Measurement and Analysis of the Direct Train to Train Propagation Channel in the 70 cm UHF-Band

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Abstract. In this paper we present first analyses and results of a comprehensive measurement campaign investigating the propagation channel in case of direct (base station free) communication between railway vehicles. The measurements cover urban, suburban and rural environments along a multifaceted regional railway network in the south of Bavaria. Beside different operational conditions like front, rear, and flank approaches of trains, we investigated several topological scenarios on both, single and double track sections along the line. We will also discuss the observed characteristic changes in narrow band signal attenuation and Doppler spectra for passages through forests, hilly areas, stations and a tunnel.

Keywords: Propagation, channel, measurement, UHF, Train-to-Train, railway, path loss, model, V2V, RCAS.

1 Introduction

The design of Vehicle-to-Vehicle communication systems requires new knowledge about the specific propagation characteristics, which are certainly different to the widely measured and accurately modeled conditions in cellular terrestrial networks, where mobile nodes communicate with base stations at advantageous levels above ground. But not only has the low height of antennas raised uncertainties. Especially in the railway environment we face very specific conditions that influence the wave propagation along the lines. Shadowing by platforms with roofs in stations, or reflections from other railway vehicles might cause high losses. On the other hand, cuttings along the lines of railway networks with relatively large curve radii, catenaries, and tunnels are likely to have guidance effects [1] that could result in unexpected low path-loss exponents at larger distances.

New safety related applications in transportation are often based on direct communication among vehicles and have stringent requirements on the communication range. As an example the German Aerospace Center (DLR) is currently developing a Railway Collision Avoidance System (RCAS) [2] [3], that will allow the train driver to have an up-to-date accurate knowledge of the traffic situation in the vicinity, and act in consequence. The basic idea of RCAS is to calculate the own position and movement vector and broadcast this information as well as additional data like

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vehicle dimensions to all other trains in the area. Thus, the train driver's cabin could be equipped with a display showing the position of the other vehicles in the region. Computer analysis of the received information, the own position and movement vector and an electronic track map allows to detect possible collisions, displaying an alert signal and advising the driver of the most convenient strategy to avoid the danger. In order to work reliable, the system requires a communication range that is in all cases larger than twice the maximum braking distances [4], which are usually in the order of 1-2 kilometers in regional networks.

Another challenge in the design of vehicular ad-hoc networks is to effectively control the common media access. While in cellular networks the media access is usually controlled by base stations, and the cell arrangement and frequency reuse is optimized to cause minimum interference from nodes in neighboring cells, the character of vehicular ad-hoc networks requires distributed solutions that strongly depend on the node density and on the communication range, respectively the interference range of nodes in the neighborhood [5]. Thus, it is important to have accurate knowledge of path loss and fading characteristics under realistic conditions, e.g. when regional lines meet shunting areas or large stations with high user densities, where both, communication with a fast approaching train and the information exchange to the multiple nodes in the close vicinity have to be reliably maintained at the same time.

2 Measurement Campaign

In the design phase of RCAS several questions arose concerning possible hindrances in fulfilling the requirements on the direct Train-to-Train communication link: Can the communication range be guaranteed to be significantly larger than the braking distances under all topological and operational conditions in different environments? How do passages through urban areas, forests, hilly areas or tunnels affect the statistics of successfully transmitted packets?

In order to be able to get an answer to these questions we performed a measurement campaign in an area covering all the interesting environmental, topological and operational aspects. We identified the regional network of the "Bayerische Oberlandbahn (BOB)" to be ideally suited for our measurement campaign and appreciated the extraordinary level of support we received from BOB upon our request for cooperation.

2.1 Railway Network and Environment

The route network of the BOB can be seen in **Fig. 1**. The 3 lines of the BOB run as a combined train-set from Munich central station to Holzkirchen. This part of the network has two tracks, is electrified and is used together with the Munich S-Bahn service. In Holzkirchen the combined train-set separates with one train-set heading off to the east running to Bayrischzell. The two remaining train-sets continue on to Schaftlach where they separate again, with one train-set going to Lenggries, while the last train-set heads off to the southeast to Tegernsee. On these 3 branches the lines are single track and are not electrified.

The BOB operates 20 diesel-hydraulic train-sets, which carry about 15000 people per day, with speeds up to 140 km/h [6]. The total network has 27 stations and covers 120 km, connecting the metropolis of Munich with the pre-alpine region in the south of Bavaria. Starting from the pure urban environment near the Munich central station the line passes through a tunnel, gradually leaving the city through suburban areas into the forest rich part around Holzkirchen. Finally in the south the three lines enter a hilly area with lakes in the alpine upland. **Fig. 2** shows two typical environmental conditions on the BOB network.

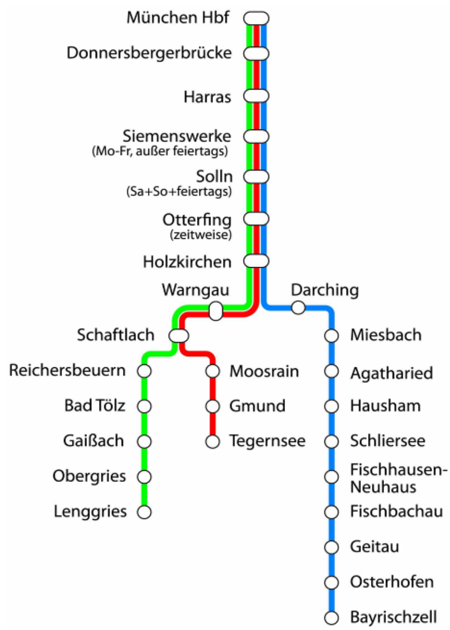

Fig. 1. Railway network of the “Bayerische Oberlandbahn (BOB)” in southern Baveria [6]

Fig. 2. A BOB train-set on the electrified two track line between Munich and Holzkirchen (left) and in the hilly alpine upland near Bayrischzell (right) [7]

2.2 Measurement Setup

In regular operation the BOB train-sets meet at 3 distinct locations: At the stations in Holzkirchen and Schaftlach, where the train-sets are separated and connected, respectively, and at a point north of Holzkirchen, where 2 trains pass by each other on their way to and from Munich. In order to measure a variety of scenarios at many different locations along the network, we decided to use a car instead of a second train as receiving station for the measurements as depicted in **Fig. 3**. The car also allowed us to simulate hypothetical railway collisions, which would not be realizable with two trains during regular operations, because of safety regulations and the general railway network topology.

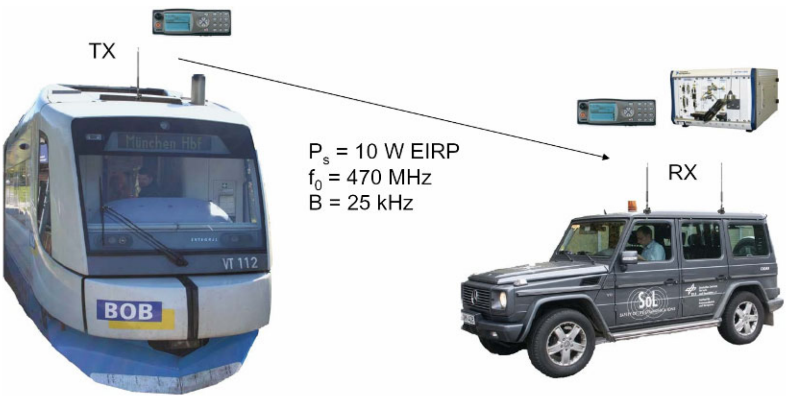

Fig. 3. Setup for the “Train-to-Train” channel measurement campaign: A car replaces the second train to allow for a variety of measurement scenarios at different locations

The transmitter was installed into one of the trains with the antenna mounted above the driver’s cabin. The measurement signal was transmitted by a Tetra radio at a carrier frequency close to 470 MHz with a power of 10 W EIRP, and had a bandwidth of 25 kHz. With a repetition rate of 1 Hz we transmitted a 150 bit SDS (Short Data Service) message containing traffic relevant information for the RCAS system as described in [8]. Prior to each RCAS message a synchronization sequence was transmitted, which is necessary for reception of the message in the Direct Mode of Operation (DMO), where the involved Tetra terminals are unsynchronized [9].

On the receiver side another Tetra radio recorded the successfully decoded messages. In addition we used a RF vector signal analyzer to record the received signal in time domain as shown in an example in **Fig. 4**. According to the call description for unacknowledged short data in direct mode of the Tetra standard [10], the synchronization covers frames 17 and 18, followed by the SDS data in slot 1 of frame 1. The pre-emption signaling indicates the priority request for further transmissions. The example in **Fig. 4** was recorded during a pass by at moderate speed, and it clearly shows the fading due to multipath. In the later analyses of the propagation channel characteristics this synchronization sequence is evaluated.

Both vehicles also carried a GPS receiver and stored PVT (Position, Velocity and Time) information during the measurements.

Although it does not scale for areas with dense railroad traffic, the first RCAS system demonstrator was built using Tetra radios. Since the provided data rate by the Tetra standard is very similar to the RCAS system requirements [8], this allowed us to investigate the message transmission performance under realistic propagation conditions. In this way both, the performance evaluation of the Tetra DMO-SDS messaging for Train-to-Train conditions and the corresponding channel characterization could be achieved.

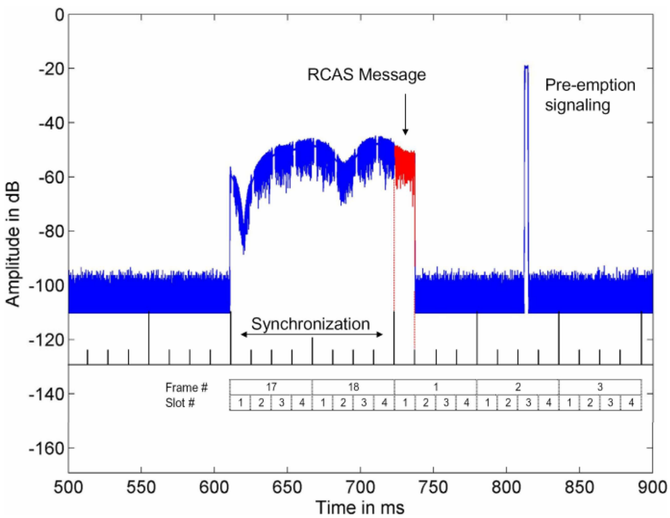

Fig. 4. Example of the recorded measurement signal during a pass by with moderate speed, clearly showing signal fading due to nearby multipath

2.3 Measurement Scenarios

During the whole measurement campaign 26 scenarios were measured, collecting 16 hours of data on more than 700 travelled kilometers. Two methods were applied:

- Static RX measurements: The car with the RX equipment was placed just aside the railway track or on a bridge above the track, and recorded the measurement signal while the train was approaching and receding the measurement location.
- Dynamic RX measurements: The car was driven along roads just aside the railway track to simulate a moving train. Thus we could investigate hypothetical collision scenarios like front, rear-end, and flank collisions with the approaching train.

Propagation conditions in railway environment, especially shadowing effects and multipath, may vary significantly depending on the local topology of the railway network. For example in stations the tracks are usually separated by platforms with roofs that might block the LOS (Line of Sight), while in shunting areas LOS is reasonable for larger distances, but it is usually accompanied by strong multipath from other vehicles and the particular environment. The speed and therefore the signal fading is significantly slower near stations than on the sections of the regional network between them. Urban, suburban and rural passages are expected to show different path loss characteristics, depending if there are houses, trees or slopes alongside the track. Thus measurements were conducted in the following environments:

- Urban main station (Munich central station)
- Suburban stations (Solln, Holzkirchen, Bad Tölz)
- Shunting area (near Munich central station)
- Tunnel (near Donnersberger Brücke)
- Forest and farmland passages (multiple locations)
- Hilly alpine upland (Bayrischzell, Lenggries, Tegernsee)

3 Data Analysis

Prior to the measurement campaign we made a calibration measurement, where we recorded an undisturbed version of the specific Tetra synchronization sequence *s(t)* that is sent by the TX radio. The power spectral density of *s(t)* can be seen in **Fig. 5**.

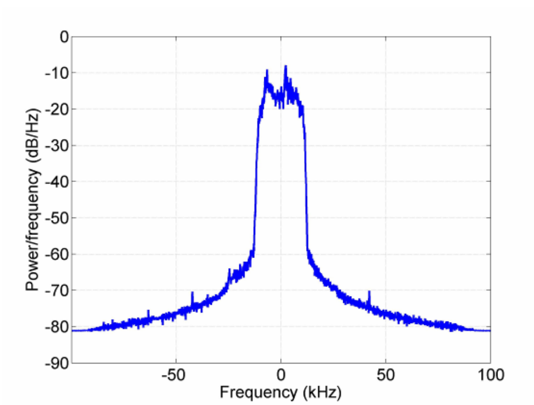

Fig. 5. Power spectral density of the Tetra synchronization burst that is used as measurement signal for the characterization of the Train-to-Train propagation channel

Distorted by the propagation channel and additional noise, the received signal *y(t)* is given by

$$y(t) = h(t) * s(t) + n(t) \ , \tag{1}$$

where *h(t)* denotes the momentary channel impulse response and *n(t)* is an additive white Gaussian noise (AWGN) signal. For AWGN the Maximum-Likelihood estimation of the channel impulse response is given by cross-correlation of the received signal *y(t)* and the transmitted signal *s(t)*, or expressed in the frequency domain, the momentary channel frequency response *H(f)* is given by

$$H(f) = Y(f)S^*(f) / |S(f)|^2 = Y(f) / S(f) \ , \tag{2}$$

with *Y(f)* and *S(f)* being the Fourier transform of *y(t)* and *s(t)*, respectively [11]. Assuming perfect synchronization between transmitter and receiver, *H(f)* can be calculated from the DFT (Discrete Fourier Transform) of the sampled receive signal divided by the DFT of the transmit signal.

In our measurements the TX and RX stations were clocked by standard internal crystal oscillators, which causes an error when calculating *H(f)*. This error is mainly a slowly varying offset in Doppler due to drift changes of the oscillators. In the measurement data this offset can be easily determined, provided that PVT data of both stations is available. For example in sections when both, RX and TX were at a stop, the Doppler of the received signal shall be zero.

Fig. 6 illustrates this correction. In the left plot we see the channel frequency response in dB over a complete measurement run that lasted more than 30 minutes. Each second the received synchronization burst was evaluated. During this measurement the receiver was static at one location. The white lines indicate the maximum possible Doppler according to the velocity of the transmitter. Thus, each stop of the train at a railway station is represented by a section where the white curves equal zero. The corrected data can be seen in the right plot of **Fig. 6**, after estimating the clock drift and removing the corresponding Doppler offset. It shows a very good match and clearly allows to distinguishing between LOS and multipath components, as we will see in the following analysis. Note that the SNR is approximately 30 dB and that the frequency resolution in these plots is about 6 Hz due to the finite length of the synchronization sequence *s(t)* and the sample rate of 200 kHz. Thus, according Fig. 6, 8, 10 and 13 there seem to be spectral components outside the theoretical Doppler bandwidth. However, these are effects of the limitations of the sampling.

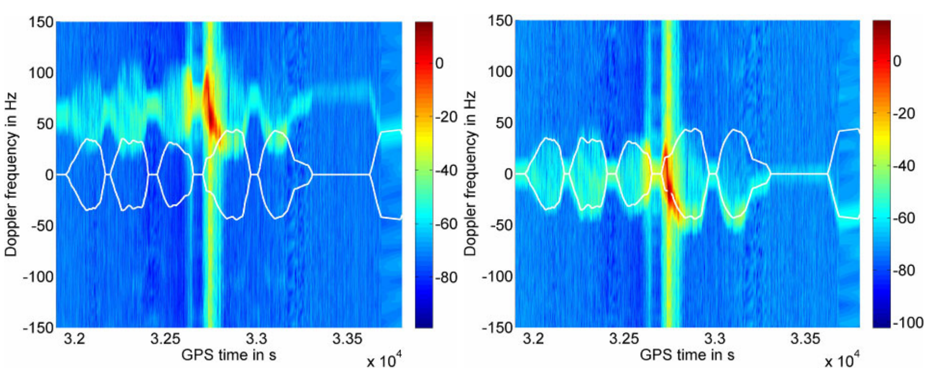

Fig. 6. Changes in the channel frequency response *H(f)* in dB during a complete measurement run. The white lines indicate the maximum Doppler due to RX and TX movement. Left: offset due to RX and TX clock drift; Right: corrected clock drift offset.

3.1 Suburban Railway Station and Forest

The following data was recorded at the railway station in the small Bavarian town of Bad Tölz in a static RX measurement. The train approached from the south west, stopped at the station just 200 meters in front of the RX position, which is marked by the yellow triangle in **Fig. 7**, and finally continued passing by the RX position, leaving the town into some minor forest passages. The TX track is indicated with red diamonds, the size of which show the HDOP (Horizontal Dilution of Precision) recorded by the GPS receiver. It can be seen, that the HDOP significantly increases in forest sections and even when passing beyond a street (see right top corner of **Fig. 7**).

When the train approached the station between time stamps 100 to 150 seconds in **Fig. 8**, we can see a clear increase in power. The direct wave components are at approximately +20 Hz, but there are as well several components from scatterers that reach

Fig. 7. Suburban measurement scenario in the vicinity of the railway station in Bad Tölz. Red diamonds indicate the route of the train; the yellow triangle shows the RX position.

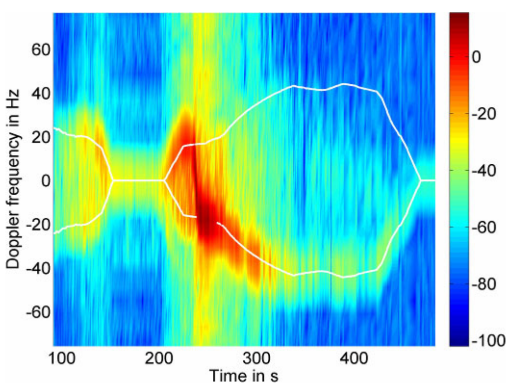

Fig. 8. Measured channel frequency response in dB at the railway station in Bad Tölz

almost the same power level. Please note, that the power in **Fig. 8** is normalized to the hypothetical FSL (Free Space Loss), i.e. we only show the additional loss due to diffraction and reflection. In other words, the red parts with 0dB refer to LOS condition.

During the halt from 150 to 200 seconds, we can see a characteristic lower power caused by the roofs on the platforms, which block the LOS signal. Immediately after leaving the station the LOS path appears, quickly changing its Doppler from +20 to -20 Hz when the train passes by the receiver at time stamp 240. In the whole area of the station strong multipath was present from different directions causing a maximum Doppler spread, until the LOS signal vanished as the train entered a forest passage.

In the last part of the measurement between time stamps 350 and 450, the relative Doppler spread is lower, but we can still see scattering from objects and vegetation on both sides of the track with a Doppler frequency around zero.

3.2 Tunnel in Urban Environment

The following measurement example was recorded near the Munich central station. Again the receiver was static at a location very close to the railway track (see yellow triangle in **Fig. 9**). The train started at Munich central station and had its first stop just beyond the Donnersberger Brücke in the upper part of the image. Right after this stop the train entered a tunnel that crosses under other tracks, allowing to directly going south passing by the receiver location. This tunnel is about 280 meters long and is indicated by the white line in **Fig. 9**. The red diamonds again show the TX track, showing increased HDOP values, when passing under the bridge, at the tunnel entrance and exit, and near higher buildings, where less GPS signals can be tracked.

The measured channel frequency response of this scenario is shown in **Fig. 10**. The train starts to leave Donnersberger Brücke at time stamp 130. Between time stamp 140 and 150 some fading is notable on the direct signal at the moments when the

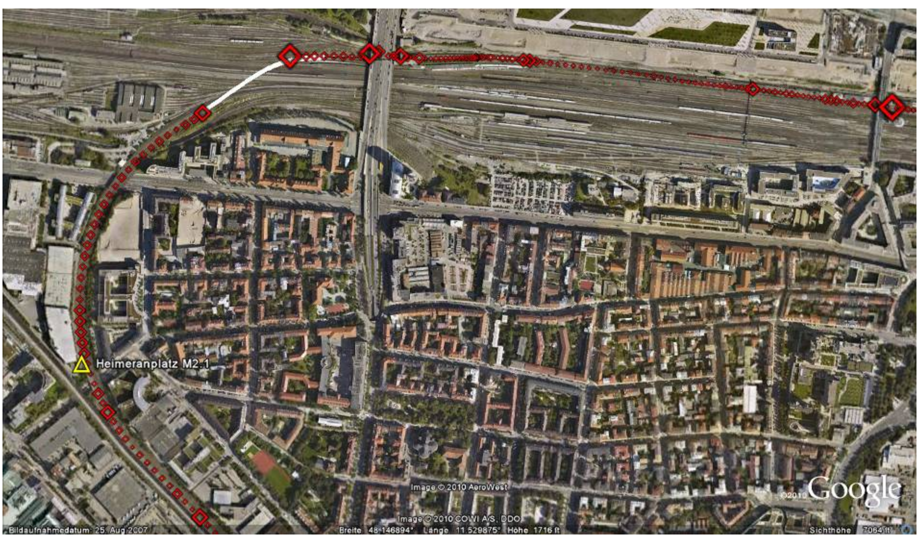

Fig. 9. Urban measurement scenario near Donnersberger Brücke in the city center of Munich. The white line marks the tunnel that is used to cross multiple other tracks.

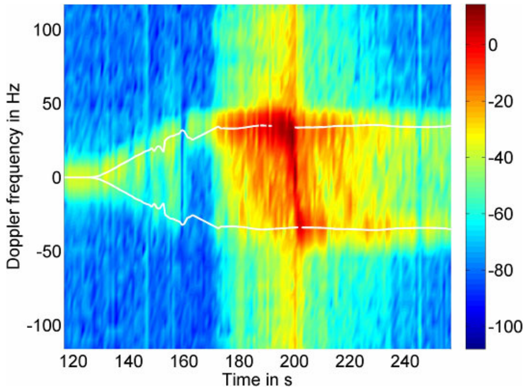

Fig. 10. Measured channel frequency response in dB in the urban environment near the tunnel at Donnersberger Brücke in Munich

antenna passed behind the abutments of the bridge. At the same time right under the bridge the GPS velocity measurements become erroneous, which can be clearly seen in the white line that marks the maximum possible Doppler. Soon after that, at time stamp 160, the train-set with the antenna entered the tunnel via a ramp. A short significant signal loss is visible at that moment and all the multipath components disappear. It is very interesting to note, that in the following 10 seconds, when the train passes through the tunnel, the received signal level is almost as high as before. This can be best observed in **Fig. 11**, which shows the evolution of the normalized received power for the same section of the measurement. Note that this corresponds to the evolution of total path loss including the FSL.

After the train exits the tunnel, the signal strength increases rapidly, as we begin to have LOS condition. At time stamp 200 the train passes by the RX station heading further south. Very strong multipath exists in this urban environment (see **Fig. 10**), which tends to show a typical Jakes spectrum characteristic [12], as the transmitter departs from the receiver location after time stamp 220.

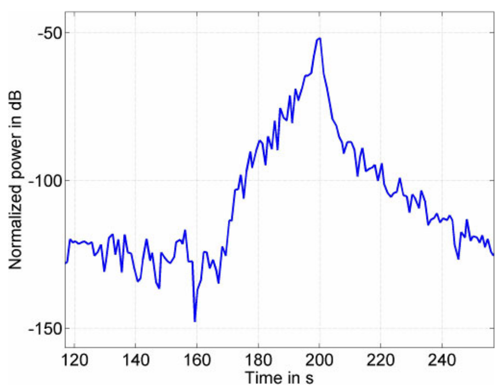

Fig. 11. Measured relative power in urban environment near the tunnel in Munich, showing the evolution of path loss in this scenario

3.3 Hilly Alpine Upland

In this scenario both, RX and TX moved towards each other. The yellow line in **Fig. 12** shows the track of the car following the railway line south along lake Schliersee, while the train approached the valley from the east. The hills east of the lake are obscuring a direct propagation between RX and TX in this scenario.

Despite these hills and the large distance of more than 10 km, we received most of the transmitted SDS messages. The channel frequency response in **Fig. 13** shows that there is reception of relatively strong multipath components in this situation. The strength of the multipath increased continuously until the train reached the village south of the lake, still under non-LOS condition. Around time stamp 250 we can also see a longer signal outage, which occurred during the halt of the train in Fischbachau (at the right lower corner in **Fig. 12**).

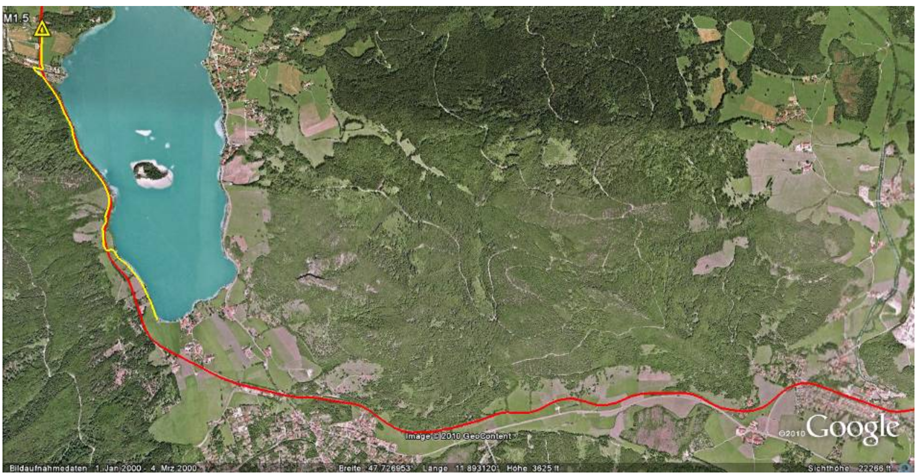

Fig. 12. Dynamic RX measurement scenario in the hilly alpine upland south of Schliersee

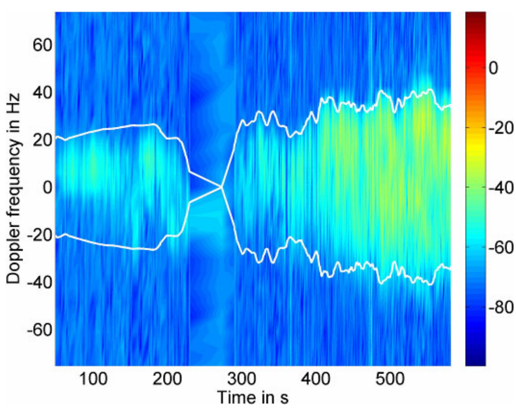

Fig. 13. Measured channel frequency response in dB in the hilly alpine upland near Schliersee

4 Path Loss Model

In [13] existing channel models for terrestrial communication and their applicability to Train-to-Train scenarios is discussed. As a result Hata-Okumura models were proposed for modeling the path loss in different railway environments. Hereby the suburban characteristic best fits the mix of scenarios that we measured during our campaign. In **Fig. 14** we compare the averaged path loss of the entire measurement data (blue dots) with the theoretical model. First of all, we note that in case of direct Train-to-Train communication the LOS condition is maintained for larger distances than in other terrestrial applications, typically up to more than 100 meters. While the exponential decay is in the expected order, the path loss for non-LOS condition was observed to be 10 dB lower than predicted, which in fact allows for a 100% increase of the communication range.

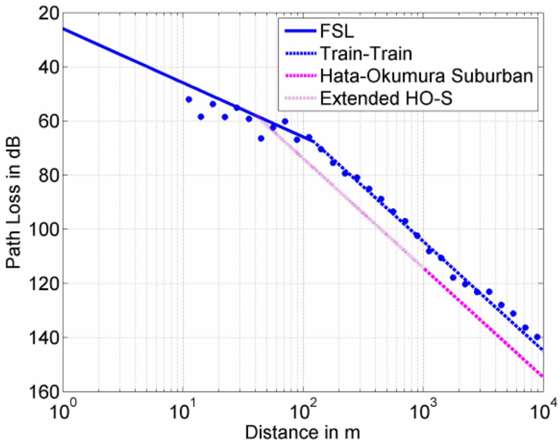

Fig. 14. Comparison of theoretical path loss model and Train-to-Train measurement result

5 Conclusion

The analysis of data from the presented channel measurement campaign shows, that applications requiring reliable direct Train-to-Train communication can benefit from the specific environmental conditions. Due to the layout of railway lines and the typical character of passages through urban, suburban and rural areas, the wave propagation for UHF frequencies is significantly better than in other Mobile-to-Mobile applications. Moreover, for higher velocities the train routes need to be straighter and the resulting longer breaking distances are likely to be still covered by the enhanced communication range. In fact, we see an unexpected high margin for timely warning of train drivers in case of a collision threat from the successfully received RCAS data during the measurement campaign. Even in critical environments with obstacles like hills, or in case of a tunnel, the performance of Tetra SDS-DMO messaging could be proved to be highly reliable.

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