On Millimeter Wave and THz Mobile Radio Channel for Smart Rail Mobility

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***Abstract*—As a widely acknowledged efficient and green transportation model, rail traffic is expected to evolve into a new era of "smart rail mobility" where infrastructure, trains, and travelers will be interconnected to achieve optimized mobility, higher safety, and lower costs. Thus, a seamless high-data rate wireless connectivity with up to dozens of GHz bandwidth is required. Such a huge bandwidth requirement motivates the exploration of the underutilized millimeter (mm) wave and Terahertz (THz) bands. In this paper, the motivations of developing millimeter-wave and THz communications for railway are clarified by first defining the applications and scenarios required for smart rail mobility. Ray-tracing simulations at 100 GHz imply that to form high-gain directional antenna beams, dynamic beamforming strategies and advanced handover design are critical for the feasibility of THz communications to enable smart rail mobility.**

***Index Terms*—millimeter wave, radio channel, railway communications, THz communications**

I. Introduction

Nowadays, rail transportation has become an important efficient and green transportation model, because it provides very high volume, is more energy efficient, has substantially lower environmental impact and is less expensive to build than other transport modes [1]. In order to meet its goals with respect to efficiency, safety, and convenience, rail transport is expected to evolve into a new era of "smart rail mobility" where infrastructure, trains, travelers and goods will be increasingly interconnected [2]. In order to realize this vision, it is required to realize a seamless high-data-rate wireless connectivity in rail traffic, which is a key factor for new generations of Intelligent Transportation Systems (ITS) [3].

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For smart rail mobility, railway communications are required to evolve from handling only the critical signaling applications, to various high data rate applications: on-board and wayside high definition (HD) video surveillance, on-board real-time high-data rate connectivity, train operation information, real-time train dispatching HD video, and journey information. These applications can be realized in various rail scenarios. The huge bandwidth requirements – up to dozens of GHz – in these scenarios form a strong motivation for developing millimeter (mm) wave and THz communications because they can offer orders of magnitude greater bandwidth than current wireless allocations and enable very high dimensional antenna arrays for further gains via beamforming [4]. In order to effectively support the design, simulation, and development of the mm wave and THz communication systems, a full understanding of the propagation channel characteristics is essential.

This paper reviews the state of the art on the mm wave and THz channel research in terms of propagation aspects, multiple-input and multiple-output (MIMO) antenna arrays, and beamforming approaches. Based on this, we identify the technical challenges, and provide recommendations for further studies particularly for smart rail mobility. Finally, preliminary ray-tracing simulations are done at 100 GHz for a "Train-to-infrastructure" scenario.

The rest of this paper is organized as follows: Section II introduces the applications and scenarios for smart rail mobility, and clarifies the necessity of developing mm wave and THz transmissions. In Section III, the limits of current technologies working at frequencies lower than 6 GHz and the feasibility of using mm wave and THz enabling smart rail mobility are discussed. In Section IV, state of the art of mm wave and THz channel research is reviewed; corresponding major challenges and solutions are highlighted. mm wave and THz channels are compared with respect to the application of smart rail mobility in Section V. Ray-tracing simulations and corresponding insights are described in Section VI. Finally, conclusions are drawn in Section VII.

II. Bandwidth Requirements of Smart Rail Mobility

A. High-data rate application requirements

For smart rail mobility, communications of railways are required to evolve to various high-data rate applications (e.g., [5], [6]):

- **On-board and wayside HD video surveillance** that is critical for safety and security concerns (e.g., cars stuck on railway crossings, terrorist attacks, emergencies, etc).
- **On-board real-time high-data rate connectivity** for web browsing, video conferencing, video broadcast, etc. Similarly, wireless HD video streaming systems for in-flight-entertainment (IFE) [7] are being developed.
- **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.
- **Journey information** that dynamically updates journey information for all passengers via multimedia, e.g. HD video transmission, virtual reality (VR) and even 3D hologram in the future as supplement of the journey.

B. Communication scenarios, challenges, and bandwidth requirements

The applications discussed in Section II-A can be realized in the five communication scenarios (see Fig. 1):

- **Train-to-infrastructure** describes links between the access points (APs)/transceivers of (the wireless local network of) the train and the infrastructure. Such links need to be robust with support for very high data rates, low latencies, as well as close to 100% availability while traveling at speeds up to 500 km/h [8].
- **Intra-wagon** describes the links providing wireless access between APs in the wagon and the transceivers of passengers' user equipment (UE) or sensors inside a wagon. Such links should support real-time HD videos with low latencies. Considering using several tens of MHz bandwidth to support compressed HD video, and assuming about one hundred passengers of a double-decker wagon want to use high-speed video, a total bandwidth of several GHz will be required for one wagon. Besides the huge bandwidth requirement, the multiuser interference problem is another major difficulty. To deal with this problem, a highly directive antenna can significantly reduce interference on distant users while a massive MIMO array with zero-forcing precoding can drastically decrease interference on users that are even close to the target user [9].
- **Inter-wagon** describes a wireless network between wagons to avoid the high expense of wiring a train for network access or the inconvenience of rewiring when a train is reconfigured. It requires a high-data rate and a low latency because the APs are arranged in every wagon such that each AP serves as a client station for the APs in the other wagons, while also serving as an AP for all the stations within its wagon [10]. Consequently, this scenario might require even higher data rates than the "Intra-wagon" scenario.
- **Inside station** describes the links between APs and UEs in train/metro stations. In this scenario, users require access to mobile broadband applications (e.g., 1 Gbps, which is expected to be supported by IMT-2020 for indoor user [8]), and the station will provide a fixed/wireless communication infrastructure to support general commercial as well as operational applications [11].
- **Infrastructure-to-infrastructure** describes HD video and other information in real-time interaction among multiple cameras and APs, e.g., a high-data-rate wireless backhaul, supported by bi-directional streams with very high data rates and low latencies [11].

Summing up, for the scenarios "Inside station" and "Infrastructure-to-infrastructure", by using the evaluation procedure 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. As the main interface between the network on-train and the fixed network, the scenario "Train-to-infrastructure" transmits an aggregated stream of the Inter/Intra-wagon scenarios. Therefore, it requires the bandwidth of dozens of GHz to accomodate over 100 Gbps data rates. Obviously, such high data rate and huge bandwidth requirements motivate the exploration of the underutilized mm wave and THz bands. Two approaches are possible to enable such high-data rate transmission. The first one is aiming at systems operating in the 60 GHz band with a few GHz spectrum but requires high spectral efficiencies. The second approach adopts moderate spectral efficiencies and requires ultra-high bandwidths beyond 20 GHz that can be identified only in the THz frequency range [13]. Systems operated at those frequencies are referred as mm wave and THz communication systems.

III. MM WAVE AND THz COMMUNICATION ENABLING SMART RAIL MOBILITY

A. Limit of current wireless access technologies in rail traffic

Over the last few years, various technologies have been presented to realize broadband wireless access in rail traffic. For non-critical applications, Fourth Generation (4G) communications technologies, such as Long-Term Evolution Advanced (LTE-A) are potentially good solutions for offering Internet access on trains [14]. WiMax is being used in the UK to provide Internet access on some railway lines [15]. In [16], the authors claimed that services aimed at travelers should be based on market connectivity standards on trains (e.g., WiFi 802.11g) and exist in stations or other relevant access points as well. Moreover, a two-hop architecture was proposed to overcome the dramatic penetration loss of radio signals transmitted into and out of the high speed train carriages, where all users in the train are considered as a big virtual user, their transmitted signals are first aggregated at a mobile relay deployed on the carriage and then delivered over the train-ground link between the mobile relay and the ground base stations. For the application of railway signaling, authors of [17] suggested that systems such as IEEE 802.20 (Mobile Broadband Wireless Access) and IEEE 802.11 can be used for railway signaling instead of the cable-based systems currently in use. Moreover,

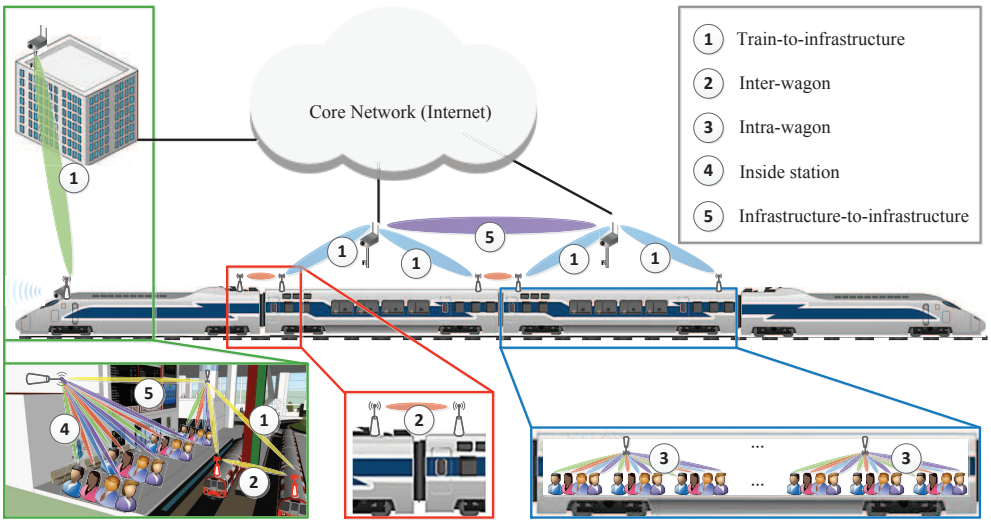


Fig. 1. Five communication scenarios of smart rail mobility

LTE for Railway (LTE-R) [18] is considered to be the broadband network solution for rail operators. However, all these current 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. One important reason is because the current technologies work at frequencies lower than 6 GHz, where the very limited bandwidth constrains the potential capacity of wireless communication systems. Thus, in order to obtain sufficient bandwidth, we are encouraged to jump in higher frequency bands.

B. MM wave and THz communication for railways

MM wave communication for railway was never a "pie in the sky", but a long and intermittent effort going back at least 32 years [19]. Some preliminary experiments were carried out in Germany using ASK modulation at 35 and 58 GHz for communications at 64 kb/s with trains. It was identified that the very high free space path loss and oxygen/water absorption of the mm wave band must be compensated by high transmit power levels, receiver sensitivity or antenna gain.

In the last couple of years, progress has been made toward the development of compact mm wave and THz band transceivers providing high transmission power, high detection sensitivity, and low noise figures [20], [21], [22]. Moreover, a comprehensive link budget analysis for the THz communication link is carried out in [23]. Ultra-wideband (UWB) and MIMO antennas have been designed for the mm wave and THz bands [24]. Beamforming and spatial multiplexing using these MIMO antenna systems [25], [21] can be used to form very high gain, electrically steerable arrays located at the base station, on the casing of a cell phone, or even within a chip [26], [27]. The frequency bands above 6 GHz are main candidates under consideration for backhaul links (outside of the vehicles) and access links (inside of the vehicles) [28]. In March 2015, the IEEE 802.15 Interest Group HRRC (Interest Group High Rate Rail Communications) was chartered to study wireless communications providing Gbps data rate with high performance to the user groups inside of fast-moving vehicles [29].

IV. State of the Art and Challenges on MM Wave and THz Channel Research

In this section, we review the related works on channel characterization, antenna arrays and beamforming, and highlight corresponding challenges and possible solutions particularly for smart rail mobility.

A. Wave propagation aspects

1) Propagation phenomena: In line-of-sight (LOS) situations at microwave frequencies, the decrease of power with distance is mainly determined by "thinning out" (spreading) of the energy. In contrast, at mm waves and especially at THz frequencies, molecular absorption [30] in the atmosphere plays a major role. This difference results in the following effects:

- *Frequency-selective and distance-dependent behaviors*: Due to the higher impact of molecular absorption on free-space propagation property as well as the frequency dependence of effects such as diffraction and reflection coefficients, the resulting path loss at mm wave and THz greatly depends on the operating frequency. As outlined in ITU-R M.2376 [28], some preliminary experiments in urban micro cell outdoor-to-outdoor and indoor scenarios, with transmitter and receiver antenna heights below rooftop, measured path losses for 10 GHz, 18 GHz, 28 GHz, 38 GHz, 60 GHz and 72 GHz in both LOS and non-LOS (NLOS) environments [31], [4], [32], [33], [34]. Generally, the path loss exponent increases with frequency (see Table I). Furthermore, the mm wave and THz bands are more susceptible to environmental effects such as gaseous (oxygen and water vapour) absorption, rain loss and foliage loss, which exhibit a high degree of frequency dependent variation (see Recommendation ITU-R P.676 and Recommendation ITU-R P.838 [35],

[36]). Atmospheric gas loss is approximately 0.50 dB/km at frequencies between 70 GHz and 100 GHz. Yet, even for the most susceptible frequencies, such as 60 GHz, 200 GHz, etc., the atmospheric gas loss is smaller than 11dB/km. The same conclusion can be drawn for rain effects: for instance, a carrier at 100 GHz will experience of 4 dB loss per 200 m in heavy rain (25 mm/h). However, when looking at several THz bands, the molecular absorption by water vapor molecules plays a critical role, and therefore, it defines several transmission windows, whose positions and widths depend on the distance and molecular composition of the medium [37], [38].

- *Multi-path propagation and frequency dispersion*: Traditionally, specular reflection attenuation from smooth surfaces can be modeled with the well-known Fresnel equations [39] given that the considered surface is sufficiently large in area and thickness with respect to the wavelength. Otherwise at mm wave THz bands, reflections within the material or multiple reflections at the interfaces of layered media have to be taken into account, causing highly frequency-dependent reflection behavior [13]. Moreover, the wavelength in the mm wave and THz bands is on the order of magnitude of surface height variations. For most building materials such as concrete or plaster, diffuse scattering from walls covered with rough materials becomes highly relevant [40], [41], [42]. In the 300 GHz frequency range, early publications, such as [43], have dealt with the characterization of typical building materials. Scattering has been subject to detailed experimental and theoretical investigation [40], [41]. Considering the huge bandwidths (for instance, beyond 10 GHz), the propagation phenomena themselves have to be treated as frequency-dependent. This frequency dispersion of the channel necessitates the broadband channel simulation in the frequency domain and can cause a certain distortion of transmitted pulse shapes [44]. Another important aspect of mm wave and THz propagation is polarization. As demonstrated by experimental studies with mm wave prototypes [28], the power degradation due to polarization mismatch between the antennas and depolarization caused by the channel can be as high as 10-20 dB. Polarization properties must be characterized in real railway scenarios in order to determine how much polarization diversity can be achieved for mm wave and THz channels.
- *Diffraction and shadowing effect*: Very high diffraction attenuations (of 30 dB and more) in the mm wave and THz bands makes diffraction effects in the shadowing region behind objects negligible. However, like in the T-G11ad channel model at 60 GHz [45], it is of importance to investigate how fast the signal drops and rises again in case of a dynamic shadowing effect. Thus, modeling diffraction is still useful to describe the dynamics of shadowing effects caused by various obstacles, such as human movement [46], buildings, or other trains, in the different defined smart rail mobility scenarios. The impact of different shadowing effects on the communication reliability is of great importance particularly for rail control and safety.

To sum up, the synergism of susceptibility of molecular absorption, the changed relationships between wavelengths and dimensions of objects, and the ultra-broadband bandwidths, results in propagation in the mm wave and THz bands distinguished from microwave frequencies. 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 rail scenarios, such as terrain, track, cutting, barriers, stations, pylons, and vegetation.

2) Existing channel models: A large body of work by industry and academia has already gone into channel measurements and modeling in the mm wave and THz bands.

- *Indoor environments*: The intra-wagon propagation channel can be reasonably approximated by an indoor office, or indoor hotspot environment. In the 60 GHz band, one of the most representative MIMO indoor models is the IEEE 802.11ad channel model, which is based on a mixture of ray-tracing and measurement-based statistical modeling techniques. Several recent studies based on it include theoretical investigations regarding capacity [47], [48] and spatial diversity techniques [49] as well as extended models for human blockage [50] and double-directional MIMO channel in a conference room environment [51]. Moreover, measurements and models of the channel response at 60 GHz are available in the literature for different environments, such as computer labs [52], offices [53], [54], hospitals [55] and aircraft cabins [56]. Apart from the IEEE 802.11ad model, the IEEE 802.15 TG3c is well established for 60 GHz indoor communications [45]. The TG3c model covers residential, office, library, desktop, and kiosk environments, whereas the TGad model covers conference room, living room, and cubicle. A thorough review of mm wave propagation both indoor and outdoor can be found in [57]. In the 300 GHz frequency range, the first ultra broadband indoor channel measurements in an office environment at 300 GHz stem from 2011 [58]. Because of the very short wavelength at a carrier frequency around 300 GHz, the waves propagate quasi-optically and can be modeled accurately using a ray optical approach [59], which can further be applied to derive stochastic channel models for simplicity and more generality [60]. An overview of research activities dealing with the THz wave propagation and radio channel modeling is given by [61].
- *Outdoor environments*: There have been recent studies regarding the outdoor channel propagation characteristics that have shown the potential for utilizing the mm wave bands for cellular communications, e.g., [32], [33]. A detailed literature review is provided in [57] and [62]. However, even though the ITU-R recommends using the spectrum above 6 GHz for supporting moving hotspot cell users such as high speed trains moving 500 km/h, channel measurements in the mm wave and THz bands in the smart rail mobility scenarios are not readily available.

TABLE I
PATH LOSS COMPARISON FOR LOS AND NLOS SCENARIOS IN THE 10 GHZ, 38 GHZ AND 60 GHZ FREQUENCIES

Frequency	10 GHz			38 GHz			60 GHz		
LOS path loss exponent	2			2			2.25		
NLOS path loss exponent	3.5			3.71			3.76		
Distance [m]	20	100	200	20	100	200	20	100	200
LOS loss [dB]	78.2	92.0	98.0	90.0	104.0	110.1	96.1	111.8	118.6
NLOS loss [dB]	90.0	114.6	125.0	104.1	130.1	141.2	108.5	134.8	146.1
Delta [dB]	11.8	22.6	27.0	14.1	26.1	31.1	12.4	23.0	27.5

Deterministic modeling approaches, such as ray-tracing simulations [63], are still the main tool. At 30 GHz, the authors of [64] stochastically modeled the channel characteristics, e.g., path loss exponent, autocorrelation and decorrelation distance of shadow fading, etc., in a typical railway scenario with a verified ray-tracing tool [65]. The authors of [66], constructed a linear high speed railway environment, and analyzed the propagation characteristics with a ray tracing method. With the simulation, it is shown that the K factor is large when the distance between the transmitter and receiver is short, and that when the distance between the transmitter and receiver is large, the level of fading becomes large, which is much different from the indoor environment. Using simulations, the authors of [67] evaluated a seamless fiber-mm-wave system for backhaul transmission from a central station to antennas on trains. The E-band (60-90 GHz) and W-band (75-110 GHz) are deemed to be more promising due to their large available bandwidth and low atmospheric attenuation.

Generally, current channel models are mainly for standard indoor and outdoor environments. Usually, railway appears as a small use case of “moving hotspot” in standard documents, e.g., [28]. How to include the railway channel features in channel models is an open challenge, e.g., how to account for the impact of vibration and wind pressure when trains move in and out of tunnels on the train-to-infrastructure links; how to evaluate various shadowing effects caused by moving objects and their influence on the link reliability. In terms of modeling approach, for high-speed environments, geometry-based models are generally better suited than tapped delay line models, because they the former can more easily model the inherent nonstationarities of such environments [68]. Such geometry-based models can either take on the form of traditional geometry-based stochastic channel models (GSCM), or combine deterministic geometrical structures with stochastic components [69], [70].

Another challenge is channel dynamics. Most of the existing measurements in mm wave and THz bands were done for static channels. In 2014, Samsung presented the world’s first demonstration for 1.2 Gbps transmission at 28 GHz at 110 km/h cruising speed using dual-beamforming [71]. This evidence shows the strong potential of the mm wave and THz bands for mobile applications. As pointed out in [46], dynamic ray shadowing causes a temporal variation of the path losses. Scattering at persons may introduce additional Doppler shifts and wider 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 mm wave and THz communications in any dynamic environment. Relationship between the channel coherence time (closely related to Doppler spread) and the beamwidth has been studied in [72], [73], [74]. The results in [74] show that there is an optimum operating beamwidth that results in a large coherence time. This should be theoretically and experimentally studied in the five rail traffic scenarios for the future work.

B. Antennas

MM wave and THz communications require the antennas to support bandwidths of tens of GHz and therefore, need ultra-broadband and multi-band antennas [20]. Furthermore, antenna arrays are necessary to provide gain to overcome the very high path loss in the mm wave and THz bands.

1) Ultra-broadband and multi-band antennas: Classical antennas, such as horn antennas, paraboloid antennas, etc., have been widely used in experimental wireless data transmission systems at 300 GHz. These antennas can provide a radiation bandwidth in the order of 10 percent of their center frequency as well as high gain. A Cassegrain antenna with a maximum gain of 51 dBi is shown in [75]. However, lack of directional adaptability makes them suitable only for infrastructure-to-infrastructure communications. For the sake of integration, potential novel antennas based on nanomaterials and metamaterials are good alternatives. For instance, it has been shown that graphene can be used to build plasmonic nano-antennas, which exploit the behavior of global oscillations of surface charges to radiate in the THz band [20]. The frequency response of graphene-based nano-antennas can be easily dynamically tuned by means of material doping, that is, dynamically changing the electrical properties by means of electrostatic bias [24].

2) Antenna arrays: The small size of a mm wave and THz antennas allows the integration of a large number of antennas with a small footprint. However, having ADC/DAC per antenna element may be challenging in terms of overall cost and power consumption. Thus, a phased array architecture in the radio frequency domain is recommended by the ITU-R

[28] because it can reduce the number of ADC/DACs while keeping the high beamforming gain. Following are discussions on different antenna array technologies:

- Full adaptive antenna array: Classic copper-based printed designs are available at 60 GHz; the challenges in the mm wave band are mainly the complexity and performance of the transmitter/receiver modules. Thus, a fully adaptive antenna array is feasible strictly from the antenna element design aspect both in cost and performance. According to [28], Table II provides the achievable data rate versus system bandwidth using different numbers of antenna elements, assuming a transmitting power of 30 dBm, and a noise figure of 10 dB, at 60 GHz frequency under outdoor LOS conditions. It can be found that the data rate increases not only along with the number of antenna elements, but also with the bandwidth. Thus, how to develop broadband or even ultra-broadband approaches for antenna arrays pattern synthesis becomes critical.

TABLE II
ACHIEVABLE DATA RATE USING DIFFERENT NUMBERS OF ANTENNA ELEMENTS AT 60 GHZ UNDER OUTDOOR LOS CONDITIONS

Number of antenna elements: 1			
Bandwidth [MHz]	10	100	1000
Data rate [Mbps]	65	320	900
Number of antenna elements: 10			
Bandwidth [MHz]	10	100	1000
Data rate [Mbps]	100	650	3200
Number of antenna elements: 100			
Bandwidth [MHz]	10	100	1000
Data rate [Mbps]	140	1000	6500
Number of antenna elements: 1000			
Bandwidth [MHz]	10	100	1000
Data rate [Mbps]	180	1300	10000

- Modular antenna array: Due to the loss on the feeding lines, traditional antenna array architectures – the antenna elements are connected to the radio frequency integrated circuits (RFIC) chip via feeding lines – allow implementing antenna arrays with relative small dimensions of up to 8×8 thus achieving gains of about 15-20 dBi. However, if we treat one traditional antenna array as a module, and construct it by using one beamforming unit, the aperture of the modular antenna array and total transmitted power may exceed that of an individual sub-array module proportionally to the number of the sub-array modules used (e.g., ten times or even more) [28]. Hence, much narrower beams may be created, and therefore, much greater antenna gains may be achieved with the modular array. Correspondingly, the issue of how to analyze the interaction and coupling effects among a large number of nearby antenna elements becomes more severe. Based on the information from ITU-R [28], Table III shows the array gains for the 60 GHz band when using different numbers of modules, where each module has 16 elements. In Table III EIRP is effective isotropic radiated power. It can be found that when using 16 modules, the array gain can achieve 27 dBi, which is sufficient to keep the link length (longer than 500 m with 10 dB SNR) in "Train-to-infrastructure" scenario. When a baseband processor connects not only one, but multiple beamforming units, beams of individual phased array module (subarray) may be steered in various directions to achieve a number of goals, such as enhanced diversity of spatial multiplexing. This is very suitable for "Inside station" and "Intra-wagon" scenarios where many users need to communicate simultaneously.

TABLE III
ARRAY GAIN OF USING DIFFERENT SUB-ARRAY MODULE NUMBERS FOR THE 60 GHZ BAND

Modular antenna array			
Sub-array module number	Tx power [dBm]	Array gain [dBi]	EIRP [dBm]
1	10	15	25
4	16	21	27
8	19	24	43
16	22	27	49

C. Beamforming approaches

Compared with analog beamforming using phased arrays with one radio frequency (RF) chain, digital beamforming offers great flexibility, but is also the most demanding in terms of power and cost – a particularly important concern for mm wave and THz frontends due to the large numbers of antenna elements, very wide bandwidths and very fast analog-to-digital converter (ADC) and digital-to-analog converter (DAC) [28], [76]. By combining analog beamforming in the RF domain and digital beamforming at baseband, hybrid beamforming [77], [78], [79] can get the benefits of both beamforming and spatial multiplexing, and therefore, is recommended by ITU as well [28]. In terms of algorithm design, among various specific schemes, we mention:

- *Codebook-based beamforming*: This approach controls the resulting antenna beams through predefined codebooks. IEEE 802.15.3c standard defined a common predefined set of beamforming codes for indoor applications and considered the numbers of antenna elements smaller than 100 [76]. The main constraint for this approach comes from the overhead for larger number of antenna elements.
- *Long-term beamforming*: When the macro-level angular directions of a channel change at a much slower timescale, the channel can be concentrated in subspaces that remain constant over longer periods. Signals can be identified and aligned on these subspaces by a standard procedure known as long-term beamforming [80]. Therefore, the feedback and tracking rate can be significantly reduced.
- *Angle of departure (AoD) estimation-based beamforming*: When using classical array processing algorithms, such

as space-alternating generalized expectation maximization (SAGE) [81], or using some new signal processing techniques, such as compressive sensing (CS) [82], path tracking algorithm [83], and sparse Bayesian learning (SBL) [84], AoDs and powers of multi-path components (MPCs) can be estimated. Given knowledge of the user's spatial channel, analog beamforming can be applied through the application of antenna phase weights [76].

- *Polarization-multiplexing beamforming*: In LOS channels, polarization can be exploited to combine the multiplexing and beamforming processes [85]. In this case, two I-Q baseband multiplex streams are supported to match the two orthogonal polarizations. In this way, multiplexing is not implemented in the spatial domain but in the polarization domain. In NLOS channels, there is still the possibility of transmitting two data streams over the two polarizations, but maybe with certain degradation due to cross-polarization phenomenon.

A proper understanding of the mm wave and THz channel behavior under specific propagation conditions in the railway scenarios is important for the design of viable beamforming schemes. Since among the five defined scenarios, links in the "Train-to-infrastructure" scenario exhibit the highest mobility, we will analyze this scenario in detail firstly, then discuss the beamforming approaches for the other four scenarios.

1) Beamforming approaches for "Train-to-infrastructure" scenario: Usually the channel has LOS in this scenario, but there are certain cases where the transceiver on the train can lose LOS, e.g., when the train passes through semi-closed obstacles, such as crossing bridges [86], train stations [87], [88], and so on. For the LOS channels, since the train trajectory can be easily predicted and there are very few users in this scenario, codebook-based beamforming as well as AoD estimation-based beamforming can be expected to work well. For NLOS locations, referring to the works in [89] (showing that the receiver in an NLOS urban core can receive two to four distinct spatial beams with strong received powers), a link length over 100 m can be kept by using coherent equal-gain combining for two to three spatial beams launched at the Tx. Also in this case, due to the preknowledge of the train locations, codebook-based beamforming and AoD estimation-based beamforming are quite promising.

Surely, the major challenge of this scenario is the high mobility of the train, which requires very fast adaptive beamforming. Here, we define a metric named "duration of a beam" as the time duration when the receiver on the train falls into the main lobe of the current beam from Tx. Correspondingly, before the receiver goes out of the current duration, the next (neighboring) beam has to be formed in time to keep seamless mobile services. Note that we define the "duration of the beam" relating to the second-order channel statistics; instantaneous channel states that might be created through small-scale fading, i.e., interference between multi-path components within one beamwidth, could change faster.

Through very simple geometrical calculations in (1), it can be found that the duration of a beam $T_{beam}(n)$ is jointly determined by the distance between the transmitter or base station (BS) and the rail $d_{BS-rail}$, the speed of the train V_{train}, and the beamwidth W_{beam}. n is the index of the beam (direction).

As shown in Fig. 2, the farther the receiver is from the Tx, the longer the duration of a beam is. Thus, the worst case – the minimum duration of a beam (the minimum value of $T_{beam}(n)$) – happens when the train passes through the transmitter beside the track.

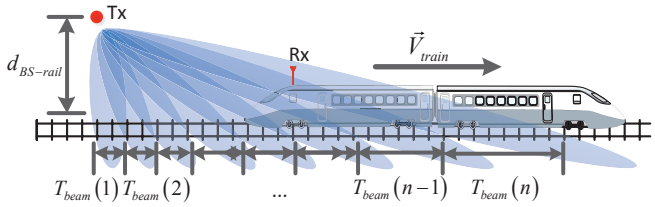


Fig. 2. Sketch of geometry for providing seamless mobile services between train-to-infrastructure using beamforming

As illustrated in Fig. 3, when the speed of the train is 500 km/h, the distance between the transmitter and the track is 3 m, and the beamwidth is 1°, the minimum duration of a beam is 0.38 ms. In this case, in order to keep seamless mobile services, the time of the link configuration must be shorter than such minimum duration of a beam.

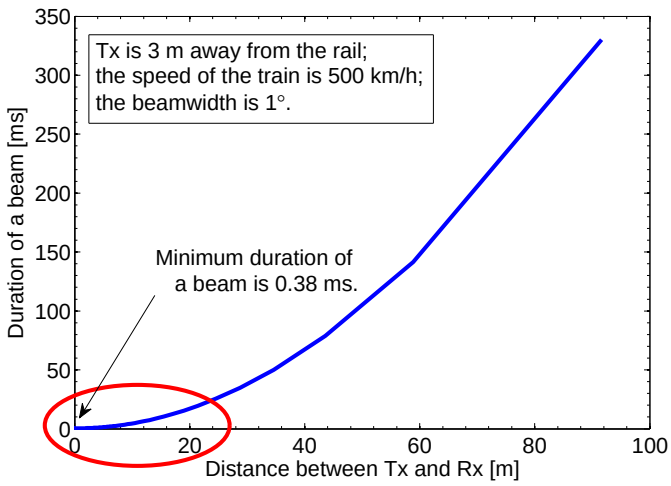


Fig. 3. Duration of a beam versus the distance between transmitter and receiver

Furthermore, Fig. 4 shows the minimum duration of a beam when assuming the transmitter is 3 m far away from the track, the beamwidth is from 1° to 10°, and the speed of the train is from 100 km/h to 500 km/h. Corresponding values are summarized in Table IV. Obviously, a narrower beam and higher speed jointly reduce the minimum duration of a beam, and therefore, require very fast beam tracking. On this point, apart from the traditional exhaustive search, some novel adaptive beam training protocols are proposed to use interactive beam training and multi-level beam training concepts for fixed and adaptive modulation, respectively [90]. In practice, it will be valuable to exploit the distinguishing feature of railway to avoid beam training. In railway control systems,

$$T_{beam}(n) = \begin{cases} \frac{2d_{BS-rail}}{V_{train}} \cdot \tan\left(\frac{W_{beam}}{2}\right), n = 1 \\ \frac{d_{BS-rail}}{V_{train}} \cdot \left[\tan\left(\frac{W_{beam}}{2} + \sum_{i=1}^{n-1} W_{beam}\right) - \tan\left(\frac{W_{beam}}{2} + \sum_{i=1}^{n-2} W_{beam}\right)\right], n \geq 2 \end{cases} \quad (1)$$

multiple communication systems, including GSM for railway (GSM-R), LTE for railway (under standardization), satellite communications (GPS, Galileo, etc.), track circuit, and Balise, are able to localize the train in time and even in advance. The advantage of trains is that their locations are predictable, so the channel does not need to be continuously measured in particular when LOS exists. Rather, the beamforming directions can be determined by an extrapolation from the stored train location information [90]. In addition to the train location, the information of the environment such as buildings can also be exploited to determine the NLOS paths. Nevertheless, even though we emphasize this technical possibility, the real performance will depend on the reliability and efficiency of the synergy of the aforementioned communication systems. More efforts on evaluating and validating this idea are urgently required for further studies.

A promising approach for reducing the impact of fast time-variations of the channel is OTFS (orthogonal time frequency space) [91], [92], which uses basis functions that are well concentrated in the delay-Doppler domain. As the delay-Doppler spectrum changes only very slowly over time, the different symbols are thus experiencing the same stable channel.

Another challenge of applying beamforming to the mm wave and THz communication is that the extremely short wavelength requires very precise phase shift of each antenna element. This problem is addressed in [93] and [94].

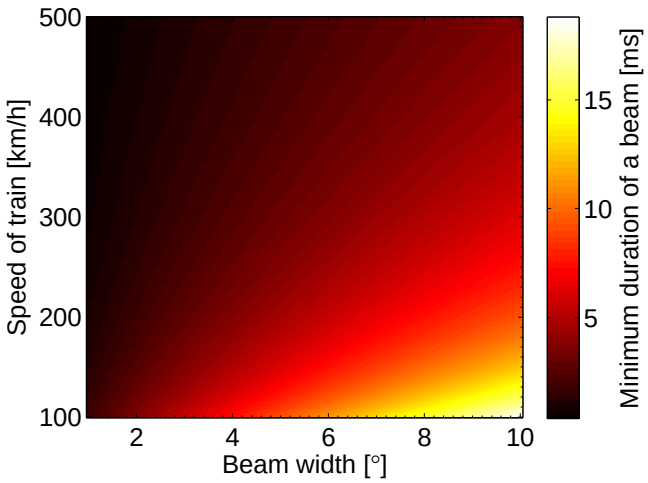


Fig. 4. Minimum duration of a beam when assuming the transmitter is 3 m far away from the track, the beamwidth is from 1° to 10° and the speed of the train is from 100 km/h to 500 km/h

2) Beamforming approaches for the other four scenarios: Unlike in the "Train-to-infrastructure" scenario, channels in the remaining four defined scenarios are not with high mobility. However, each scenario has different features, and their impacts on channels and beamforming approaches are discussed as follows:

TABLE IV
MINIMUM DURATION OF A BEAM, ASSUMING THE TRANSMITTER IS 3 M AWAY FROM THE TRACK

	Speed of train [km/h]				
W_{beam}	100	200	300	400	500
1°	1.88 ms	0.94 ms	0.63 ms	0.47 ms	0.38 ms
2°	3.77 ms	1.88 ms	1.26 ms	0.94 ms	0.75 ms
3°	5.65 ms	2.83 ms	1.88 ms	1.41 ms	1.13 ms
4°	7.54 ms	3.77 ms	2.51 ms	1.88 ms	1.51 ms
5°	9.42 ms	4.71 ms	3.14 ms	2.35 ms	1.88 ms
6°	11.30 ms	5.65 ms	3.77 ms	2.82 ms	2.26 ms
7°	13.17 ms	6.58 ms	4.39 ms	3.29 ms	2.63 ms
8°	15.05 ms	7.52 ms	5.01 ms	3.76 ms	3.01 ms
9°	16.92 ms	8.46 ms	5.64 ms	4.23 ms	3.38 ms
10°	18.80 ms	9.40 ms	6.26 ms	4.70 ms	3.76 ms

- "Inter-wagon" scenario: This is a LOS and quasi-static channel with very limited time variance. Thus, it is less sensitive to the necessity of beam tracking. All the aforementioned beamforming approaches can be exploited. AoD estimation-based beamforming would be very advantageous because of the fixed AoDs in this scenario and the "Inter-wagon" scenario. On the other hand, the main challenge is how to address antenna pointing errors due to fluctuations and relative movements of communicating wagons, particularly when the train runs on curved or tilted tracks, or suffers strong cross-wind. In order to overcome this effect, some efficient beam alignment techniques, for instance, using adaptive subspace sampling and hierarchical beam codebooks [95] become necessary.
- "Intra-wagon" scenario: This is an indoor environment with more than 100 users with low mobility. Since the users are quasi-static (nomadic), the system overhead of beamforming would not be much of an issue, and therefore, all the four aforementioned beamforming approaches can be considered. For a given wagon, the structure of the wagon and the facilities therein are fixed, the angular regions that are preferred by users (passengers on seats) or the directions from which radiation can physically occur can be known through site-specific channel simulations or measurements in advance. This is especially true for mm wave and THz bands, because in these bands physical obstacles can constitute very strong attenuators, thus greatly restricting the angular range from which useful signals can come in a given wagon. Thus, the whole angular regions can be divided into sectors and ordered by priority. This information can be used in interactive beam training, which consequently realizes a fast link configuration. In the simulations of [34], the link can be set up within the delay bounds of video and VoIP

services as summarized in [96]. Thus, even if the wireless link is disconnected while it serves video or VoIP streams, we can re-establish the link before the disconnection of the session.

- "Inside station" scenario: This scenario is similar to "Intra-wagon" scenario, but with more users and even shorter inter-user distances (shorter than 0.5 m). The low mobility of the users allows to use all the four approaches. Codebook-based beamforming would provide higher gain than AoD estimation-based beamforming because of the rich scattering in this scenario. Moreover, degradation of mutual-orthogonality and dynamic shadowing may influence the performance of beamforming approaches in this scenario and the "Intra-wagon" scenario.
- "Infrastructure-to-infrastructure" scenario: Similar to the "Inter-wagon" scenario, all the four approaches are feasible in this scenario. However, as a fixed backhand link, the longer communication link distances, combined with the severe path loss at mm wave and THz frequencies, make aligning the transmit and receive beams a challenging and important problem. Even though certain beam alignment techniques can be exploited, it is still not possible to use larger arrays without risking a corresponding performance loss from wind-induced beam misalignment [95].

All the discussions on the five scenarios are summarized in Table V, which can guide the R&D efforts of proper beamforming approaches for smart rail mobility.

V. Comparison between mm wave and THz for smart rail mobility

In the previous parts of this paper, we mainly discuss the features of mm wave and THz as distinguished from microwave. In this section, we compare mm wave and THz communications mainly from a channel viewpoint to find which one is more advantageous for smart rail mobility.

The first consideration is the available bandwidth for wireless mobile communications. For the mm wave band, available bandwidths are from 1 GHz (at 28 GHz) to 9 GHz (at 60 GHz). Thus, it is practical to achieve 1 Gbps or even 10 Gbps data rate with moderate spectral efficiencies. On the other hand, there are ultra-high bandwidths beyond 20 GHz available in the THz frequency range, and therefore, higher-data-rate transmission (i.e., beyond 100 Gbps) is more easily possible. Thus, for every single link between a UE and AP (inside station or wagon), mm wave should be enough for providing unsuppressed real-time HD video applications; but for the aggregate channels, e.g., in "Train-to-infrastructure" scenario, THz frequencies are more promising.

The second consideration is the beamwidth. In order to compensate the higher path loss at THz frequencies, much narrower beamwidth will be required (even 1°). For the "Train-to-infrastructure" scenario, if using current beam training protocols involving exhaustive search or prioritized sector search ordering, mm wave may be more practical, because a relatively wider beam makes it easier to keep the link configuration time within the latency bounds of HD video or VoIP services. Otherwise, if we can accurately predict the train location information, it is possible to avoid (or at least greatly mitigate) beam training and then the aforementioned disadvantage of longer link configuration time at THz can be neglected. For "Inter-wagon" and "Infrastructure-to-infrastructure" scenarios, to overcome the performance loss from wind-induced beam misalignment, it is still necessary to develop efficient beam alignment techniques, which are more challenging for THz with narrower beamwidth.

The third consideration is the motivation of developing new communication schemes. Although classical communication schemes can be used at THz frequencies, they cannot fully benefit from the very strong distance-frequency-dependent characteristics of the THz band [20]. These peculiarities of the channel motivate the development of novel communication schemes, such as, distance-aware multi-carrier modulation (DAMC) [97], hybrid beamforming scheme with DAMC transmission [98], etc. In this regard, THz communications will have even broader prospects.

Thus, to sum up, mm wave communications are more practical to enable the basic version of smart rail mobility in the next five years. In the subsequent five to ten years, we expect that full and enhanced versions of smart rail mobility providing a seamless high-data-rate connectivity beyond 100 Gbps can be enabled by THz communications. Table VI summarizes the comparisons between mm wave and THz communications for smart rail mobility.

VI. Ray-Tracing Simulation at 100 GHz for "Train-to-Infrastructure" Scenario

In this section, various specific beamforming approaches are abstracted as two dynamic beamforming strategies. They are integrated into our ray-tracing simulations at 100 GHz for a "Train-to-infrastructure" scenario in a typical urban environment. This gives us the chance to quantitatively discuss how to steer the beams at transmitter and receiver for real railway scenarios.

A. Simulation setup

TABLE VII
Simulation setups

Scenario	Urban area in Beijing
Constituting materials of building exteriors	Concrete (60%), glass (30%), metal (10%)
Antenna type	Directional antenna [99]
Antenna gain	25 dBi at 100 GHz
Antenna HPBW	10° - E plane, 12° - H plane
Heights of Tx and Rx	10 m and 3 m
Interval between BSs	1 km
Speed of train	360 km/h
System Bandwidth for a Link	1 GHz
Carrier frequency	100 GHz
Transmit Power of RF	20 dBm [100]
Interval between channel samples	1.25 mm

Main parameters of the simulation setup are given by Table VII, with the following detailed descriptions:

TABLE V
FEASIBILITY OF BEAMFORMING APPROACHES IN SMART RAIL MOBILITY SCENARIOS

Scenarios (Smart rail mobility)	Train-to-infrastructure		Inter-wagon	Intra-wagon	Inside station	Infrastructure-to-Infrastructure
Indoor/outdoor	Outdoor		Outdoor	Indoor	Indoor	Outdoor
Fixed/mobile link	Mobile link		Quasi-fixed 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	NLOS	LOS	LOS with shadowing	LOS with shadowing	LOS
Codebook-based beamforming	√	√	√	√	√	√
AoD estimation-based beamforming	√	√	√	√	√	√
Long-term beamforming			√	√	√	√
Polarization-multiplexing beamforming	√	√	√	√	√	√
Technical challenges	Fast beam tracking is needed, or beam tracking by an extrapolation of train locations		No need for beam tracking, but beam alignment techniques are required	Fast beam training is possible through prioritized sector search ordering; degradation of mutual-orthogonality and shadowing should be addressed		No need for beam tracking, but beam alignment techniques are required

TABLE VI
COMPARISONS BETWEEN MM WAVE AND THZ COMMUNICATIONS FOR SMART RAIL MOBILITY

Frequency band	MM wave	THz	Comments
Available bandwidth	1 GHz - 9 GHz	Beyond 20 GHz	MM wave: achievable data rate: 1 Gbps - 10 Gbps THz: achievable data rate: beyond 100 Gbps, suitable for aggregated channels, e.g., in "Train-to-infrastructure" scenario
Beamwidth	Wider	Narrower	THz needs longer beam training time, and is more sensitive to wind-induced beam misalignment
Motivation of developing new communication schemes	Less	More	The very strong distance-frequency-dependent characteristics of the THz band motivate the development of novel communication schemes, e.g., DAMC modulation [97], hybrid beamforming scheme [98]
Implementation for smart rail mobility	In the next five years	In the subsequent 5-10 years	MM wave: enable the first version of smart rail mobility by 2020 THz: enable the full and enhanced versions of smart rail mobility with a seamless high-data-rate connectivity beyond 100 Gbps

- Environment and system setup: As shown in Fig. 5, a part of the CBD (Central Business District) in Beijing, China, is chosen to represent the "Train-to-infrastructure" scenario when the railway is in an urban area. The map in the black frame in Fig. 5 shows one part of the CBD in Beijing, in which a 1 km-long rectangular area (the red rectangle) is reconstructed in the ray-tracing simulator. In the simulation scenario, the distance between successive base stations (BSs) is set as 1 km. Furthermore, heights of Txs at the BSs are 10 m; heights of Rxs on the train are 3 m; the speed of the train is set as 360 km/h. Concrete is assumed as a main material for building exteriors with a dielectric constant $\varepsilon = 5.31 - j0.24$ at 100 GHz [101]. Glass and metal are assumed as parts of building materials. Their dielectric constants are $\varepsilon = 6.27 - j0.19$ and $\varepsilon = 1 - j10^7$ at 100 GHz, respectively [101]. The road surface is asphalt for which the dielectric constant is assumed as $\varepsilon = 3.18 - j0.10$ at 100 GHz [102]. The carrier frequency is set as 100 GHz and the system bandwidth for one communication link is 1 GHz. The roughness root mean square (RMS) height for concrete, glass, metal and road are 0.2 mm, 0 mm, 0 mm, 0.34 mm, and the correlation lengths for them are 38.6 mm, 0 mm, 0 mm, 4.2 mm, respectively [102], [103], [104].
- Antenna parameters and beamforming strategies: In the simulation, we adopt the directional antenna from [99] with the maximum gain of 25 dBi at 100 GHz; the half-power beamwidths (HPBWs) for E plane and H plane are 10° and 12°, respectively. Fig. 6 indicates that the BSs are deployed with two directional antennas pointing in two directions along the rail. Meanwhile, the train has two directional antennas at the head and the tail [105], [106]. $d_{BS-rail}$=10 m indicates the distance between BS and rail. In the following section, we focus on the channel of the link between the nth transmitter and the first receiver. Two dynamic beamforming strategies are considered to be equivalent to the steering effect of the directional antennas. Fig. 6(a) depicts the dynamic-

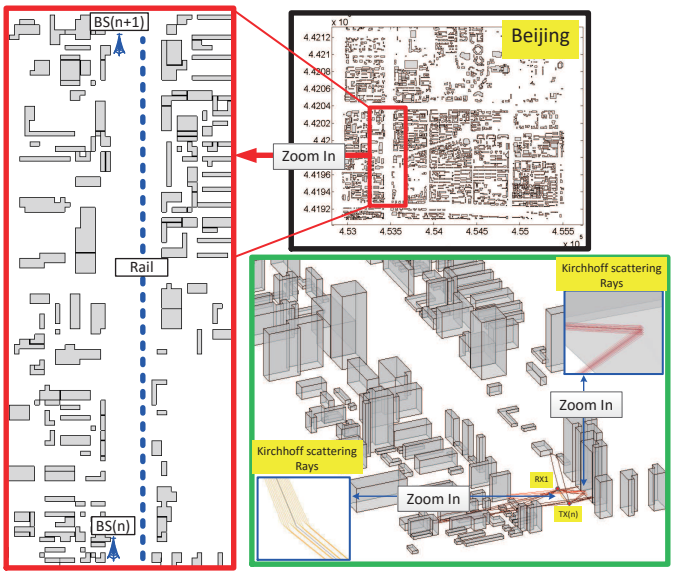


Fig. 5. Schematic diagram of the urban scenario in this study, where the black frame indicates the map of a part of CBD in Beijing, red frame shows the 1 km-long scenario, and the green frame gives one snapshot in the ray-tracing simulation.

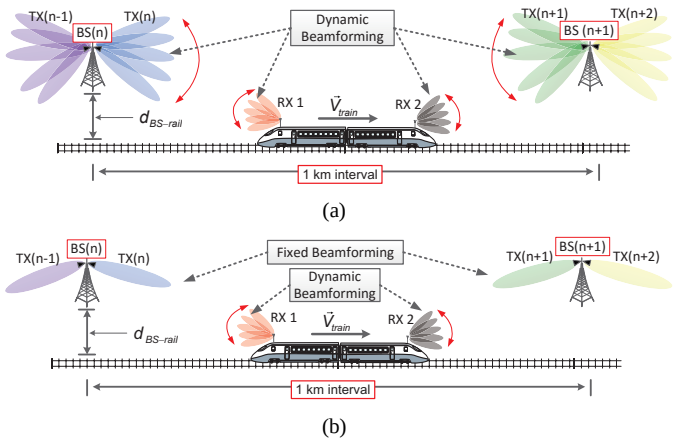


Fig. 6. (a) Dynamic-to-dynamic beamforming strategy. (b) Fixed-to-dynamic beamforming strategy.

to-dynamic beamforming strategy. It requires automatic tracking of signals of moving targets at both transmitter and receiver sides. Fig. 6(b) shows the fixed-to-dynamic beamforming strategy. It requires automatic tracking for the receiver, which means that the direction of the antenna at receiver is always pointing to the Tx. At the same time the direction of the antenna at the transmitter is statically pointing to the midpoint of the rail between the two base stations.

- Propagation mechanisms: For the simulation, we utilize a self-developed broadband and dynamic channel ray-tracing simulator that combines a vehicle-to-vehicle ray tracing simulator [65] and a broadband THz ray tracing simulator [107]. The former is validated by extensive measurements in [65], [108]; the latter is calibrated and verified by a large number of measurements in [107], [109]. For the reflection, in our prior simulations in the same urban scenario, we find that to trace the 4th-order of reflection considerably increases the workload but only adds less than 1% power. Thus, up to the 3rd-order of reflections are traced in the simulations for the trade-off between simulation accuracy and computational complexity. For the scattering, the Kirchhoff scattering model is employed in this simulation, which is widely used to provide suitable accurate prediction for wave s-cattering from random rough surfaces [110], [111], [112]. With the information of the RMS heights and surface correlation lengths of all the materials, the Kirchhoff scattering model [113] can be evaluated and implemented in the ray tracing simulator.
- Broadband and dynamic channel ray tracing method: As the system bandwidth for one communication link is 1 GHz, we use a subbanding ray-tracing method which means that the channel impulse response (CIR) for one snapshot is generated by a number of subbands at multiple center frequency points [109], [114]. Based on our prior simulations in the same scenario with 1 GHz bandwidth, 30 subbands are determined as a proper setup in this study. In order to capture both large-scale and small-scale channel characteristics, the interval between two channel sampled snapshots is 1.25 mm, which is less than half wavelength at 100 GHz.

B. Simulation results and discussions

In this subsection, signal-to-noise ratio (SNR), delay spread, and Doppler spread of the channel between the nth transmitter and the first receiver at 100 GHz are characterized with two beamforming strategies, respectively.

1) Signal-to-noise ratio (SNR): Fig. 7 shows the SNRs of the two beamforming strategies versus distance between transmitter and Rx. The SNR is calculated by:

$$SNR\,(dB) = P - (-174 + 10 \cdot \log_{10}(W) + N_F) \qquad (2)$$

where P is the received power of which the small-scale fading is eliminated by averaging samples at interval 40 wavelengths [115]. The system bandwidth W is 1 GHz. -174 is the spectral noise power density for 1 Hz bandwidth (in dBm/Hz). The noise figure N_F is set as 10 dB.

From Fig. 7, it can be found that with the aid of beam-forming, the high path loss at 100 GHz can be effectively compensated, and therefore, the link length could be longer than 500 m (10 dB SNR as a threshold). For distances between 100 m and 1000 m, more than 85% of SNRs between 10 dB and 30 dB can be achieved by both beamforming strategies. However, in the area where the distance is shorter than 100 m, the SNR of fixed-to-dynamic beamforming strategy deteriorates rapidly. This reflects a drawback of utilizing the fixed-to-dynamic beamforming – the LOS component will be out of the main lobe of the fixed beam when the receiver is close to the Tx.

2) Delay spread: For the channel characteristics in the delay domain, an overview of simulation results can be ob-tained by normalized moments of the power delay profile (PDP) [116]. The cumulative distribution functions (CDFs)

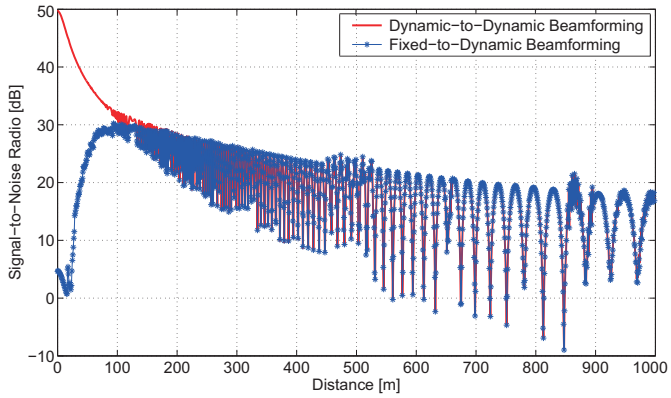
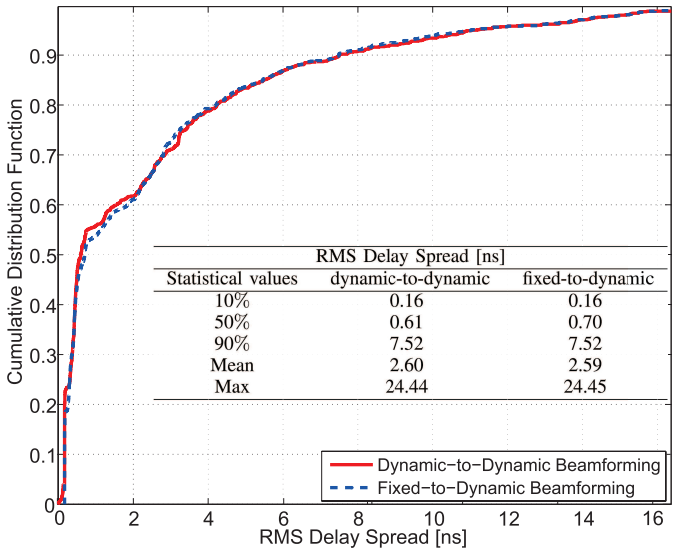


Fig. 7. SNR of the channel with two different beamforming strategies versus distance between transmitter and Rx

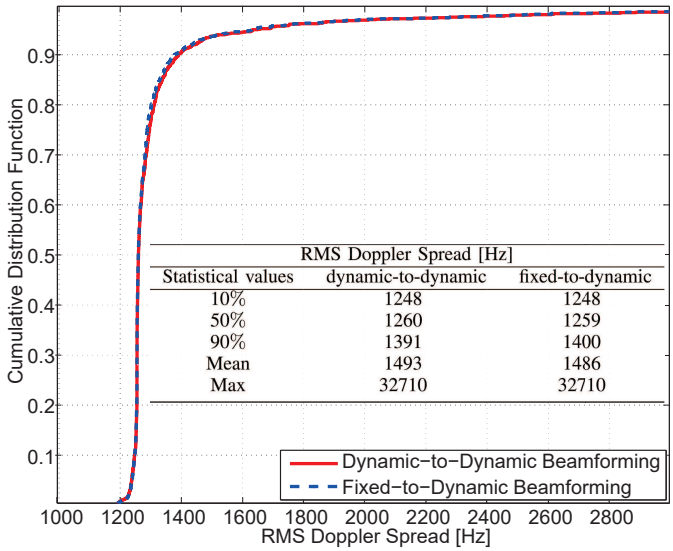
of RMS delay spreads are illustrated in Fig. 8. 50% of the RMS delay spreads are less than 1 ns, and the mean values are around 2.6 ns for both beamforming strategies. So short time delay spreads come from the high path loss at 100 GHz and the spatial filtering effect of beamforming strategies. However, they are still long enough to introduce inter-symbol interference (ISI) to the signal with 1 GHz bandwidth, i.e., 1 ns symbol duration.



RMS Delay Spread [ns]		
Statistical values	dynamic-to-dynamic	fixed-to-dynamic
10%	0.16	0.16
50%	0.61	0.70
90%	7.52	7.52
Mean	2.60	2.59
Max	24.44	24.45

Fig. 8. Cumulative distribution function of RMS delay spreads with two different beamforming strategies

3) Doppler spread: The Doppler effects demonstrate the physical interpretation of the frequency shift by the movement of transceivers and objects [116]. In the ray-tracing simulation results, the Doppler shift for each ray is given by multiplying the velocity with the cosine of the angle between velocity and ray. The two CDFs of RMS Doppler spreads are compared in Fig. 9, where for both beamforming strategies 80% of the RMS Doppler spreads are between 1248 Hz and 1400 Hz. Even though the directive antenna beam reduces the number of effective multipaths, and thus usually decreases Doppler spread, this metric is still much higher than the cases at frequencies below 6 GHz. However, since a much wider bandwidth will be used as well, shorter symbol duration may be used, depending on the channel delay spread, pilot scheme, and the particular transmission scheme used. The effect of a large Doppler spread as a limiting factor will thus need to be evaluated carefully in future studies. Thus, whether Doppler spread will be a limiting factor for mm wave and THz communications should be evaluated in future study.



RMS Doppler Spread [Hz]		
Statistical values	dynamic-to-dynamic	fixed-to-dynamic
10%	1248	1248
50%	1260	1259
90%	1391	1400
Mean	1493	1486
Max	32710	32710

Fig. 9. CDFs of RMS Doppler spreads with two different beamforming strategies.

4) Discussions: From the channel characteristics analyzed above, we can obtain the following insights and suggestions for the physical layer and system design:

- The usage of high-gain directional antennas or beamforming strategies is mandatory for keeping the "Train-to-infrastructure" link with sufficient length (longer than 500 m) at THz band. As shown in Fig. 7, the link length can achieve longer than 500 meters by using directional antennas or beamforming both on transmitter and receiver sides. Thus, in terms of the link length, it is feasible to provide outdoor mobile communications in the THz band to moving vehicles.
- Dynamic beamforming is critical to keep the channel with high SNR, low delay spread and low Doppler spread. More specifically, dynamic beamforming at both transmitter and receiver sides performs better than the dynamic beamforming only at one side. The spatial filtering effect of beamforming can effectively suppress the delay spread and Doppler spread, making Gbps data rate with high performance to the users inside fast-moving vehicles achievable.
- The fixed-to-dynamic beamforming strategy can be a good choice if implementing the dynamic beamforming at both sides (e.g., the one presented in [106]) is overly complex or not economic. However, advanced handover strategies shall be employed when the channel condition becomes worse. For instance, as shown in Fig. 7, when the receiver is close to the Tx, the channel suffers

very high loss. Then, a handover shall be made here, a strategy that is very different from the current cases of cellular communications at frequencies below 6 GHz, where usually the handover happens in the middle place of successive base stations.

VII. Conclusion

The future smart rail mobility requires high performance communication system. In this paper, we introduced the applications and scenarios required for smart rail mobility, analyzed the bandwidth requirements and clarified the motivations of developing mm wave and THz communications for railway. Corresponding technical feasibility is proved by the state of the art of channel studies in terms of wave propagation, antenna arrays and beamforming approaches. However, numerous challenges still need to be addressed in each aspect.

Regarding wave propagation aspects, more research efforts should be made on revealing the essence of complex propagation phenomena, such as frequency-selective and distance-dependent behaviors, frequency dispersion, different shadowing effects. MM wave and THz channel models including railway features are still open issues, and therefore, further dynamic measurements and ray-tracing simulations are required.

For antenna arrays, ultra-broadband and multi-band antennas become necessary for mm wave and THz communications. Potential novel antennas based on nanomaterials and metamaterials are good alternatives for mobile and personal devices of passengers. Furthermore, multi-antenna transmission using modular phased antenna structures is very suitable for "Inside station" and "Intra-wagon" scenarios where many users require to communicate simultaneously.

Exploiting hybrid beamforming architecture for railway can potentially get benefits from both spatial-multiplexing and beamforming. AoD estimation-based beamforming approach can be widely used in the five rail scenarios. The performance of codebook-based beamforming depends on the mobility. Long-term beamforming as well as AoD estimation-based beamforming are more feasible for the quasi-fixed scenarios, i.e., "Inter-wagon" and "Infrastructure-to-infrastructure" scenarios. Both for LOS and NLOS channels, polarization-multiplexing can be exploited to improve throughput.

For the "Train-to-infrastructure" scenario, we ought to exploit the distinguishing feature of railway, i.e., the predictable train locations, to reduce the stringent latency requirements for beam training – an important technical possibility that should be validated through further experimental studies. In the other four scenarios, degradation of orthogonality, dynamic shadowing effects, and beam alignment techniques are open issues urgently required to be addressed.

After comparing mm wave with THz in terms of available bandwidth, beamwidth, motivation of developing new communication schemes, and standardization, we conclude that it is more promising for mm wave to enable the basic version of smart rail mobility in the next five years, while the full and enhanced versions of smart rail mobility will more rely on THz in the subsequent five to ten years. Finally, the ray-tracing simulations at 100 GHz and corresponding quantitative discussions emphasize that to form high-gain directional antenna beams both at transmitter and receiver sides, dynamic beamforming strategies and advanced handover design are of importance for the feasibility of THz communications enabling smart rail mobility.

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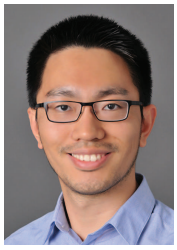

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