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Millimeter Wave and THz Propagation Channel Modeling for High-Data Rate Railway Connectivity—Status and Open Challenges

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Abstract

In the new era of railways, infrastructure, trains and travelers will be interconnected. In order to realize a seamless high-data rate wireless connectivity, up to dozens of GHz bandwidth is required. This motivates the exploration of the underutilized millimeter wave (mmWave) as well as the largely unexplored THz band. In this paper, we first identify relevant communication scenarios for railway applications. Then the specific challenges and estimates of the bandwidth requirements for high-data rate railway connectivity in these communication scenarios are described. Finally, we outline the major challenges on propagation channel modeling and provide a technical route for further studies.

Keywords

millimeter wave; radio channel; railway communications; THz communications

1 Introduction

In order to meet the goals with respect to efficiency, safety and convenience, rail traffic is expected to evolve into a new era where infrastructure, trains, travelers and goods will be increasingly interconnected [1]. To realize this vision (one part of the objective of "smart, green and integrated transport" supported by Horizon 2020 [1]), calls and initiatives, such as "Shift2Rail" [2], are inviting proposals concerning the following topics [3]: intelligent rail infrastructure [4], intelligent mobility management, smart rail services (seamless multimodal travel and logistic services), and a new generation of rail vehicles (trains with smart power and wireless technologies). All these specific topics ultimately impose requirements for a seamless high-data rate wireless connectivity in rail traffic. Correspondingly, railway communications are required to evolve from only the critical signaling applications, to various high-data rate applications, which need to be realized in five rail scenarios: train-to-infrastructure, inter-wagon, intra-wagon, inside station, and infrastructure-to-infrastructure. The huge bandwidth requirements—up to dozens of GHz—in these scenarios form a strong motivation for employing millimeter wave (mmWave) and THz communications, because they can offer orders of magnitude greater bandwidth than current spectrum allocations and enable very large antenna arrays which in turn provide high beamforming gains [5]. In order to effectively support the design, simulation, and development of the mmWave and THz communication systems, a thorough understanding of the propagation channel characteristics is critical.

This paper clarifies the bandwidth requirements of high-data rate railway connectivity by defining and analyzing the five communication scenarios in Section 2. Based on this, we identify the technical challenges and provide a technical route for further studies on mmWave and THz channels in Sections 3, 4

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and 5. Conclusion and future work are drawn in Section 6.

2 Bandwidth Requirements of High-Data Rate Railway Connectivity

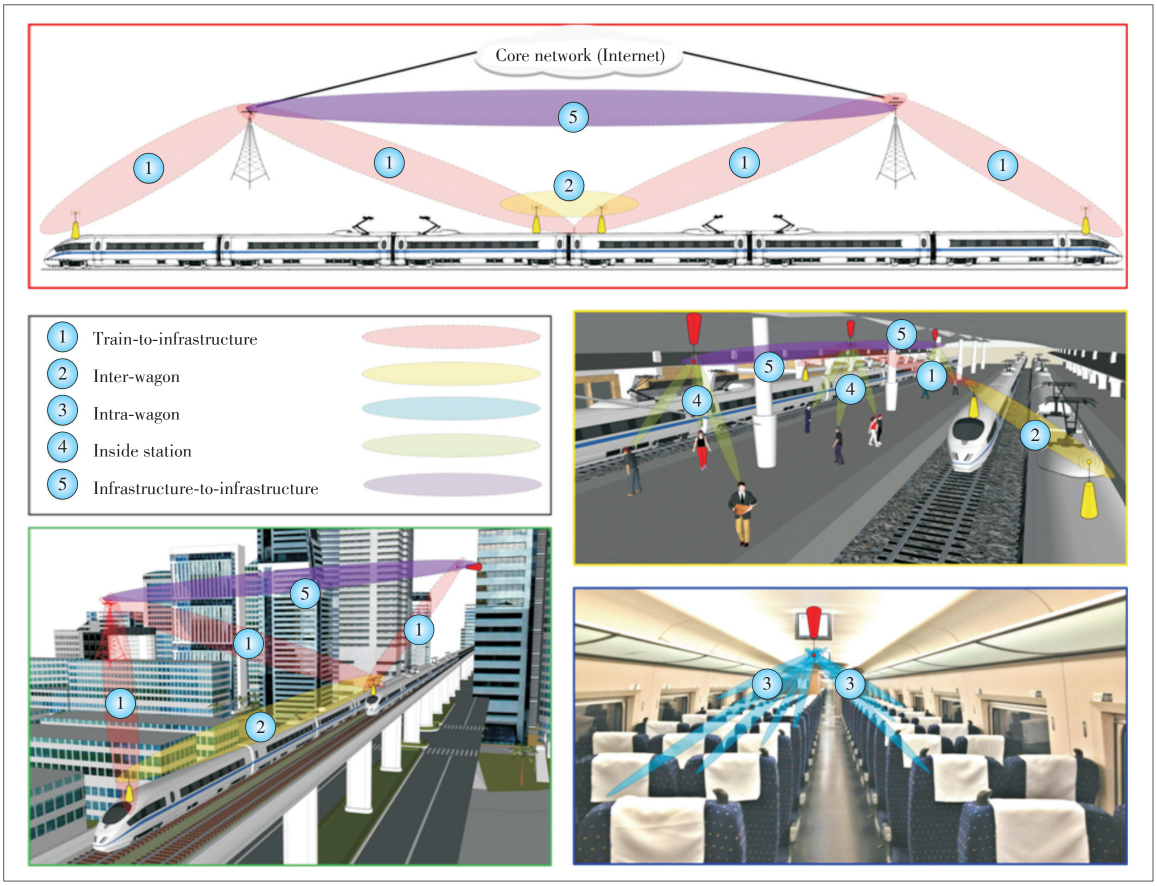
In the future, railway communications are required to evolve to various high-data rate applications (e.g., [6], [7]): on-board and wayside high definition (HD) video surveillance that is critical for safety and security concerns (e.g., cars stuck on railway crossings, terrorist attacks, etc.); on-board real-time high-data rate connectivity for web browsing, video conferencing, video broadcast, etc.; train operation information that provides critical information regarding voice and control signaling, on-route train performance, and train equipment status; real-time train dispatching HD video between train and train control centers (TCCs) required for train dispatching and driverless systems; and journey information that dynamically updates journey information for all passengers via multimedia.

As shown in **Fig. 1**, the aforementioned applications can be realized in five communication scenarios [8]: train-to-infrastructure (T2I) (HD video and other information in real time transmitting among various infrastructures), inter-wagon (wireless network between wagons), intra-wagon (links between user equipment and access points of a wagon), inside station (links between access points (APs) and user equipment (UEs) in train/metro stations), and infrastructure-to-infrastructure (I2I) (HD video and other information in real time transmitting among various infrastructures).

The EU project METIS (which stands for Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society) [9] has identified four main challenges for 5G communications: very high data rate, very dense crowds of users, very low latency, and very high mobility. Since each of the mentioned communication scenarios in rail traffic meets the challenges similar to one or more test cases (TCs) defined in METIS, the corresponding TCs in METIS are cited here when analyzing the bandwidth requirements:

1) Train-to-infrastructure, corresponding to the combination of "TC12: traffic efficiency and safety", "TC8: real-time remote computing for mobile terminals" and "TC1: virtual reality office" in METIS, describes links between the infrastructures and the APs/transceivers of the wireless local network for the train. It requires bi-directional streams with very high data rates and low latencies (millisecond level), as well as robust links with low latencies together with an availability that is close to 100% while moving at a speed up to 500 km/h [10].

2) Inter-wagon requires a high-data rate and a low latency because the APs are arranged in every wagon and each AP serves as a client station for the APs in the other wagons



◀**Figure 1. Five communication scenarios of high-data rate railway connectivity.**

while also serving as the AP for all the stations within its wagon [11]. Therefore, this scenario requires two or more times (depending on how many wagons are connected) of bandwidth of the “intra-wagon” scenario.

3) Intra-wagon, corresponding to the “TC1: virtual reality office” in METIS, requires capability for real-time HD videos with low latencies. Considering using a 40 MHz channel to support compressed HD video and assuming 50% of the 180 passengers of a double-decker wagon want to use high-speed video, a total of 3.6 GHz bandwidth will be required for one wagon.

4) Inside station corresponds to “TC3: shopping mall” in METIS. In a shopping mall, users are strongly interested to get access to mobile broadband applications (e.g., 1 Gbps, which is expected to be supported by IMT-2020 for indoor users [10]), and the station will provide a fixed/wireless communication infrastructure to support general commercial as well as operational applications [9].

5) Infrastructure-to-infrastructure, corresponding to the “TC1: virtual reality office” in METIS, describes HD video and other information in real-time interaction among multiple cameras and APs, e.g., a high-date-rate wireless backhaul, supported by bi-directional streams with very high data rates and low latencies [9].

To sum up, for the scenarios “inside station” and “infrastructure-to-infrastructure”, it is convenient to roughly estimate their bandwidth requirements (**Table 1**) by referring to their corresponding TCs in METIS. With the evaluation procedure already described in [12], the bandwidth requirements are from several hundred MHz to several GHz, depending on concrete conditions. For the scenarios “intra-wagon” and “inter-wagon”, up to 3.6 GHz and up to dozens of GHz bandwidths will be required, respectively. In the scenario “train-to-infrastructure”, the main interface between the network on a train and the fixed network transmits an aggregated stream of the inter/intra-wagon scenarios. Therefore, it requires the bandwidth from 7.2 GHz to dozens of GHz to realize over 100 Gbps transmission. Table 1 summarizes the communication scenarios, corresponding TCs in METIS, challenges (with detailed data from IMT 2020 defined by ITU-R [13]), and bandwidth requirements. Obviously, such high data rate and huge bandwidth requirements motivate the exploration of the underutilized mmWave and THz bands. Systems operated at these frequencies are referred as mmWave and THz communication systems.

3 Millimeter Wave and THz Communication Enabling High-Date Rate Railway Connectivity

Various technologies working at frequencies lower than 6 GHz, such as Long-Term Evolution Advanced (LTE-A) [14], WiMax [15] and LTE for Railway (LTE-R) [16], have been presented to realize the broadband wireless access in rail traffic. However, these existing technologies support data rates from several Mbps up to 100 Mbps, which are still up to three orders of magnitude lower than the desired throughput.

▼Table 1. High-data rate railway connectivity scenarios, corresponding TCs in METIS, challenges, and bandwidth requirements

Scenarios		Train-to-infrastructure	Inter-wagon	Intra-wagon	Inside station	Infrastructure-to-infrastructure
Corresponding TCs in METIS		TC12: traffic efficiency and safety; TC8: real-time remote computing for mobile terminals; TC1: virtual reality office		TC1: virtual reality office	TC3: shopping mall	TC1: virtual reality office
Applications	On-board and wayside HD video surveillance	√				√
	Train operation information	√	√	√		√
	Real-time train dispatching HD video	√			√	√
	On-board real-time high-data rate connectivity	√	√	√		
	Journey information	√	√	√	√	√
Challenges (detailed data from [13])	Very high data rate (peak data rate up to 20 Gbit/s and user experienced data rate up to 100 Mbit/s)	√	√	√		√
	Very dense crowds of users (up to 10^6 devices/km^2)		√	√	√	
	Very low latency (down to 1 ms)	√	√	√	√	√
	Very high mobility (up to 500 km/h)	√				
	Bandwidth requirements	7.2 GHz to dozens of GHz	Up to dozens of GHz	Up to 3.6 GHz	Up to several GHz	Up to several GHz

HD: high definition METIS: Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society TC: test case

MmWave communication for railway is not completely new but rather a long effort reaching back as far as 32 years ago (first literature in 1983 [17]). However, in the era of single-input and single-output (SISO) systems, the link distance and the mobility of the mmWave users were very limited. Nowadays, outstanding progress has been made toward the development of compact mmWave band transceivers providing high transmission power, high detection sensitivity, and low noise figures [18], [19]. Moreover, ultra-wideband (UWB) and multiple-input and multiple-output (MIMO) antennas have been designed for mmWave bands. It thus seems an opportune time to recall and initiate the mmWave communications enabling high-date rate railway connectivity. Today even frequencies as high as 300 GHz are considered for wireless communications as the so-called THz communications [20]–[23]. Recent advances in semiconductor technology have triggered even standardization activities. In IEEE 802.15, the first standard for fixed point-to-point links at 300 GHz is under development [24]. At the World Radio Conference in 2019 (WRC' 19), spectrum allocations beyond 275 GHz for fixed and mobile applications will be investigated under agenda item 1.15 [25].

4 Related Work and Open Challenges

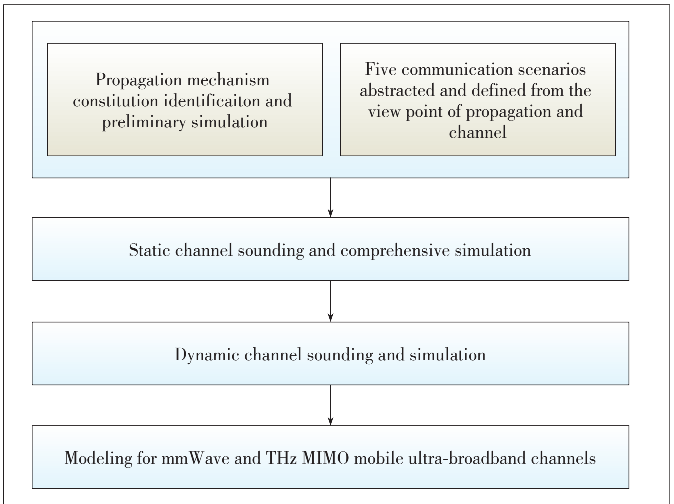
Whenever a wireless communication system is applied the first time in either a new environment or in a new frequency band, the propagation channel is subject to detailed investigations. This holds also for mmWave and THz communication systems in general and for the application of these systems in railway environments specifically. In the following the main challenges are described.

1) Wave propagation mechanisms: The synergism of susceptibility of molecular absorption, the changed relationships between wavelengths and dimensions of objects, and the ultra-broadband bandwidths, makes propagation in the mmWave band and THz distinct from microwave frequencies. Even though the main propagation mechanisms have been identified to some extent [26]–[28], more research efforts should be made on interpretation of the complex propagation phenomena, such as frequency-selective and distance-dependent behaviors, frequency dispersion, different shadowing effects, taking into account the main objects and geometries in railway environments.
2) Characterization of static channel: For indoor environments, MIMO mmWave channels were characterized in a range of environments [29]. The IEEE 802.11ad and 802.15 TG3c models were established for 60 GHz indoor communications [30]. The TG3c model covers the residential, office, library, desktop, and kiosk environments, whereas the TGad model covers the conference room, living room, and cubicle. A thorough review of mmWave propagation both indoor and outdoor can be found in [31]. For outdoor environments, there have been recent studies regarding the outdoor channel propagation characteristics that have shown the potential for utilizing the mmWave band for cellular communications [32], [33]. A detailed literature review is provided in [31] and [34]. First investigations on even more complex scenarios beyond 300 GHz have been published, focusing on static channels including both deterministic and stochastic channel models [19], [35]. A compilation of channel models for fixed-point-to-point applications at 300 GHz for various environments covering outdoor, indoor and even intra-device environments can be found in [36]. However, even though ITU-R recommends using the wide spectrum in above 6 GHz for supporting moving hotspot cell users such as high speed train moving 500 km/h, channel measurements in rail communication scenarios have been rarely reported in the mmWave and not at all in THz frequencies. Usually, railway appears as a small use case of "moving hotspot" in standard documents [37], without parameterized definition for details. How to include the railway channel features in even static channel models is an open challenge.
3) Dynamic channel modeling: Most of the existing measurements in mmWave band and all measurements in the THz band were done for static channels. In 2014, Samsung presented the world's first demonstration for 1.2 Gbps transmission at 28 GHz and 110 km/h cruising speed using dual-beamforming [38]. This evidence shows the strong potential of the mmWave band for mobile applications. As pointed out in [28] and [39], dynamic ray shadowing causes a temporal variation of the path losses. Reflections at persons may additionally be subject to Doppler shifts and entire Doppler spectra may result. The same holds if the transceiver units move relative to each other. The lack of insight into such dynamics inhibits the realization of the mmWave communications in any dynamic environment, particularly the five rail traffic scenarios.

5 Technical Route for Further Studies

In order to address the above open challenges, a technical route for further studies can be formed, as shown in **Fig. 2**.

To begin with, the propagation characteristics of the main objects in the five scenarios with various geometrical and physical configurations can be measured in the mmWave and THz bands using a Vector Network Analyzer (VNA) or even Time-Domain Spectroscopy (TDS). The frequency-dependent coefficients of every propagation mechanism can be derived empirically from the measurements or semi-empirically by considering some theoretical modeling as well. After evaluating the influence of various objects, the most significant objects should be modeled in detail to build the ray optical scenarios enabling the simulation of static channels. The propagation mechanism constitutions in every scenario can be quantitatively identified, which guides the design of measurement campaigns for more complex static scenarios. Then, as given by **Table 2**, the five



MIMO: multiple-input and multiple-output

▲**Figure 2. Technical route for further studies on mmWave channel for high-data rate railway connectivity.**

scenarios can be defined from the viewpoint of propagation and channel. With various combinations of factors, such as link lengths, line of sight (LOS)/non-LOS (NLOS), and MIMO antennas, static measurements can be conducted in the rail scenarios. More detailed data can be found in [40], where six scenario modules for mmWave and THz train-to-infrastructure channels are defined and constructed for the first time. All the main objects, such as tracks, stations, crossing bridges, tunnels, cuttings, barriers, pylons, buildings, vegetation, traffic signs, billboards, and trains, are modeled according to the typical geometries and materials in reality. After calibration by the measurements, extensive comprehensive simulations can run to catch the frequency - dispersion effect of the ultra - broadband mmWave and THz channels in frequency, time, angular and polarization domains.

Afterwards, dynamic channel measurements can be designed and performed with various configurations, such as different moving transceivers and scatterers with variations of speed and motion direction. Similarly, dynamic simulations can be made by adding the same mobility to the corresponding scenarios. To perform measurements in dynamic scenarios a channel sounder (CS) operating in time-domain is necessary. Such measurements have been reported already at 60 GHz [41]–[45] but not at 300 GHz. An especially promising approach for future measurements is channel sounding employing orthogonal time frequency space (OTFS) waveforms, which are well suited for data transmission in quickly changing environments, and also provide a natural basis for identifying objects in the delay-Doppler domain [46], [47]. Based on both the measurement and simulation results, the correlations between the mobility and channel dynamics can be revealed. For instance, it is critical to evaluate the influence of the mobility and the variation of mobility on the first- and second-order statistics of the channel dynamic parameters.

Finally, based on extensive measurements and simulations done in the previous steps, all the static and dynamic channel parameters in full-dimensions can be extracted and modeled for channel realizations. This stochastic spatio-temporal model can provide a basis of the system design by generating the channels in the five rail traffic scenarios, without the need for in-depth understanding of mmWave propagation or ray tracing tools.

A general challenge for measurements using either a VNA or a CS is the limited distances (up to a few 10s of meters) between the transmitting and receiving units of the measurement system due to the requirement to connect the transmitter and receiver with cables to a central unit. This will make it especially challenging to perform measurements for the train-to-infrastructure and infrastructure-to-infrastructure scenarios for which specific measurement equipment has to be developed. As a "DFG State Funded Major Instrumentation" funded by the German federal government and the federal state of Lower Saxony, one custom-made mmWave and THz MIMO channel sounder was delivered to Technical University of Braunschweig in August 2016. This sounder supports 8 GHz bandwidth and uses high-gain (15 dBi–25 dBi) antennas. It sends a pseudo random sequence repeatedly with a very fast rate to realize fast time-domain measurements for mobile channel links up to

▼**Table 2. Scenario definition from the viewpoint of propagation and channel**

	Scenarios	Train-to-infrastructure	Inter-wagon	Intra-wagon	Inside station	Infrastructure-to-infrastructure
Setup	Indoor/outdoor	Outdoor	Outdoor	Indoor	Indoor	Outdoor
	Fix/mobile link	Mobile link	Mobile link	Mobile link	Mobile link	Quasi-fixed link
	Velocity of user	High, up to 500 km/h	Light, fluctuation of wagons	Low, pedestrian, ca. 1 m/s	Low, pedestrian, ca. 1 m/s	Light, antenna mispointing
	LOS/NLOS	LOS	LOS	LOS and NLOS	LOS and NLOS	LOS
	Weather	Dry and wet	Dry and wet	-	-	Dry and wet
Common	Scatters	Mobile scatters: pedestrians, passengers, moving cars, wind blades, and so on				
	MIMO antenna setup	From 2 × 2 to practical massive MIMO, setup linear/rectangular/cylindical array, with vertical/horizontal polarization				
	Frequency band	MmWave band, from 100 MHz to dozens of GHz bandwidth				

LOS: line of sight MIMO: multiple-input and multiple-output NLOS: non-LOS several tens of meters for the 60 GHz and 300 GHz bands. Using correlation techniques, the receiver can extract the channel impulse response at a rate of more than 14,000 CIRs/s. These features enable the investigation on the channel dynamics with mobile transceivers and scatterers in the mmWave and THz bands.

6 Conclusions and Future Work

In this paper, we provide elementary discussions on bandwidth requirements of high-data rate railway connectivity, and highlight the open challenges in terms of wave propagation, static channel, and dynamic channel. More research efforts are expected to reveal the essence of complex propagation phenomena, such as frequency-selective and distance-dependent behaviors, frequency dispersion, different shadowing effects, for several GHz of bandwidths in the mmWave and THz bands, taking into account the main objects and geometries in rail scenarios. MmWave and THz channel models including railway features are still open issues, and therefore, a technical route for further studies on mmWave and THz propagation channel for high-date rate railway connectivity should be defined.

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