Identifying Multipath Propagation in Vehicular Repeater Deployments by LTE Measurements

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***Abstract*—This paper introduces a simple measurement methodology that can identify extreme cases of multipath propagation for in-train repeater (ITR) deployments, which may cause performance impairments for users. Differential timing advance measurements allow to detect the relative power of multipath components in the range of -20...20 dB, as we have verified through laboratory measurements. The experimental results for an existing ITR deployment inside an express passenger train show that this method can, in fact, be used to pinpoint the specific locations for which the interplay between the base station configuration and the ITR is still not optimal. Therefore, it is possible to use the proposed method to continuously collect measurement points, e.g., by crowdsourcing from standard handsets running on Android. This enables to continually improve deployments with active components such as ITRs.**

I. Introduction

In the last decade, the demand for fast and reliable internet access in transportation has dramatically increased. However, the challenge to provide mobile service and coverage for passengers of express trains has no simple solution. First, being inside a train cabin causes mobile cellular signals to have strong penetration losses. Second, the train travels at high speeds as it traverses the rural areas between cities—places that typically have no dense network of base stations (BTSs). Consequently, railroad operators have recently started to deploy repeater systems in train cabins. To assist the vehicular repeater deployment, operators have increased the density of BTS along the rails, partly by deploying trackside BTS towers for rail coverage only. However, such deployments result in scenarios in which the train will commute in dense urban city centers, close to trackside deployments, and in sparsely populated rural areas. These scenarios have significant differences in coverage; a generic static repeater configuration cannot cover those elements all at once. Using digital repeater technology allows operators to have advanced features that are not available to analogue systems, e.g., fixed power share between operators by sub-band filters with symmetric uplink (UL) and downlink (DL) gain. However, these features come at the cost of additional processing delay. The resulting impulse response of the channel will have two components with a large delay in the order of several microseconds—the desired path passing through the in-train repeater (ITR) and the direct path without additional delay. In extreme cases, depending on the deployment, the power from the direct path might be in the order of the desired path through the ITR. In orthogonal frequency division multiplexing (OFDM) systems, like LTE, channels with relative multipath delays exceeding the length of the cyclic prefix (CP) cause intersymbol interference (ISI) [1], [2]. The standard CP in LTE is 4.7 µs, which is short when compared to the processing delay of a typical ITR. Therefore, we need to identify, classify, and analyze the presence of such extreme cases based on measurements to understand how we can improve the ITR deployment as well as the BTS deployment along the tracks. Hence, measurements need to be collected inside the train and along the railway. Mobile networks continuously evolve; thus, it is also important to continuously run such measurements.

Related Work

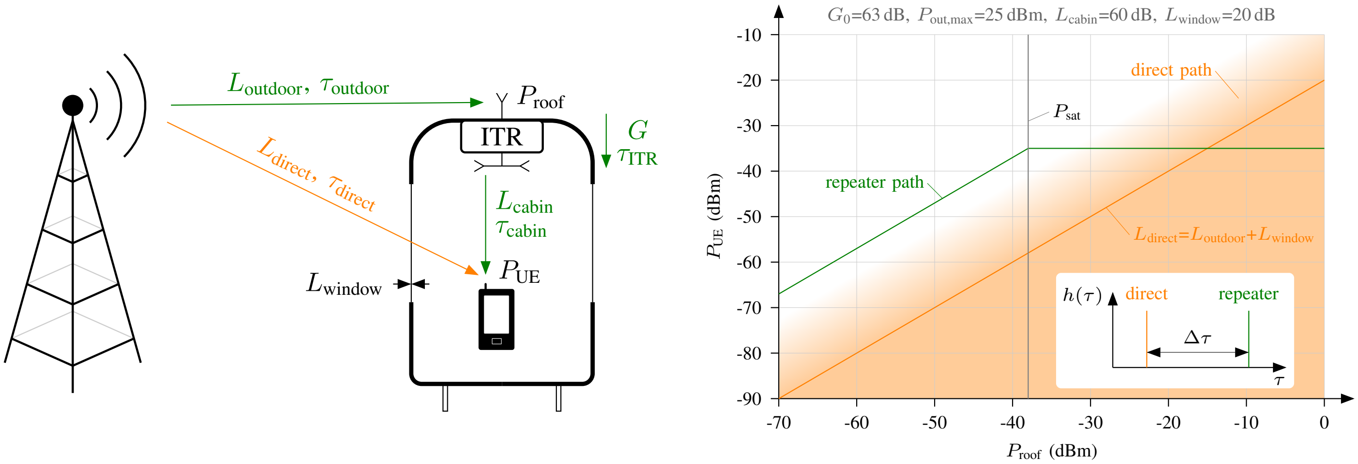
Several researchers have studied channels by measuring on trains, see [3]–[6]. In particular, the papers have covered channel measurements, analysis, and models for communication systems that are connected to high-speed trains. Channel sounding measurements are very complex and costly. To date, experimental studies are still analyzing the service impact of a repeater deployment by drawing measurement samples along a track, see [7], [8]. Although these experiments will show that there is performance degradation due to multipath effects, they cannot pinpoint the specific reason for the degradation. To our knowledge, there has not been any study that has proposed an approach for measuring the interplay in a repeater deployment of vehicular deployments in a mobile cellular network.

Our Contribution

We show that timing advance (TA) measurements can be used to identify extreme cases of two-path propagation in ITR deployments. Based on our laboratory measurements, we show that it is possible to identify the power of either the desired repeater or the direct signal path by using two differential TA measurements, e.g., inside and outside the train cabin. We then analyze this method through an actual ITR deployed in an express train along the track between Wien and Salzburg in Austria. The experimental results show that the differential TA measurement can help us to better understand the interplay between the ITR deployment and the BTS placement alongside the track.

II. Two-Path Propagation in Repeater Deployments

We model a train equipped with an ITR based on the model given by [9]. Figure 1a illustrates the model with all the param-



(a) (b)

Fig. 1. Modeling an ITR deployment as a two-path channel: (a) Pathloss model (b) Received power of a specific setup.

eters considered in our study. We model the channel between a user equipment (UE) on board the train and the BTS where the UE is attached to as a two-path model. First, there is the *direct path* that corresponds to the channel that the UE would experience in the absence of the ITR. Second, the *repeater path* is the path through the ITR. Its pathloss is given by $L_{\text{outdoor}} - G + L_{\text{cabin}}$, whereas, due to the limited output power of the ITR, the actual gain G of the repeater depends on the power P_{roof} at the input of the ITR. The ITR is characterized by its maximum output power $P_{\text{out,max}}$ and its nominal gain G_0. For input powers $P_{\text{roof}} < P_{\text{sat}} = P_{\text{out,max}} - G_0$, the ITR operates in the linear region. The input signal is amplified by the nominal gain G_0. At input powers exceeding P_{sat}, the ITR transmits with its maximum output power, and the actual gain $G = P_{\text{out,max}} - P_{\text{roof}}$ decreases with increasing input power P_{roof}. To preserve reciprocity between the DL path and the UL path, the gain of the UL path is linked to the gain of the DL path. The propagation delay of the repeater path is then given by $\tau_{\text{repeater}} = \tau_{\text{outdoor}} + \tau_{\text{ITR}} + \tau_{\text{cabin}}$.

A. Received Power

Figure 1b shows the power received by the UE on board a train as a function of the power P_{roof} from the rooftop antenna. The model is parametrized using values measured from a real ITR deployment, see [9]. The power going through the repeater path increases with P_{roof} for $P_{\text{roof}} \leq P_{\text{sat}}$. At higher powers, the ITR saturates. On the other hand, the power going through the direct path is independent of the actual operating state of the ITR. Its actual value depends on the BTS deployment and on the environment. A special case is given when the direct path is not blocked and differs only from the path to the rooftop antenna by the window penetration loss [10], $L_{\text{direct}} = L_{\text{outdoor}} + L_{\text{window}}$. For the general case, considering that BTS antennas are mounted on towers, we can expect that the power received from the direct path would be smaller than the power for this special case. In general, there are two effects that cause a pronounced two-path propagation with a small power difference between the two paths. First, there would be a strong direct path, and second, the repeater path would saturate due to the limited output power of the ITR.

B. Delay

The relative delay $\Delta\tau$ between the two paths calculates to $\tau_{\text{outdoor}} + \tau_{\text{ITR}} + \tau_{\text{cabin}} - \tau_{\text{direct}}$. Assuming that $\tau_{\text{direct}} \approx \tau_{\text{outdoor}}$ and that τ_{cabin} is negligible, the relative delay $\Delta\tau$ is approximately the delay τ_{ITR} of the ITR. Considering OFDM with a CP shorter than the delay of the ITR, the two-path propagation channel introduces ISI.

III. Using Timing Advance Measurements to Identify Pronounced Two-Path Propagation

To identify and localize pronounced two-path channels in ITR deployments, we propose to measure the propagation delay through TA measurements at two different locations of the train. Therefore, UE_{roof} is connected to a rooftop antenna, where the propagation delay is τ_{outdoor}, while UE_{cabin} performs measurements inside the train cabin. In case of a negligible direct path, the propagation delay for UE_{cabin} should be approximately $\tau_{\text{outdoor}} + \tau_{\text{ITR}}$. A difference of propagation delay smaller than τ_{ITR} indicates a non-negligible direct path. We evaluate the capabilities of such TA measurements by conducting the measurements under controlled laboratory conditions. This enables us to identify channels with pronounced two-path propagation.

A. The Timing Advance Command

In mobile communications, the BTS reports TA commands to all active UEs in the cell in order to time-synchronize the received UL signals. Thereby, the TA value reported through the TA command is measured by the BTS. This value corresponds to the round-trip time from the BTS to the UE and back. Hence, considering reciprocal propagation channels, the TA is twice the propagation delay for one direction. Note that,

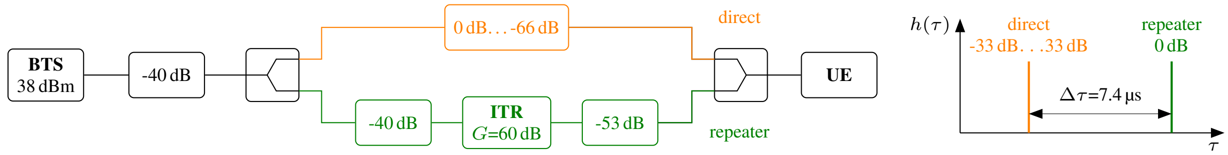


Fig. 2. Setup used to perform the controlled measurements using the two-path channel.

especially for multipath propagation, the TA reported depends on the time-synchronization implemented in the BTS and in the UE. In LTE, the value of the TA command is quantized in steps of approximately 0.52 µs, see [11].

B. Measurement Setup

We implement the measurements using the two-path channel described in Section II and the setup illustrated in Figure 2. The setup is located in a shielded laboratory and consists of the following components:

- The BTS is part of the live network of an Austrian operator and provides a 20 MHz LTE carrier at a center frequency of 801 MHz. To simplify, the BTS uses single-antenna transmission only.
- The UE is a modified Nemo [12] measurement phone with external antenna connectors, whereas we use only the first antenna port. Using just one antenna port of the UE will not affect the time-synchronization of the system. Although we lose receive diversity in the DL direction, it does not affect the UL transmissions at all. There, only the first antenna port of the UE is used.
- The direct path has a variable attenuation in the range of 0 dB. . .66 dB.
- In the repeater path, we use an ITR with a delay of 7.4 µs in each direction. We fix the input power of the ITR to ≈ -45 dBm. For a gain of 60 dB, the ITR then operates in the linear region, independent of the actual cell load.

This setup allows us to implement two-path channels with a power difference of ± 33 dB, whereas the power of the repeater path is fixed. For a dominant repeater path, the reference signal received power (RSRP) in the UE is fixed at ≈ -78 dBm while it increases as the power of the direct path also increases to a maximum value of ≈ -45 dBm. Note that this region is a region of high signal-to-noise ratio (SNR) where the performance of a single antenna LTE system is independent of the RSRP, see [13].

C. Measurement Results

We evaluate the TA at different power differences P_{direct}-P_{repeater} between the direct path and the repeater path over a range of -33 dB. . .33 dB. The UE continuously performs downloads using iPerf [14] while we decrease the power of the direct path by 3 dB every 20 s. The recorded TA values are averaged over each block of 20 s. Assuming reciprocity, the results plotted in Figure 3 correspond to one direction, where ΔTA is the difference between the actual TA and the TA for the reference case without the repeater path. Note that due to

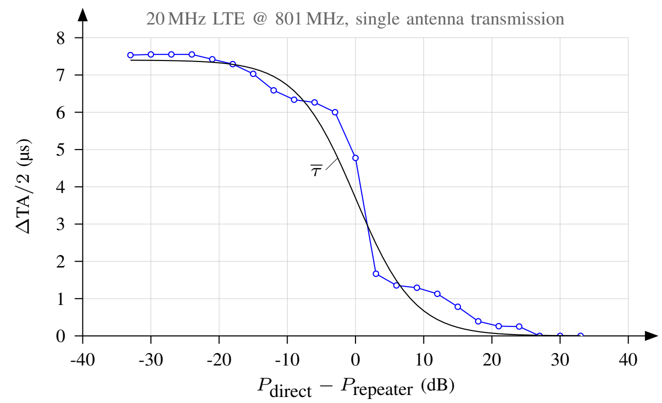


Fig. 3. Measured TA over power difference of the two paths of the two-path model.

the quantization of the TA, the maximum value of $\Delta\text{TA}/2$ is larger than 7.4 µs. The characteristics of the measured curve is very similar to the theoretical mean delay

$$\overline{\tau} = \frac{\int_0^\infty \tau \, |h(\tau)|^2 \, d\tau}{\int_0^\infty |h(\tau)|^2 \, d\tau} \tag{1}$$

of the two-path channel. At power differences exceeding approximately 20 dB, the $\Delta\text{TA}/2$ corresponds to the delay of the dominating path. At smaller power differences, on the other hand, we observe a smooth transition from $\Delta\text{TA}/2 = \tau_{\text{ITR}}$ to $\Delta\text{TA}/2 = 0$ that corresponds to a dominant direct path. We then conclude that in case $\Delta\text{TA}/2$ takes values between zero and τ_{ITR}, a power difference between the two-path and the dominating path can be inferred. A reasonable sensitivity can be reached for –20 . . . 20 dB.

IV. Application in Drive Tests

We analyze our method through a drive test while on board a train equipped with ITRs. The train travels from Wien to Salzburg, Austria. Both, the phones and the BTSs deployed are of the same kind as those in the laboratory.

A. Measurement Setup

The train used for the drive test is a high-speed train, namely, railjet, operated by the National Austrian Railway company ÖBB. It is the same type of train as that in the model in Section II. The train is equipped with ITRs that use radiating cables to supply signals to the users on board the train. The ITR has a delay τ_{ITR} of 7.4 µs, a nominal gain G_0 of 63 dB, and a maximum output power of 25 dBm. During the whole drive test, the UL gain is linked to the DL gain of the ITR. Thus,

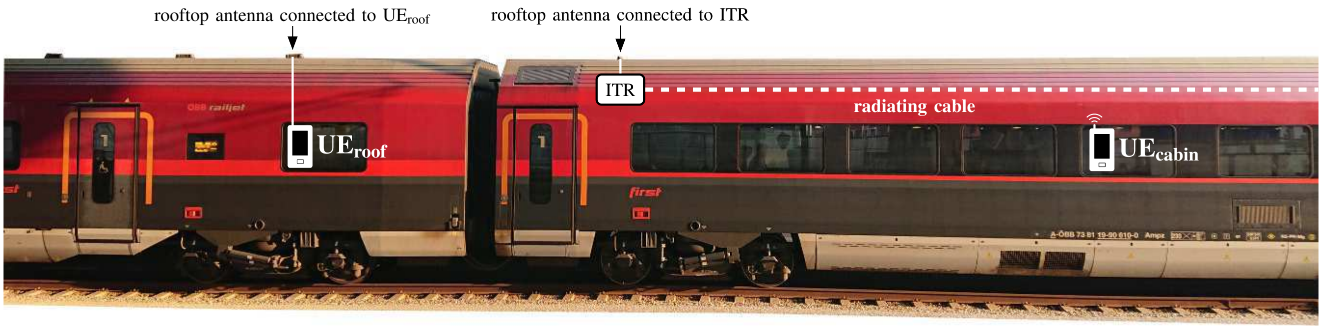


Fig. 4. Setup used to measure at the rooftop antenna of a high-speed train and inside the cabin of the train.

we can assume reciprocity. The measurement setup is shown in Figure 4. We perform measurements with two NEMO measurement phones, UE_{roof} and UE_{cabin}, whereas the UE_{cabin} is placed in a typical location inside a cabin that a passenger would also use. The second measurement phone, UE_{roof}, performs reference measurements and is directly connected to rooftop antennas close to the pick-up antennas of the ITR. Thus, we assume that the UE_{roof} experiences the same channel conditions as the ITR. During the whole drive test, both UEs are locked to the same 20 MHz LTE carrier in the 800 MHz band, and perform continuous upload and download tests.

B. Evaluation

The measurement results have shown that in some regions, the measurement phones were not attached to the same cell. For that reason, we consider only the measurement results from those locations where both UEs were attached to the same cell. To estimate the actual operating state of the ITR, we estimate the input power at the ITR using the received signal strength indicator (RSSI) measured with UE_{roof}. Thus, we consider the presence of a second LTE carrier at 800 MHz band. Assuming that the receive powers in both carriers are equal, the ITR saturates at RSSI values larger than $RSSI_{sat} = P_{sat} - 3\,dB = P_{out,max} - G_0 - 3\,dB = -41\,dBm$.

C. Measurement Results

Figure 5 shows the measurement results from four sections of the railroad track. In all sections, there are regions where $RSSI_{roof}$ exceeds $RSSI_{sat}$; therefore, the ITR saturates. Although we can clearly see in two of the sections that the difference of TA/2 between UE_{roof} and UE_{cabin} drops below the delay of the ITR, this does not happen in the other two sections. The different types of BTS deployment along the railroad track can explain this results:

① The UEs are attached to a remote radio unit (RRU) system inside a tunnel. There, the antennas are mounted at a height that is approximately the height of the train. The large absolute TA is due to the fiber optic cables connecting the RRUs and the BTS. There are repeated drops in the $\Delta TA/2$ at every feeder antenna on the outside, infering a pronounced two path situation in these locations. The $\Delta TA/2$ reaches half the ITR delay, indicating that both paths have the same power.

② The UEs are attached to an outdoor RRU system. Similar to the antennas set up inside the tunnel, the antennas here are mounted close to the railroad track, but at a much higher height. The roof of the train blocks the direct path. Furthermore, the received power on the roof is smaller than that in the tunnel. The repeater path dominates the direct path by far. In this situation there is no extreme case of two path propagation and therefore no degradation in service for the user can be expected.

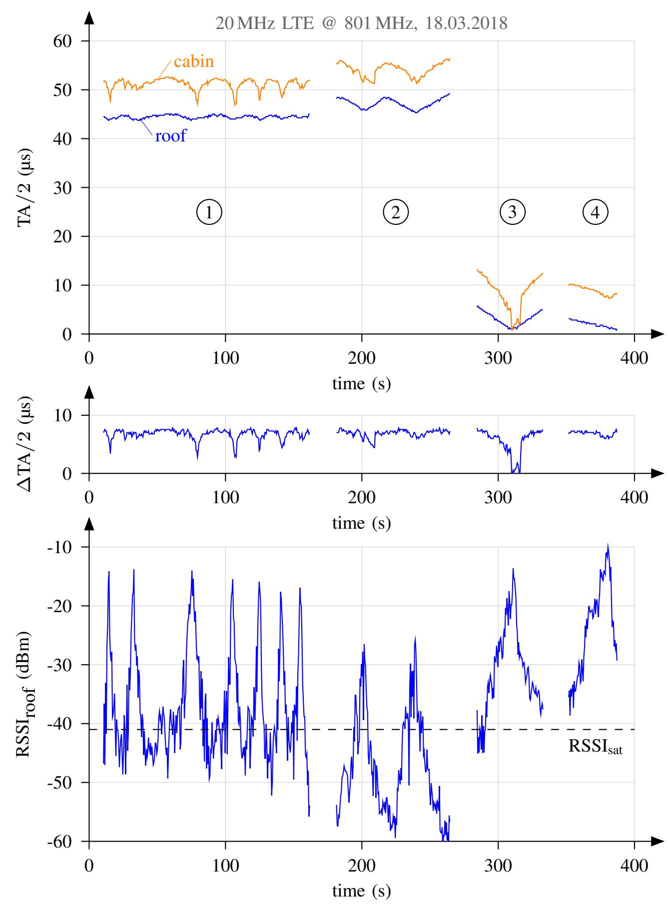


Fig. 5. Measurement results from four sections of the track over time. Top: Absolute TA. Middle: Difference of TA. Bottom: Received signal power on the roof.

③ The difference in TA/2 between UE_{roof} and UE_{cabin} is approximately zero when passing an outdoor macro site. The distance between the BTS and the railroad track is 120 m and the direct path is not blocked. Since the ITR is saturated, the direct path is much stronger than the repeater path.

④ The train is approaching an outdoor macro site 18 m from the railroad track. Although the power on the roof is very high, the desired repeater path dominates, as the direct path is blocked by the roof of the train.

Figure 6 shows the statistics of $\Delta TA/2$ along the whole railroad track and compares the results between the case in which the ITR operates in the linear region ($RSSI_{roof} \leq RSSI_{sat}$) and the case in which the ITR ($RSSI_{roof} > RSSI_{sat}$) is saturated. The theoretical reference curve corresponds to the case of single path transmission through the repeater path. Therefore, we consider the quantization of the TA and assume an equally distributed common delay $\tau_{outdoor}$. We observe that the small difference in $\Delta TA/2$ of the propagation delay is much larger in the case of the saturated ITR than that in the case of the ITR operating in the linear region. The outside situation in case ③ and ④ is such that both generate very high values of $RSSI_{roof}$. However, in ④ the $\Delta TA/2$ indicates that the desired repeater path stays dominant, because of a more suitable positioning of the base station antenna.

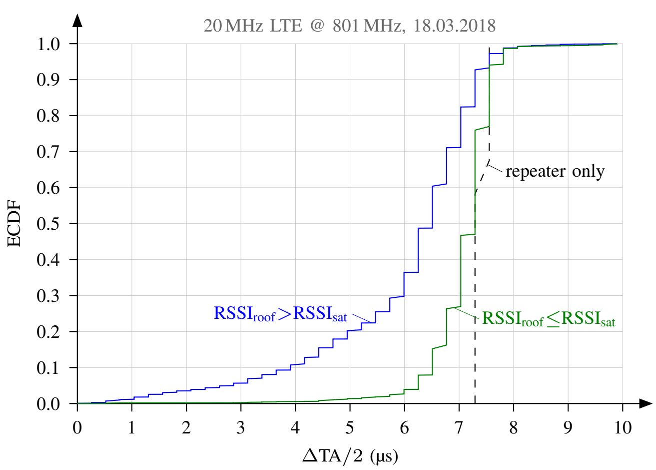


Fig. 6. ECDF of the difference of TA.

V. Conclusions

We introduced a simple measurement methodology that can identify extreme cases of multipath propagation for ITR deployments. The differential analysis of TA measurements allows us to detect the relative power of multipath components in the range of -20. . . 20 dB, as we have verified through the lab measurements. The experimental results for an existing ITR deployment in an express passenger train show that this method can, in fact, be used to pinpoint the specific locations where the interplay between the BTS configuration and the ITR is still not optimal. The method is based on TA measurements, which can be extracted from standard handsets. Therefore, it is possible to use the proposed method and analysis as a way of continuosly collecting measurement points, e.g., by crowdsourcing. This research enables to continually improve the interplay between vehicular repeater deployments and mobile networks.

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