Reasoning Functional Requirements for Virtually Coupled Train Sets: Communication

Riccardo Parise, Holger Dittus, Joachim Winter, and Andreas Lehner

VCTS, the equivalent of road vehicle platooning for railways, has attracted the attention of industry in the past few years due to their potential to increase the line capacity without massive investments in the infrastructure. The goal of this article is to reason out functional communication requirements for virtually coupled train sets using a bottom-up approach and introduce challenges of the railway domain to readers of the communication community.

Abstract

Virtually coupled train sets (VCTS), the equivalent of road vehicle platooning for railways, have attracted the attention of industry in the past few years due to their potential to increase the line capacity without massive investments in the infrastructure. The goal of this article is to reason out functional communication requirements for VCTS using a bottom-up approach and introduce challenges of the railway domain to readers of the communication community. Three different VCTS configurations in terms of sensor and communication concepts are presented, and quantitative examples of communication requirements are given for different application scenarios. To conclude, the ability of some technology candidates to fit these requirements is analyzed and compared in relation to each application scenario.

Introduction

Environmental concerns, especially global warming, are increasingly pressuring governments to reduce greenhouse gas emissions and fossil fuel consumption in the transport sector. One solution currently discussed is shifting transport volume from road to rail, as trains are considered as one of the most energy-efficient and ecological means of transport. This will increase the demanded transport capacity in coming years, which is already approaching its operational limits.

Virtually coupled train sets (VCTS) are an approach that could increase the capacity of the railway network without extensive investments in the track infrastructure and without lowering the safety standards of the railway industry [1]. Coupled trains can effectively increase traffic density on busy tracks. For a signaling system with fixed blocks, a set behaves as one train and therefore occupies only one block while transporting more passengers or goods.

Generally, reliable and fast communication among trains is assumed to be essential for safe operation of VCTS; however, the requirements of the communication should be a result of specific constraints, and not a prerequisite or an assumption. The goal of this article is to reflect on the role of the communication in VCTS and define functional requirements for communication technologies in different application scenarios. Thus, a bottom-up approach is used by starting with these questions: Why does VTCS require any communication? Why does it have to be reliable and fast?

To answer these questions, VCTS without any communication between trains are analyzed. In this first concept, trains control the distance between each other based only on measurements of onboard sensors such as lidar, radar, and cameras. In the second concept, trains can only measure their own absolute dynamic state (position, velocity, acceleration) and communicate it via direct (train-to-train, T2T) or indirect (train-to-infrastructure, T2I) wireless communication. In the third concept, a mixture of both ideas is discussed.

VCTS Characteristics

In VCTS, trains are not physically connected; they use the information of the dynamic state (position, speed, and acceleration) of other trains in the set to control the distance between them, similar to platooning of road vehicles. In terms of maneuvers, VCTS can be separated into three processes: approach, virtually coupled driving, and separation.

Due to the lack of physical connection, a train in VCTS can couple or decouple from sets easily, even en route. This feature introduces new functions that are not or hardly implementable with mechanically coupled trains:

- VCTS can reduce or increase the size of a set on demand, that is, assembling longer sets during peak hours of traffic and taking trains out of the set to reserve them during off-peak times.
- VCTS allow longer trains to use shorter platforms by splitting and using parallel tracks in a station.
- VCTS allow trains inside the set to have different destinations, and also join trains with different origins and common destinations.
- VCTS allow single trains to separate from the set in order to stop without having to brake the whole convoy.
- VCTS can improve the compatibility between different trains, allowing a larger variety of trains to couple with each other.

With these features the train flow can be optimized to improve the network capacity, train punctuality, and operational flexibility, and potentially reduce maintenance costs and improve

The authors are with the German Aerospace Center (DLR).

Digital Object Identifier:
10.1109/MCOM.2019.1800936

0163-6804/19/$25.00 © 2019 IEEE

energy efficiency by reducing the aerodynamic drag [2].

Basic Assumptions

A VCTS can be formed by several trains; however, a set with more than two trains introduces challenges such as chain stability and more complex decoupling, coupling, and emergency protocols that are not addressed within this article. For the sake of simplicity a convoy of two trains is analyzed.

Furthermore, train characteristics such as maximal allowed speed, acceleration, and braking capability are assumed to be identical. In reality, however, train characteristics can change dynamically; for example, the maximal acceleration changes with occupancy rates, or a train in degraded mode may not be able to provide the nominal traction power.

VCTS Using Only Relative Sensors

From the control's perspective, VCTS could theoretically work without any communication between trains, similar to the communication-less adaptive cruise control developed for cars in the 1990s. In this case, sensors are used to determine the relative dynamic state — relative position (or distance), relative speed, and relative acceleration — in relation to the vehicle ahead or behind, and control the distance between trains by regulating its own acceleration and speed. In principle, the first train could use rear facing relative sensors as well in order to take appropriate actions to control the distance.

An extensive survey of different sensors for vehicles that could be used for this application, like lidar, radar, and stereographic cameras, is presented in [3]. The range of commercial relative sensors is normally in the distance of 10–250 m, and it can be affected by several factors such as weather, light, and obstacles on the side of the track blocking the line of sight (LoS) in curves.

Reaction Delay and Admissible Minimum Distance

Purely in theory, if the relative sensors, the powertrain, and the brake system as well as the control were perfectly accurate and fast (time constant = 0), both trains could safely drive with no distance in between, as the control's error signal would always be zero. However, real sensors have a limited sampling time and accuracy, and, especially for trains, the brake and powertrain systems have time constants sometimes in the range of seconds. Therefore, the error signal is not necessarily zero during transient states, and the minimum distance between trains is limited. For VCTS without communication the reaction delay (RD) would be equal to the delay of the brake system, considering delays and errors of the sensor and control processing as negligible.

With the concept of RD, an admissible minimum distance (AMD) is defined as the lower bound for the distance between trains that allows the rear train to brake in time to avoid a collision. In steady state, the AMD depends only on the RD and their current speed. Figure 1 shows the AMD calculated for different RD and absolute speeds. Analogously, trains need to be inside a distance where they can detect each other, so the maximal range of the relative sensors acts as an upper bound for the distance between trains.

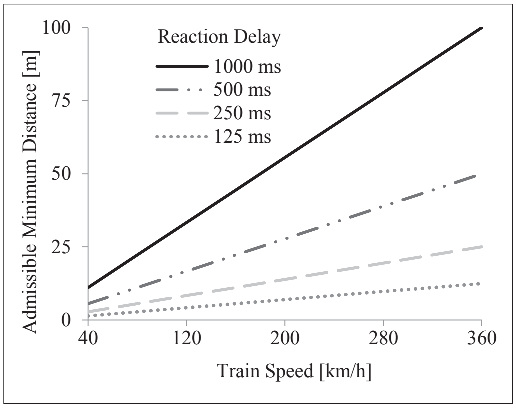

Figure 1. AMD between trains as a function of speed and reaction delay, considering both trains on steady state and with identical braking profiles. During transient states the AMD also depends on the relative speed and relative acceleration.

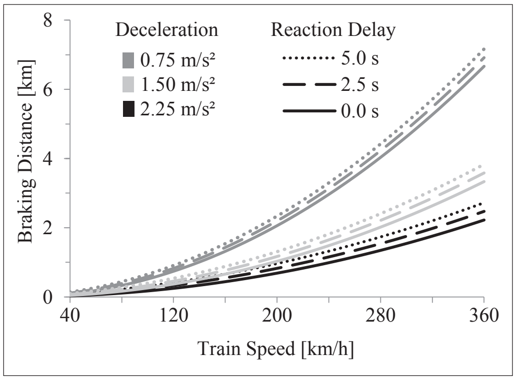

Figure 2. Braking distances as a function of initial speed, reaction delay, and train maximal deceleration.

For identical braking profiles, the AMD grows linearly with the speed, while the maximal range of the sensors is speed-independent. Thus, the maximal speed for VCTS is limited by the fact that the AMD is not allowed to exceed the maximal range of the relative sensors. For higher speeds, there is no possible distance that allows trains to be close enough for the relative sensors to detect each other and at the same time far enough to react in time.

Required Minimum Range of Relative Sensors

During the approach phase, the range of the rear train's sensors needs to exceed the absolute braking distance, considering that in the worst case the front train may be at a standstill when the rear train first detects it.

As seen in Fig 2, the absolute braking distance in most cases is an order of magnitude larger than typical ranges of relative sensors. For VCTS without communication, the limited sensor range restricts coupling maneuvers to low speeds.

VCTS Using Absolute Sensors and Wireless Communication

As an alternative to using only relative sensors, the absolute dynamic state of each train — absolute position, speed, and acceleration — could be measured using onboard (or abso-

In VCTS trains are not physically connected, they use the information of the dynamic state (position, speed and acceleration) of other trains in the set to control the distance between them, similar to a platooning of road vehicles. In terms of maneuvers, VCTS can be separated into three processes: approach, virtually-coupled driving and separation.

In contrast to the short range of the relative sensors, T2I communication has unlimited range but depends on signal availability, which restricts VCTS to locations with good coverage. T2T communication also presents a limited range, although it can be significantly larger than the typical range of relative sensors.

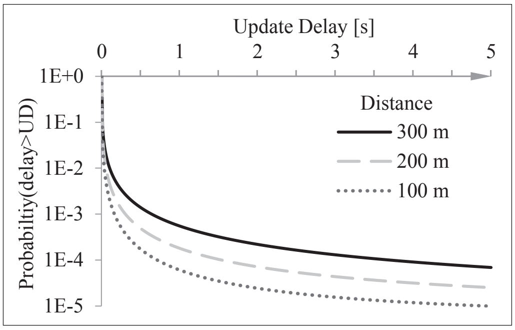

Figure 3. The vertical axis gives the probability that the time between two received messages will be larger than a given update delay. It tends asymptotic to zero, considering unlimited bandwidth.

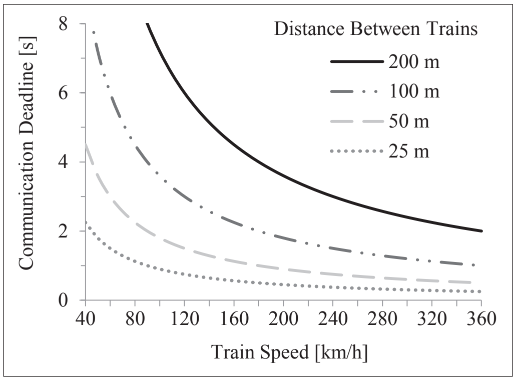

Figure 4. The communication deadline as a function of speed and distance.

lute) sensors. The measured data is exchanged between trains via a suitable communication link. In this concept the role of the communication extends to negotiating coupling and decoupling maneuvers as well as transmitting static (e.g., train type, length) and variable (e.g., current payload, current traction power) train characteristics.

The communication could be carried out either directly (T2T) or indirectly (T2I) and can mitigate some limitations from the previous concept. In contrast to the short range of the relative sensors, T2I communication has unlimited range but depends on signal availability, which restricts VCTS to locations with good coverage. T2T communication also presents a limited range, although it can be significantly larger than the typical range of relative sensors. Furthermore, communication is typically more tolerant toward weather conditions and lack of direct LoS than relative sensors.

However, VCTS using only absolute sensors have their own limitations. Positioning of trains is an ongoing topic of research with no easy commercial off-the-shelf solution. A survey on positioning solutions is presented in [4]. It is challenging to accurately measure the absolute train position and speed using odometers and speedometers because of wheel slip and uncertainties in the wheel radius, which can vary significantly due to wear. In addition to that, measuring the position by integrating speed signal or integrating the acceleration twice adds up errors, which can be only partially solved by utilizing absolute reference points to calibrate the measurements (e.g., beacons). Signal-based positioning systems like the global navigation satellite system (GNSS) or WiFi positioning system (WPS) depend on signal availability, and may not be available in tunnels or remote areas. Joining different sensors using sensor fusion algorithms can improve the measurements, and usage of several sensors provides redundancy, which improves reliability. In any case, the functional sensor requirements for VCTS are to be investigated in further works.

Update Delay and Communication Deadline

Communication can improve the RD of the VCTS because the information bypasses the time constant of the powertrain and brake system: Trains can exchange data at the moment a control command is changed, which is even before the train's own sensor can detect any change in dynamic state. The time it takes between two status updates are received is called update delay (UD) [5], which is given as a specific probability distribution for each combination of communication technology and external conditions (distance, landscape, etc.). The UD probability distribution as a function of the distance based on measurements in a regional railway network [6] is shown in Fig. 3.

In this concept the combination of speed and distance between trains will define the maximum admissible delay in communication, or *deadline*, as shown in Fig. 4 for selected distances. This is analogous to calculating the RD for a given speed, considering the AMD as current distance between trains.

Communication failing to meet the required deadline does not directly impose a collision risk. If the communication fails to update the dynamic state by the given deadline, a fallback process has to be applied. For example, the rear train could assume the worst case scenario (e.g., braking maneuver of the first train) and take appropriate actions, which by the definition of the deadline should be sufficient to safely stop the set. Alternative fallback processes could be implemented using safety margins — either for the communication deadline or the distance — and using redundant systems (e.g., additional communication devices). In general, because of the probabilistic nature of the delay, a shorter communication deadline means that more status updates will be late, which would require more corrective measures from the control and may decrease energy efficiency and passenger comfort, and increase wear of the brake system.

Required Minimum Range of Communication

In this concept, the minimum range of communication has to exceed the absolute braking distance to enable communication between the coupling trains from a safe distance. However, this does not guarantee safe operation during an approaching maneuver in all cases because it is not assured that every train on the line is communicable. Therefore, VTCS without relative sensors still depend on the signaling to confirm that there are no obstacles between trains during a coupling maneuver en route.

Representative scenarios	Speed (km/h)	Worst case RD/ deadline (s)	Typical service deceleration (m/s^2) (maximal[a])	AMD (m)	Absolute braking distance (km)
Electric multiple unit HST	350	2.5[b]	0.7 (1.0)	243	6.99 (4.97)
Electric multiple unit intercity	180	2.5[b]	0.7 (1.0)	125	1.91 (1.37)
Loco-hauled intercity	180	5.0[c]	0.7 (1.0)	250	2.04 (1.50)
Electric multiple unit regional	140	2.5[b]	0.8 (1.0)	97	1.04 (0.85)
Loco-hauled freight train	120	5.0[c]	0.6 (1.0)	167	1.09 (0.72)
Suburban and metro	80	1.5[b]	0.9 (2.0)	33	0.31 (0.16)

[a] DIN EN 13452-1: 2003 Railway Applications. Braking. Mass Transit Brake Systems. Performance Requirements.
[b] DIN EN 15734-1: 2013 Railway Applications. Braking Systems of High SpeedTrains. Requirements and Definitions.
[c] DIN EN 14198: 2016 Railway Applications. Braking. Requirements for the Brake System of Trains Hauled by Locomotives.

Table 1. Example of requirements for different scenarios.

A significant potential to further improve comfort and safety can be raised when speed trajectories based on detailed maps of the line characteristics are predicted for a defined time horizon and regularly exchanged between the trains in the set. Together with optimized procedure protocols, corrective measures can be avoided, offering the opportunity to increase energy efficiency of VCTS.

VCTS with Absolute and Relative Sensors and Wireless Communication

VTCS combining relative sensors, absolute sensors, and wireless communications could overcome the drawbacks of the previously described concepts. In the combined concept, the measurements of both trains can be compared via the communication channel in order to further increase the accuracy and reliability.

Coupling maneuvers at low speeds, where the absolute braking distance is smaller than the relative sensor's range, could be carried out using only relative sensors. The communication in this case would act as a redundant system. Coupling at higher speeds, where the absolute braking distance exceeds the relative sensor's range, requires direct or indirect communication between trains. In this case, the relative sensors would act as a redundant system in the final moments of the approach.

In general, it is desired to drive in a spectrum of distance and speed where both concepts can work independently. Therefore, the communication deadline should be equal to or faster than the reaction delay of the train. With a faster deadline, trains could drive closer, but at the expense of redundancy, because the relative sensors would not notice changes in the dynamic state in due time. In addition to that, as some changes in the dynamic state are not caused by active decisions of the control system (e.g., decelerations due to track gradient changes or increased aerodynamic resistance in tunnels), they will not bypass the RD.

A significant potential to further improve comfort and safety can be raised when speed trajectories based on detailed maps of the line characteristics are predicted for a defined time horizon and regularly exchanged between the trains in the set. Together with optimized procedure protocols, corrective measures can be avoided, offering the opportunity to increase the energy efficiency of VCTS.

Requirements Example

In order to give specific examples of communication requirements in different railway scenarios, the relevant standards have been analyzed to determine typical train parameters. The resulting requirements are presented in Table 1. However, in modern trains with electro-pneumatic and/or electro-dynamic brakes, RD can be significantly lower.

The typical service deceleration in Table 1 was chosen inside comfort limits, because control should be able to correct errors inside these limits; in addition, the maximum comfort value (in parentheses) is also considered to show its impact on the resulting braking distance. The RD used in the table is based on the maximum allowed reaction time (worst case), according to the respective standards; however if for real trains a shorter RD is proven, the AMD can be reduced.

Technology Candidates

Some currently available and future communication technologies that could be used for VCTS are presented and evaluated against the requirements in Table 1.

Train-to-Train

TETRA: The Terrestrial Trunked Radio, or TETRA, is a European standard for radio communication and is used for emergency services, public safety networks, train radios, and the military. It can be used for T2T communication without network coverage in direct-mode operation (DMO) [7]. TETRA is especially interesting because of its reliability at high relative speeds and good performance in strong multipath environments. It has a typical range of 3 km for urban environments and up to 20 km for rural. The update delay distribution was investigated on a high-speed train (HST) in Italy in [8], and its performance shows that the delay is below 4–12 s for more than 99 percent of time for distances between of 25 km, respectively.

The technical characteristics of this technology are not favorable for use in coupled driving because of its relatively large update delays. However, because of its range it is relevant during the approaching phase as a redundant reliable system to communicate non-time-critical information.

IEEE 802.11p/ITS-G5: IEEE standard 802.11p is an amendment to 802.11 focused on vehicular environments, and was used as the basis for the European standard ITS-G5. Its ability to support real-time operations vehicle-to-vehicle is discussed in [9], and because of its characteristics it is a promising technology to support VCTS applica-

VCTS performance can be improved if both measurement systems (relative sensor and absolute sensors) are used together with communication. In general, T2T communication technologies with a longer range and T2I technologies (e.g., LTE-R, GSM-R) with more coverage will improve the flexibility of the VCTS.

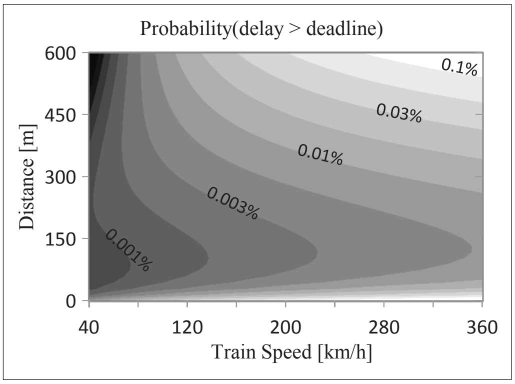

Figure 5. Probability (in percentage of time) the update delay exceeds the required deadline for a given speed and distance. (Based on the measured data for ITS-G5 at 3 Mb/s and transmit power of 24 dBm.)

tion. The theoretical delay lower limit (DLL) of this standard is below 0.26 ms. Considering the standard's lowest data rate and a payload of 128 bytes, the theoretical delay is still under 0.6 ms [10], which is still at least three orders of magnitude faster than the most ambitious deadline for the communication in Table 1. The actual performance, however, depends on several variables such as distance between trains, direct LoS, and interference [11]. Based on experimental data for 100 m, 200 m, and 300 m, the probability that this technology can meet the specific deadline for each speed and distance combination has been extrapolated for a wider range distance, and is presented in Fig. 5.

C-V2X: Lately, cellular vehicle-to-everything (C-V2X) short-range communication technologies were defined by the Third Generation Partnership Project (3GPP). While Release 15's LTE-V2X is based on 4G cellular standards, the upcoming Release 16 shall also include V2X application layer services for 5G. The strength of C-V2X is that it provides interfaces to both the traditional 4G/5G cellular-based long range communication, and a new vehicle-to-vehicle (V2V) communication, which is base station coordinated or even self-scheduled (Mode 4) in areas without coverage. Proof of concept testing has started recently demonstrating latencies around 20 ms in the case of direct communications between mobiles. However, compared to ITS-G5, the latency is much higher, and the update delay performance in Mode 4 is less promising if the channel is congested (e.g., next to a rural freeway), as the ITS-G5 medium access control (MAC) layer achieves significantly lower correlation between errors [12], most notably at distances of more than 100 m, which is of great importance for VCTS. However, in places with infrastructure coverage (i.e., stations and rail yards), radio scheduling management can be used (in Mode 3), which can improve the latency significantly by ensuring packet collision avoidance.

Millimeter Wavelength: Millimeter wavelength or mmWave is generally referred to as communications in the range of 35–40 GHz. Because of the higher propagation and penetration losses, it normally presents a lower range than longer waves such as ITS-G5 and Tetra [13]. Nonetheless, it has become a recent topic of research in the railway industry for T2I communication as lower frequencies are becoming increasingly more congested. Communication in the mmWave range could possibly be used for T2T communication, allowing a fast data exchange between trains at lower distances. It could be used in combination with other technologies as a redundant communication link.

Train-to-Infrastructure [14]

GSM-R: The GSM-R system was developed based on GSM specifically for railway communication. It is the data carrier chosen for ETCS technology, and it is already implemented in real railway applications. It has a typical delay in the range of 400 ms, which in theory is fast enough to allow trains to join VCTS. However, signal coverage is challenging, and its reliability depends on propagation conditions such as shadowing and multipath.

LTE-R (4G): LTE-R is a standard based on LTE, and will most likely replace GSM-R for railway applications in the future. It is under implementation; however, in order to be compatible with ETCS-L3, it is expected to be able to provide transmission of control information with a delay less than 50 ms. LTE-R could possibly be used for coupled driving of HST, provided enough coverage.

5G: 5G is still under development, and it will probably be available after 2020. However, in particular, one of its expected service categories, ultra-reliable low-latency communication (URLLC), could be used for VCTS, providing a fast data link between trains.

Conclusion

Based on previous discussion, VCTS performance can be improved if both measurement systems (relative sensor and absolute sensors) are used together with communication. In general, T2T communication technologies with a longer range and T2I technologies (e.g., LTE-R, GSM-R) with more coverage will improve the flexibility of the VCTS.

The recommended metric to evaluate communication performance for VCTS application is the probability distribution of the update delay as a function of distance. There are communication technologies that could already serve VCTS applications in a wide variety of scenarios; however, the actual requirements for the communication depend deeply on the control concept, sensors, protocols, and fallback strategies.

The dynamic state of a train is affected by passive forces (e.g., changes in the track gradient and aerodynamic drag), as well as active forces (i.e., braking or accelerating). Active forces can be communicated at the moment the control decides to apply it. Thus, control signals bypass the RD, and the time it takes for those changes to be propagated to the next train depends only on the update delay of the communication. Passive forces, in contrast, act directly on the dynamic state, so they require an AMD based on the RD of trains.

For future work, the impact and predictability of passive forces have to be assessed in detail to analyze their effect on control strategies and procedure protocols. The functional requirements for sensors need to be defined in more detail, and further developments in control concepts, protocols, and fallback strategies have to be elaborated. Besides technological challenges, the legal implementations and regulations are critical obstacles for VCTS [15]. Also, the economic potential is a decisive factor to justify the implementation costs; for example, the impact of VCTS on energy demand and on the electric grid needs to be investigated.

For future work, the impact and predictability of passive forces have to be assessed in detail to analyze their effect on control strategies and procedure protocols. The functional requirements for sensors need to be defined in more detail, and further developments in control concepts, protocols, and fallback strategies have to be elaborated.

References

[1] J. Winter, A. Lehner, and E. Polisky, "Electronic Coupling of Next Generation Trains," *Proc. Third Int'l. Conf. Railway Technology: Research, Development and Maintenance*, Civil-Comp Press, 2016, Paper 189.

[2] H. Wilhelmi *at al.*, "Aerodynamic Investigations of the Effects of Virtual Coupling on Two Next Generation Trains," *Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, Springer, 2017, pp. 695–704.

[3] F. de Ponte Mller, "Survey on Ranging Sensors and Cooperative Techniques for Relative Positioning of Vehicles," *Sensors*, vol. 17, no. 2, Jan. 2017, p. 271.

[4] J. Otegui *et al.*, "A Survey of Train Positioning Solutions," *IEEE Sensors J.*, vol. 17, no. 20, Oct. 2017, pp. 6788–97.

[5] B. Kloiber *et al.*, "Update Delay: A New Information-Centric Metric for a Combined Communication and Application Level Reliability Evaluation of CAM Based Safety Applications," *Proc. 19th ITS World Congress*.

[6] P. Unterhuber, A. Lehner, and F. De Ponte Mller, "Measurement and Analysis of ITS-G5 in Railway Environments," *Proc. 10th Int'l. Wksp. Nets4Cars/Nets4Trains/Nets4Aircraft*, San Sebastian, 2016, Springer. ISBN 978-3-319-38920-2

[7] A. Lehner, C. Rico Garca, and T. Strang, "On the Performance of TETRA DMO Short Data Service in Railway VANETs," *Wireless Personal Commun.*, vol. 69, no. 4, May 2012, pp. 1647–69.

[8] A. Lehner, T. Strang, and P. Unterhuber, "Direct Train-to-Train Communications at Low UHF Frequencies," *IET Microwaves, Antennas & Propagation*, vol. 12, no. 4, Mar. 2018, pp. 486–91.

[9] K. Bilstrup *et al.*, "On the Ability of the 802.11p MAC Method and STDMA to Support Real-Time Vehicle-to-Vehicle Communication," *EURASIP J. Wireless Commun. and Networking*, vol. 2009, 2009, pp. 1–13.

[10] Y. Wang *et al.*, "Throughput and Delay Limits of 802.11p and its Influence on Highway Capacity," *Procedia — Social and Behavioral Sciences*, vol. 96, Nov. 2013, pp. 2096–2104.

[11] H. Q. Le, A. Lehner, and S. Sand, "Performance Analysis of ITS-G5 for Dynamic Train Coupling Application," *Lecture Notes in Computer Science*, Springer, 2015, pp. 129–40.

[12] A. Bazzi *et al.*, "Study of the Impact of PHY and MAC Parameters in 3GPP C-V2V Mode 4," *IEEE Access*, vol. 6, Nov. 2018, pp. 71,685–98.

[13] H. Song, X. Fang, and Y. Fang, "Millimeter-Wave Network Architectures for Future High-Speed Railway Communications: Challenges and Solutions," *IEEE Wireless Commun.*, vol. 23, no. 6, Dec. 2016, pp. 114–22.

[14] R. He *et al.*, "High-Speed Railway Communications: From GSM-R to LTE-R," *IEEE Vehic. Tech. Mag.*, vol. 11, no. 3, Sept. 2016, pp. 49–58.

[15] F. Rüsch, *Zukunftskonzept virtuelle Kupplung*, Ph.D. dissertation, Technische Universität Berlin, Germany, 2018.

Biographies

Riccardo Parise completed his undergraduate degree in mechanical engineering at the University of Campinas (UNICAMP) in 2017. He has been with the German Aerospace Center (DLR) in Berlin since 2018, where he works on the concept of virtual coupling in the project Next Generation Train.

Holger Dittus received his Dipl.-Ing. degree in mechanical engineering from the Rheinisch-Westfälische Technische Hochschule Aachen in 2006. He has been the Group Leader of Energy Management and Verification at the Institute of Vehicle Concepts of DLR since 2011.

Joachim Winter received his Dipl.-Ing. degree in aerospace engineering from the Technische Universität Braunschweig in 1981 and his Ph.D. degree in engineering from the Mercator-Universität Duisburg in 1987. He is a senior scientist and project leader of the Next Generation Train at the Institute of Vehicle Concepts of DLR since 2008.

Andreas Lehner received his Dipl.-Ing. degree in mechatronics from Johannes Kepler University in Linz in 2001 and a Ph.D. in electrical engineering from the University Erlangen-Nuremberg in 2007. Currently he is a senior research scientist at the Institute for Communications and Navigation at DLR. His research and project work focuses on safety systems in transportation, the design of vehicle-to-vehicle communication systems, and the characterization and analysis of multipath and interference effects in satellite navigation and communication systems.