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Transport Research Arena (TRA) Conference

Millimetric waves communications for Railways

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Abstract

The mmW4Rail project explores the millimeter wave band for train-to-train and train-to-infrastructure communications. It involves the definition of new channel models based on measurements in railway environments in the 60 GHz and the design and integration of specific antennas. The Doppler shift due to high train speed requires a specific design of the beamforming codebooks and the channel state information feedback mechanism. In addition, new solutions for radio resource management will be proposed. The performance will be assessed via system level simulations integrating the measurements-based channel model, antenna and beamforming design. This paper will focus on some preliminary results related to channel characterization and enhancement of the communications thanks to system level simulations.

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Keywords: wireless communications, millimeter waves; railways; train-to-train and train-to-infrastructure communications;

1. Objectives and research hypothesis

The FRMCS (Future Railway Mobile Communication System) under development has the ambition to bring bearer flexibility to the railway telecom essential services using the capabilities of 5G NR. It will be the system that will offer a full migration towards 5G for the railway industry as GSM-R will become obsolete in 2030. One of the main problems not yet completely solved for railway, is spectrum scarcity. This has motivated the exploration of the millimeter-wave (mmW) frequencies. 5G mmW networks are able to support very low latency and high reliability

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thanks to 5G features. Developments for high data rate and very low latency are very active between 24 GHz and 100 GHz Shafi et al. (2017), Shah et al. (2018).

They are suitable for high-speed mobile applications and other railway safety Train-to-Infrastructure (T2I) applications identified Mottier et al. (2017) such as virtual coupling of trains (platoons of trains) from different manufacturers based on Train to Train (T2T) wireless communications Goikoetxea (2016).

T2I communications for train operation are safety critical particularly in the context of train automation and with the evolution of signaling towards moving block where the trains will run close to each other's Flammini et al. (2018). They require high reliability degree and stringent delay constraints under very high mobility. The technical barrier is the high Doppler Effect due to the high transmitting frequency and ultra-high speed of the train. There is only a few studies on this scenario in the literature. In 3GPP, some primary assessments for the high-speed train scenario have been made in the beginning of Release 15 on scenarios and requirements for next generation access technologies TR38.913 (2018), and train-specific requirements further listed in TS 22.289 (2019), TR 22.889 (2017). For the T2T communication scenario, one particularly crucial use case is the Virtual Train Coupling System (VTCS). Since all trains in the platoon have the same speed profile, safety headway between trains can be further reduced and the line capacity can be further improved. The key characteristics for this mmW link are also reliability, availability, and latency for critical train control. The technical barrier is to provide a reliable physical layer design given specific probability of failure, data rate, delay, and jitter and communication range constraints.

In order to develop reliable mmW T2I and T2T communication systems, the propagation conditions and channel behaviour have to be well known to avoid communication outages particularly in the context of mobility. Dedicated channel models for mmW in railway environments are needed. So far, only mmW channel model based on stationary or slow-moving vehicles scenario assessment has been studied. The state-of-the-art works on mmW band channel modelling are generally based on ray-tracing simulations. Only limited measurements in the mmW band are used to calibrate the ray-tracing simulator. Synthetic data generated from the ray-tracing simulator is then used for mmW band channel modelling. To the best of our knowledge, there is no direct channel modelling based on measurements in the mmW bands in the railway context including mobility He et al. (2018).

2. Characterization and modelling of mm-Wave radio channels for dynamic scenarios (moving transmitters, receivers and scatterers)

2.1. Introduction

Characterization and modelling of radio channel in the mmW frequency bands are needed for the development and analysis of T2X communication systems in this band. For several years, this domain is very active in the context of 5G NR deployment but only a few works considered the case of Railway communications. In He et al. (2018), the authors tuned a Ray tracing simulator for operation at 60 GHz based on material characterization but no mmW channel sounding is performed. T2T channel at 300 GHz is characterized through channel sounding and ray tracing for the first time Rey et al. (2017), Guan et al. (2019). In Gaddar et al. (2015), the authors present mmW propagation measurements in underground mine using directional MIMO (Multiple Input Multiple Output) antennas and a VNA (Vectorial Network Analyser). This approach could be used in stationary environments but is not suitable for mobility environment. A wideband digital sweep 2x2 MIMO channel sounder at 60 GHz is presented in Salous et al. (2016). However, this sounder is not suitable for measurements in railway context. Recently, Soliman et al. (2018) presents dynamic measurements at 60 GHz using equipment based on a classical channel sounder (RUSK) and mmW front-end. Only results on path loss are presented. They highlight two main contributions: the LOS component and a ray reflected on the ground. In Soliman et al. (2019), the impact of wagon vibration on the channel is evaluated. The influence on antennas is presented in Soliman et al. (2017).

Today, to our knowledge, there is no quasi-3D channel sounding based on a beamforming technique for MIMO channel modelling in the mmW band. Salous et al. (2016) gives an interesting overview of channel measurements and models in the mmW band, but the Railway domain is not considered. Some channel models in the mmW band for railways were published recently using Ray tracing tool He et al. (2018). The main interest of a MIMO full digital beamforming is the capacity to detect simultaneously the direction of arrival in multipath environment. This allows channel modelling for MIMO application in mobility context. IMT-Atlantique designed a channel sounder with digital

beamforming for frequencies up to 6 GHz. A mmW front-end is currently being designed and will be integrated in the channel sounder platform. This will enable measurements in the 57-64 GHz band. The current drawback of the system is the limited bandwidth of 160 MHz imposed by ETTUS SDR (Software Defined Radio) equipment. In the mmW4Rail project, solutions to improve the bandwidth will be explored, and implemented with the challenge to keep a good sensitivity.

2.2. Channel sounder description

A channel sounder in mmW band is under development at IMT-Atlantique Attwood et al. (2022). The 60 GHz frequency band is obtained by using the RF front-end board HMC6300 designed by Analog Device. It covers the frequency from 57 to 64 GHz with a maximum channel bandwidth of 500 MHz. The input and output signals are a differential baseband modulated signal. The modulated signal is generated by a Rohde & Schwarz SMJ. The output signal of the HMC6300 board is also a baseband signal received by the USRP X310 for a digital processing. For long distance, a power amplifier could be added and provide an output power of 25 dBm at 60 GHz.

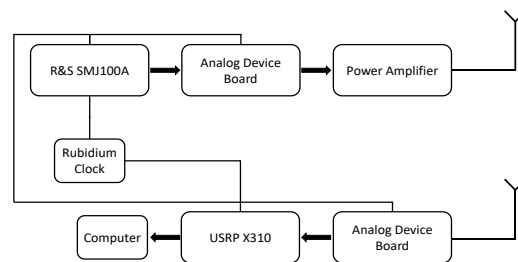


Fig. 1. Transmitter and Receiver structure

Today, the arbitrary generator Rohde & Schwarz with a bandwidth of 80 MHz introduced a limitation. A study is ongoing to replace it by a generator with more bandwidth to use the full capacity of the ETTUS SDR equipment (160 MHz). To avoid risk of breakage during measurements in railway environments, the controller part of the sounder is fully integrated in rack with silent bloc and the front-end is integrated inside a box. The Fig. 2. presents the transmitter part with the rack that contains a computer, an inverter and the SMJ, and the box that contains a commercial card and a power amplifier.

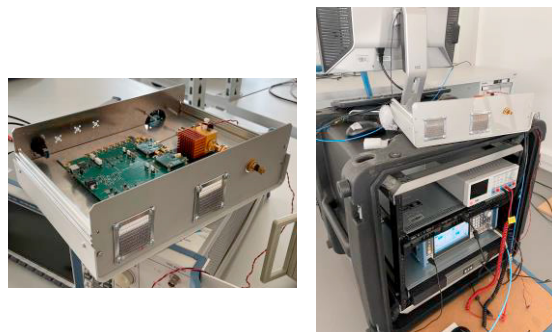


Fig. 2. Transmitter front-end (left) and rack (right)

Nowadays, the channel sounder can realize static SIMO measurements. We use a single antenna for the transmitter and the receiver. The receiver can move in azimuthal axis with the help of an angular controlled motor. To realize dynamic SIMO measurements, the commercial front-end receiver part by will be replaced by a multibeam antenna developed at IMT-Atlantique. This system consists of 8 frequency downconverters synchronized and connected to an antenna patch array and a bi-focal transmit array to generate the beams Pajusco et al. (2017). The bi-focal configuration of the transmit array allows decreasing the scan losses and provides higher gain. The signal received by each beam

can be processed simultaneously with several SDR systems in parallel or can be switched quickly to use just one SDR equipment. This last configuration is chosen when the environment changes slowly compared to the switching speed. The multibeam RF front-end is presented on the **Error! Reference source not found.**. The goal is to do a quasi-3D scan with a mechanical scan with a fixed beam in the azimuthal plane and an analog/digital beamforming in the vertical plane.

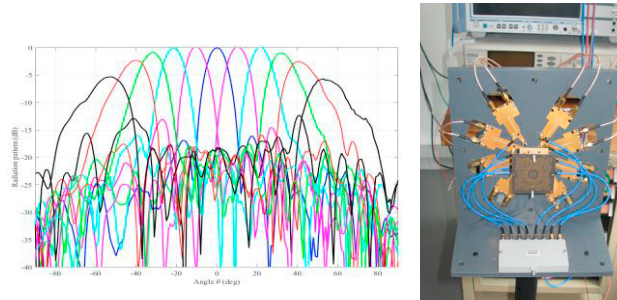


Fig.3. Multibeam RF front-end.

2.3. Preliminary results

As first measurement, we compare 2 input modulated signals. The first one has a flat spectrum. It consists of an addition of multiple subcarriers with random phases. The second one is a chirp signal. It consists of sliding a frequency during a period. The measurement are performed with the same card configuration and environment. We can note that the dynamic of measurement is 10 dB higher for the chirp signal than the flat spectrum. This difference is due to the way the signal is generated. The flat spectrum signal is the superposition of all the subcarriers, so the emitted power is divided by the number of subcarriers. For the chirp signal, only one carrier is sliding in time, so the final power emitted is higher than the flat spectrum signal one. After these first measurements, the decision is made to use a chirp signal instead of a flat spectrum. Moreover, the chirp signal is short in time, no more than 10 μ s, so the environment of measurement even in dynamic scenario does not have the time to change. A second measurements campaign was realized in a 30-meter-long corridor. The first objective is to check the correct functioning of the full system with the computing in real time of the channel impulse responses. Secondly, we evaluate the capacity of the system for dynamic measurement. The installation consists of the transmitter and the receiver spaced by a fixed distance for the static part. For the dynamic part, the distance between the transmitter and the receiver varies from 30 m to 5 m at a speed of a pedestrian. A 10 MHz reference signal is used to synchronize and is transmitted from the receiver to the transmitter throw a cable. For future measurements we will synchronize the receiver and the transmitter independently by a GPS or a rubidium calibrated clock.

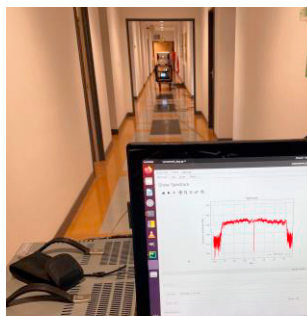


Fig. 4. Presentation of the measurement in the corridor.

The results of the first measurements in laboratory are presented in the Fig. . We can see in red the LOS (Line Of Sight) path which is sliding during the time representing the movement performed during the measurement. Moreover, we can also see multiple paths. These multipaths moved alongside the LOS path, that shows the impact of the corridor

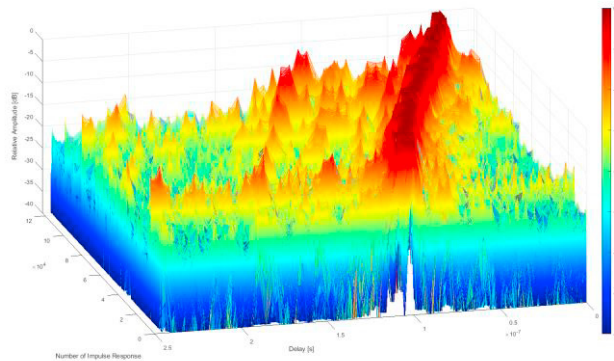


Fig. 5. Result of dynamic measurement in laboratory corridor at 60 GHz.

on the propagation channel. These measurements permitted to validate the functioning of the channel sounder and to characterize its performances. Even with a 160 MHz bandwidth, we can observe some multipath and determine a channel sounding of a corridor.

2.4. Evolution and future measurements

Measurements in real conditions are scheduled end of June in railway environment at C.E.F (Railway Test Center) in Valenciennes (France). We will perform static and dynamic measurements in different tracks environments such as concrete, wood, and ballast. This will allow us to test the impact of different materials on the propagation channel. Using a specific testing train (Fig. 6.), we will perform channel sounding with the presence of catenary and other obstacles in the vicinity of the tracks and also in the case of a curved track. The impact of rain and wet ground plane on the propagation channel will be also analyzed due to the foreseen degradation of the communication link.



Fig 6. Views of the test tracks and testing train

3. Antenna specification, design and prototyping for T2T / T2I applications in the mmW

Specification, design, integration and prototyping of mmW antenna systems for T2X communications and channel characterization/modelling are two intimately related tasks. Requirement specification for T2X antenna systems in the mmW band is still an open issue. Antenna systems and their integration aiming specifically at vehicular data communication in the mmW band after ITU-R M.1452-2 (05/2012) and ECC/DEC/(09)01 have so far, to our knowledge, not been presented. Oko et al. (2006) presents some general considerations. ITU-R M.1452-2 (05/2012) Annex 3 mentions communication methods one-way, simplex, half duplex, full duplex, multicast. Several parameters such as the number of (simultaneous) beams, the number of ports available for genuine MIMO (in the sense of exploiting spatial or polarization diversity or spatial multiplex), duplex modes to be supported, beam selection vs.

continuous beam steering, scan range have to be defined. Results from dynamic and static mmW channel characterization in railway environment for the given T2T and T2I use cases will constitute essential inputs to derive antenna specifications. Current trends in research on mmW antennas focus on future 5G applications, Radar systems and technological challenges for increasing operating frequencies to sub-mmW THz frequencies. The requirements for Massive MIMO base station antennas or tiny user equipment antennas are, however, substantially different from those for T2X use cases. Besides, related work focuses on the 24.25-29.5 GHz and 37-43.5 GHz bands. For applications in the 57-66 GHz range, extensive research work on antennas has been carried out in connection with WLAN (IEEE 802.11ad) and short-range communication (IEEE 802.15.3c) systems Dadgarpour et al. (2016). Commercial solutions are already available. Due to their focus on low cost, chip integration and at the same time, moderate efficiency, beamforming and gain requirements, related designs cannot directly be extended for T2X applications. One notable application where mmW technology has already hit the mass market, and which bears some technological commonalities with the application under consideration, is vehicular radar in the 76-77 GHz and 77-81 GHz ranges according to ETSI EN 301 091 and ETSI EN 302 264. These systems, being designed predominantly for Frequency Modulated – Continuous Wave (FMCW) radar, however, also come with different antenna requirements. Aspects of platform integration shall have a major influence on the overall design concept and need to be investigated. Debris, ice, snow, water and contamination by conductive particles Seetharamdoe et al. (2017) are to be considered, as well as vibrational stress and extended temperature range. The antenna system must be integrated with and electromagnetically matched to a mechanically robust radome while preserving pattern quality Oko et al. (2006) and efficiency.

Requirements specification, architecture and platform integration concepts for mmW antennas in both T2I and T2T antenna systems are so far not available. Consequently, limitations as well as new features of such antenna systems cannot adequately be accounted for in radio channel models. Within the mmW4Rail project our objectives are to propose dedicated specifications for Railway use cases where mmW frequencies are relevant such as virtual coupling or remote driving. Based on these specifications, antenna architecture for the requirements of the use cases (antenna performances, integration scenarios) will be proposed. Suitable parametrizable antenna models for inclusion into system-level mmW simulations and prototypes for experimental validation are among the expected original outputs of the project.

4. Enhancement of reliability at Physical layer for T2T / T2I mmW communications

System level simulation (SLS) has served a significant role in standardization bodies as a powerful tool for evaluating, comparing and selecting the most beneficial technologies during the evolution of the technology roadmap. For modern systems, characterized by plentiful users, heterogeneous architecture, various air interface and complicated interference environments, SLS makes it possible to evaluate the physical layer behaviors of multi-cells and multi-users in a high-density deployment. Regarding the T2I/T2T communication in the mmW band, SLS can be adopted to evaluate train-specific communication phenomena. The MIMO family signal processing technologies such as static/dynamic beamforming, interference alignment, and coordinated multi-point transmission for T2I/T2T can be evaluated. The multi-hop relaying in a heterogeneous deployment with different routing and radio resource allocation strategies can be analyzed. The high Doppler effect, which is induced by high train mobility can be evaluated with SLS as well. An example of the SLS-based mmW band T2I/T2T evaluation is the work Li et al. (2021) on heterogeneous multi-hop relaying for mmWave band train radio that targets both throughput-/delay-aware train applications. As it is shown in Fig. 7, communications based on the sub-6 GHz Uu interface are envisaged for the gNB to RSU links. Communications based on mmW band PC5 interface are considered for the inter-RSU and RSU to train links. Based on the SLS, a joint radio resource management and routing topology optimization is evaluated to either maximize the minimal end-to-end throughput or minimize the maximal end-to-end transmission delay for multi-hop transmissions towards several trains.

To counter losses in the channel and to assure robustness in T2I or T2T mmW communications in the context of mobility and safety, the integration of multiple antenna array with different potential applications (beamforming, diversity and/or spatial multiplexing) are required. Beamforming techniques, which have gained much of interest in mmW communications are required Kutty et al. (2016). It is essentially a spatial filtering operation typically using an array of radiators to capture or radiate energy in a specific direction over its aperture. Beamforming can offer both

diversity and multiplexing gains, which are crucial for reliable communications in T2I and T2T. Many studies deal with the importance of such techniques Molish et al. (2017). Codebooks are needed to support beamforming mechanism at the transmitter and the receiver sides. The aim is to design the beam search space (at the transmitter and the receiver sides, respectively) and represent it by a predefined codebook containing multiple codewords. The design of a codebook can be done in order to improve many metrics including the data rate and the system performance. There are few studies in the literature on codebook designs for beamforming techniques, especially for T2I and T2T communication systems Chen et al. (2019). Few studies have examined new codebook designs using channel state information (CSI) with Doppler shift or high mobility Chen et al. (2019), Zhang et al. (2019), Nosrati et al. (2019). Therefore, it is critical to study the effects of T2I and T2T mobility on beamforming techniques and codebook designs to check the reliability and robustness of such communication systems. In the framework of the project, Mabrouki et al. (2022) has provided a state of the art regarding codebook designs for mmW communication systems in both low and high-mobility with advantage and drawbacks comparison and also open research directions. There is a clear lack of research works dedicated to T2T and T2I communications in the use cases defined in the mmW4Rail project. Consequently, we aim at developing codebooks designs taking into account mobility. The new algorithms and designs for physical layer enhancement of train radio can be evaluated in a simple and fast manner with the system level simulation tool developed also within the project.

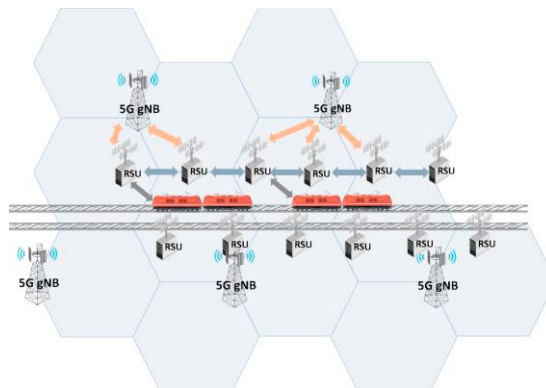


Fig. 7. Heterogenous multi-hop relaying from gNB via RSUs to trains.

5. Conclusion and future work

Increasing communication needs and spectrum scarcity in the railway domain have conducted to the exploration of mmW in the context of FRMCS developments based on 5G NR deployment. IN this context, the mmW5Rail project focuses on the enhancement of T2T and T2I communications in the mmW bands. In this paper we have proposed the preliminary results obtained particularly regarding channel characterization.

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