LTE Downlink Performance in High Speed Trains

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***Abstract*—Long Term Evolution (LTE) is expected to substitute the Global System for Mobile Communications (GSM) as the radio access technology for railway communications. Recently, especial attention has been devoted to high-speed trains since this particular environment poses challenging problems in terms of performance simulation and measurement. In order to severely decrease the cost and complexity of high-speed measurement campaigns, we have proposed a technique to induce effects caused by highly-time varying channels on Orthogonal Frequency-Division Multiplexing (OFDM) signals while conducting measurements at low speeds. In this work, we evaluate this technique by comparing the results of LTE measurements at different velocities as well as by simulations. Additionally, we use this technique to show the performance of LTE for high-speed train scenarios up to 600 km/h. To accomplish this, we use both a controlled high-speed measurement setup as well as a channel model developed according to the guidelines of the ITU Radiocommunication Sector (ITU-R) for the evaluation of radio interface technologies for IMT-Advanced systems.**

I. Introduction

During the last few years, broadband communication between nodes moving at high speeds has attracted special attention. One of the most relevant research topics in this field is the High-Speed Train (HST) channel modeling. Nowadays, the most widely used communication system between trains and the elements involved in operation, control, and intercommunication of the railway infrastructure is based on the GSM. This technology, namely the GSM for Railways (GSM-R), is not well-suited for supporting advanced services such as automatic pilot applications or provisioning broadband services to the train staff and passengers. Next to trains, the increasing number of broadband services available for mobile devices motivated the migration from third-generation mobile networks to fourth generation ones, mainly LTE. Therefore, LTE seems to be a good candidate to substitute the GSM as the basis technology for railway communications.

Several radio channel models have been proposed for moving radio interfaces, such as the International Telecommunication Union (ITU) channel models [1]. The first channel modeling approach for the high-speed train environment was proposed by Siemens in 2005 [2]. More recent proposals are the WINNER Phase II model (high-speed moving networks included [3]) and the radio channel models approved by the ITU-R for the evaluation of IMT-Advanced Technologies (high-speed train scenario explicitly considered [4]), such as LTE-Advanced (LTE-A). However, only a few results based on empirically obtained data which can validate the aforementioned channel models are available. An example for high-speed train channel modeling contributions based on the results obtained by means of measurement campaigns is the propagation path-loss model proposed in [5]. The same experimental results were also used for the definition of the large-scale model proposed in [6]. An efficient channel sounding method for the high-speed train environment using cellular communications systems is proposed in [7] by considering Wideband Code Division Multiple Access (WCDMA) signals.

One of the reasons that explains the small number of measurement campaigns in high-speed environments is their complexity and cost. Furthermore, it is not possible, in most cases, to measure at high speeds in controlled environments in a reproducible and repeatable way. In addition, measuring in high-speed train environments demands for specific hardware and software solutions (see [8]). In order to address those problems we proposed a technique to induce the effects caused by highly time-varying channels in OFDM signals while conducting the measurements at much lower speeds [9]. This technique consists basically in reducing the subcarrier spacing of the OFDM signal by scaling down the bandwidth of the whole OFDM signal. More specifically, we propose to interpolate the transmit OFDM signal in the time domain before being transmitted. The time-interpolated signal still conveys exactly the same information as the original one but with a reduced subcarrier spacing, thus artificially increasing the sensitivity to the Inter-Carrier Interference (ICI). For example, if we time-interpolate the transmit OFDM signal by a factor I, the subcarrier spacing will be reduced by the same factor I, which is similar to what would happen if the transmission was conducted at I times the original speed.

In this work we evaluate experimentally the accuracy of this technique by transmitting standard-compliant LTE signals using a measurement setup that allows for repeatable measurements at different speeds. We complete the validation by means of simulations, considering a channel model based on the guidelines of the ITU-R for evaluation of radio interface technologies for IMT-Advanced systems [4]. The obtained results show not only that our technique induces highly time-varying channels with excellent agreement, but also that the considered evaluation setup and measurement methodology allow for repeatability of the measurement results.

II. Emulating High Speeds by Time Interpolation

Let us consider an OFDM modulation where N subcarriers are multiplexed to construct each OFDM symbol. OFDM symbols are cyclically extended by adding N_g samples, thus having a total length of $N_t = N + N_g$ samples that are transmitted at a rate $F_s = 1/T_s$. Therefore, symbols have a time duration $T_t = T_s N_t$ and a bandwidth F_s. When the k-th

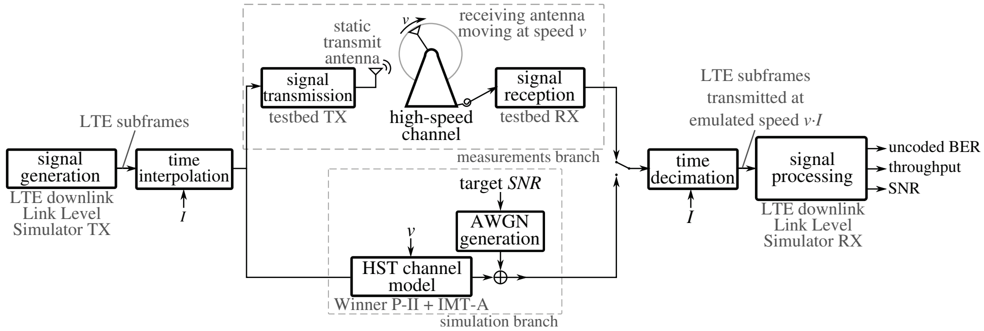

Fig. 1. Block diagram of the setup used for the evaluations.

OFDM symbol is transmitted, the received signal, namely $\mathbf{r}_k$, can be represented as

$$\mathbf{r}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{w}_k,$$

where $\mathbf{x}_k$ is a $N \times 1$ vector containing the k-th OFDM symbol, $\mathbf{H}_k$ is a $N \times N$ matrix defining the channel frequency response, and $\mathbf{w}_k$ is a $N \times 1$ vector containing uncorrelated complex-valued white Gaussian noise entries with variance σ^2.

If the channel is time invariant, $\mathbf{H}_k$ will be a diagonal matrix. In time-selective channels, however, non-zero entries will appear outside the main diagonal of $\mathbf{H}_k$ and ICI arises in the received signal. The amount of ICI relates to the normalized Doppler spread of the channel, which is given by $D_n = f_d T$, f_d being the maximum Doppler frequency and $T = T_s N$ the duration of the OFDM symbol excluding the cyclic prefix. As proposed in our previous work [9], parameter T can be adjusted by time interpolation by a factor I, yielding an OFDM symbol duration $T^I = I T_s N$. Therefore, given the actual velocity v of the mobile receiver, the normalized Doppler spread, impacting the time-interpolated OFDM signal can be written as

$$D_n^I = f_d T^I = f_d I T_s N = \frac{T_s N I f_c v}{c} = \frac{T_s N f_c}{c} v^I,$$

with f_c the carrier frequency, c the speed of light, and $v^I = Iv$ the emulated speed as a result of an actual mesurement speed v and an interpolation factor I. Consequently, enlarging the symbol length T^I by adjusting I allows for the emulation of a velocity v^I while conducting measurements at a speed v.

In our setup, time-interpolation factors $I = 1, 2, 3$ were applied to standard-compliant downlink LTE OFDM signals before the over-the-air transmission to emulate situations with I times higher velocity than the actual speed of the receiver. The same principle was considered for the simulations.

III. Evaluation Setup and Procedure

A. Evaluation Setup

We use the evaluation setup shown in Fig. 1 to test the technique of emulating high speeds by time interpolation of OFDM signals. The setup consists of:

1) Signal generation (transmitter side) and signal processing (receiver side): at the transmitter side, standard-compliant LTE subframes are generated using the LTE Downlink System Level Simulator developed at the Vienna University of Technology [10]. At the receiver side, the same simulator is used to process the received signals and to estimate the following figures of merit: uncoded Bit Error Ratio (BER), throughput, and Signal-to-Noise Ratio (SNR).

2) Time interpolation and time decimation: the signal is time-interpolated by a factor I at the transmitter and decimated by the same factor I at the receiver side. This way we emulate a Doppler spread similar to that obtained with a speed increase by the factor of I.

3) Signal transmission and reception under actual high-speed conditions: signals are transmitted over the air by using a testbed developed at the Vienna University of Technology [11]. The testbed transmitter is placed outdoors on a roof of a building in downtown Vienna, Austria. The receiver is placed indoors in the fifth floor of an adjacent building at a distance of 150 meters. While the transmit antenna is fixed, the receive antenna is rotated around a central pivot in a controlled and repeatable way [12], recreating an infrastructure to vehicle scenario. Different channel realizations are created by measuring at different initial positions of the receive antenna. Note that the trajectory of the antenna is well approximated as a transversal movement since the diameter of the trajectory is two meters and each LTE subframe is 1 ms long. Note that no feedback channel was used in our experiments, consequently no adaptive modulation and coding schemes were applied. Therefore, Channel Quality Indication (CQI) values were fixed in advance. Notice also that the testbed is equipped with a highly precise time and frequency synchronization system based on Global Positioning System (GPS)-disciplined rubidium oscillators and a custom-made synchronization unit [13]. As a result, we can assume perfectly time and frequency synchronized measurements, thus the results are not affected by time or frequency offsets due to imperfect synchronization.

4) Signal transmission and reception through an High Speed Train channel model: We use the setup shown in Fig. 1 (simulation branch) to test by means of simulations the technique of emulating high speeds by time interpolation. We select noise variance values that lead to the same SNR values estimated from the measurements. A channel model suited for high-speed train scenarios was defined. To accomplish this, the model defined by the D2a link of the D2 scenario of the Winner Phase II Channel Models [3] was tuned according to the guidelines of the ITU-R for evaluation of radio interface technologies for IMT-Advanced systems [4]. More concretely, the values of parameters such as delay spread distribution, arrival and departure angle distributions, shadow fading, K-factor, cross-correlations, delay scaling parameters, number of clusters, rays per cluster, etc. were adjusted according to [4, Table A1-7]. This scenario models the channel between an

TABLE I. COMBINATIONS OF VELOCITIES AND INTERPOLATION FACTORS WHICH LEAD TO EQUAL DOPPLER SPREADS.

Emulated velocity	$I = 1$	$I = 2$	$I = 3$
100 km/h	$v = 100$ km/h	$v = 50$ km/h	–
150 km/h	$v = 150$ km/h	$v = 75$ km/h	$v = 50$ km/h
200 km/h	$v = 200$ km/h	$v = 100$ km/h	$v = 66.6$ km/h

antenna placed at the roof of a train carriage and a network of fixed eNodeBs installed in a rural environment, which usually leads to Line-of-Sight (LoS) propagation conditions. The key characteristic of this scenario is continuous wide area coverage by large cells, leading to noise-limited and/or interference-limited conditions. The building density is expected to be low and the height of the antennas much higher than the average building height. Speeds up to 350 km/h can be considered for the train. Notice that the considered channel model does not intend to model the channel exhibited by the measurements. Our intention is to complement the evaluation of the proposed technique in a simulation environment, as well as to assess the LTE performance using a realistic channel model.

B. Evaluation Procedure

In order to evaluate the impact of high-speed conditions on LTE transmissions, actual velocities ranging from 50 km/h to 200 km/h were considered. Furthermore, interpolation factors of $I = 1$ (no interpolation), $I = 2$, and $I = 3$ were used for generating Doppler spreads equivalent to those associated to velocities ranging from 50 km/h to 600 km/h. Note that it is possible to generate exactly the same Doppler spread value from different combinations of the actual measurement velocity and the interpolation factor (see Table I). We considered this fact to show that our technique allows for the evaluation of wireless communication systems at high speeds while measuring at much lower speeds. In order to do that, we generated the same Doppler spread by means of different velocities and interpolation factors and then we compared the obtained results. Table I shows the combinations of actual speeds and interpolation factors which lead to equal Doppler spreads (each row of the table corresponds to a different Doppler spread factor).

Several measurements are conducted for each velocity and interpolation factor. More concretely, three different linear-shift values of the whole receiver (including the antenna rotation unit) along rails installed on the floor are considered. For each linear-shift value, 10 measurements per velocity and interpolation factor are carried out, each starting at a given angular-shift on the circumference defined by the receive antenna rotating around a central pivot. We always transmit the same subframe of an LTE radio frame, thus ensuring the same payload for each measurement. This enables us to fairly compare the results of different measurements as the subframe structure is kept invariant all the time.

To be able to compare the results gathered from different interpolation factors, we consider the following aspects:

1) Equal receive antenna trajectory (measurements case): when a subframe is interpolated by a factor of I and the rotation speed keeps unchanged, the arc length described by the rotating antenna during the transmission of such a frame increases also by a factor of I. However, in order to maintain a constant Doppler spread, the rotation speed has to be decreased by the same factor (see Table I). Therefore, the trajectory of the receive antenna during the transmission of one LTE subframe does not vary as the Doppler spread is maintained.

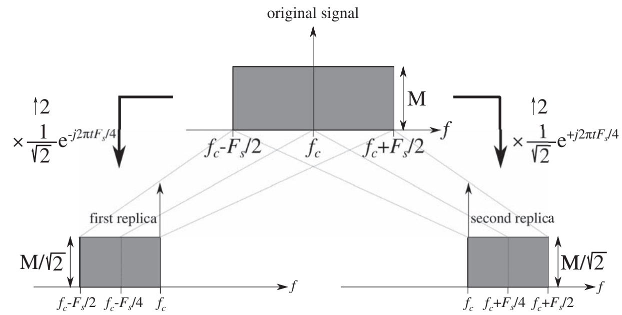

Fig. 2. Ensuring equal spectrum usage for interpolation factor $I = 2$. 2 replicas of the interpolated signal are transmitted to ensure that the whole frequency range of the original signal is used. The procedure is similar for the cases where $I = 3$ (three replicas are generated in those cases).

TABLE II. MAIN PARAMETERS USED IN THE EXPERIMENTS.

parameter	value
Signal bandwidth, F_s	10 MHz (9 MHz used)
FFT size, N	1024
Number of used subcarriers	600 (excluding DC)
Velocities, v	50, 66.6, 75, 83.3, 100, 125, 150, and 200 km/h
Carrier frequency, f_c	2.5 GHz
Interpolation factors, I	1, 2, and 3
SNR	38, 31, 21 and 11 dB
CQI values	1 (4-QAM), 8 (16-QAM), and 12 (64-QAM)

2) Equal mobile simulated trajectory (simulations case): to fairly compare the results, the channel model was fed with identical initial conditions (e.g., delays and mean power per path) for each evaluated interpolation factor. This way, we model a situation in which the receiver moves along the same path for each interpolation factor.

3) Equal spectrum usage: when a subframe is interpolated by a factor of I, its bandwidth is decreased by the same factor, which in principle reduces the effect of the frequency diversity of the channel. In order to experience the same spectrum, I replicas of the interpolated signal are transmitted to ensure that the whole frequency range of the original signal is used. The results are then averaged. Figure 2 shows an example of this procedure for $I = 2$.

4) Equal average transmit energy per OFDM symbol: in order to preserve the average energy per OFDM symbol, the interpolated signals are scaled in amplitude by a factor of $\sqrt{I}$ before being transmitted.

Table II details the most relevant parameters for the experimental evaluations as well as the simulations.

IV. RESULTS

Both measurement and simulation results are presented in this section. Three types of curves are included in the result graphs, which are:

- **Red solid lines**: they correspond to the cases with no interpolation ($I = 1$). According to the speed values considered for the measurements as well as for the simulations, the red solid curves range from 50 km/h to 200 km/h.

- **Green dashed lines**: they correspond to the cases with $I = 2$, so the emulated velocity is twice the measured or simulated speed. Therefore, the green curves range from 100 km/h to 400 km/h.
- **Pink dotted lines**: they correspond to the cases where $I = 3$, so the curves range from 150 km/h to 600 km/h.

We gauge the precision of the results by calculating the 95% confidence intervals for the mean. This confidence intervals are plotted as an area around each curve and in the same color as the corresponding curve.

Due to limitations of the inverter driving the motor used to rotate the receive antenna, the actual velocity range considered for the measurements (and also for the simulations) starts at 50 km/h, while the maximum actual speed value is set to 200 km/h. Given that we consider interpolation factors $I = 1, 2, 3$, in the speed range from 150 km/h to 200 km/h the three curves for the different interpolation factors overlap, thus allowing for evaluating the level of agreement of the results between actual and emulated velocities.

The SNR is estimated considering exclusively the data subcarriers. Firstly, noise samples in the time domain are captured when no signals are transmitted (measurement case) or generated directly (simulation case). After process noise samples as if they were actual data samples (e.g., down-sampling by the factor I, removing the cyclic prefixes and performing FFT operations), instantaneous noise power per subcarrier is estimated as the power of the data subcarriers. An analogous procedure is followed when the actual signal is being transmitted, so the instantaneous data plus noise power per subcarrier is estimated. The average SNR for a given velocity v and interpolation factor I is then estimated by averaging out the instantaneous SNR of all the subcarriers.

Figure 3 shows the measured uncoded BER for different CQIs and SNR values. It can be seen that the higher the emulated speed is, the worse the uncoded BER becomes, as expected. However, the higher the CQI, the higher the dependency level with the emulated velocity. Notice that the obtained results are severely affected by the speed for high SNR values, showing that the main source contributing to the signal distortion is the ICI. As the SNR decreases, the performance is less affected by the speed because the noise is the main contributor to the signal distortion. Finally, note that the curves for different interpolation factors (as well as their associated confidence regions) overlap despite of the CQI and SNR values, which demonstrates that the proposed technique of emulating high speeds by time interpolation performs adequately.

Figure 4 shows the simulated uncoded BER for different CQIs and SNR values. Similar effects to the ones described for the measurement case can be observed. However, the obtained uncoded BER values are lower. The reason is that the channel model considered for the simulations is easier to equalize. In fact, such a channel model leads to frequent LoS propagation conditions [4]. However, the receiver used for the measurements is located inside a building, while the eNodeB

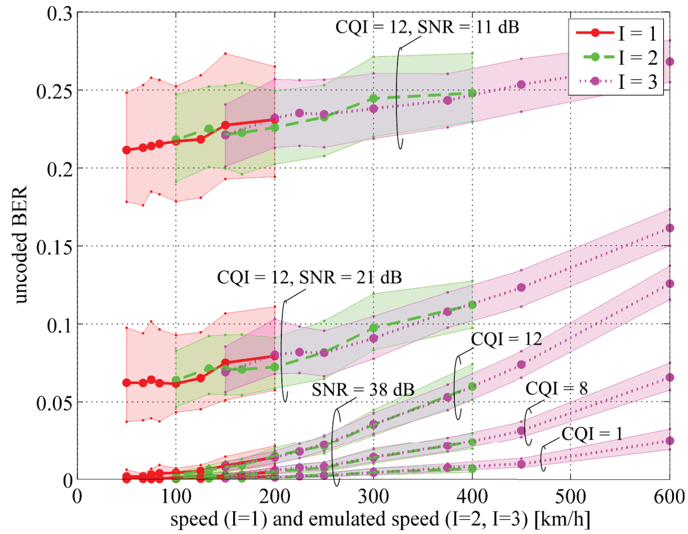

Fig. 3. Measured uncoded BER for different CQIs and SNR values.

is placed on a roof of another building, thus Non-Line-of-Sight (NLoS) propagation conditions arise, leading to a much more relevant multipath effect. This causes that the variability of the results obtained by simulations is lower than those of the measurements. In fact, the confidence region of each simulated curve completely overlaps the curve itself, which causes that the confidence regions cannot be distinguished although they are included. Additionally, curves simulated for different interpolation factors completely overlap, showing the good behavior of the proposed technique also in this case.

Finally, Fig. 5 shows the measured throughput for different CQIs as well as SNR values. Since no feedback channel was used in our experiments, no adaptive modulation and coding schemes were applied, being the CQI values fixed in advance. Take also into account that the maximum throughput values are 1.192 Mbit/s, 15.288 Mbit/s, and 31.192 Mbit/s for CQI $= 1$, CQI $= 8$ and CQI $= 12$, respectively. The considered CQI not only determines the maximum throughput available, but also limits the robustness of the system. Thus, it can be seen that for not so high SNR values, a better throughput can be achieved by reducing the CQI. In fact, the system works in absence of errors even for SNR $= 11$ dB when CQI $= 1$ and despite of the velocity. Simulated throughput results (figure not included) show that channel coding succeeds to correct all the errors introduced by the channel despite of the CQI and speed values, as the reached throughput is always maximum for SNR values up to 11 dB.

V. Conclusions

The main conclusions of this work are summarized below:

- A novel methodology for evaluating the performance of OFDM transmissions in real-world scenarios affected by large Doppler spreads while conducting the experiments at low speeds was tested both by transmitting standard-compliant LTE subframes in a controlled measurement scenario and by applying a channel model suitable for high speed train scenarios.
- The obtained results show that the proposed technique emulates high speed channels by inducing large

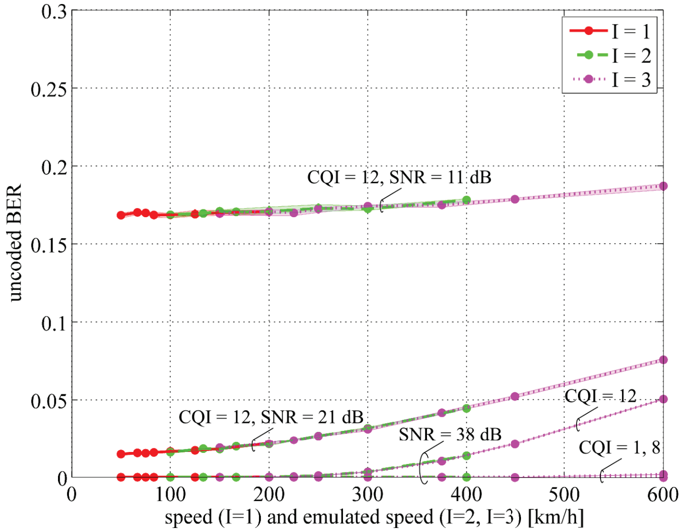

Fig. 4. Simulated uncoded BER for different CQIs and SNR values.

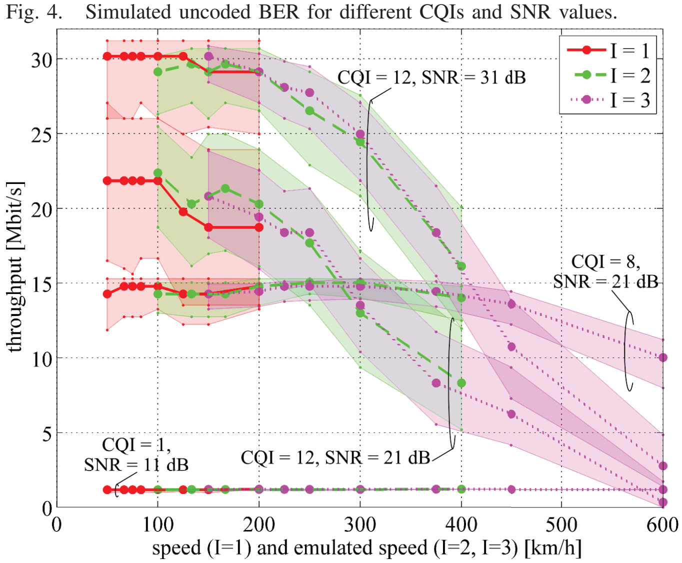

Fig. 5. Measured throughput for different CQIs and SNR values.

Doppler spread values while measuring or simulating at low speeds. In fact, the proposed technique can be used to accurately estimate the performance of LTE in high speed channels of different types while measuring (or simulating) at low speeds.

- The frequency diversity reduction inherent to the bandwidth decrease caused by the time interpolation does not seem to affect to the simulation or measurement results. This would affect more in channels exhibiting a very high frequency selectivity, which is unlikely in high speed conditions in which the channel response changes fast.
- The performance of LTE was evaluated in terms of uncoded BER and throughput both by measurements and by means of simulation using a channel model suited for high-speed train scenarios according to the guidelines of the ITU-R for evaluation of radio interface technologies for IMT-Advanced systems. For high SNR conditions, the results are severely influenced by the ICI induced by the train movement, while for low SNRs the noise becomes the main source of signal distortion. Lower CQIs provide more robustness at high speeds, although reducing the maximum achievable throughput. Notice that, as expected, the higher constellation size, the higher the sensitivity it exhibits with respect to the speed.

As a future research line, the proposed methodology will enable the study of the impact of the feedback delay in both the performance of the physical layer downlink throughput as well as in the delay of the communication link.

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