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Review Article

A Survey of Channel Measurements and Models for Current and Future Railway Communication Systems

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Modern society demands cheap, more efficient, and safer public transport. These enhancements, especially an increase in efficiency and safety, are accompanied by huge amounts of data traffic that need to be handled by wireless communication systems. Hence, wireless communications inside and outside trains are key technologies to achieve these efficiency and safety goals for railway operators in a cost-efficient manner. This paper briefly describes nowadays used wireless technologies in the railway domain and points out possible directions for future wireless systems. Channel measurements and models for wireless propagation are surveyed and their suitability in railway environments is investigated. Identified gaps are pointed out and solutions to fill those gaps for wireless communication links in railway environments are proposed.

1. Introduction

In modern and future trains a huge amount of wireless communication devices is operating. Wireless communication is needed in terms of train-to-train (T2T) and train-to-ground (T2G) communication for safety like train collision avoidance and railway management or customer oriented services such as passenger internet access. Therefore, wireless communication is a key technology to increase railway transport efficiency and safety. Furthermore, to reduce costs and maintenance time, replacing wired connections with wireless communications is foreseen. Wireless connections may be used for simple sensors up to connecting whole train consists for the Train Control and Management System (TCMS). Applications like Closed Circuit Television (CCTV) especially may need connections with data rates in the Gbit/s domain. As a consequence, a lot of wireless communication devices operating at different frequencies will be widely deployed in trains. The performance evaluation of such communication systems should be based on simulations employing realistic channel models used in order to evaluate the key performance metrics for T2T, T2G, and intraconsist wireless communication systems related to railway application requirements.

Today, transmitter and receiver design, physical layer technologies selection, and cross layer and architecture optimization are adapted to the wireless propagation channel that is related to the electromagnetic wave propagation environment. T2T and T2G wireless propagation channels exhibit different properties compared to classical mobile communication channels. One reason is the large relative speed between two trains in the T2T case or the large total speed of more than 300 km/h for High Speed Trains (HST) in T2G communications. In such cases, the channel exhibits rapidly time-varying and nonstationary properties. Comparing road traffic and railway traffic, many similar propagation effects can be expected. Differences result from the nature of trains as large and bulky but similar metallic objects using rails and mostly catenaries. Additionally, the traffic on railways is limited such that a line-of-sight (LOS) component exists in most of the T2T and T2G scenarios, and the obstacles and scatterers are limited in the propagation environment. Therefore, obstacles are visually seen for a longer period of time causing multipath components to affect the received signal for a long travelled distance. A lot of literature is devoted to the optimization of key signal processing techniques (such as synchronization, channel estimation, spectrum sensing, and precoding techniques [1–4]) in the context of HST, metros, or T2G domains. Generally, the communication quality is poor as the channel is nonstationary [5, 6].

Wireless channels are closely coupled to the surrounding environment, of transmit and receive antenna. Special scenarios must be considered in T2T and T2G channel models, such as tunnels, cuttings, viaducts, railway stations, inside of the trains, obstacles, and some combined scenarios. This makes channel characterization in the railway environment different to the automotive domain. Still, many methods used to characterize car-to-car (C2C) and car-to-infrastructure (C2I) channels are applicable for T2T and T2G with some modifications. In terms of modelling approaches, T2T and T2G channel models can be divided into three main classifications: deterministic channel models, geometry-based stochastic channel models (GSCM), and stochastic channel models (SCM) [7].

This paper gives a survey on present propagation channel measurements and models. The focus is on the analysis of channel models from the railway manufacturer and operator point of view for T2T, T2G, and interconsists communications. Customer related services and independent wireless links of passengers are neglected. The resulting gaps are pointed out that should be filled by dedicated measurement campaigns.

The structure of this paper is as follows. Section 2 gives an overview of railway communication systems inside and outside of the train including the nowadays used and future wireless applications. In Section 3 the theoretical background of channel sounding and modelling as well as existing channel models is described. An investigation on several channel measurements and different models leads to obvious gaps for T2T and interconsist communications. In Section 4 conclusions are drawn and open issues for future railway channel measurements and modelling in railway environment are formulated.

2. Railway Communication Systems

Railway communication systems can be divided into different application groups: safety and control, operator oriented services, and customer oriented networks. Note that customer oriented networks and services are out of scope of this paper. In this section we first describe the communications inside trains and then the one outside trains commonly employed nowadays. Next we address the current wireless systems for railway applications and finally we sketch possible future directions of wireless systems in railways.

In railways similar nomenclatures are used as in road traffic. A consist contains coupled vehicles and can operate independently. Several consists can be coupled to one train. Vehicles within a consist can be locomotives or coaches, also called cars or wagons in the literature.

2.1. Inside Train Communications. On-board communication networks were installed aboard trains since the end of the 1980s to reduce the cable beams used to transfer information between different devices like human to machine interface (HMI), passenger information system (PSI), or heating, ventilating, and air conditioning (HVAC) (cf. Figure 1). Multiplexing digital information technics over a serial cable have tried to replace most of the classical point-to-point copper lines or so-called train lines. Wired communication networks were standardized for on-board railway applications in the end of the 1990s (standard [8, 9] by defining Wire Train Bus/Multifunction Vehicle Bus (WTB/MVB) networks for TCMS applications as shown in Figure 1). In [10] a survey of railway embedded network solutions is presented.

Standard technologies such as WorldFIP, CANOpen, LonWorks, Profibus, or Train Communication Network (TCN) are deployed either for metro or trains. Since the 2000s, manufacturers considered the Real-Time Ethernet (RTE) technologies by adding new standards to IEC 61375 standard series, such as Ethernet Train Backbone or Ethernet Consist Network (ETB/ECN). In addition to the control-command functions offered by the classical fieldbuses technologies, RTE provides Internet Protocol (IP) traffic. In recent years, Power Line Communication (PLC) technology for communications inside vehicles in the field of aerospace and automotive industries experiences important developments.

2.2. Outside Train Communications. The vehicle to infrastructure communication is widely deployed for train applications. T2G systems using GSM-R or IEEE 8002.11 are used to communicate with wayside units. More details about these systems are explained in Section 2.3.

Communication between vehicles in the public transport sector covers several applications. The first one, often referred to as the concept of *carrier pigeon*, consists in providing information on the fly between two vehicles. The use case is often a disabled vehicle, out of range of a communication network, that will transmit information to another vehicle passing nearby [40, 41]. A second use case currently investigated in research is *virtual coupling* of two vehicles (car trains, subways, and trams). By virtual coupling two vehicles shall be interconnected without mechanical connectors. Therefore, the coupling process itself could be accelerated and specific mechanical connectors that deteriorate quickly under the rough vibration conditions in railway operations could be avoided. Nevertheless, for virtual coupling, T2T

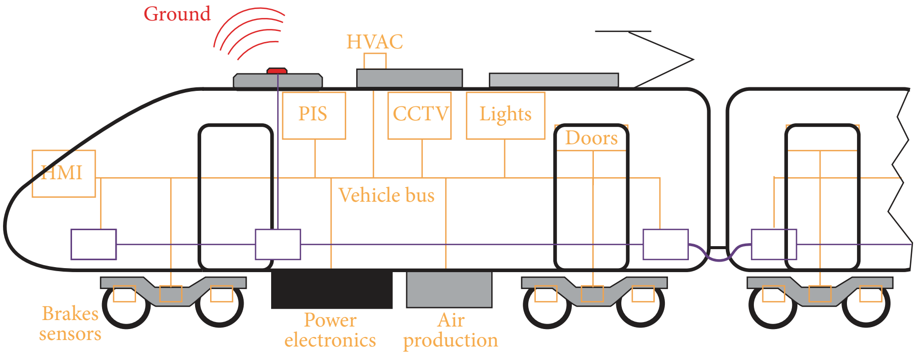


Figure 1: State-of-the-art train communications.

communications are essential to interconnect high speed networks embedded in both vehicles. One of the candidate technologies for the wireless connection is UWB (Ultra Wideband) such as the IEEE 802.15.4a standard. A survey of applications for UWB based communications in the railway domain is given in [42]. The UWB links are deemed more robust to frequency selective fading [43]. New technologies at 60 GHz carrier frequencies like IEEE 802.11ad and machine-to-machine type communication systems as being defined in 4G and future 5G may also be considered.

2.3. Current Wireless Systems. Apart from legacy systems (usually analogue) that started their development in the early 1980s, the trend of applying wireless systems in railways is still in its first decade of life. There are three types of systems: first, those based on open standards, like Terrestrial Trunked Radio (TETRA), Global System for Mobile Communications (GSM), General Packet Radio Service (GPRS), and IEEE 802.11 family of standards; second, slight modifications on some layer, but already based on open standards (e.g., GSM-R); and, finally, proprietarily developed technologies for railways, for example, ECTS-EUROBALISE.

Within the first type, there are many success cases, not only in the train-to-wayside field, but also in the sensor network field, with sensors all over the train, linked by a Bluetooth or ZigBee network. Within the vehicles, another common solution is to use a Wireless Local Area Network (WLAN) to provide passengers' access to the internet. The uplink between the train and the internet is provided by a mobile operator using Long Term Evolution (LTE), Universal Mobile Telecommunications System (UMTS), or GPRS. Moreover, ticket validation equipment based on Low Frequency (125–135 kHz) and High Frequency (13.56 MHz) RFID bands should be considered and also vehicle tagging based on Ultra High Frequency RFID solutions: 865–869 MHz (EU), 902–928 MHz (USA), and 952–955 MHz (JPN).

GSM-R is the most famous system based on GSM standard phase 2+ [44] with major modifications to fulfil many railway-based needs, like functional or regional addressing and many more. In subways, it is very likely to have some implementations of IEEE 802.11g with optimizations at certain communication layers to improve the performance, in terms of mobility aspects, for example, like done for the TEBATREN solution that is already in service in Metro de Madrid and in some others. In the signaling field, the use of IEEE 802.11-based radio for the CBTC solutions exists since several years [45]. Examples are systems from Bombardier and Dimetronic (now part of Siemens) and also Alstom's Urbalis System.

Moreover, proprietary wireless communication solutions have also its niche in the market. Traincom by Telefunken (recently acquired by Siemens) is a good example with a great acceptance in the railway sector. It is currently used in many places around the world, where the driverless line of Barcelona Metro is perhaps its most famous implementation. Another case is the Israeli company Radwin in Moscow Metro, launched last summer.

Further, new developments are LTE for CBTC applications for metro and tramways [46] and the railway proprietary ETCS-EUROBALISE application standardized at 27.095 MHz for telepowering of the trackside beacon and 4.234 MHz for the communications itself [47].

2.4. Possible Directions for Future Wireless Systems. The future wireless systems for railways need to address many issues like costs, spectrum allocation, and interoperability between different railway systems. Depending on the point of view, actual technology is very expensive and sometimes it is not interoperable at all. GSM-R is a possible exception in terms of interoperability only. However, open standards like 3GPP LTE imply heavy costs and possible dependence on mobile operators, which is something unlikely to be accepted by railway operators apart from other disadvantages.

Despite of all these issues, one of the aims of several research groups in Asia and Europe and projects all over the world, for example, Roll2Rail Project [48], is to study feasible wireless communication technologies for both T2G and T2T and inside train communications (cf. Figure 2). It is not a secret that 3GPP LTE has introduced some functionality on its last release that targets the railway sector, like mobile relays, public safety issues, Device-to-Device (D2D) communications, and so forth. On the other hand, for C2C communications, IEEE 802.11p is planned to be deployed in smart cars in near future. So, IEEE 802.11p could be an option for T2T communications if high data rates are

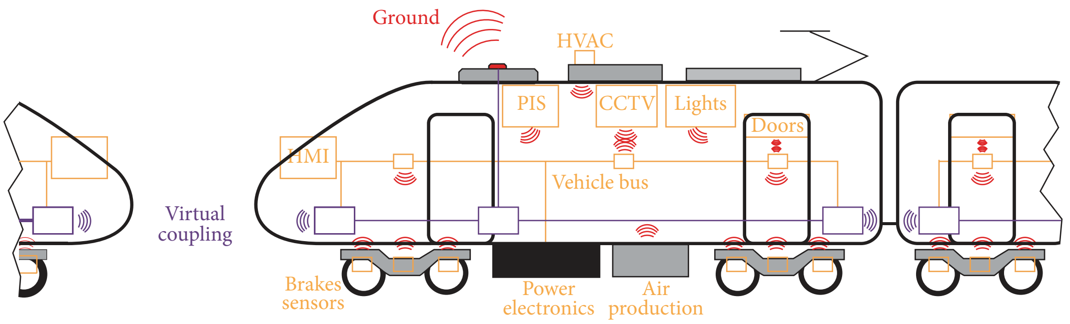


FIGURE 2: Future wireless train communications.

not required. Other solutions based on UWB technology or millimeter wave solutions in the range of 60 GHz carrier frequencies are foreseen.

Furthermore, spectrum allocation is always a challenge. Industrial Scientific and Medical (ISM) bands at 2.4 and 5 GHz are always a possibility but imply potential problems, in terms of security. Additionally there is some discussion on the possibility of using the Intelligent Transportation System (ITS) band at 5.9 GHz for urban rail systems. Facing the problem from the business perspective, partnerships with mobile operators to deploy mobile networks and also provide some nonsafety services to operators and stakeholders is possible but implies some regulatory challenges that should be addressed, too.

Moreover, it is also important to account for the ongoing work on cognitive radio. The concept of cognitive radio was highlighted as an attractive solution to the problem of congestion of the radio spectrum occupied by licensed users [49, 50]. Cognitive radio (CR) is a radio or a system capable of analyzing its electromagnetic environment and be able to adjust dynamically and independently operational radio parameters to modify the operation of the system, that is, throughput, interference cancellation, the interoperability, and access to other radio networks. This field of research is very active at European and international level. For instance, the French project CORRIDOR (COgnitive Radio for RailIway through Dynamic and Opportunistic spectrum Reuse) is paving the way for the development of cognitive radio technologies for railway applications. The project objectives were to design, develop, and evaluate fundamental bricks of a CR system adapted to the requirements and constraints of High Speed Railway (HSR), for example, high speed, electromagnetic interference, and poor coverage of systems in rural area. More details and publications can be found in [51].

To summarize this section, the main focus for future wireless train communications as depicted in Figure 2 needs to be on providing reliable and real-time data links with the required data rate for safety critical applications while providing best-effort high data rate links for other applications. In a first step research should focus on removing cabling and connectors that suffer from mechanical and environmental stress: consist-to-consist autocoupler, rail car-to-car cabling, and bogie-to-car body cabling. In conjunction with new railway applications such as virtual coupling, future train wireless communications will enable the railway operators to reduce downtime of trains and increase efficiency and safety of the railway system.

3. Existing Channel Models

In general, the characterization of the mobile propagation radio channel can be developed from the general description of linear time-variant channels. The wireless channel between the receive and the transmit antenna can be completely characterized by its channel impulse response (CIR) $h(\tau)$ or by its Fourier transform, the frequency response $H(\omega)$, provided that the channel can be modelled as a linear time-invariant system. If the transmitter, receiver, or objects which interact with the electromagnetic waves are not static, we obtain a time-variant CIR $h(\tau, t)$ (using the representation $h(\tau, t)$, we inherently assume a linear time-invariant impulse response $h(\tau, t_0)$ at a specific time instant t_0). This CIR can be transformed to frequency domain with respect to the delay τ or the time t, giving rise to several equivalent descriptions as illustrated in Figure 3. These representations in time and frequency domain of the linear time-variant channel are described in detail in Bello's classical paper [52].

In order to characterize the wireless propagation channel for later system simulations, a representation for the CIR $h(\tau, t)$ needs to be found. The representation might be based on pure deterministic calculations where the geometrical relations and electrical properties of the environment, transmitter, and receiver are fully known. Other well-known approaches ignore the geometrical relations or electrical properties and represent the CIR $h(\tau, t)$ as a random variable.

3.1. Channel Sounding or Measurement Methodology. A channel sounder is a system consisting of a transmitter and a receiver that is designed to measure the properties of the wireless propagation channel. One can distinguish channel sounders working in the time domain or in the frequency domain [53]. In the following description, we will describe the principle operation of a single-input single-output (SISO) channel sounder (an extension to single-input multiple-output (SIMO) or multiple-input multiple-output (MIMO) is straightforward), using the Medav DLR-RUSK channel

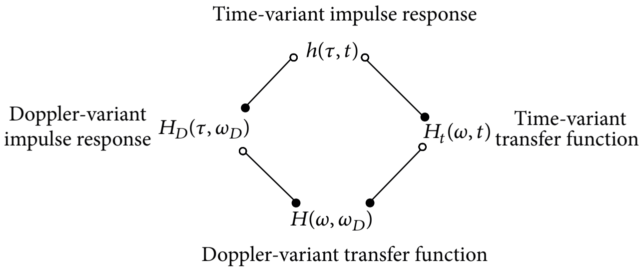


Figure 3: The time-variant impulse response and its frequency-domain equivalents.

sounder [54] owned by the German Aerospace Center (DLR) as an example.

In a practical measurement setup as depicted in Figure 4, the channel sounder transmitter generates a periodic wideband signal $s(t)$ with bandwidth B and period t_p. In a postprocessing step, the CIR $h(\tau, t_0)$ at a certain time instant t_0 is calculated from the received signal starting at t_0 with time duration of t_p. Figure 5 shows an example of CIRs recorded within 1 s in a T2T measurement scenario. Using the theory by Bello in [52], we assume that the CIR is time-invariant and bounded at t_0; that is, $h(\tau, t_0)$ can be described by a linear filter. Therefore, the period t_p of the transmitted signal $s(t)$ needs to be short such that we may assume that $h(\tau, t_n)$ is constant for a time duration t_p. Therefore, the following condition should be met:

$$t_p \cdot v_{\max} \ll \lambda, \tag{1}$$

where λ stands for the wavelength of the carrier frequency and $v_{\max}$ the maximum relative velocity (assuming a static environment, $v_{\max}$ would be the relative velocity between the two trains in a T2T scenario, e.g.). Restricting the time duration of $h(\tau, t_n)$ to $0 \leq \tau < t_p$ allows resolving occurring multipath signals with a maximum excess delay of t_p relative to the first arriving path (usually the line-of-sight path). In other words

$$t_p > \tau_{\max} - \tau_0, \tag{2}$$

where $\tau_{\max}$ is the highest delay of receivable multipath components and τ_0 the delay of the first receivable path.

In order to measure the time variation of the propagation channel, the time duration between the measurements of two consecutive CIRs $t_r = t_{n+1} - t_n$ needs to be short enough such that the maximum possible Doppler frequency can be resolved without aliasing. As the maximum possible Doppler frequency is a function of $v_{\max}$ and λ, the condition can be expressed as

$$t_r \cdot v_{\max} < \frac{\lambda}{2}. \tag{3}$$

Especially in T2T scenarios, the distance between both trains may vary between $d_{\min} \approx 4.5$ m, the distance between two parallel tracks, and several kilometers. Therefore, the adaptive gain control (AGC) should be able to supply a large dynamic range such that the received signal amplitude can be adjusted to the input range of the analogue-to-digital converter (ADC) when the transmitter-receiver distance is $d_{\min}$ and the maximum distance $d_{\max}$ given by the link budget. Assuming free space path loss, the AGC should supply a dynamic range a_{range} in dB of

$$a_{\text{range}} = 20 \log_{10} \left(\frac{(4\pi d_{\max}) / \lambda}{(4\pi d_{\min}) / \lambda} \right) = 20 \log_{10} \left(\frac{d_{\max}}{d_{\min}} \right). \tag{4}$$

Taking a typical configuration of the Medav DLR-RUSK channel sounder, $t_p = 12.8\,\mu$s, $t_r = 1.024$ ms, and $a_{\text{range}} = 52$ dB. Therefore, using a carrier frequency of 5.2 GHz, that is, $\lambda = 5.77$ cm at a maximum relative speed of $v_{\max} = 25$ m/s, the first condition in (1) can be fulfilled as $12.8\,\mu\text{s} \cdot 25\,\text{m/s} = 0.3\,\text{mm} \ll \lambda$. According to fast-train measurements described in [55], the maximum value for $\tau_{\max} - \tau_0 < 1.5\,\mu$s; therefore, the condition in (2) is fulfilled with $t_p = 12.8\,\mu$s. To measure the time variation of the propagation channel, that is, to be able to resolve the maximum possible Doppler frequency, the condition in (3) needs to be achieved. Taking the value for t_r and $v_{\max}$, we notice that the maximum Doppler can be measured with only a little margin. Therefore, in the configuration with $t_r = 1.024$ ms, the relative speed is limited. In a HST T2T propagation scenario with relative speeds of about 600 km/h, t_r would need to be decreased to 0.173 ms in order to measure the maximum possible Doppler frequency. Using a dynamic range 52 dB of the AGC and $d_{\min} = 4.5$ m allows measuring up to 1.791 km using the maximum input range of the ADC.

3.2. Types of Channel Models.

One can distinguish three main categories of channel modelling approaches for performance evaluation that are used within the context of vehicle to vehicle channels: deterministic, geometrical-stochastic, and stochastic.

3.2.1. Deterministic Channel Models.

Deterministic channel models characterize the C2C or C2I channels in a completely deterministic way. They may be based on rigorous solving of Maxwell's equations like Method of Moments (MoM) and Finite Difference Time Domain (FDTD) or on asymptotic approaches introducing the concept of "rays," that is, ray tracing. Ray tracing is, computation-wise, able to simulate much bigger scenarios compared to MoM or FDTD which is the most widely used technique in characterizing channels in a deterministic manner. The main idea of ray tracing is to regenerate "rays" from the transmitter to the receiver, taking into consideration reflections and diffractions occurring due to objects in the environment. Therefore, it is required to define the shape, properties, and location of all the involved objects in the radio environment. Hence, the detailed description of the environment and the following intensive computations are time and effort consuming, and the extracted CIR cannot be easily generalized to different scenarios. In [56] ray tracing was applied to the car-to-car channel. The implementation was divided into three distinguishable parts. The first part was the modelling of the road traffic, that is, other cars. To characterize the channel's Doppler shift and Doppler spread accurately, the dynamic behavior of

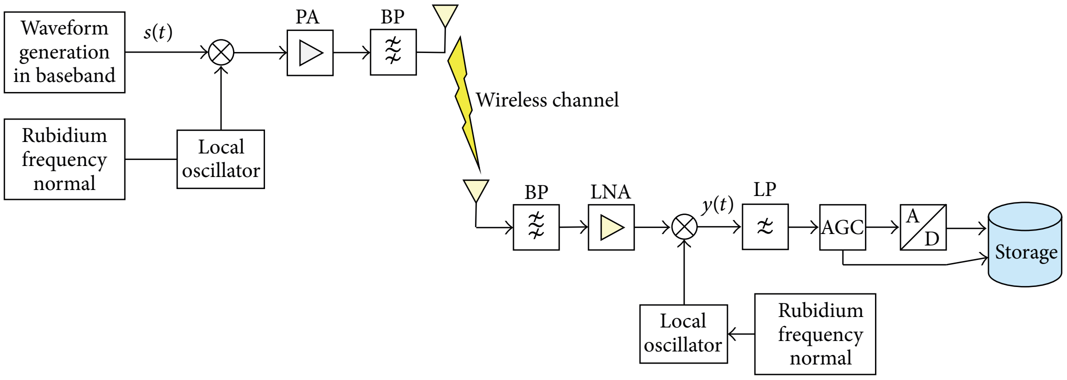


FIGURE 4: Principle of channel sounding.

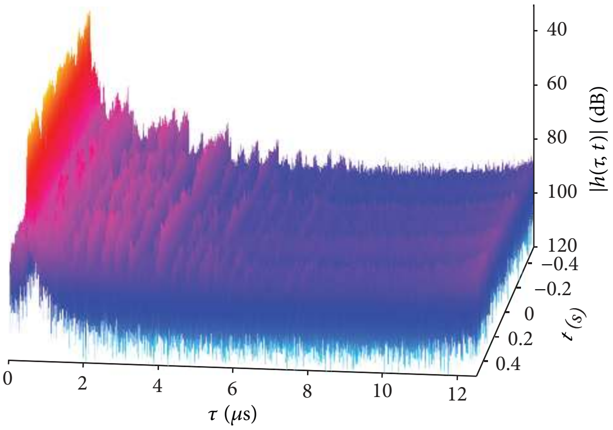


FIGURE 5: Example of a CIR $h(\tau, t)$ measured in a T2T link scenario.

the transmitting and receiving vehicles as well as the adjacent vehicles has to be simulated in a realistic manner. Authors considered microscopic modelling to simulate each vehicle separately, resulting in a realistic instantaneous position and velocity for each vehicle at each snapshot in the simulation. The Wiedemann traffic model was implemented to describe road traffic for different scenarios. The second part was the modelling of the environment, where a stochastic model was chosen to draw the environmental surroundings such as buildings, parked vehicles, and trees. The third and last part is the modelling of the wave propagation. Here, ray tracing was used to simulate the multipath propagation from the transmitter to the receiver. A carrier frequency of 5.2 GHz was used in the simulation. Results were validated against measurement data obtained using a RUSK ATM vector channel sounder operating at the same carrier frequency. The comparison between measurement and simulation showed that the proposed deterministic channel model fits well to measurement results and real-life scenarios. Ray tracing for T2G environments was investigated in the mm-wave band in [57], where a HST environment was considered including a transmitter mounted on the top of a fence while the receiver antenna was located on the top of the train. For the scenario, the ray tracing simulator RapLap was used to simulate the wireless propagation channel. Results, such as received power, delay spread, and angular spread, were provided. A dynamic channel model was also proposed using obtained statistical parameters from the deterministic simulation method. A comparison to measurement data was omitted. In [58] the authors focused on the propagation channel inside a train wagon using ray tracing based on the EM CUBE software simulator from Emag Technologies Inc. [59].

3.2.2. Geometry-Based Stochastic Channel Models (GSCM). In GSCM, scatterers, representing individual propagation paths, are distributed in a virtual geometrical environment. Using the geometrical relations between the transmitter, a scatterer, and the receiver, the delay and angle of arrival of different propagation paths can be calculated according to a simplified ray tracing procedure. Diffuse multipath contributions may be included by considering clusters of points as scatterers. GSCM can be easily adapted to different scenarios by changing the geometrical distribution of the scatterers, making a good compromise between complexity and accuracy. Furthermore, GSCM can be easily adapted to nonstationary environments based on the geometrical relations, making them a good candidate to describe T2T and T2G channels. In recent years, GSCM gained a lot of research interest in the C2C domain; their flexibility is tempting to extensively use them in the T2T and T2G domains. Authors in [60] adopted a GSCM to characterize the MIMO channel in the C2C domain. Distributed scatterers were divided into three different groups. The first group represents paths occurring due to wave interactions with moving objects, that is, other vehicles. A second group represents propagation paths from static objects like road signs or other structures next to the road or in the middle between both traffic lanes. The last group describes diffuse components originating from trees, buildings, or walls. Each group is given different stochastic and deterministic properties (such as geometrical density, path loss exponent, and reference power). The model was validated by comparing simulations to measurements performed with the RUSK LUND channel sounder in both rural motorway and highway environments. Detailed discussion on vehicular channel characterization was presented in [61, 62], where the authors discussed C2C channel and GSCM in detail. A GSCM for HST was developed in [63] where a nonstationary wideband MIMO channel model was proposed that includes the LOS component and propagation paths occurring due to one-time scattering.

3.2.3. Stochastic Channel Models (SCM). SCM tend to describe the propagation channel based on stochastics without considering the underlying geometrical relations. In this type of channel models a certain structure (such as tapped delay line structure, Saleh-Valenzuela structure, or finite-state Markov chains structure) is assumed and modelled by random processes. Stochastic parameters for the characterization depend on predefined generalized environments (such as rural or highway environments) as well as different assumptions. To parameterize a model, intensive measurements in different scenarios have to be performed. Channel model parameters are then tuned to fit the results of the measurements. A tapped delay-Doppler profile model was proposed in [64, 65] for the C2C channels. This model was also adopted by the IEEE 802.11p standards group for the development of its system. However, the Wide-Sense Stationary Uncorrelated Scattering (WSSUS) assumption in the channel model does not reflect the nonstationarity of the channel impulse responses reported in the measurements for the C2C environments. Authors in [66] provided parameters for C2C channel models based on the tapped delay structure. Three model types were provided, where two are non-WSSUS based and the third one was based on the WSSUS assumption. Parameters were given for channel bandwidths of 5 and 10 MHz using measurements performed by the authors in both highway and urban scenarios. These measurements were taken at different times and under different traffic conditions. The model was updated by results in [67] using the same type of channel model to characterize propagation for channel bandwidths of 1, 20, 33.33, and 50 MHz, where the same data from the measurement campaign in [66] was used. In [68], the Rayleigh fading channel was modelled using a finite-state Markov structure as an evolution of the two-state Markov channel known as the Gilbert-Elliot channel [69, 70]. Finite-state Markov models were later developed to model tunnel channels [71] and the fast time-varying C2I channels [72]. Measurements of T2G in viaduct environment and agricultural environment were performed in [73, 74]. In [73] an evaluation and development of LTE technology for HSR communications were presented. In [74], authors proposed a two-dimensional Ricean K-factor channel model based on the measurement results.

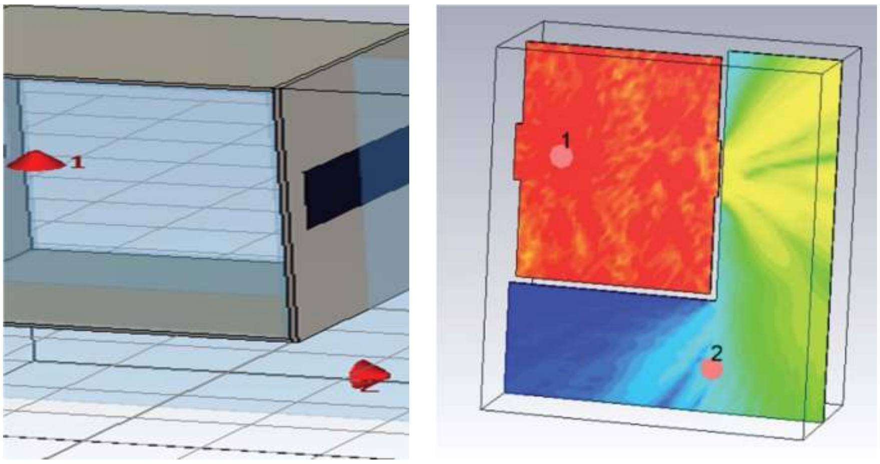
3.3. Inside Vehicle. Before reviewing the inside vehicle channel models for trains, we first summarize the literature on similar environments, that is, bus and airplane cabins. At the end of this subchapter, all publications are listed and the main aspects are highlighted in Table 1.

Table 1: Intra- and intervehicle publication overview.

References	Vehicle	Frequency	Bandwidth	
[11]	Bus	2 + 5 GHz		Passengers
[12]	Airplane			Passengers
[13]			UWB	
[14]		2 + 5 GHz		
[15]			Narrow band	
[16]		3–8 GHz	UWB	
[17]				
[18]			Wideband	
[19]		2 + 5 GHz		
[20]			UWB	
[21]				
[22]	Train			
[23]				
[24]		2.35 GHz	Wideband	Intra/intervehicle
[25]		2.45 GHz	100 MHz	
[26]		434 MHz	Narrow band	
[27]				Intravehicle
[28]		2 GHz		
[29]		2.45 GHz	Wideband	Intervehicle

Whereas only [11] measured channels inside a bus, [12–21] measured channels inside airplane cabins. All measurements have been conducted for stationary vehicles. Further, [11, 16, 17] consider the influence of passengers on the channel measurements. For the large wide-body cabin of an A380 airplane with two aisles, [16] shows a reduced delay spread for UWB measurements between 3 and 8 GHz. Clearly, these results are not directly applicable to the train environment as passenger trains usually are single aisle. In contrast [11, 17] conclude that human movement causes larger delay spreads at 5 GHz for a measurement bandwidth of 50 MHz inside a bus or medium-sized airplane with a single aisle. The airplane cabin measurements of [12, 13, 15, 16, 18, 19] show consistently a path loss exponent between two and three for medium to large aircrafts depending on the measurement setup, carrier frequency, and bandwidth. As an exception to these findings, the estimated path loss exponents are below one in the cargo bay of a military airplane [20, 21]. Here, the different behavior stems from the metallic cabin containing no equipment that absorbs the UWB signals. Similar behavior could be expected inside an empty cargo compartment of a train vehicle.

When considering the bandwidth of the measurements, we can distinguish narrow band, wideband, and UWB measurements. For the UWB measurements [13, 16, 19–21], the findings vary greatly depending on the exact measurement setup, often requiring a large number of multipath components to model the channel characteristics accurately, for example, [20]. The wideband models exhibit for carrier frequencies around 2 or 5 GHz frequency selective fading [11, 14, 17, 18] and contain both Ricean and Rayleigh fading paths. A 3-path taped delay line model can be sufficient to describe the in-cabin channel behavior [11, 17]. For a bandwidth of up to 1 MHz, the resulting channel model is a flat fading model [15]. The influence of signals propagating outside the cabin and then reentering it is not considered, apart from the environmental description in [11].



(a) (b)

Figure 6: Diffraction phenomena around car: electromagnetic simulation model (a); simulated electric field (b).

In [22, 23] intravehicle and intervehicle communication links were analyzed using 2 GHz and 5 GHz center frequencies. Measurement results showed that the signal can reenter the cars through the windows and that its contribution to intervehicle propagation can be more relevant than the LOS signal. In [24] wideband propagation analysis was done with a channel sounder using planar and omnidirectional antennas in different locations at a carrier frequency of 2.35 GHz. The performance of both types of antennas was compared, obtaining a larger path loss in the case of the planar antennas, while showing similar performance regarding delay spread.

The authors in [25] also analyzed the path loss and delay spread for both intervehicle and intravehicle communication links. All the measurements were done with a Vector Network Analyzer (VNA) using a bandwidth of 100 MHz centered at 2.45 GHz; results showed a path loss slightly smaller than in free space transmission. In [26] the authors studied wave propagation around the train, focusing on Wireless Sensor Network (WSN) applications, and taking into account that the wireless devices need to be installed under the train, for example, for bogie condition monitoring. A narrowband approach was followed for wireless channel characterization at 434 MHz by means of a signal generator and a spectrum analyzer. Results showed an increase in the path loss for the case where antennas are located under the train compared to the case where antennas are inside the train.

Ray tracing simulators can also be used for characterizing in-vehicle propagation [27, 28]; however, results are highly dependent on the accuracy of the simulation model.

In order to characterize the propagation environment for intervehicle communications, a wireless channel measurement campaign was carried out in [29]. This campaign was done at La Sagra maintenance facilities in Mocejón, Spain. For these measurements the train was positioned in an open field in order to obtain multipath from the train itself rather than from outside surrounding objects. It was observed that, in absence of reflections outside the train, the radio communication between the inside of the car and the bogie occurs due to the diffraction of the signal on the window edge and on the bottom edge of the car. Electromagnetic simulations were carried out with CST Microwave Studio [75] that confirm the behavior (see Figure 6). As an example, Figure 7 shows the simulated and measured power-loss results at 2.45 GHz between two polarization-matched antennas placed with a separation of 3 meters following the setup described in Figure 6, where the transmitter antenna has been depicted as 1 and the receiver antenna as 2. A good agreement is observed between simulations and measurements; the main difference is that in simulations higher power rays are received after the first 20 meters, which are due to the perfect conducting structures used in the car for obtaining reasonable simulation times, which make the inside of the car more reflective than in the real situation. On the other hand, it can be noted that

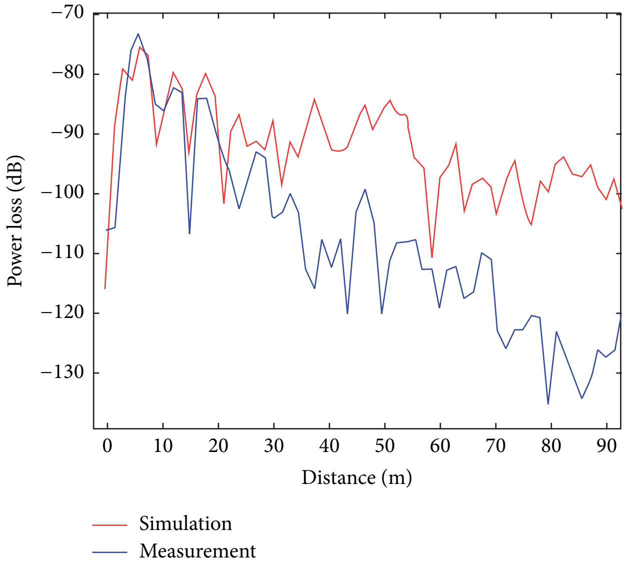


Figure 7: Simulated and measured power-loss results for 3-meter setup with vertical polarization at 2.45 GHz.

the losses of −75 dB for the first ray are a combination of 50 dB free space losses (i.e., 3 meters at 2.45 GHz) plus 25 dB of diffraction losses at the window edge.

It was also observed that when the base station is inside the car and the sensor nodes are under the car, the coherence bandwidth B_c varies between 1.5 and 4 MHz at 2.45 GHz and decreases with larger distances between the base station and the sensor node. When both the base station and sensor nodes are under the car, B_c varies between 15 and 25 MHz. On the other hand, the delay spread is larger when the base station is inside the car (13.3 ns to 100 ns) than when is it under it (8.7 ns to 13.3 ns), due to the stronger multipath.

Finally, the attenuation of the links, when the base station is inside, goes from 85 to 88 dB at 2.45 GHz, while it varies from 34 to 53 dB when it is under the car. Cross-polarization of the antennas has an influence when the LOS path prevails and causes an attenuation increase of 10–15 dB.

From these results it was concluded that positioning the base station under the vehicle provided a more stable link, with lower delay spread and higher B_c. However, it must be noted that WSNs operating with a bandwidth lower than B_c will suffer from flat fading, and therefore spatial antenna diversity and/or frequency agility will need to be implemented to overcome this issue.

3.4. Outside Vehicle. Several works exist related to the characterization of train-to-ground wireless propagation [30, 31]. The effect of structures like viaducts and terrain cuttings (canyons) onto a train-to-ground communication link with GSM-R has been analyzed in [32–35]. In [36] a survey on T2G channel measurements and models for HST is provided. Overall results show that the classical models for propagation loss are not accurate for attenuation prediction.

While the research of the T2G channel is comprehensive, the propagation channel of the T2T is hardly described in literature. A measurement and analysis of a T2T channel were done in [37] considering the use of TETRA. Authors in [38] describe a channel model for a direct T2T link at 400 MHz center frequency based on known mobile radio communication models. First measurement results of T2T measurements using ITS-G5 in railway environment are presented in [39]. An overview of all mentioned publications from outside vehicle wireless communication is listed in Table 2.

Table 2: T2G and T2T publication overview.

References	Frequency	Bandwidth	Application
[30]	2.35 GHz GSM-R	5 MHz	T2G
[31]			
[32]		10 MHz	
[33]		40 MHz	
[34]		50 MHz	
[35]	930 MHz	Narrow band	
[36]	0.9–5.2 GHz		
[37]	470 MHz	Narrow band	T2T
[38]			
[39]	5.9 GHz	10 MHz	

Table 3: Railway environment.

Area	Urban
	Suburban
	Rural
Special scenarios	Curves
	Tunnels
	Bridge/viaduct
	Cuttings
Obstacles	Cross bridge
	Noise barrier
	Catenary
	Signaling system
	Roof
	Building
	Vegetation (tree)
	Open field

3.5. Identified Gaps. The summary of existing channel measurements and models shows that important aspects for modern wireless T2T applications are missing. The small amount of investigations on T2T aspects is limited on either low train speed or lower frequency bands. Most of the measurements and the resulting channel models refer to T2G. As shown in [36] T2G is well investigated. In several publications channel models designed for cellular communications (C2I) are used for C2C communications. Next to the points mentioned in Section 2.4 following gaps have been identified.

3.5.1. Railway Environment. Depending on the location of a track, the environment of railway can be quite different compared to the car environment. Furthermore, the shape of cars on a street differs much more severely compared to the profile of trains for wave propagation. On the other side, most of the artificial and nonartificial obstacles that are found next to roads (see Table 3) may occur also next to railways.

One of the most challenging and diverse environments for communications in railway traffic is tunnels. Underground trains especially but also HSR and commuter trains are operating in tunnels. The shape and the material of the tunnel are heavily influencing the propagation: tunnels excavated with boring machines (i.e., smooth walls, with almost no changes on their cross section; see Figure 8(a)), man-made tunnels (i.e., frequent changes on tunnel section, walls made of bricks, etc.), one-track tunnels (Figure 8(b)), and stations (both pit-shaped and tunnel-shaped, Figures 8(c) and 8(d), resp.).

3.5.2. High Total Velocity. Previous measurements reported in underground or general railway environments have been mostly focused on the T2G links. Future measurements shall focus on intravehicle, intervehicle, interconsist, and T2T links from mid velocities in subway networks up to high total velocities for HSR.

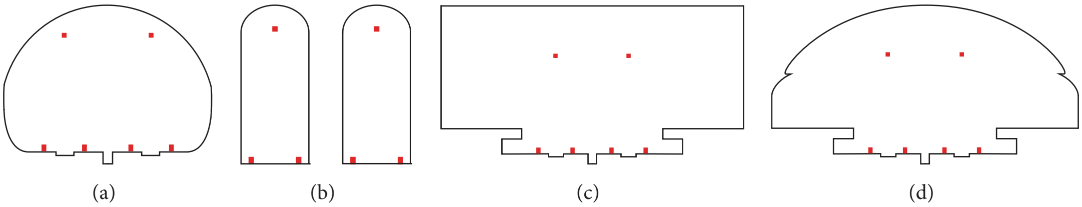

(a) (b) (c) (d)

Figure 8: Different lateral cuts of tunnels.

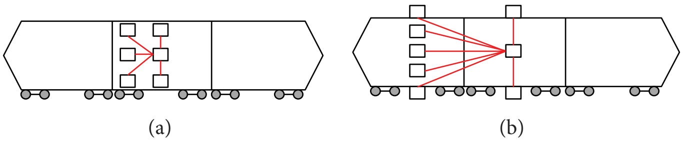

(a) (b)

Figure 9: Intravehicle (a) and intervehicle (b); note that the vertical gray lines depict the boundaries between rail vehicles.

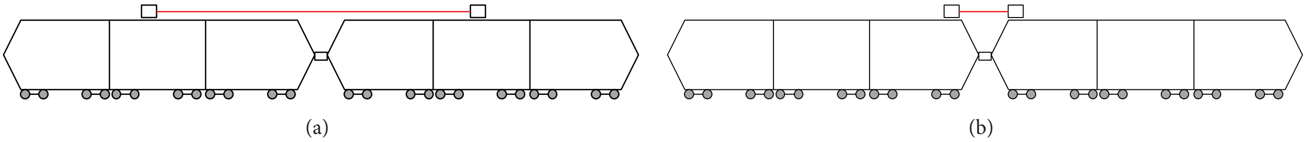

(a) (b)

Figure 10: Interconsist: (a) center; (b) edge.

The *intravehicle* scenario investigates the wireless link between different elements inside a single vehicle (see Figure 9(a)). These will be line-of-sight links, mostly affected by the internal structure of the vehicle and passengers. Here several scenarios shall be measured, such as person presence/movement and narrow/wide train gauge, as well as vehicles with/without corridor in between (i.e., continuous and noncontinuous trains; see Figure 11).

Intervehicle scenarios include wireless links that go beyond a single vehicle, involving both the next vehicle and the exterior of the vehicle (both roof and bogie); see Figure 9(b). In this case the environment inside (see Figure 11) and outside of the train in combination with the velocity is influencing the propagation channel. Hence, it will be necessary to measure and model different propagation environments with different speeds.

An *interconsist* connection establishes a wireless link between one consist and another one, with the antennas located on the roof of the train. The antenna position may vary between the center and the edge of the cars (see Figure 10). In case of omnidirectional antennas, high Doppler shifts resulting from the high speed of the train in combination with reflected or scattered multipath components located in the surrounding environment may cause the main influence on the received signal. If directional antennas are used curve radii and train vibrations need to be considered for the beam-width of the employed antennas.

3.5.3. High Relative Velocity. The channel between two moving trains regarding the T2T communications as well as the interference between adjacent trains using the same wireless technology is hardly discussed in literature. The scenarios differ from two trains stopped and located in parallel on depot (i.e., continuous interference) to two trains driving next to each other on parallel tracks in the same or opposite direction. The antennas should be placed both inside and on the roofs of the vehicles as shown in Figure 12. Highly interesting is the influence of the Doppler shift on the receiver side. Due to possible relative speeds of 600 km/h and above, high Doppler shifts may occur.

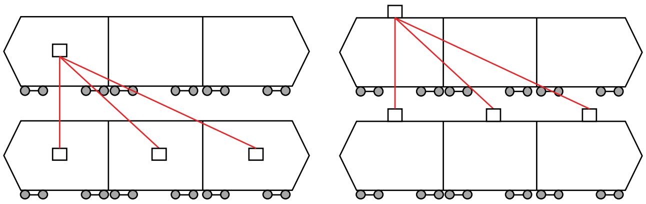
4. Conclusions

In this paper, we provided an overview of existing communication systems in trains and proposed new possible directions for future wireless systems. Currently, communication systems inside the train are mainly wired. To improve the uptime of trains, communication systems need to be more reliable by replacing cables and connectors that suffer from mechanical vibrations during railway operations. Moreover, wireless systems may enable new applications such as virtual coupling to improve the efficiency and safety of the railway system.

Next, we surveyed channel models suitable for being used for simulations for railway applications, where we distinguished between deterministic, geometry-based stochastic, and sole stochastic channel models. While on the one hand the deterministic channel models have the drawbacks of requiring a very detailed environmental description, is computationally expensive, and cannot be generalized easily, nevertheless, the approach offers the benefit of providing spatial coherent radio propagation simulations. This is beneficial

(a) (b)

Figure 11: Continuous (a) and noncontinuous (b) trains.



(a) (b)

Figure 12: Train-to-train: inside (a); roof (b).

for future adaptive communication systems that predict the state of the wireless channel to determine if reliable communications with the required quality of service are possible or if an alarm needs to be raised. On the other hand sole stochastic channel models do not need a detailed description of the environment, are computationally inexpensive, and can be easily generalized. The drawback of SCM is that the spatial coherence of the propagation channel simulation is hard to achieve. The geometry-based stochastic channel models offer the benefits of both models while countering their drawbacks.

A lot of literature has been published containing channel models that are relevant for wireless communication inside and outside of trains; see [11–35, 37, 38] and references therein. For inside vehicle models, channel measurements made in buses or airplanes can be applied to train vehicles due to similar forms. However, these neglect the influence of the railway environment in contrast to the train dependent measurements and models [22–28]. Most of the measurements reported in metro or general railway environments and their resulting channel models refer to T2G communications based on cellular mobile networks [30–35]. In the literature a minority of investigations on propagation channels are done for T2T links. The investigated aspects in this short list of publications are limited on either low train speed or lower frequency bands.

Hence, we identified gaps for channel characterization in the railway environment, high total velocity, and high relative velocity for radio propagation measurements.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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