of approx. 200 ms.

If the CAN transceivers are permanently active, the connection is established very quickly. The initialisation time for a train with 50 wagons is assumed to be less than ten seconds.

7.7 Radio system concept

Like the CAN system, the (short-range) radio system is a segmented communication system. The antennas for the radio connection are positioned between the wagons in the coupling heads where the electrical contacts are installed. This is because the radio channel is very well shielded here. Thus, the system can be interpreted as a quasi near-field communication solution with a point-to-point connection. In contrast to CAN, the system design does not offer the possibility of bridging a wagon in the event of a fault (unless the radio system is designed to be completely redundant). For this reason, the availability of the radio interface must be comparable to the availability of the electrical contacts in the CAN and powerline system.

Figure 29: Wagon-to-wagon radio system as a train communication system

Source: Owita GmbH

The radio transceiver that generates the radio signal can either be installed directly near the coupling or centrally in a wagon box.

If the radio transceivers are centrally located in a wagon box (Wagon 2 in Fig. 29), they are directly connected to the communication node in the wagon and the radio signal is routed to the respective antenna in the couplings via a high frequency line.

Note: No functional, normative regulations were found for the use of antenna cables in RFT applications. For this reason, an RG213 cable is recommended, especially when using frequencies up to 3 GHz [24]. The attenuation should be less than 15 dB at a length of 30 m and with a nominal signal frequency of 2400 MHz. The characteristic impedance should be 50 Ω.

If the transceiver is installed near the coupling, there must be an internal communication connection between the transceivers (Wagon 4 in Figure 29), or between the radio transceivers and the communication node in the wagon. An Ethernet connection is proposed for this purpose, as shown in Figure 29.

Note: Cables with 2x2 twisted pair wires (Cat 5e) must be used for Ethernet connections. The cross-section is usually 0.5 mm² [25].

7.7.1 Technology parameters and system definitions

The selection of a suitable radio system was based on the following requirements:
Dissemination of technology,
Availability of the technology,
Costs,
Applicability in railway technology,
Robustness of the technology,
Performance of the technology.

Bluetooth, Zigbee, NFC or WiFi technologies all offer possible approaches here. When all the requirements are considered, IEEE 802.11 technologies (WiFi) emerge as the best candidate. The only critical issue under discussion is the compatibility of current and future standards – this applies to all wireless technologies whose main field of application is the consumer market. However, as WiFi technology is now widely used in industrial applications, it is expected that compatible hardware will still be available in 20 years. WiFi has therefore been selected as the system for the radio-based communication link between the wagons in the trial (standards b/g).

*Note: This approach can be transferred directly (with very few modifications) to a two-wire Ethernet system, using an electrical contact point in the same way as for the CAN system.*

The focus continues to be on the 2.4 GHz ISM band. Many chipset suppliers operate in this area and the costs are very low. Thus, an 802.11 b/g compatible transceiver is used.

The location where the antennas are installed is particularly relevant for the design of the WiFi radio system. The design is based on the following conditions:

- The aim is to achieve a very short communication range between the connected sides of the wagon. Communication across the whole length of the wagon would pose a risk to the correct determination of the wagon order and orientation.

- Low interference levels must be ensured. Trains pass through inhabited areas where home networks also operate in the 2.4 GHz band. Interference from outside sources (and interference to other networks by the train) should be minimised by using an appropriate antenna configuration and shielding.

- The possibility of crosstalk with other trains must be excluded, especially during the train setup. A further problem is that the communication connection must be clearly established with the mechanically coupled wagon in the same train and not with an adjacent wagon on the siding (see Figure 30).

The solution here is to install the antenna in the electrical coupling. With a distance of just a few centimetres between the antennas, the channel attenuation can be assumed to be only a few 10 dB. This makes it possible, e.g. to evaluate the authenticity of the connection on the basis of signal attenuation. In addition, the coupling housing provides excellent shielding.
7.7.2 Communication nodes

A communication node for a radio-based train bus system with transceivers close to the coupling point is a distributed system in the wagon. Each transceiver (at the ends of the wagon) needs a power supply and a communication link to the actual central communication node in the wagon. Power can be supplied via a connection to the 24 V\textsubscript{DC} network in the wagon, or alternatively by a PoE\textsuperscript{25} connection via the communication node. The actual radio transceiver chip is then connected to Ethernet via an intelligent converter, as shown in Fig. 31.

Figure 31: Components of radio communication systems

Source: Owita GmbH

7.7.3 Functional description of communication nodes

“Start up”:

With the radio system, it is first necessary to establish a connection between the communication partners. For this purpose, all radio transceivers in the “Start-up” state are initially configured as WiFi clients (see Figure 32, (1)). The locomotive is configured as a WiFi access point. The connection to the first wagon is established from the master (locomotive). Once the connection between the wagon and the locomotive has been established, the other end of the wagon is configured as the access point. The next wagon can then connect to the transceiver configured as an access point (2). In this way, the communication system is initialised along the train to the last wagon. (Basic train setup process).

\textsuperscript{25} PoE: Power over Ethernet
In the “Initialisation” state, the communication protocols (communication SAP) address the wagon in the train via the master (locomotive). After being successfully addressed, the wagon can be reached via the allocated logical address. Only when the addressing procedure has been completed does the master switch the communication into the “Operation” state.

In the “Operation” state, the network layer of the communication system operates in switch mode. This means that logical/physical addresses of the wagons are stored based on the direction, and frames are only passed on in the direction of the destination addresses. This is necessary to relieve the bus and send the data in a targeted manner.

The “Fault” state is reached when the communication node in the wagon does not receive any frames for a defined period of time. If, on the other hand, a large number of packet errors are detected, the system should switch to an emergency mode in which only high priority frames are transmitted (integrity check).

7.7.4 Performance parameters

For the implementation of the radio system with IEEE 802.11g, the net bandwidth can be assumed to be in the range of 5 to 10 Mbit/s (gross 54 Mbit/s). Critical factors in the implementation are a connection time of approx. one second between the access point (AP) and client and the switching time per wagon from client mode to AP mode. The train setup time is therefore estimated to be approx. 120 seconds for 50 wagons.

The latency per wagon is assumed to be max. 10 ms. The round trip time (RTT) from the master to the last wagon and back for a train with 50 wagons is assumed to be max. 1000 ms.
Consequence:
Detailed specifications are required for each of the communications systems and especially for the interface (SAP). These specifications must also be suitable for standardisation at a later date. The preliminary specifications and limiting conditions outlined here must be considered as basic conditions, but require further development outside this project.

Functioning communication systems must be available as samples for the DAC selection process. If possible, these should be implemented using existing industrial components (e.g. control systems) to eliminate the need for developing specific hardware for each train bus system. It is important to recognise that optimisation (of power requirements, costs, suitability for railways) can only take place once the technology has been determined in a product development process, and that this also requires the agreement of a standard.
8 EP braking system (EP-Light)

The presence and functionality of the main brake pipe as a control line for the indirect pneumatic braking system is considered to have been set in the areas of revising the requirements and limiting conditions for the system.

However, the wagons should still be able to brake smoothly. This can be done by venting the MBP simultaneously at many points in the train. This enables the train to brake more evenly than previously using the standard braking system. However, the fallback level of emptying the MBP exclusively by the locomotive is retained. Thus, the EP system is not initially relevant to safety.

The EP braking system can be controlled in two ways:

- **EP line:** The EP line is an electrical line that runs through the train. It carries a 110 V\textsubscript{DC} control signal directly to the EP valves, which then vent the MBP and act as an indirect brake control. For this purpose, two lines are routed through the train from the locomotive. For freight trains, this variant has the advantage that systems with appropriate controls in the locomotives are already available today. The braking system also functions independently of other systems. The disadvantage is that two additional, separate lines with corresponding coupling contacts must be laid in each wagon.

- **EP control via communication:** Here, the EP brake valve in the wagon is controlled via a control variable transmitted by the communication system. The advantage of this is that no separate lines have to be laid in the wagon. The disadvantage is that the availability of the EP brake depends on the availability of the communication system. If this is less than the availability of the 110 V\textsubscript{DC} EP line, this is a critical problem. A further disadvantage is that a brake control for a 110 V\textsubscript{DC} EP brake has already been implemented in several series of locomotives. In any case, an additional device for implementing the braking signal in the locomotive’s communication system would have to be implemented.

The variant first mentioned in this section, with a separate EP line, was successfully implemented as an EP-Light system during the project “Construction and Testing of Innovative Freight Wagons”. It should also be considered here. This system can be seen outside the energy and communication system. However, it must be considered for the electrical lines and coupling points in the DAC.

8.1 Approach of the EP-Light brake

With the EP-Light system (see Fig. 33), the main brake pipe is vented via an electrically controlled valve in each wagon. These valves are controlled via the traditional EP line. However, the train is still braked indirectly. This means that the brake control operates independently of the EaC and will function even if these new systems fail.
The EP line, which is newly integrated in the freight train, is used to control EP valves in the individual wagons. At the same time, the driver brake valve (DBV) is used to vent the MBP, thus securing the purely pneumatic fallback level (for train lengths up to 750 m).

*Note: The electrical connection must be implemented for the DAC tests, at least as an electrical test system. The brake itself need not be implemented.*

However, for new automation functionalities in freight trains, such as brake monitoring or automatic brake testing, an additional functionality with communication capability must be integrated (standardisation). This must be able to measure signal states and evaluate sensors. This function could also provide a method for communication-based brake control (instead of the EP line).

*Note: These functionalities are important for a future standard and must be defined. This does not have to be done for the tests to evaluate the migration options.*

**Consequence:**

The introduction of an EP-Light system in freight trains requires a separate EP line and the necessary coupling point in the DAC. This must be taken into account when defining a system.

### 8.2 Design of the cable cross-section and protective measures

The following requirements are assumed when designing the cable cross-section for a cable-based EP-Light brake:

- Brake valves: One valve per wagon up to approx. 25 m wagon length, beyond that two valves per wagon
- Train length of 720 m not incl. the locomotive
- Contact resistances at coupling: 7 mΩ
- Rated voltage $110 \, V_{DC}$, minimum voltage at the last wagon: $77 \, V_{DC}$[7]
- Power per valve: 8 W.

From these parameters, a cable cross-section of 4 mm² can be determined for EP cables using the energy tool developed by OWITA GmbH (see Annex 2). The rated current for the EP-valves is 7.5 A at 13 W per wagon and 50 wagons. Protective measures must be provided in the same way as for the $110 \, V_{DC}$ supply.
9 Recommendations for further action

The work package for the identification of standards for electrical power/data supply has identified the following key points, which are summarised here:

The power supply and data communication systems in freight trains provide the foundation for the implementation of automation functions in RFT based on a DAC. Both these systems must be standardised and allow open, transparent connections for automation functions.

At 2.5 W per metre of wagon length, the power transmission requirements for core functions are manageable. They can easily be implemented using a 110 V\(_{\text{DC}}\) solution and a two-wire power line (16 mm\(^2\) cross-section [1]). However, such a system is not currently in use and therefore not immediately available.

With a required net data rate of approx. 30 kbit/s, the demands on the communication system are very manageable for the core functions, as are the latency requirements of approx. one second.

The standardised communication systems primarily used in passenger transport today are not directly suitable or designed for use with a DAC in freight trains. System modifications and enhancements are always necessary (even in the standard system). Therefore, from today's point of view, new approaches should be pursued to minimise the number of connections at the coupling point (DAC). These should be based on robust, basic, cost-effective technologies that have been tested in industry and are available. A variety of very different system and technology approaches (powerline, radio, segmented CAN or two-wire Ethernet) show promise. However, these are currently neither standardised for this field of application nor available in the required form as a transparent communication system.

The following problem has been clearly identified: a technology decision is required not only for the DAC with its coupling points, but also for the communication and power supply systems. Only when these technology decisions have been made will it be possible to standardise protocols for the communication system itself, for the automation functionalities and, especially, for the interface between automation functionalities in the vehicle and the communication system for transparent transmission.

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The selection process should continue in three steps. Firstly, the DAC and EaC systems must be selected. This selection must be based on measurements in a test train and using agreed decision metrics.

Functional models based on industrially available hardware must then be set up as a demonstration and development system for the EaC (and the DAC) in a demonstration train, with the aim of tackling standardisation through parallel working groups. The aim of the demonstrator is to obtain approval for the DAC and produce the design standard for the EaC.

In the third step, various manufacturers will develop the special components for the EaC. These systems should be tested in a European demonstrator, their interoperability ensured, and standards fixed, resulting in the approval of the EaC.

This will then provide the basis for development, testing and approval of the automation functions in the train.
9.1 System selection

To ensure the necessary interoperability for rail freight transport, the essential system decisions and standardisation work take on a European dimension.

Criteria are required for making these system decisions and there are still open questions relating to several aspects, particularly the reliability of the systems. These can only be answered by practical testing of the power supply and communication systems in combination with the DAC. For this reason, the production of detailed specifications for the communication system (two system approaches) has not yet been possible in a meaningful way. It is therefore necessary to set out a reasonable pathway for the successful development of a standard. To this end, the following steps are considered useful and necessary:

- Development and agreement of decision metrics. In the first step, a newly established working group of experts from the sector should agree quantified requirements (parameters) and clarify the procedure for making technology decisions – not only for the DAC but also for the power supply and communication systems. The final decision-making body should be determined – via the EU.

- Metrological tests with the available technological approaches: These tests are initially used to quantify evaluation parameters and gain experience with a basic communication technology in combination with a DAC. For this purpose, functional models must be built for the systems under consideration and evaluated in a test train. The aim should be to realise the necessary functional models, if possible using existing industrial components (e.g. industrial control systems). This platform should be used to implement at least the necessary functions for the power supply system, the data communication system being considered and the interface (SAPs). The development of initial protocols and detailed preliminary specifications – in a way that also allows them to be used as a starting point for a standardisation process – is therefore necessary for this step of the implementation. Based on this system, extensive measurements and tests must be performed and documented for use by the relevant body in the decision-making process.

  Note: Annex 1 contains more detailed proposals for the implementation of the functional models.

- Decision on the DAC, power supply and communication systems:

  Drawing on the results of tests and measurements, the decision-making body must not only select the DAC system, but also the energy and communication systems. The standardisation process should then be started on the basis of this technology decision.

9.2 Draft standards

For the standardisation of the energy and communication systems, the following parallel steps are useful for developing the standard in a sufficiently short time:

- 1 - Development of the SAPs for two interfaces:

  The following section provides a detailed description of the interfaces for accessing the train bus communication system via SAPs. This is specified in detail for two communication connections. The system should use a vehicle bus (CAN proposal) and a direct transparent connection via a serial interface. Once this interface is defined (and
implemented), it will be possible to develop the actual automation functions in the freight train in parallel and then simply connect them to the communication system.

- **2a - Development of the communication system and communication standard:**

  For the selected technology, the preliminary specifications for the communication system must be supplemented as required to ensure implementation of all core functions of the communication system (train setup, troubleshooting, etc.). In addition, the defined SAPs must be implemented as specified so that the functions can be connected. This preliminary specification must be implemented on the corresponding hardware of the functional model. This will allow a first demonstrator train to be realised as a demonstration and development platform based on the functional model. The available industrial hardware platform will continue to be used for this purpose.

  - This process of extending the preliminary specifications to the standardisation of the communication system should be re-established by a standardisation group made up of expert representatives from the railway and industrial sectors, as well as research institutions. The group must be provided with the appropriate professional and financial resources. The group’s task (“WG Communication”) is to supervise the standardisation of the communication system up to the introduction of the standard.

    *Proposal: It is proposed to allow an initial testing of the communication system in a demonstrator train, and to validate the basic approaches.*

  - A good solution for an effective implementation would be to bring together suitable representatives of the various institutions in a structured team with the task of developing this standard and then, if necessary, implementing it as a suitable railway system in hardware and software applications. The team would also set up the test structures for interoperability tests.

- **2b Development of the power supply system and energy standards:**

  The power supply system must be developed further and implemented as a functionality in the specification. In particular, this concerns the implementation of the energy management system (connected to the communication system via an SAP). The implementation can take place based on the functional models in the test train, where the implementations are refined in such a way that a complete implementation is available as a demonstration and development platform. Here, too, it is proposed that this step be supervised by “WG Energy”.

  - *Proposal: A first allowance for this should be implemented and validated in the demonstrator train.*

- **2c Development of further automation functions:**

  Once the SAPs have been defined, the parallel development and implementation of further functions (e.g. automatic brake test, brake system, train integrity, etc.) could be started immediately. Here, the authors suggest first developing a “simple sample system” for concept validation and validating this in the demonstrator train. The development and standardisation processes for more complex functions should then be started. For this purpose, a parallel project should be created with teams responsible for the development of prototypes and specification of the automation functions, as well as for working out the basis for the function standards.
9.3 Component development, interoperability and approval

After validation of the basic functions in the demonstrator train with measurements and development iterations based on the functional model (hardware), a first draft of a standard for the communication system can be produced by the “Communication” working group. The “Energy” working group can do the same for the power supply system. These standards should then be used as the basis for developing the specific hardware and software for components in the train bus system and also the power supply system.

One proposal for further action is as follows:

- Different companies should be involved in product development for the communication and power supply systems. This would integrate various manufacturers into the development process and address the issue of interoperability from the outset. These systems could then be tested and approved in a European demonstrator train.

- Test structures and facilities for the qualification of components and interoperability tests should be set up in parallel by the “Communication” and “Energy” working groups.

- The development and standardisation of automation functions in RFT should also be implemented using the function standards. Once the energy and communication systems have been approved, they could also be tested and approved in a European demonstrator train.

These standardisation, development and implementation processes are very extensive undertakings and require intensive (European) support with the necessary human and financial resources. An interdisciplinary project team of experts (railway operators, railway and supplying industries, licensing bodies, universities, authorities, etc.) could greatly accelerate this process, help to ensure successful joint development of the system, and thus lay the foundations for strengthening rail freight transport throughout Europe.
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<td>AC</td>
<td>Automatic Coupling</td>
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<tr>
<td>BMS</td>
<td>Battery Management System</td>
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<tr>
<td>CAN</td>
<td>Controller Area Network</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital Automatic Coupling</td>
</tr>
<tr>
<td>DBV</td>
<td>Driver Brake Valve</td>
</tr>
<tr>
<td>EP</td>
<td>Electro-Pneumatic</td>
</tr>
<tr>
<td>ETCS</td>
<td>European Train Control System</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>ISM</td>
<td>Industry Scientific Medical</td>
</tr>
<tr>
<td>HMI</td>
<td>Human Machine Interface</td>
</tr>
<tr>
<td>LoB</td>
<td>Length over Buffer</td>
</tr>
<tr>
<td>MBP</td>
<td>Main Brake Pipe (pneumatic braking system)</td>
</tr>
<tr>
<td>MTU</td>
<td>Maximum Transfer Unit</td>
</tr>
<tr>
<td>NFC</td>
<td>Near Field Communication</td>
</tr>
<tr>
<td>PKI</td>
<td>Public Key Infrastructure</td>
</tr>
<tr>
<td>PoE</td>
<td>Power over Ethernet</td>
</tr>
<tr>
<td>RFT</td>
<td>Rail Freight Transportation</td>
</tr>
<tr>
<td>RTT</td>
<td>Round Trip Time</td>
</tr>
<tr>
<td>SAP</td>
<td>Service Access Point</td>
</tr>
<tr>
<td>SIL</td>
<td>Safety Integrity Level</td>
</tr>
<tr>
<td>SOA</td>
<td>Service Oriented Architecture</td>
</tr>
<tr>
<td>SPE</td>
<td>Single Pair Ethernet</td>
</tr>
<tr>
<td>TCN</td>
<td>Train Communication Network</td>
</tr>
<tr>
<td>TCP</td>
<td>Transport Control Protocol</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TLS</td>
<td>Transport Layer Security</td>
</tr>
<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
</tr>
<tr>
<td>UI</td>
<td>User Interface</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>WTB</td>
<td>Wire Train Bus</td>
</tr>
</tbody>
</table>
Annex 1: DAC tests – System selection

Four manufacturers are currently designing and building different DAC prototypes. In the next phases, the aim is to select a system based on trials and tests.

A dedicated proposal for a possible test concept for the energy and communication system is presented here.

1. Basis for system selection

To make meaningful statements about the reliability of the electrical connections, and thus derive statements about the individual communication systems, the couplings must be examined. This requires general measurements, e.g. communication channel measurements with network analysers, to determine the frequency response of the connections and identify communication restrictions at an early stage.

Observation of changes over a many coupling cycles will be important for assessing the reliability of the system.

For the powerline system, the test on a block train using a locomotive as the power feed is particularly relevant. The powerline system must be able to communicate over the full 750 m length of the train.

The results of the coupling evaluations on the individual wagons will lead to the selection of a coupling system. This affects the communication system. The evaluations should also form the basis for the selection of a communication system, which can be further developed and tested in a demonstrator train.

Standardisation of the overall approach requires the definition of three core areas, as shown in Fig. 34:

- The DAC as the coupling point between the vehicles.
- The definition of the functionalities in the overall system (train setup, brake test, integrity, ...).
- The definition and specification of the energy and communication system.

Figure 34: Structuring the areas of responsibility for standardisation

Source: Owita GmbH
The following framework conditions have been or are being developed:

- Four different DAC systems are being developed by four manufacturers. As well as the mechanical coupling, these all couple the MBP, the power line (two wires), a communication line (two wires) and the EP line (two wires), as shown in Fig. 35. In addition, an installation space will be available for an antenna (radio channel) and the DAC systems are expected to be able to query the coupling status.

**Figure 35: Connections in the DAC**

- Analysis of the power supply system identified a 110 V\textsubscript{DC} system with a minimal design (2.7 W per metre of wagon length) as a suitable solution. Systems in the wagons should operate on a 24 V\textsubscript{DC} power supply.

- For the definition of the communication system, the analysis showed that – due to a lack of experience in the freight transport environment – the final evaluation and selection criteria cannot be determined without extensive system tests and practical trials. For this reason, three to four technological approaches were selected as a basis for further study:
  - A powerline transmission
  - A segmented CAN system (and possibly a two-wire Ethernet with APL technology IEEE 802.3cg)
  - A contactless system (short-range radio at the coupling point).

From this, it becomes clear that standardisation cannot be achieved within the scope of the present study because technology-dependent issues must be taken into account and the functionalities must also be specified.

The selection process for the system will be accompanied by measurement and testing programmes. Testing is divided into two phases:

- Tests with one coupling point (**individual tests**);
- Tests with groups of wagons in the train (**groups of wagons**). 

Source: Owita GmbH
2. **Individual tests**

The individual tests are aimed at investigating exactly one coupling point, with particular regard to the relevant selection parameters for power and data transmission. This must be done for all communication system variants under consideration.

**Figure 36: System structure for testing a DAC coupling point**

Various basic components must be realised for the tests, as shown in Fig. 36 (using a powerline system as an example). The following are required:

1. The feed into the power line, as designed in the power supply system. The feed system must have suitable operating interfaces and the parameterisation options required for the tests.
2. The consumer system (converter/battery in the wagon) and the energy extraction system must be set up.
3. For powerline transmission, a signal coupling into the power line is required. For the CAN system, a corresponding connection to the communication line is required. For the radio system, a radio channel must be established with antennas at the coupling point.
4. A communication node is required for the powerline system, as shown in Fig. 36. Likewise, this communication node must be implemented for the CAN system and for the radio system.
5. The respective communication node is equipped with a service access point that is independent of the communication system.
6. Test hardware with a test functionality is required to realise communication and implement a data exchange between the functional elements via the SAP. This test application should be usable for all the communication systems being examined.

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26 Of course, additional tests will also be performed to evaluate the mechanical properties as well as the pneumatic and operational handling of the system. These are not considered here.
In addition to these core components 1 to 6, for which preliminary specifications must be produced and implemented, cable connections and lines are required. The measuring processes (with the required automation where appropriate) and data acquisition must also be implemented.

*Note: The data from the test application could also be fed into all three communication systems in parallel. However, the results may be distorted by mutual interference.*

3. **Wagon groups**

In addition to the examination of a single coupling point, the first wagon groups will be studied. For this purpose, three wagons will be equipped for each DAC system, as shown in Fig. 37. However, no locomotives will be equipped with a DAC during the test phase.

**Figure 37: Suggested wagon groups for the DAC trials**

One feature is worthy of special note: As the individual couplings are not compatible with each other, the individual wagon groups must be coupled together using a separate interface (screw coupling, MBP, electrical connections). The intention is to use only one integrated cable (plug/socket) for this purpose at the interface.

*Proposal: Check whether the cable system used in the “Innovative Freight Wagon” project is suitable.*

A special problem arises for the radio communication system in this constellation – radio communication would not be representative at DAC-free interfaces (different channel, different sensitivity to interference). A solution for this problem must be found. This could be implemented either using an antenna cable or another communication cable.
When testing groups of wagons, all the test wagons must ultimately be equipped with the system elements already described for the single wagon tests. An initial list of the necessary system components to be built or procured is derived from the conceptual design described in Chapter 0.

4. Implementation of the test system (concept idea)

It is proposed that standard automation technology components be used for the test setups. This applies to the CAN communication system and the radio system, in particular. Of course, the consequence of this is that the hardware is not yet able to map all desired functionalities. However, it can be used to carry out the tests necessary for the selection of a system. It is a first test system.

The aim of this test system is to provide a comparable communication test for all three solution variants. It is proposed that the test system be implemented in the locomotive using an industrial computer for test control and data acquisition as well as for the test application (master functionality). In addition, all communication systems should be connected to the test control system via Ethernet (SAP hardware). A VLAN-capable switch can be installed to separate the Ethernet data traffic for the individual communication systems (during parallel tests) and to control the communication paths. The SAPs for the individual communication systems are then configured as Ethernet ports with corresponding IP addresses and VLAN tags.
The individual communication technologies must be connected via an SAP of this type. To test the CAN system, a controller (with Ethernet port) is used. The CAN adapters can be connected to this. The communication functionality must then be implemented on the control unit/industrial PC.

For the powerline solution, a corresponding connection to the existing modules must be implemented (if not already available). The communication system for powerline technology has already been implemented and is currently undergoing initial tests at SBB Cargo.

For the radio system (2.4 GHz radio channel), the channel operation (access points) can be implemented using industry standard components via WLAN or Bluetooth modules (but probably not the train setup).

Furthermore, it is proposed that the system in the locomotive be equipped with a permanent power supply in order to minimise system start-up times during the connection process.

Table 17 shows the basic components of the master system for the communication technology tests:

**Table 17: Test components in the locomotive (communication)**

<table>
<thead>
<tr>
<th>Component</th>
<th>No. per locomotive</th>
<th>Description/Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial PC</td>
<td>1</td>
<td>Linux-based</td>
</tr>
<tr>
<td>CAN/Ethernet gateway</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Ethernet switch</td>
<td>1</td>
<td>Managed switch with VLAN function</td>
</tr>
<tr>
<td>RF gateway (e.g. WiFi, Bluetooth)</td>
<td>1</td>
<td>Switching between client and access point mode via Ethernet interface</td>
</tr>
<tr>
<td>Powerline modem</td>
<td>1</td>
<td>HS Lucerne/plc-tec AG</td>
</tr>
</tbody>
</table>

Source: Owita GmbH
To set up a test system for the power supply, a 110 V DC feed must be installed. For this purpose, the intermediate voltage could be converted from 1500 V AC to 110 V DC. This could be performed by static on-board converters used for battery charging as these are currently used in railway technology. An isolating transformer may be installed before feeding the power into the converter. Protection in the form of a circuit breaker must be provided between the 110 V DC output of the converter and the feed into the DAC. Furthermore, it must be possible to switch off the voltage at least manually.

The test system in the wagon (see Fig. 40 and Table 18) resembles the test system used in the locomotive. The systems here are also connected to a central computer-controlled instance via a common Ethernet system. In contrast to the locomotive, two CAN modules are provided. These are designed as an Ethernet gateway and could be used to route the CAN connection through the train via a relay.

Figure 40: “Wagon” test system

![Figure 40: “Wagon” test system](source: Owita GmbH)

Since relatively little computing capacity is required, an ARM-based hardware solution can be used as an embedded PC for the test application. When selecting this, however, it is important to ensure that the start-up time of the system is relevant.

Table 18: Wagon test components

<table>
<thead>
<tr>
<th>Component</th>
<th>No. per wagon</th>
<th>Description/Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embedded PC</td>
<td>1</td>
<td>Linux-based, low electrical output</td>
</tr>
<tr>
<td>Ethernet switch</td>
<td>1</td>
<td>Managed switch with VLAN function</td>
</tr>
<tr>
<td>CAN/Ethernet gateway</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Relay module</td>
<td>1</td>
<td>Two separate channels for CAN-H, CAN-L</td>
</tr>
<tr>
<td>RF gateway (e.g. WiFi, Bluetooth)</td>
<td>2</td>
<td>Switching between client and access point mode via Ethernet interface</td>
</tr>
<tr>
<td>Powerline modem</td>
<td>1</td>
<td>HS Lucerne</td>
</tr>
</tbody>
</table>

Source: Owita GmbH
Note: Even if the test system can be built from available hardware, the precise definition of the system (components and structure), implementation of the necessary software and implementation of metrology systems are urgently required. The overall function must be validated under ideal conditions and set up in the laboratory before implementation for the measurement of DAC systems.

A power supply unit from 110 V\textsubscript{DC} to 24 V\textsubscript{DC} can be used to supply the wagons in the train. This converts the voltage in the train network to the on-board voltage. A standard 24 V UPS\textsuperscript{27} from the automation technology sector can be used to test the battery supply for the wagon. When designing the test system, care must be taken to ensure that the total power consumption of the components does not exceed the limit of 2.7 W/m of wagon length.

\textsuperscript{27} UPS: Uninterruptible Power Supply
Annex 2: Tool for the analysis of power distribution in freight trains

An Excel-based "energy tool" was created (see Fig. 41) to determine the power consumption from the train’s power line under various conditions (parameters). This can be used to calculate the power available in the wagon.

The following parameter entries are possible:

- **Input voltage**: The input voltage is the voltage fed into the train by the locomotive.
- **Minimum voltage in the system**: This parameter describes the minimum permissible voltage at the last wagon.
- **Cable cross-section**: Cross-section of the (copper) cable in mm².
- **Permissible current density**: A maximum permissible current density can be specified. This is dependent on how the cable is laid and the cable cross-section. Depending on the length of the train (especially for shorter trains), the current density can limit the maximum power for the wagons.
- **Specific resistance of the cable**: Usual resistance of a copper cable. Different values could be selected here for other materials (e.g. aluminium).
- **Contact resistance per plug contact**: The contact resistance describes the aggregate resistance of the contact points between the couplings and the connection from the coupling to the wagon wiring. The value is included in the calculation twice, once for the outward conductor and once for the return conductor.
- **No. of wagons**: The number of wagons in the train defines the number of contact points.
- **Train length**: The train length defines the length and thus the total resistance of the line.
- **Minimum/maximum wagon length**: Test values to verify the plausibility of train length and number of wagons.
- **Length allowance for the line**: In many cases, it is not possible to lay the cables in the wagons using the most direct route. The length of the line in the wagon is therefore greater than the wagon length. This parameter can be used to define a line allowance (percentage value) in addition to the train length.
The internal calculation functions are activated by clicking the "Calculate" button. A solver function is then used to solve the differential equation for determining the power in the wagon.
Annex 3: Supervision by partners from the railway sector

Two workshops were held with industry partners on the topic of energy and data communication in freight trains.

Companies from the automation technology sector were invited to the first workshop on 12.09.2019. The aim of this workshop was to discuss the draft concepts for energy and data communication in the DAC and to hear the assessments of these industrial partners. Details can be found in the minutes of the meeting.

Participating companies: Aspöck, DB Systemtechnik, Deutsche Bahn, DB Cargo, GATX Rail Germany, Harting, hwh, Owita, Phoenix Contact, SBB Cargo, Siemens, VTG.

Companies from the railway sector, especially coupling manufacturers, were invited to the second workshop on 15.10.2019. At this workshop, the concepts were also discussed, and the results and consequences from the workshops were incorporated into the concepts. Details can be found in the minutes of the meeting.

Participating companies: Axtone/ITT, DB Systemtechnik, Deutsche Bahn, DB Cargo, Ermewa, GATX Rail Germany, hwh, Knorr Bremse Systeme für Schienenfahrzeuge, Owita, Rail Cargo Austria, SBB Cargo, Tensor, Voith, Wabtec Europe, VTG.