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Experimental mmWave channel sounding in the 60 GHz band in railway environments

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Abstract—Railways are facing an ever increasing needs for safe and secure wireless communications with the generalisation of automatic and driverless trains. In this context, frequency scarcity is a real bottleneck. To overcome this blockage, opportunities offered by mmW frequency bands are explored. Due to the specificity of environments, researches conducted for general 5G and beyond deployments can not be transposed easily. Channel sounding in the mmW bands in real railways environments should be conducted. In this context, this paper presents preliminary experimental results in a railway environment with a relative low cost and reconfigurable channel sounder operating at 60 GHz.

Index Terms—channel sounder, mmWave, antennas, propagation, measurements, railways.

I. INTRODUCTION

Trains are entering the era of full automation in order to increase capacity, reliability and quality of service. To this end, the needs for safe and secure wireless communications systems is increasing drastically. A new communication system called Future Railway Mobile Communication System (FRMCS) is under development. It will be based on 5G New Radio (NR) standard. In this context, it should cope with spectrum scarcity for Railway applications. This has motivated the exploration of the millimeter-wave (mmWave) frequencies. Developments for high data rate and very low latency are very active between 24 GHz and 100 GHz [1], [2]. These bands can answer the needs for high-speed, high data rate and ultra low latency mobile applications and other railway safety applications such as Train-to-Infrastructure (T2I), Train-to-Train (T2T) and intra Train identified in [3]. Among these applications we can mention high demanding ones such as virtual coupling of trains (platoons of trains) from different manufacturers based on T2T wireless communications [4]. These wireless links should experience very low probability of failure, high data rate, sometimes ultra low latency in the context of important communication range constraints due to specific propagation conditions in the mmWave band in typical railways environments well known to be harsh with multiple scatters and reflectors due to tracks, pylons, ballast, trains stopped or in movement.

Characterization and modelling of Railway radio channel in the mmWave frequency bands are needed for the development and analysis of Train to everything (T2X) communication systems in this band. This are the main goals of the mmW4Rail project supported by the French national research agency.

It involves the definition of new channel models based on measurements in railway environments in the 60 GHz band and performance evaluation in these channels. In this paper, we will present a new channel sounder operating in the mmWave bands able to perform dynamic measurements and the results obtained during a first measurement campaign in a typical Railway environment in France. The paper is organized as follows. Section II highlights the related works concerning measurements in Railway environments in the mmWave band and the existing channel sounders. Section III details the channel sounder developed and the validation stage. Section IV presents the measurements scenarios. Section V describes and analyses the measurements results. Conclusion and perspectives are then proposed in Section VI.

II. RELATED WORK ON CHANNEL CHARACTERIZATION IN MMWAVE BANDS

Channel characterization and modelling in the mmWave bands is a very active field of research in the context of developments for 5G and beyond. Nevertheless, only few of these works focus on railway domain. Stationary MIMO (Multiple Input Multiple Output) propagation measurements at mmWave in underground mine with a VNA (Vector Network Analyser) are presented in [5]. Influence of railway environment on antenna performances at mmWave frequencies is analysed in [6]. Static measurements with regional trains for T2T communications are reported in [7]. Dynamic measurements at 60 GHz using a channel sounder based on a classical RUSK sounder and mmWave front-end are reported in [8]. The results highlight two main contributions: the LOS (Line Of Sight) component and a ray reflected on the ground. The impact of wagon vibration on the channel is evaluated in [8]. Influence of typical railway objects in a mmWave propagation channel is analyzed in [9] for T2I and intra train communications. Twelve of the most common railway materials are characterized experimentally and the corresponding electromagnetic parameters are obtained to calibrate a 3-D ray tracing (RT) simulator. Influence of atmospheric attenuation on the channel characteristics for high speed railway at the mmWave is discussed in [10].

III. DESCRIPTION OF THE CHANNEL SOUNDER

This section presents the architecture of the SISO (Single Input Single Output) mmWave channel sounder developed in the framework of the mmWave project for measurements in the

60 GHz band in railway environments. First, existing channel sounders are presented. Then the hardware configuration, the software part and the calibration process are described.

A. Existing Channel sounders in the mmWave band

With, increasing complexity of wireless systems, more and more channel parameters are required to model correctly the radio channels. These parameters are extracted from the statistical variations of either the channel time-variant impulse response or its time-variant frequency response in SISO or MIMO configuration. Channel sounders can be differentiated according to the used waveform, the number of antennas, the operational frequency, the bandwidth related to time resolution and their capability to extract various channel properties. Mainly four types of excitation signals are considered in sounding techniques [11]: pulse waveform, pseudo random binary sequences, frequency chirp, OFDM (Orthogonal Frequency Division multiplexing) signals. A few number of mmWave channel sounders have been proposed in the literature due to the high component cost, the calibration difficulties and the complexity of the mmWave front-end RF to have a good sensitivity [12]. In [5] the authors considered a VNA. A wideband digital sweep 2x2 MIMO channel sounder at 60 GHz is presented in [13]. However, this sounder is not suitable for measurements in railway context. Recently, [8] presents dynamic measurements at 60 GHz based on the RUSK channel sounder and mmWave front-end. The front-end up and down converters allow the channel sounder to operate with a center frequency between 55.2 and 70.2 GHz. This sounder is used in railway environments. An industrial mmWave channel sounder is developed by Keysight Technologies [14]. The excitation signal is a wide-band signal correlation with switching antennas. In the sub 6 GHz band, several MIMO channel sounders based on Software Defined Radio boards have been developed. We can refer to some interesting examples to [15], [16], [17]. Today, to our knowledge, there is no flexible and open source SDR based channel sounder operating in the 60 GHz band.

B. Channel sounder Hardware Configuration

The SISO channel sounder developed by IMT Atlantique in the framework of M5hestia and mmW4Rail projects is build upon components from Analog Device. This equipment is modular, relatively low cost and open source. The 60 GHz frequency band is obtained by using the RF front-end board HMC6300. 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 SMBV100B. 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.

On the transmitter side, a base-band chirp signal and a clock signal at 71.42857 MHz are generated. The clock frequency is chosen to allow a 250 MHz band. An USRP X310 allows

TABLE I
MAIN CHARACTERISTICS OF THE CHANNEL SOUNDER

Type	Value
Center Frequency	57 - 60 GHz
Bandwidth	160 MHz
Maximum Excess Delay	10 μ s
Rx & Tx Antenna	5 - 15 dBi horn antenna
Polarization	Vertical, Horizontal

to synchronize the signal generator with a GPS signal. The chirp signal is used for the measurements. A PC control all the process. On the receiver side, an other USRP X310 is used for synchronisation and signal processing. Figure 1 illustrates the transmitter and the receiver.

C. Channel sounder Software Configuration

The different components of the channel sounder are controlled with computers thanks to an ad'hoc open source software devopped in Python language. The equation of the chirp signal $c(t)$ is given by (1) where T is the duration of the chirp. Only one frequency is emitted. The signal corresponds to 6000 frequency samples. The sampling frequency is equal to 600 MHz. Consequently, the signal duration is equal to 10 μ s that corresponds to the maximal time window for the measurements. The bandwidth is equal to 160 MHz, then the spatial resolution is equal to 6.25 ns. Table I recaps the main characteristics of the channel sounder.

$$c(t) = \begin{cases} A \exp^{i2\pi(\frac{\delta f}{2T}t - \frac{\delta f}{2}t)} & \text{if } 0 \leq t < T \\ 0 & \text{else} \end{cases} \quad (1)$$

D. Channel sounder measurement principle

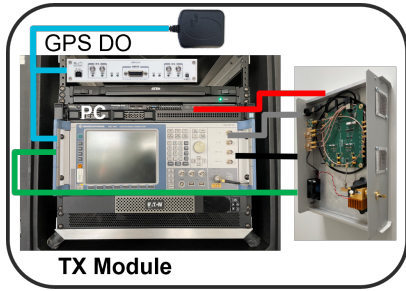
The channel sounder developed permits the measurement of the channel complex impulse responses (CIR) thanks to the transmitted chirp signal $c(t)$, following equation (2).

$$Y_{Measure}(f) = X(f)H_{TX}(f)H_{RX}(f) \times \underbrace{G_{TX}(f)H_{Prop}(f)G_{RX}(f)}_H \quad (2)$$

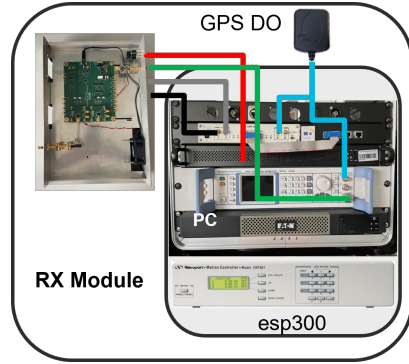
where H_{TX} and H_{RX} are respectively the complex channel transfer functions (CTF) at transmitter and receiver side, G_{TX} and G_{RX} are the transmitter and receiver antenna gain respectively, H is the transmission transfer function and H_{Prop} the propagation transfer function. X and $Y_{Measure}$ are the emitted and received signal spectra respectively.

E. Channel sounder calibration principle

The calibration can be done with a back-to-back measurement with a cable connecting the transmitter and receiver parts. An other solution in the mmWave band is to perform a measurement in open space with a sufficient distance between Tx and Rx to consider that the far field case is established. The measurements were done at 1 m. $X_{Reference}$ is given by equation (3).



(a) TX Module



(b) RX Module

Fig. 1. TX and RX modules of the IMT-Atlantique Channel Sounder

$$X_{Reference}(f) = X(f)H_{TX}(f)H_{RX}(f) \quad (3)$$

where $X_{Reference}$ is the reference signal spectrum and X is the spectrum of the signal generated by the R&S SMJ equipment.

IV. MEASUREMENTS DESCRIPTION

A. Railway environment considered

A first measurements campaign was conducted at Centre d'Essais Ferroviaire (C.E.F) near Valenciennes in France. This trial center is dedicated to rolling stock performance testing. Several railway lines can be used depending on the on-going tests. We had access to a specific track named VES2 as illustrated on figure 2. The other tracks were occupied by other trains corresponding to a station scenario. The communication system was installed in P1 at the end of the platform. The acquisition were performed from S_1 to S_9 as shown on figure 2.

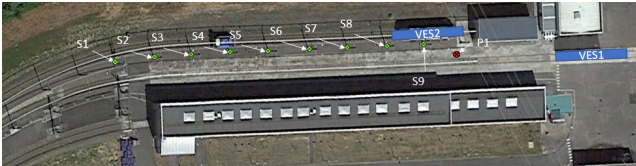


Fig. 2. Map of the C.E.F center.

B. Measurements scenarios description

The channel sounder transmitting part, Tx, was installed on a small carriage able to travel on the tracks to perform dynamic measurements. A measurement consists of a set of 1 250 000 CIR recorded over 12 m. The carriage is pulled in order to avoid any masking effect between Tx and Rx. The receiving part, Rx, is fixed at 0.9 m height in P1. There is a train parked at 1 m far from P1 as shown in figure 3. Both Tx and Rx horn antennas offer a 5dBi gain and can be used in vertical or horizontal polarization. Tx and Rx are synchronized with GPS disciplined oscillators.



Fig. 3. Environment of the measurements

V. PRELIMINARY RESULTS

A. Post-Treatment description

In order to reduce the total number of CIR and to increase the signal to noise ratio, a first coherent average is performed in order to reduce the size of the file to be treated. At the end, the file contains one CIR every $\frac{\lambda}{10}$ associated with all the measurement parameters. The complex CTF is obtained with (5). Then the CIR are obtained with a inverse Fourier Transform considering a Hanning window as follows:

$$h(t, \tau) = TF^{-1}[H(f)Window_{hanning}] \quad (4)$$

$$H(f) = \frac{Y_{Measure}(f)}{X_{Reference}(f)} \quad (5)$$

The Power Delay Profile (PDP) estimation is an average of the individual delay profiles defined as the power of the CIR at time t_i following equation (6) [11]:

$$PDP(\tau) = \frac{1}{N} \sum_{i=1}^N |h(\tau, t_i)|^2 \quad (6)$$

where N is the number of CIR considered. A certain number of impulse responses are averaged in order to cope with the random character of the channel and to guarantee a stationary area if the average length is sufficiently long. This average reduce the noise peak as explain in [11]. A large number of N impulse responses ensure a noise smoothing. From the

PDP, different parameters can be extracted as the first arrival delay, the maximal excess delay, the average delay, the RMS (Root Mean Square) delay spread and the associated coherence bandwidth. The PDP is obtained by a sliding average along the length of the measurement. The window size is 30λ and it is applied over 10λ . The Doppler spectrum is computed for fixed delays corresponding either to line-of-sight (LOS) component or multi paths. The Fourier transform is applied on the CIRs over a distance equal to 30λ . The process is repeated each 10λ up to the end of the measurement length.

$$Doppler_i = TF[h_{iN+(1,\dots,N)}(\delta_\tau)] \quad (7)$$

where $Doppler_i$ is the i^{th} delay Doppler and δ_τ is all index that correspond to LOS or multipath component.

B. Measurements analysis

This section analyzes two measurement examples performed in horizontal polarization with 5 dBi gain antenna horn (both at TX and RX). The measurements performed between S8 and S9 then between S2 and S3 are presented (cf figure 2).

1) *Measurements between S8 and S9*: The first example was performed between S8 and S9 location. The PDP along the measurement path is plotted in figure 4. The main path delay is shifted along the path due to the TX-RX distance change. Despite the LOS propagation condition, the main path presents fading. It means that several path exists and interferes in the path.

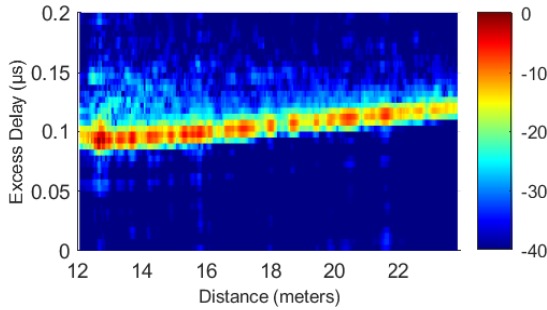


Fig. 4. Evolution of the main peak during the measurement between S8 and S9

The average gain over the whole bandwidth G_{wb} is depicted in the figure 5. The fading is also visible and the average gain is close to the Friis attenuation. Examples of PDP are given in figure 6. The time spreading of the PDP is usually low (Red curve), but can increase in some locations (Black curve). The corresponding Doppler is represented in the 7. The Doppler shift of the main path is corrected according to the measurement configuration (direction and speed of the TX). However, it is interesting to notice that multipath comes from other direction and spreads the Doppler shape. A possible explanation could be reflected rays on the two trains stopped on each side of the measurement line (canyon effect).

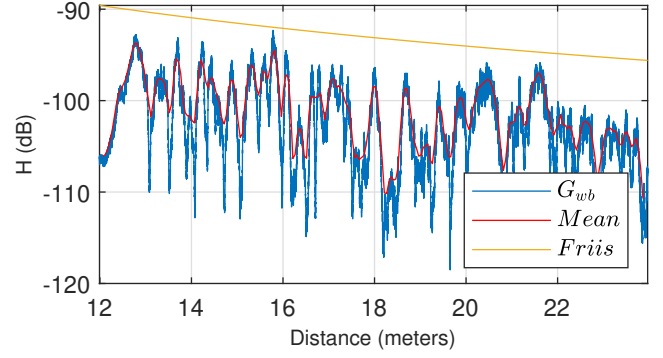


Fig. 5. Evolution of G_{wb} between S8 and S9.

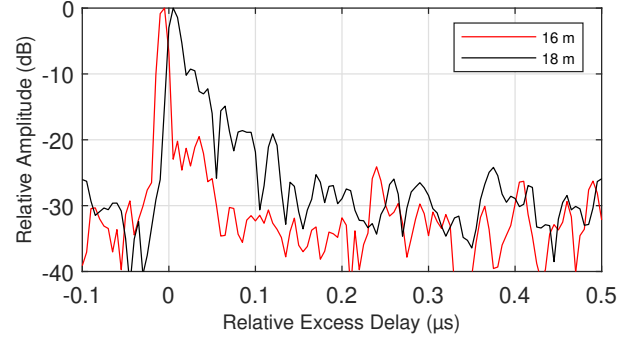


Fig. 6. PDP of the Measurement between S8 and S9.

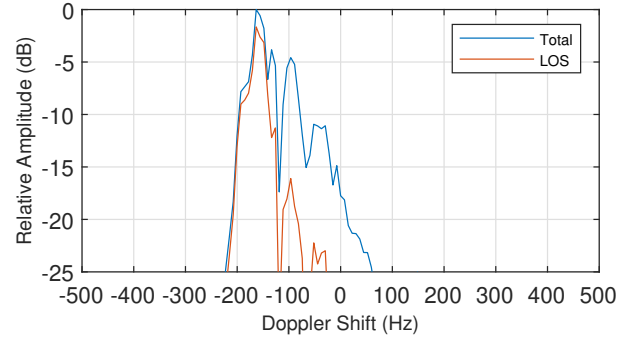


Fig. 7. Doppler shift for measurement at 18 m.

2) *Measurements between S2 and S3*: Another measurement between the section S2 and S3 is presented. The mean distance of this section is around 90m from the RX system. The average gain is depicted in the figure 8. Fast and slow fading is also observed. The PDP at two distance 85.8 m and 86 m are presented on the figure 9. Some path are clearly identifiable at 86 m but not at 85.8 m. According to the distance, the multipath environment changes very quickly. This could be explained by the interaction with the environment at mmWave frequency. On the figure 10, the Doppler Shift is not spread. This means that the DOA (Direction of Arrival) of the reflected paths are closed to the LOS path.

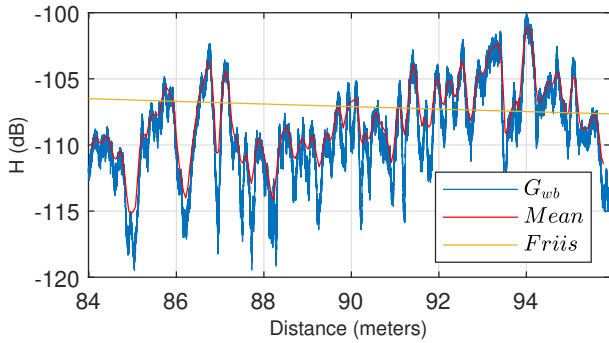
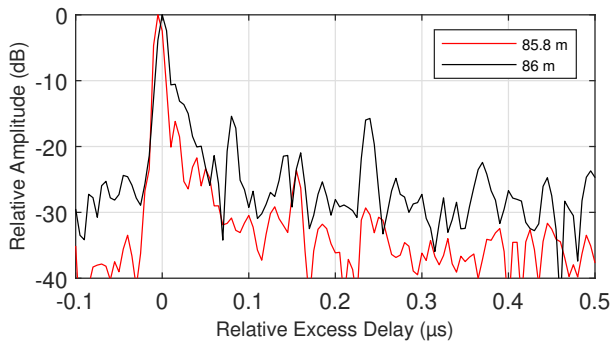
Fig. 8. Evolution of G_{wb} between S2 and S3.

Fig. 9. PDP of the Measurement between S2 and S3.

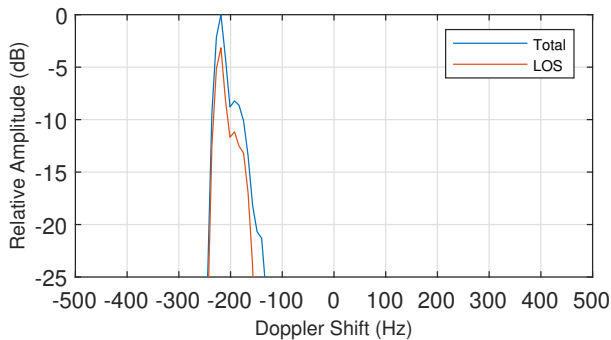


Fig. 10. Doppler shift for measurement at 86 m.

VI. CONCLUSION

An SDR based channel sounder at 60 GHz has been developed in open source by IMT Atlantique in the framework of the mmW4Rail project. The channel sounder considered uses USRP X310 and allows dynamic measurements at relative low-cost. A measurements campaign was performed at the Centre d'essais Ferroviaires in Valenciennes (France) in railway environments allowing us to characterise a tunnel effect between two trains stopped. We have presented preliminary resultat with the PDP and power loss along the path, the PDP and Doppler shift at specific position. This preliminary analysis has permitted to identify fading occurred, despite the 60 GHz LOS condition.

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