Train Communication Networks - Status and Prospect

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Abstract—**This paper presents an overview of communication systems in mainline railways and in particular the Train Communication Network TCN defined in IEC 61375. Current systems and ongoing developments are systematized by traffic, technological and organizational topics. TCN is displayed in detail with a prospect to possible future wireless extensions.**

Index Terms—**Train Communication Network, TCN, IEC 61375, railway vehicle, Ethernet, Wireless, TCMS**

I. INTRODUCTION

High-performance communication systems for the transmission of Train Control and Monitoring (TCMS) data in railway vehicles have seen an increasing demand since the 1970s and 1980s. Especially for railways several requirements have to be considered, such as environmental conditions and robustness requirements, but also highly available, secure and real-time communication of railway-specific data.

As an extension of the so-called UIC-cable (according to the International Union of Railways (UIC) Leaflet 568 [1]) for passenger trains, which connects audio transmission, light and door control through the train, the Train Communication Network (TCN) bus system Wired Train Bus (WTB) was added to the new UIC-558-cable.

The TCN [2] units a series of railway-specific bus systems and networks as well as communication and application profiles. The TCN is currently being developed as an IEC standard and is available as European standard series in various national standards, e.g. DIN EN 61375. The TCN standard is under further development with support of several research projects [3].

A. Motivation

For an overall overview on railway communication and in particular TCN, this paper displays a review of common used systems, actual systems in use and ongoing developments. This provides a common ground to classify current developments based on former technological status. Additionally, further developments of the TCN as well as new and parallel technologies and their interfaces are described.

This paper focuses on mainline railway communication. Light railway, subway and commuter traffic are out of scope of this paper. The second chapter points out the state-of-the-art for three traffic categories such as freight transport, conventional passenger transport and high-speed traffic. As a different point of view, the wired transmission technologies are systematized. The main architectures and properties of TCN are introduced in the third chapter. The fourth chapter describes the concept of wireless transmission that extends the previously wired busses or networks of the TCN.

II. METHODICAL CLASSIFICATION OF COMMUNICATION SYSTEMS

A. State-of-the-Art of Communication Systems for different Types of Trains

The following section introduces the existing communication systems of railway vehicles. A distinction is made between the three main types of railway traffic.

1) Cargo: The rail freight transport is characterized by fully equipped freight locomotives with side buffers and screw-type coupling. The other connection is the pneumatic main brake pipe (BP), which is a compressed pneumatic air pipe expanding through the entire train. The pressure level provides the braking demand for all brakes of the train and is also used as a pneumatic energy supply system. This is one of the first train-wide communication systems for railways. However, the main brake pipe

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is still present today on every railway vehicle for active braking or as a fallback system.

For multiple traction control additional communication systems between the locomotives exists. Freight cars usually have no electrical components and infrastructure along the train. This has changed in recent years by equipping individual freight wagons with self-sufficient energy systems for vehicle tracking and condition monitoring. The devices usually contain a Global Positioning System (GPS) receiver to document their position and mileage. Position and other measurement data from sensors can be transmitted to servers or the *cloud* via mobile connection. The number of components is increasing rapidly due to the digitalization offensive of large freight wagon operators. Increased automation of freight trains and better logistics integration is being investigated in research projects [4].

2) Conventional Passenger Trains: The passenger traffic is roughly divided into conventional passenger trains and modern train sets, while conventional passenger trains are increasingly being replaced by modern train sets. A conventional passenger train consists of a locomotive at one end, often a control car with cab at the other end of the train and multiple queued passenger cars in between. The mechanical coupling is conventional with side buffers and screw-type coupling.

The operating conditions result in additional requirements for communication devices. Cars of different operators and manufacturers should be combinable, i.e. interoperable. This requires uniform and compatible interfaces that are often defined by standards. It is common for trains to be extended or shortened during normal operation. The number and order of the communication participants, as well as the direction of travel, can change on every train formation.

The so-called UIC-cable and the pneumatic main brake pipe (BP) are present on every passenger train. The main brake pipe is used for braking, unless an electropneumatic brake with a UIC standardized ep-cable transmits the braking request electronically [5] [6]. Many non-standardized functions such as electropneumatic brake and emergency brake override are also transmitted in special solutions via the UIC-cable. Consequently, the coupling of different cars is often not possible.

3) Modern Train Sets and High Speed Trains: Modern train sets such as the German InterCityExpress (ICE) trains of Deutsche Bahn AG (newest version: Velaro platform by Siemens AG) consist of firmly interconnected car groups, which can be changed only in workshops. The vehicle technology can be distributed to several cars within fixed train parts and the communication network can be designed quasi-statically. Multiple train sets are usually coupled by Scharfenberg couplings with high-pole electrical connectors. The coupling of multiple (different) train units must be provided by the manufacturers and operators.

B. Wired Communication Technologies

Communication systems are categorized into three main groups:

1) Direct Wire Connections: The simplest form is the direct connection with a cable from a source to a sink. Higher switching currents (typically <10 A) can be transmitted as a power supply. On one line, one or few signals (e.g. voltage levels) may be transmitted with a relatively low bandwidth (typically <100 kHz). The transmission is distinguished between analogue and digital transmission. For the transmission of several independent signals, a single electrical line is usually used for each signal. However, this method becomes unwieldy for the transfer of multiple data.

2) Bus Technologies: Data is transmitted digitally and coded in time in a bus system. The individual devices are usually connected in succession. Each device can read the data. Depending on the access method, the bus users can also write to the bus. For instance, the Controller Area Network (CAN) [7] bus uses the Carrier Sense Multiple Access (CSMA) methods and priorization of messages with an arbitration method. On the other hand, the TCN-MVB is a clocked bus system with a bus master that sets the cycle. At previously configured time slots of the cycle, the bus nodes write their data on the bus. The data transfer rate of 1.5 Mbps is sufficient for TCMS applications. Bus systems are increasingly being replaced by industrial network systems.

3) Switch Network Technologies: Newer applications (e.g. video transmissions) need a higher bandwidth, such that bus systems are no longer sufficient in the future. Switching technologies, such as Ethernet, are increasingly used as a general trend in industrial communications, but also in railways. With networks, higher data rates of up to

10 Gbps and higher, a stronger structuring of the data streams, active network components (gateway, switch, router) and an encapsulation of data streams are possible.

Networks are not inherent real-time capable communication systems. Special extensions, that must be supported by the network components, enable real-time communication. In TCN, a real-time communication of TCMS data is provided by the Train Real Time Data Protocol (TRDP) with the optional safety extension Safe Data Transmission (SDT). Other networks in the field of Industrial Ethernet are ProfiNet (PN) [8]. The focus in the railway sector is in the further development of IP-based communication systems.

C. General Data Classes of Networks

From a different perspective, data and data streams can be transmitted via bus systems and switch networks. For differentiation and classification of data transmission, five main data classes according to IEC 61375-1 [2] are used: process data (PD), message data (MD), supervision data, stream data and best effort data.

D. Communication Partners and Path

Another common way to categorize railway communication is to distinguish between communication partners and path.

1) Intra-Train Communication: Communication within a train is divided into two levels. The train backbone level in which data is transmitted trough the entire train. It has a dynamic topology that also changes with each new train composition.

The consist level represents a static, preconfigured bus system and/or network within a wagon or a fixed wagon group. The communication between consists may only be possible via the train backbone. Consist internal data is only transferred within consists. End devices (ED) are usually connected to a consist, but can also be connected directly to the train backbone node (TBN). The train backbone and the consists should be redundant.

Parallel to TCMS communication, many trains also provide networking for mobile Internet access, local web and streaming servers. The data is distributed via separate ethernet networks and Wi-Fi to the passengers' mobile devices.

2) Train-to-Infrastructure Communication: Analog radio is the most basic form of communication between a train driver and the dispatchers in the interlocking or the control center. The most important application of digital communication is cab signaling with a digital communication between train and infrastructure. In Germany, for this purpose, the system *Linienzugbeeinflussung* (LZB) consisting of a leakage cable in the middle of the track and an antenna under the vehicle is used. In modern communication-based train control and protection systems such as the European Rail Traffic Management System (ERTMS) with the European Train Control System (ETCS), a modified Global System for Mobile Communication - Rail(way) (GSM-R) is used for data transmission from a Radio Block Center (RBC) to the ETCS on-board unit (OBU). From ETCS eurobalises on the track to an antenna under the vehicle, data is transmitted with a so-called air-gap interface.

Current research projects are investigating the use of Long Term Evolution for Railways (LTE-R) and 5th generation (5G) mobile radio as a successor to GSM-R. An increasingly important application is the state determination for condition-based maintenance strategies. Wear conditions have to be estimated and maintenance have to be carried out before an impending failure. Sensor signals and aggregated states are transmitted to the infrastructure system (e.g. *cloud*) and further processed there. The data stream of the mobile Internet for the passengers must be connected to the land-side communication infrastructure. Currently the available mobile network is used, but it is limited by bandwidth and not available nationwide. For non-mainline Communication-Based Train Control (CBTC) systems various communication paths e.g. Wi-Fi, Terrestrial Trunked Radio (TETRA) and satellite communication are used operationally and further developed in research projects.

3) Train-to-Train Communication: Rather new is the concept of direct communication among trains without a base station network. This is not provided in the conventional, infrastructure-oriented communication architecture of railways, except for voice radio and innovative systems like the Railway Collision Avoidance System RCAS [9].

In general a train knows itself, its infrastructure side counterpart and a one-dimensional released guideway in front of it. The dispatching of trains is the task of the control center and the safe train separation is the task of interlocking. In the project Next Generation Train [10] the virtual coupling is examined over longer distances in order to realize a distance control between two trains. A directly linked communication between trains has the advantage that it does not have to rely on the base station network's hardware and supply, nor on the network's backbone, which leads to very high availability and much lower latency. This functionality in combination with ETCS level 3 could increase line capacity by more closely spaced trains. Another application is the wireless connection of two mechanically coupled trains, where the complex and error-prone mechanical contacts on a Scharfenberg coupling could be replaced.

E. Redundancy Concepts

Redundancy of communication paths and devices is used to increase the operational availability and reliability of safety systems. Individual malfunctions or failures do not lead to system failure due to multiple implementation. The disadvantage is an increased expenditure on costs, installation space, weight and technical complexity.

III. TRAIN COMMUNICATION NETWORK AT IEC 61375

The TCN is the central standard for standardized networking for mainline railway vehicles in Europe. The standard forms the basis for interoperability using a common communication standard between trains or individual components of different suppliers, manufacturers and operators. In particular, the requirements of railways, e.g. rough environmental conditions, robustness requirements, but also highly available, secure and real-time transmission of railway-specific data in relatively long trains are considered. A special feature is the automatic reconfiguration (inauguration) of the train backbone when changing the train composition.

A. Basic Communication Architecture

In the TCN, two communication systems are standardized at train backbone level. Technical implementations are the Wired Train Bus (WTB) as the bus technology and the Ethernet Train Backbone (ETB) network as the switch technology. The train backbone has a dynamic topology that also changes with each new train composition. Additional legacy networks for multimedia, streaming and mobile internet are possible.

Within consists there are so-called consist networks for TCMS data, which are the Multifunction Vehicle Bus (MVB), CANopen Consist Network (CCN) as bus technologies and the Ethernet Consist Network (ECN) as switch technology. Consists may integrate with gateways other non-TCN communication systems, e.g. ProfiNet [8], Controller Area Network (CAN) [7] or Local Operating Network (LON) [11] for peripheral control or Integrated on-Board Information System (IBIS/IBIS-IP) [12] for passenger information. The train backbone node (TBN) is a controller that translates data between the train backbone and the consists. A train may use WTB and ETB in parallel. They can also be connected by a gateway. The consist network technologies MVB, CCN or ECN can also be used individually or in combination.

Fig. 1 shows an example of a train backbone with consists. The two consists form a closed train, which is integrated in an overall train set. The left consist extends over two cars, while the right consist has three consist networks and a directly connected end device. The network can additionally be configured redundantly. Virtual Private Networks (VPN) on ETB and ECN can be used to organize and separate different data streams e.g. TCMS or multimedia.

B. Redundancy of TCN Bus Systems

The UIC cable (with WTB) is normally duplicated. This can be seen e.g. in InterCity wagon transitions that a UIC cable is connected on the left and on the right side. Both lines are connected to the WTB nodes. At consist level, the MVB is created as a line structure and can be duplicated to the redundant channels A and B. Within an important consist, there is one active and at minimum one passive (fail-active) gateway node.

C. Redundancy of TCN Switch Networks

The ETB contains one to four full duplex 100BASETX lines between two ETB nodes (ETBN). Link aggregation described in IEEE 802.1AX is managed at OSI data link layer. The aggregated and redundant lines are abstracted to one logical line. Via ETB node (ETBN) gateways,

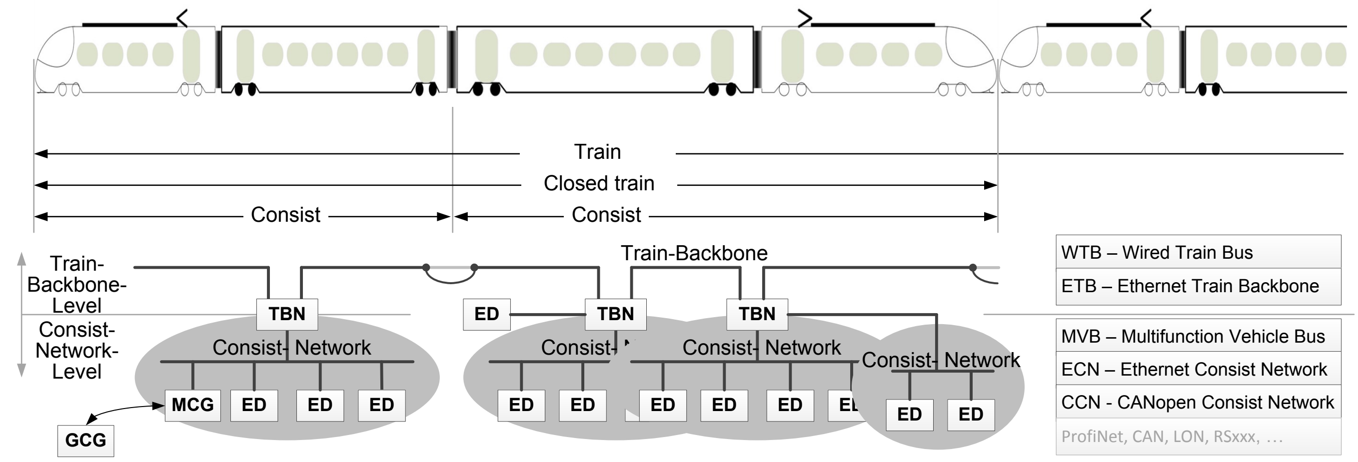

Fig. 1. Consist Configuration [2].

the ETB is connected to consist networks that are standardized in TCN (ECN, MVB, CCN) as well as other networks and bus systems (ProfiNet, ProfiBus, CAN, LON, IBIS, ...). Each consist should be connected for redundancy by an active ETB node and additionally by a passive (fail-active) node. At ECN, redundancy is managed at network level and node/end device level. The common network topologies are linear/parallel, ring and leather topologies. At node level, a node can be connected to the same network through multiple ports (dual homing). A node may also be connected to multiple ECN networks with multiple ports.

D. Train Inauguration with Automatic Adressing

One special features of the TCN is the ability to determine the topology of the backbone by itself. Each WTB/ETB node transceiver is doubled/redundant and is able to disconnect the line onesided by relays. Then the node can send in both sides individually and store the answering nodes. With the Train Topology Discovery Protocol (TTDP) the order and orientation of the ETBN and consists in the train is recognized. The topology and all properties are stored in an object database.

E. Concept of IP Network Address Range

The ETB uses the private IP range 10.0.0.0/8. The address range is only valid in a local network and must not be routed on the Internet. Since the TCN is reconfigured each time of an inauguration process, there is a system in which the network addresses are formed within the ETB. A distinction is made between a train-wide addressing within a train or train part (closed train) and a local, relative addressing within and between consists.

F. Packet Based Data Transmission over Switch Networks

The advantage of Ethernet-based networks like ETB or ECN is that many proven internet protocols, such as Domain Name System (DNS), Simple Network Management Protocol (SNMP) and Hypertext Transfer Protocol Secure (HTTPS) can be transferred. Thus, many functions used in common networks such as web portals, updates, monitoring or terminal services can also be used here. In addition, railway-specific protocols are added. One of the most important enhancements of ETB and ECN (compared with Ethernet) is the Train Real Time Data Protocol (TRDP), which (with the corresponding hardware) can realize real-time communication of process data with cycle times of up to 1 ms. A safety layer without encryption is provided by the extension Safe Data Transmission (SDT).

G. TCN Technology Evolution

The research of the new generation TCMS (NG TCMS) started with the EU Joint Undertaking Shift2Rail lighthouse project Roll2Rail and is continued in the projects CONNECTA and Safe4RAIL. The NG TCMS shall interconnect all on-board devices (TCMS, signalling, operator and customer oriented services) and can be connected to other trains and ground networks.

It supports the transport of safety critical data up to SIL4, time- and mission-critical functions, as well as non-critical train functions. The system architecture consist of the Drive-by-Data concept for communication layers and the Functional-Distribution-Framework (FDF) for application and function distribution. Several wireless technologies for TCN, including the wireless ECN (WLCN), the wireless ETB (IEC 61375-2-7 WLTB), the train-to-ground communication (IEC 61375-2-6) and the train-to-train communication (IEC 61375-2-9 Virtual Coupling) are under development. The project results are exchanged with IEC TC9 WG43, CENELEC WG15 and others for further development of TCN standard series IEC/EN 61375. The NG TCMS general specification, test specifications and a generic certification process were defined. For validation and virtual certification a simulation framework is developed in which all subsystems can be simulated by software/hardware-in-the-loop scenarios.

The NG TCMS is demonstrated to door and brake-by-wire applications as well as Onboard Multimedia and Telematic Services (OMTS). Interfaces or application profiles to signalling (ETCS Level 3 onboard equipment), Automatic Train Operation (ATO), Doors and Bogie Monitoring System (BMS) applications are defined.

IV. ENHANCED WIRELESS COMMUNICATION FOR TCN NETWORKS

State of the art TCN networks contain an increasing number of wires interconnecting functional elements within a consist, which are often doubled for safety relevant data exchange according to redundancy requirements. From a manufacturing perspective a reduction of complexity is desired, which would also reduce maintenance and repair costs. With integration of wireless communication this demand can be addressed. But also in case of power failures within the chain of connected consists or train sets, a wireless link can bridge the communication in order to maintain operations. Wireless links have advantages when upgrading existing installations and offer new options for retrofitting. With wireless links between train sets compatibility among vehicles can be increased, and maneuvers like coupling, de-coupling, and even slip coaching can be realized effectively.

A general difference to wired connections is that wireless links are more susceptible to interference and attacks. Security and robustness are major topics for the enhanced wireless TCN design. However, GSM-R faces similar conditions and with the use of redundant wireless links very high reliability is reached. In any case methods like sink time supervision of real time and delay critical data on the WTB have to be used and appropriate procedures in case of interruptions or authentication failures have to be implemented to guarantee fail-safe train operations.

Modern signaling and control systems rely on data exchange through a network of base stations like in GSM-R. Such communication paths are not suitable to assist the delay critical data exchange within the TCN network or an extended wireless TCN between electronically coupled train sets due to call setup times, hand over delays or possible outages. However, a few wireless communication standards already support a direct communication among devices or mobiles with very low latency, and more of them are to come in the near future.

1) TETRA: The Terrestrial Trunked Radio (TETRA) standard was developed for emergency services, public safety and military. Although limited to kbit/s data rates it can be used for communication among train sets or trains in Direct Mode Operation (DMO). The coverage is several kilometers and by using the group call functionality, data can be broadcasted to all receivers within range [13]. Because of these features TETRA is used for the Railway Collision Avoidance System (RCAS).

Another use case are virtually coupled train sets which may couple anywhere on the network even at high speeds [10]. TETRA is not favorable for virtually coupled driving at short distance because of low message rates when sharing a channel with other transceivers. However, because of its range it is enabling the approaching maneuvers.

2) ITS-G5: The IEEE standard 802.11p is an amendment to classical WLAN standards supporting vehicular environments and is implemented in the European standard ITS-G5. Data rates of up to 27 Mbit/s and communication ranges of a few hundred meters support a vast set of applications such as real-time vehicle-to-vehicle operations [14], redundancy in the TCN of consists and train sets, as well as electronically coupled driving maneuvers.

3) mm-Wave: Millimeter wavelength wireless communications between 30-300 GHz offer very high data rates in the order of Gbit/s. Because of the higher propagation and penetration losses, the communication range is much lower than for ITS-G5 and TETRA [15]. Data transmission is typically limited to the line of sight, and rain and snow can drastically decrease the performance. Nonetheless, it offers added value in many different scenarios like intra-consist and inter-consist communication, and for a redundant high rate link on couplers or between closely spaced trains in a platoon.

4) C-V2X: Cellular V2X (C-V2X) has been introduced by the 3rd Generation Partnership Project (3GPP). It provides interfaces to the cellular based long range communication and a new direct mobile to mobile communication (sidelink), which is base station coordinated (Mode 3) or self-scheduled (Mode 4). Besides an extension to LTE, the next 'Release 16' shall include V2X application layer services for 5G networks.

V. CONCLUSION

Communication systems in rail vehicles are complex. Due to long lifecycles and necessary compatibilities, there is a wide range of communication systems of current and past technology generations. The TCN standard has now included switch networks and adapted them for railway applications. Wireless networks are a current research topic. New digitization topics ranging from predictive maintenance, mobile internet to autonomous driving will require high-performance communication systems inside and outside of rail vehicles in the future.

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