Wide Band Propagation in Train-to-Train Scenarios - Measurement Campaign and First Results

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***Abstract*—Within the next decades the railway systems will change to fully autonomous high speed trains (HSTs). An increase in efficiency and safety and a reduction of costs would go hand in hand. Today's centralized railway management system and established regulations can not cope with trains driving within the absolute braking distance as it would be necessary for electronic coupling or platooning maneuvers. Hence, to ensure safety and reliability, new applications and changes in the train control and management are necessary. Such changes demand new reliable control communication links between train-to-train (T2T) and future developments on train-to-ground (T2G). T2G will be covered by long term evolution-railway (LTE-R) which shall replace today's global system for mobile communications-railway (GSM-R). The decentralized T2T communication is hardly investigated and no technology has been selected. This publication focuses on the wide band propagation for T2T scenarios and describes a extensive channel sounding measurement campaign with two HSTs. First results of T2T communication at high speed conditions in different environments are presented.**

***Index Terms*—train-to-train, high speed train, propagation, measurement.**

I. Introduction

Fully autonomous vehicles will be the future on our streets as well as on the railway tracks. Several manufacturers are testing prototypes on the road already and national railway operators are promising driverless train operation within the next 5 years. For these new applications in traffic new technologies are necessary. Hence, the interest in vehicular communications have been increasing tremendously the last years. The challenging propagation environment for vehicle-to-vehicle (V2V) communication in road and railway traffic demand comprehensive investigations of the propagation channel and new channel models.

While the road domain is well investigated and first standards are defined as the intelligent transport systems (ITS-G5) standard, the railway domain has been mainly focusing on T2G systems like GSM-R and LTE-R. Beside investigations for low frequency and medium speed presented in [1], the propagation aspects of T2T links are hardly investigated. A survey of T2T channel measurements and models are presented in [2].

Therefore, two important question emerge. First, how does the railway environment influence the T2T link for frequencies above $1\,\mathrm{GHz}$ and second, how does the high absolute speed (up to $300\,\mathrm{km/h}$) and high relative speed (up to $600\,\mathrm{km/h}$) influence the T2T communication. To answer these questions, a measurement campaign was performed with the focus on wagon-to-wagon measurements (intra-consist) with one, and T2T measurements with two HSTs. These world wide first high speed railway (HSR) channel sounding measurements took place on a HSR track between Naples and Rome in Italy. The measurements were performed with a wide band channel sounder. Furthermore, the runs were used for evaluating an ITS-G5 system and a terrestrial trunked radio (TETRA) system under high speed conditions. In this paper, the measurement campaign is described in detail and first results of ITS-G5 T2T links are presented.

II. Environmental aspects for High Speed Railway

The environment along a railway track is highly influencing the terrestrial propagation. The environment can be divided in different areas, special scenarios, and obstacles as listed in Table I and explained in more detail in [2]. A train driving from city A to city B drives through random combinations of all three different classes.

The variation of environments for HSRs is limited in comparison to other railways. HSRs are built to connect big cities with each other. Between the stations, the track sections are mainly placed in rural areas or are shielded with noise barriers in sub-urban environments. Due to the high speed, the curve radius of the track is rather large (up to several kilometers) and the gradient is limited. This leads to the four main special scenarios with the largest impact on the T2T but also T2G communication: tunnels, viaducts, cuttings and open field. While the first three are influencing the propagation tremendously, open field has hardly any influence. Channel measurements and models for T2G links are well investigated. [3] gives a survey on T2G channel measurements and models. Similar investigations and measurement based channel models for T2T in these special environments can be hardly found in the literature.

Level crossings are not used for HSRs, therefore cross bridges for road traffic and other railway traffic are necessary. Most of the HSTs are powered by electrical units, hence, catenary and pylons are placed along the track. The pylons and the supporting metal constructions for the catenary or the signaling system are very close to the antennas on the train. These obstacles can be seen as reflectors or scatterers and causes frequent appearing multi path components (MPCs).

TABLE I: Environments in railway traffic [2]

Area	Special Scenario	Obstacles
Urban	Curve	Cross Bridge
Sub-Urban	Tunnel	Noise Barrier
Rural	Bridge/Viaduct	Catenary
	Cutting	Signaling System
	Open field	Roof
		Buildings
		Vegetation (tree)

TABLE II: Measurement scenarios

Speed / Maneuver	Slow	Fast
Overtake	Urban Sub-Urban Rural	Sub-Urban Rural
Opposing	Sub-Urban	Rural

III. Measurement Campaign

To fill up the gaps pointed out in [2] a comprehensive HST channel sounding measurement campaign was performed. The campaign was split in two parts. One part was the investigation of the intra-consist propagation. The first night was used for this measurement by using one HST. The second part and main focus of the campaign were the T2T channel measurements with different antenna setups. In night two, three and four two HSTs were used. One train was equipped as transmitter (Tx) and one as receiver (Rx).

A. Scenarios and maneuvers

The measurements took place on the track between the stations Napoli Centrale and Roma Termini as shown with the red line in Figure 1. On this $220\,\mathrm{km}$ long double track all interesting environments are covered in different sections with speeds up to $300\,\mathrm{km/h}$.

During the measurements three different maneuvers were performed with different speeds:

- Train A and train B drive in the same direction.
  - A and B in a platoon: Zero relative speed and constant distance
  - A overtakes B: Different speeds and varying distance
- Train A and train B drive in opposing direction.
- Train A stands still and train B passes by.

The main focus was on maneuver one and two which were performed for low speed (in average $\nu = 50\,\mathrm{km/h}$) and a relative speed $\Delta\nu_{\mathrm{max}} = 70\,\mathrm{km/h}$, as well as for high speed (in average $\nu = 250\,\mathrm{km/h}$) with $\Delta\nu_{\mathrm{max}} = 600\,\mathrm{km/h}$. Maneuver three was performed incidentally by changing the direction on the track or rearranging the trains for maneuver one or two.

The combination of the different environments with different maneuvers and speed led to the scenarios listed in Table II. The fast maneuvers are not possible in urban environments because HSTs do either stop in a city and drive with average or low speed or pass by the city in rural areas.

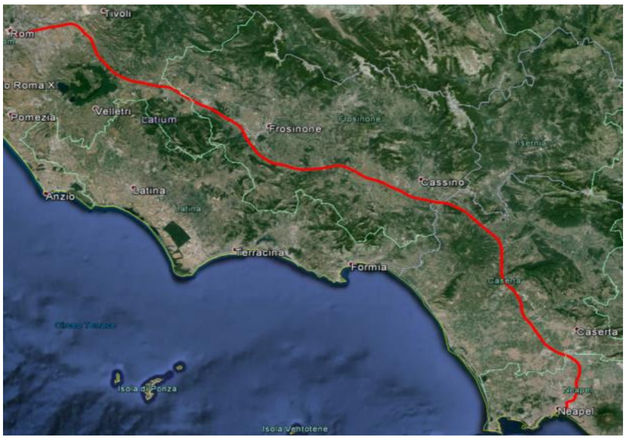

Fig. 1: HSR line Naples-Rome. Image by Google, Map Data 2016 NOAA, U.S. Navy, NGA, GEBCO Image Landsat (2015).

Fig. 2: Trenitalia Frecciarossa ETR 500 HST.

B. Measurement equipment and setup

As platform for our measurements, our partner Trenitalia provided two Frecciarossa ETR 500 HSTs as shown in Figure 2. Each train is composed of two locomotives and 11 coaches for a total of 574 seats with a total length of $330\,\mathrm{m}$ [4]. For the test runs, the trains were specially equipped with different measurement systems. For the runs with two trains, train one was always set up as Tx (orange boxes) and train two as Rx (green boxes) shown in Figure 3.

a) Channel Sounder: The main measurement system was the Medav RUSK-DLR channel sounder. For all measurements the operating center frequency was $5.2\,\mathrm{GHz}$ with a bandwidth $B = 120\,\mathrm{MHz}$ and a snapshot rate of $488\,\mathrm{Hz}$. The transmitted signal was similar to an orthogonal frequency division multiplex (OFDM) signal. The receiver unit recorded the channel impulse response (CIR). The channel sounder was set up in two different ways in three nights as listed in Table III:

- Intra-Consist: A single-input multiple-output (SIMO) system was built up with one rubidium frequency normal. This setup was used for the intra-consist measurement

TABLE III: Channel Sounder measurements and setup for each night

Night	Type	Antenna	G_{Tx} [W]	G_{Ant} [dBi]	EIRP [dBm]	Distance [m]
1	Intra-Consist	Omni	5	8	20	3, 29
3	T2T	Omni	40	8	33	variable
4	T2T	Direct	40	9	34	variable

TABLE IV: ITS-G5 measurements and setup for each night

Night	Type	Antenna	G_{Tx} [W]	G_{Ant} [dBi]	EIRP [dBm]	Distance [m]
1	Intra-Consist	Omni	5	4	31	26, 52, 70
2	T2T	Omni	5	8	31	variable
3	T2T	Direct	5	9	31	variable
4	T2T	Omni	5	8	31	variable

for two different link distances in the first night. Figure 3 shows the antenna position of the Tx (Omni 1_1) and Rx 1 (Omni 1_2) in a distance of $3\,\mathrm{m}$ and Rx 2 (Omni 1_3) $29\,\mathrm{m}$ away. The Tx unit was placed in Coach 1 and the Rx unit in Coach 3, both as close as possible to the antennas; Omni 1_2 was connected with a $25\,\mathrm{m}$ cable to the Rx unit. Both, Tx and Rx used the rubidium frequency normal from the Rx side. At the Tx-side a $5\,\mathrm{W}$ amplifier was used; on the Rx-side a multi-switch was switching between the two Rx antennas.

- T2T: A single-input single-output (SISO) system with independent Tx and Rx was set up. In night three the T2T propagation was measured with omni-directional (see Figure 3: Omni 1_1 and Omni 2_1) and in night four with directional antennas (see Figure 3: Direct 1 and Direct 2). A $40\,\mathrm{W}$ amplifier was used on the Rx-side. The synchronization of the rubidium frequency normals were done before each measurement run.

Additional calibration measurements were done before each measurement run. Due to synchronization problems the second night could not be used for channel sounder measurements.

b) ITS-G5: A second measurement system was build up with ITS-G5 transceivers in parallel to the channel sounder. ITS units operate in the $5.9\,\mathrm{GHz}$ frequency band on five $10\,\mathrm{MHz}$ channels. The maximum allowed equivalent isotropically radiated power (EIRP) is $33\,\mathrm{dBm}$ and direct mobile to mobile communication links with ranges up to $3\,\mathrm{km}$ can be achieved. Data rates up to $27\,\mathrm{Mbits/s}$, and negligible call setup times are possible. Thus, it supports a range of new applications in railway transportation like electronic coupling or platooning. More detailed information on electronic coupling can be found in [5].

For the measurements two ITS-G5 Cohda MK5 transceiver modems were used to investigate intra-consist and T2T communication scenarios. First analysis of intra-consist (inside train) communication is presented in [6], first results of the ITS-G5 T2T measurements are presented bellow in Section IV-B. For all measurements, the radios were set up for the control channel at $5.9\,\mathrm{GHz}$ with an EIRP of $31\,\mathrm{dBm}$. The data rate was set to $3\,\mathrm{Mbps}$ and BPSK modulation with a coding rate of 1/2 was used. The packet length was set to $400\,\mathrm{Byte}$, with a repetition rate of $100\,\mathrm{Hz}$. Table IV gives an overview of all ITS-G5 measurements and related settings.

The ITS-G5 measurements were performed in parallel to the channel sounder measurements. In one night the channel sounder was connected to omni-directional antennas and ITS-G5 to directional antennas and the next night vice versa.

c) TrainCAS: A special version of the train collision avoidance system (TrainCAS) based on DLR's railway collision avoidance system (RCAS) was used to monitor the various maneuvers every night. Unusual for and very much appreciated by the train drivers, they could see the current location on the track and other information about the other train long before in visibility range.

Both Trenitalia Frecciarossa have been equipped with a TrainCAS onboard unit consisting of three core technologies: a TETRA based T2T communication system as introduced in [1], an accurate localization system and a cooperative situation analysis an decision support system. The onboard units were connected to the TETRA antennas one and two (see Figure 3). During the measurement campaign, the system's capabilities have been used to illustrate information to the train drivers and the mission responsibles about the other train involved in the measurement campaign which would hardly be available at this level of accuracy and up-to-dateness otherwise.

d) Antennas: For the different measurements four different antenna types from Huber+Suhner were installed. Roof mounted antennas had to be train specified for security reasons; this reduced the choice of omni-directional antennas and no standard measurement antenna could be used. One benefit of the train specified antennas was the integrated global navigation satellite system (GNSS) antenna. The following antennas were used:

- SWA-0859/360/4/0/DFRX30_2: This omni-directional antenna is railway specified and fits best in case of RF-characteristics at $5.2\,\mathrm{GHz}$ as well as for $5.9\,\mathrm{GHz}$. Three antennas were installed on the roof of train one and one antenna on train two. These antennas were used for the intra-consist measurement and for the omni-directional T2T measurements.
- SPA-2456/75/9/0/DF_1: These directional antennas were used for measurements in front of the train. Therefore the antennas were installed inside the nose of the locomotive. When the lid of the nose is closed, the antenna was in an upright position right in front of the coupler.
- SWA-0459/360/4/25/DFRX30: This multi-band omni-directional railway specified antenna was used for the TETRA-based system and mounted on the roof of one locomotive of each train.
- SWA-2459/360/7/20/V_1: This antenna was used for ITS-G5 indoor measurements presented in [6].

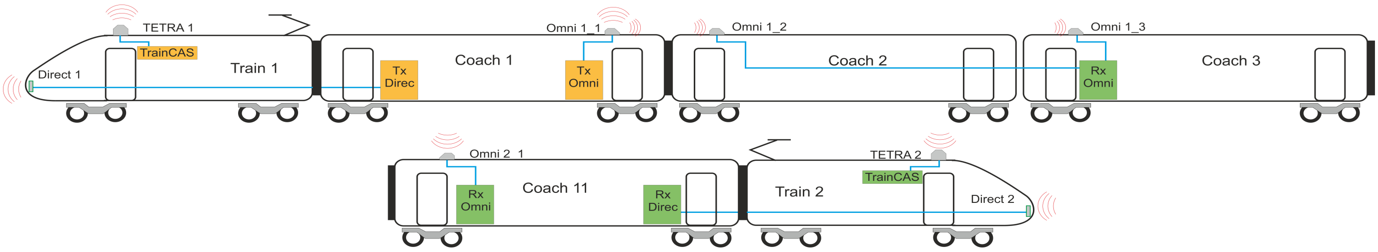

Fig. 3: Antenna setup for Train 1 (top) and Train 2 (bottom).

TABLE V: Additional sensors

Name	Sensor	Update rate
Septentrio PolaRx4TR	GNSS	1 Hz
uBox NEO-M8T	GNSS	1 Hz
KVH 1750	IMU	100 Hz
Xsens MTi-G700	IMU	200 Hz

e) GNSS and IMUs: For accurate localization throughout the measurements, each train was equipped with two GNSS receivers and inertial measurement units (IMUs). The installed sensors and their measurement rates are listed in Table V. The GNSS receivers were used to record the train position, velocity and raw measurements. These raw measurements include pseudo range, carrier phase and Doppler. The used track contains multiple tunnels and therefore track sections where GNSS signals are completely blocked. In this GNSS denied areas the position and velocity can be determined by using the acceleration and turn rate measurements from the IMUs. Another advantage of the inertial measurements is an increased update rate of the position estimate.

The combined GNSS and IMUs units were placed in the locomotives of both trains and screwed to the floor frame. The GNSS signal was provided by the TETRA antennas.

IV. Data Analysis

A. Channel Sounder measurements

The evaluation of the channel sounder data is split in two parts. The intra-consist measurements are investigated and will be published within [7]. The analysis of the T2T measurements and the generation of related channel models is ongoing.

B. Evaluation of the ITS-G5 for HSR T2T links

The most interesting ITS-G5 measurement run was in night four with omni-directional antennas. Slow and fast overtaking maneuvers were performed in different environments like rural or tunnels. In the following figures the measured received power and the free space model is plotted over time. The related link distances and the train speeds are shown over time as well. Figure 4 shows an overtaking maneuver at low speed and Figure 5 an overtaking maneuver at high speed, both times in rural environment.

In all maneuvers and environments the same effect was observed by using the roof mounted omni-directional antennas. For Direction I (blue marked received power in all figures) the measured received power fits well to the Free Space Model. For Direction II the measured power is up to $15\,\mathrm{dB}$ lower than the theoretical values (see green parts of the received power in all figures). Direction I describes the link, when the Rx is in front of Tx. The attenuation is caused by the imperfect omni-directional antenna pattern of Omni 1_1 and Omni 2_1. The elevation patterns show a difference of approx. $7\,\mathrm{dB}$ between $90°$ and $-90°$. The antennas were mounted in opposite direction on the trains. In this way, for Direction I the estimated total antenna gain fits the real gain, for Direction II the real antenna gain is in total $15\,\mathrm{dB}$ less. This effect can be seen in Figure 4 and 5 for received power over time as well as in Figure 6 with received power over distance. In Figure 6 the measured received power is shown for high speed measurements of Direction I and II in rural environments and for Direction I in tunnels. The free space model is plotted in red as a reference.

Due to the high speed, the density and the depth of the fades are increased; the second effect is mainly caused by the environment and resulting MPCs. For link distances larger than $250\,\mathrm{m}$ a strong fading can be observed. As shown in Figure 6, the measured received power in direction I fits well to the free space model. Up from $250\,\mathrm{m}$ a mixture of line of sight (LOS) and non-LOS paths can occur. Further investigations and a comparison from the ITS-G5 and the channel sounder data will provide a more detailed analysis of the environmental influences on the ITS-G5 link. In rural environments a stable connection was established up to $1.2\,\mathrm{km}$ even for direction two. For tunnels and big buildings as in urban environments a higher link distance up to $2.2\,\mathrm{km}$ could be achieved because of wave guiding effects.

C. TrainCAS evaluation

The TrainCAS was installed during the measurement campaign on HSTs for the first time ever. It has been verified that the TETRA link worked stable also at this high speed. The trains could connect to each other using the link way before one of the other direct T2T radio links under test. This includes a new range record of $39.6\,\mathrm{km}$, as well as a new record of $560\,\mathrm{km/h}$ relative speed where the trains reliably exchanged information early enough to be able to safely brake into stillstand in case of a detected conflict. A more detailed analysis is given in [8].

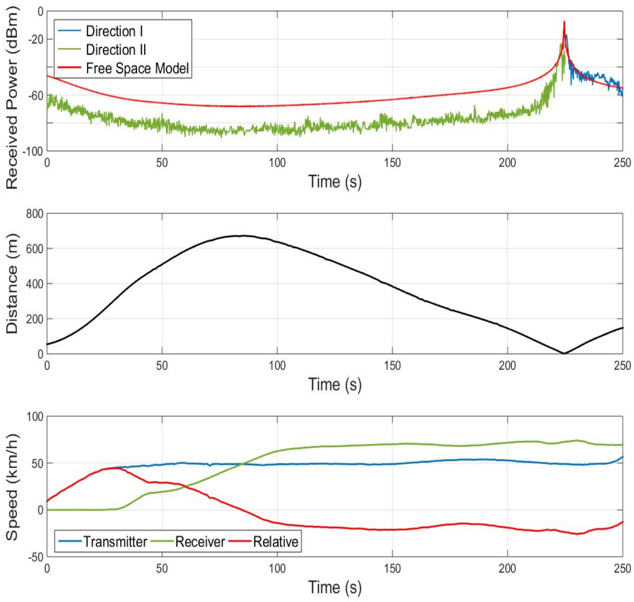

Fig. 4: Low speed overtaking maneuver in rural environment.

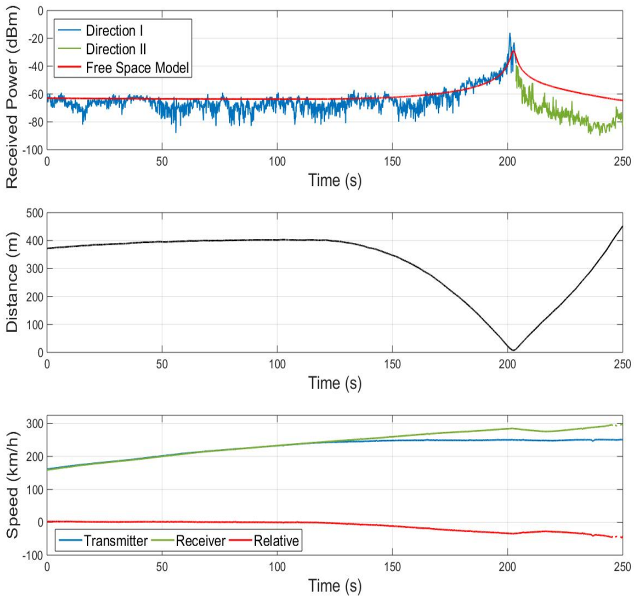

Fig. 5: High speed overtaking maneuver in rural environment.

V. Conclusion

In this paper we presented an extensive HSR measurement campaign for intra-consist and T2T communication with two HSTs. The intention of this measurement campaign, all used measurement equipment and setups were described in detail. Typical environments and maneuvers for HSTs were investigated technology independent with DLR's wide band channel sounder. In parallel existing wireless communication standards like ITS-G5 and TETRA were tested and the behavior in the railway environment analyzed. For comparison studies all

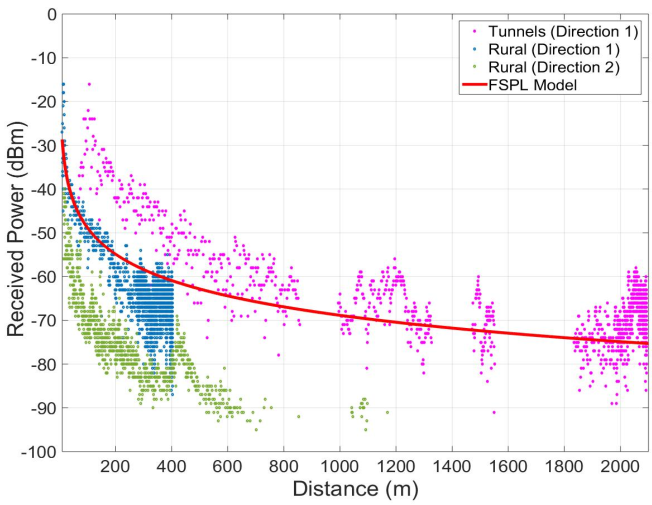

Fig. 6: Comparison of different environments at high speed.

measurements were performed for low and high speed.

First results of the ITS-G5 T2T measurements were shown for HSR typical scenarios. Effects of the environment, the influence of the train speed and the used equipment on ITS-G5 operating as T2T communication were investigated. The performance analysis in case of coverage and high speed behavior was satisfying considering future applications for railways.

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