Analysis of LTE in Two-Path Vehicular Repeater Channels

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***Abstract*—In recent years, many public high-speed trains have been upgraded with active in-train repeaters in order to improve mobile service coverage for train passengers. With a repeater in place, the user equipment perceives a wireless channel with a direct path and an indirect path through the repeater delayed by several micro seconds. In vehicular scenarios, the pick-up antenna experiences a wide range of signal levels. Due to the limited output power of the repeater, the paths may arrive with similar power, which can be a problem for OFDM based systems like LTE. Drive tests in LTE have shown that uplink performance degrades, even if the delay stays within the cyclic prefix. In order to gain a better understanding, we conducted a laboratory experiment to measure, quantify, and analyze the impact of two-path channels, with different delays and power levels, onto a live LTE network. Results show uplink performance degradation and increased transmit power even for delays smaller than the cyclic prefix due to non-optimal time-synchronization. In the system under test this degradation already starts at a path power difference of 15 dB and reaches up to 50% at equal path power levels.**

I. Introduction

In recent years, the demand for cellular coverage in challenging scenarios has resulted in a network rollout pushing for denser deployment of cells. Today, even vehicular mass transport solutions, e.g., trains, are supposed to offer mobile service coverage. However, traditional solutions are in conflict with the efforts of thermal isolation. Especially the metal coating of windows poses a significant additional attenuation in the propagation path. One solution is a structured coating of the windows that features a bandpass with low attenuation values for mobile communication, see [1]. In general, this is achieved at the cost of reduced thermal isolation performance. Another state-of-the-art method of addressing this attenuation problem is by using in-train repeaters (ITRs). such repeaters pick up the signal from the train roof, apply digital signal processing, and then amplify and distribute the signal inside the train using a leaky feeder. The pick-up antenna will see a high dynamic of input power levels. As shown in the model [2], such systems comprise of two paths: a direct one through the window and an indirect one through the ITR. The limited output power of the repeater system results in scenarios in which the direct path has a similar or even greater contribution. Figure 1 illustrates an example of an existing ITR deployment, see [2], with the received power of the repeater path in green and the direct path in orange. The additional factor of digital processing delay in the repeater adds a time shift between the two paths, thereby creating a two-path channel (TPC).

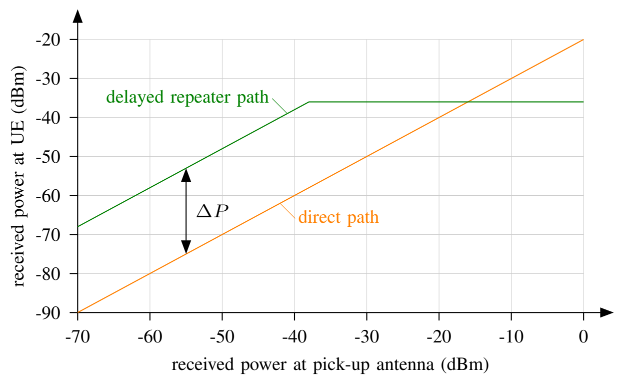

Fig. 1. Two-path propagation in ITR setups. In regions of good coverage, due to the limited output power of the ITR, the power of the direct path may be equally strong or may even exceed the power received through the ITR.

Depending on the configuration of the ITR, the relative path delay can exceed the length of the cyclic prefix (CP) of LTE. e.g., 2.6 µs and 7.4 µs in [2]. Due to the vehicular scenario and the wide range of signal strength values at the pick-up antenna, in combination with the limited power of the repeater, the power difference ΔP between the two paths can strongly vary.

Related Work

Similar channels are observed in single-frequency networks, such as DVB-T, and in remote radio unit (RRU) deployments. See [3], [4] for corresponding channel measurements along railroad tracks. In such deployments, a TPC with equally strong paths and extensive relative path delays is mainly caused by unequal lengths of the fibers connecting the RRUs [5]. The impact of such channels on the performance of WiMAX was analyzed in [6] where a performance degradation for relative path delays smaller than the guard interval is reported.

Our Contribution

We set up a laboratory experiment in a live LTE network in order to understand the interplay of the two limitations of ITR systems, namely, output power and processing delay with an operational LTE system. This enables us to understand the interaction of the physical channel with LTE system procedures, something challenging to consider in simulation tools. We conduct extensive analysis over a wide range of

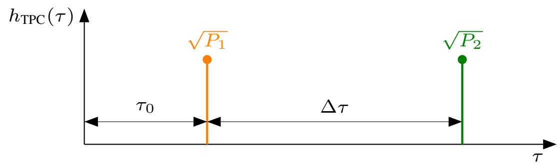

Fig. 2. Impulse response of the TPC. The first path is the direct path, the second path is the path through the repeater.

path power differences and delay differences of the TPC. As expected, due to the limitation of OFDM, the LTE system shows a severe performance degradation if the echo is spaced beyond the CP duration. However, even for values below the CP duration, the system experiences performance losses. The analysis shows uplink (UL) throughput degradation along with an increase of physical uplink shared channel (PUSCH) power. We show that the root cause for both effects is a non-optimal time-synchronization method implemented in the base-station (BTS).

II. Two-Path Vehicular Repeater Channel

In order to analyze the impact of a vehicular repeater on the performance of LTE in the laboratory, we transform the repeater deployment discussed in Section I into a static two-path channel illustrated in Figure 2. The impulse response of the two-path vehicular repeater channel is given by

$$h_{\text{TPC}}(\tau) = \sqrt{P_1} \cdot \delta(\tau - \tau_0) + \sqrt{P_2} \cdot \delta(\tau - \tau_0 - \Delta\tau). \quad (1)$$

There are four parameters. The relative path delay $\Delta\tau$ corresponds to the processing delay of the ITR. The path power P_1 is the power of the direct path, and P_2 is the power of the repeater path. The excess delay τ_0 is necessary to account for the quantized timing advance (TA) used for time-synchronization of the UL and allows for a fair comparison of different channels, see Section III-C.

III. Measurement Setup and Methodology

In order to perform controlled experiments with the TPC where we can independently control each parameter of the channel, we perform our experiments in a laboratory and use channel emulators to implement the TPC. Furthermore, this setup allows to separately evaluate the effects of the TPC in the downlink (DL) and UL direction.

A. Measurement Setup

We perform our experiments with the TPC inside a shielded laboratory using the setup illustrated in Figure 3. It consists of the following components:

- The BTS provides a 20 MHz LTE carrier at 801 MHz and is connected to a live network of an Austrian operator. It is of the same kind as the BTSs the operator deployed in its network. Without loss of generality, the BTS is set to single-antenna transmission. The cabled connection between the BTS and the laboratory setup prevents other user equipments (UEs) from using the BTS. This ensures that all resources are reserved for our UE at any time.
- We use two channel emulators to apply the TPC in the DL and UL direction separately. The two directions are separated by diplexers.
- The UE is a modified NEMO [7] measurement phone with external antenna connectors. Due to the limitation of the setup to one antenna port, we use only the first of the two available antenna ports of the UE. This limitation does not affect UL transmissions as the UE is only capable of transmitting from the first antenna port. In DL direction, the loss of receive diversity is neglectable as noise is not the limiting factor.
- We generate the traffic using a native command-line cross-compiled iPerf [8] version 3.6 for Android with ten parallel TCP/IP flows in UL or DL direction.
- The iPerf server infrastructure features symmetric 5 Gbit/s links to the Internet and is validated not to limit the test results.

The total pathloss of our setup is approximately 88 dB in each direction. This corresponds to a DL reference signal received power (RSRP) of approximately -80 dBm. Thus, we operate the BTS and the UE in a region where the performance is not limited by thermal noise, see [9]. Considering a single path channel and the case where all UL resources are used, the PUSCH power is approximately 8 dBm and therefore in the linear region.

B. Measurement Methodology

In order to separately evaluate the impact of the TPC in the DL and in the UL direction we apply the TPC in the direction under test, and apply a single-path channel $h(\tau) = \delta(\tau)$ with zero-delay and maximum power in the other direction. This methodology is essential for the analysis of the time-synchronization algorithms used by the UE and by the BTS by TA measurements, see Section V. By fixing the channel in one direction, TA measurements solely reflect the time-synchronization method used in the other direction.

C. Quantized Timing Advance

When performing UL measurements, the quantization of the TA used for UL time-synchronization needs to be taken into account. Figure 4 shows the UL throughput and TA measured over excess delay τ_0 with equally strong paths and relative path delays $\Delta\tau$ smaller than the CP duration. For such channels, as explained in Section V, the throughput degradation observed is caused by the way the BTS performs time-synchronization. Then, due to the quantization of the TA, the throughput periodically varies over excess delay τ_0. The period is equivalent to the quantization step size $T_{\text{TA}} = 16/(2048 \cdot 15\,\text{kHz}) \approx 0.52\,\mu\text{s}$ of the reported TA [10]. Thus, measuring at a fixed excess delay τ_0 does not allow for a fair comparison of different channels. That is why we repeat each measurement $N = 5$ times with different excess delays $\tau_0 = n \cdot T_{\text{TA}}/N$, $n = 0 \ldots N-1$ and average the results.

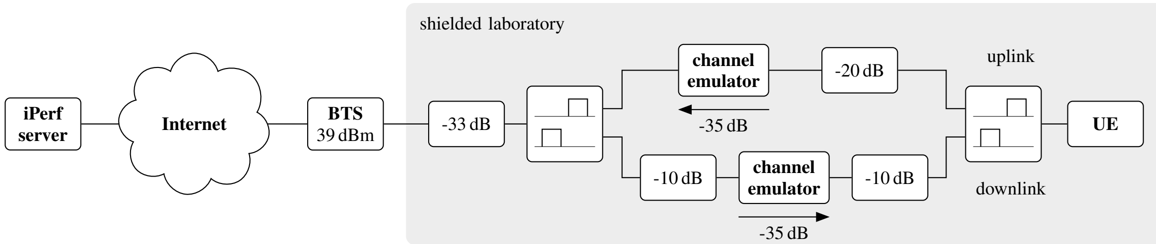

Fig. 3. Measurement setup.

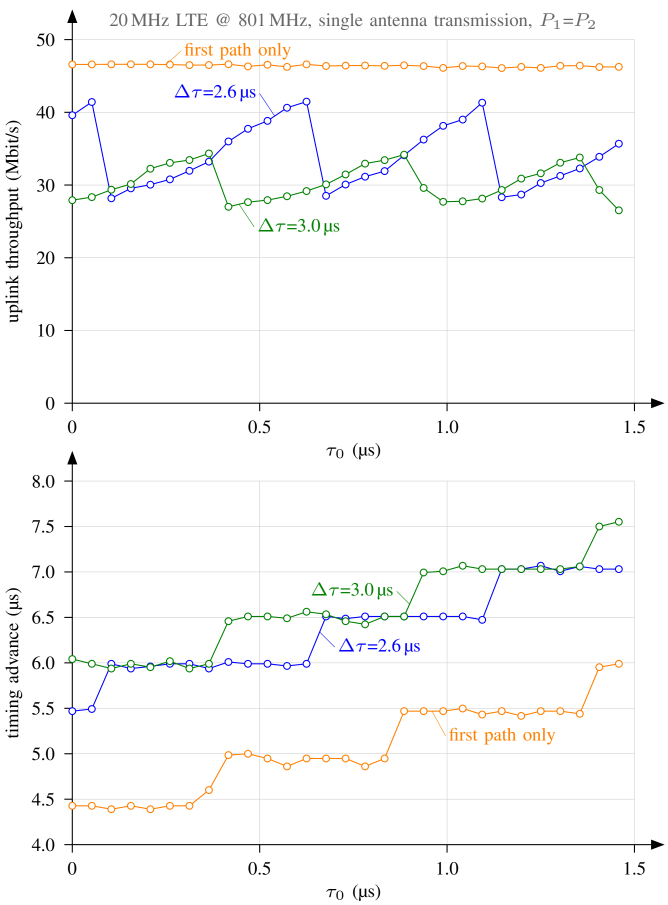

Fig. 4. UL throughput and TA over excess delay τ_0. Due to quantized TA, the throughput depends on the excess delay

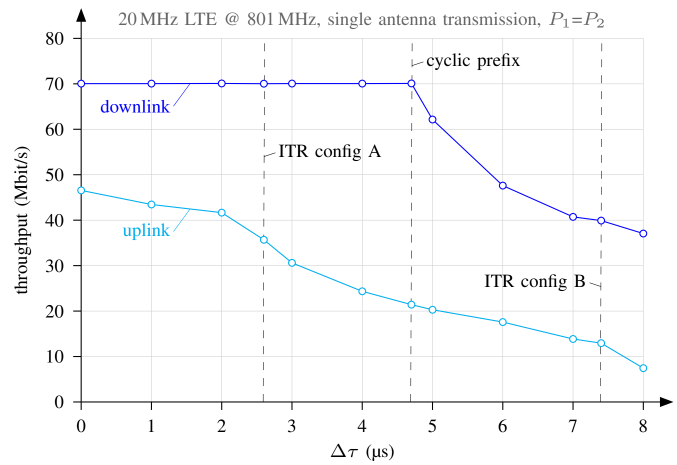

Fig. 5. Throughput for DL and UL transmissions over relative path delay. The delays marked correspond to two possible delays of the ITR in [2].

IV. Measurement Results

In order to analyze the impact of the TPC on the performance of our LTE system, we evaluate the throughput in DL and UL direction. Furthermore, in the UL, we evaluate the PUSCH power. All results are extracted from the NEMO trace file, which features detailed system information of the LTE link, e.g., resource block (RB) usage. Therefore, we require iPerf for stable traffic generation only.

A. Throughput

Figure 5 shows the measured throughput over relative path delay $\Delta\tau$ for equally strong paths ($P_1 = P_2$). In the DL, as expected, we observe a degradation of performance for $\Delta\tau$ exceeding the length of the CP and maximum performance for $\Delta\tau$ smaller than the length of the CP. The characteristic is different for the UL. There, we observe a degradation of performance even for relative path delays smaller than the length of the CP. Note that due to the limitation of the UE to 16-QAM modulation, the maximum throughput in the UL is smaller than in the DL. Figure 6 shows the measured throughput over path power difference $\Delta P = P_1 - P_2$ and for different relative path delays $\Delta\tau$. In the DL, we observe a symmetric throughput degradation over a range of approximately $\Delta P = -15\,\text{dB}\ldots 15\,\text{dB}$. The range decreases with decreasing relative path delay $\Delta\tau$. In the UL we observe a similar characteristic for $\Delta\tau = 7.4\,\mu\text{s}$. For relative path delays smaller than the CP duration, the performance degradation is limited to regions $\Delta P = -15\,\text{dB}\ldots 0\,\text{dB}$ where the second path is equal or stronger than the first path.

B. PUSCH Power

We can observe from the UL transmissions over the TPC that the PUSCH power increased up to the maximum possible power level. Figure 7 shows that this effect is even observed for relative path delays as small as 0.05 µs. Figure 8 shows the measured PUSCH power over path power difference ΔP. The characteristic is similar to the characteristic of the UL throughput. For relative path delays $\Delta\tau$ smaller than the

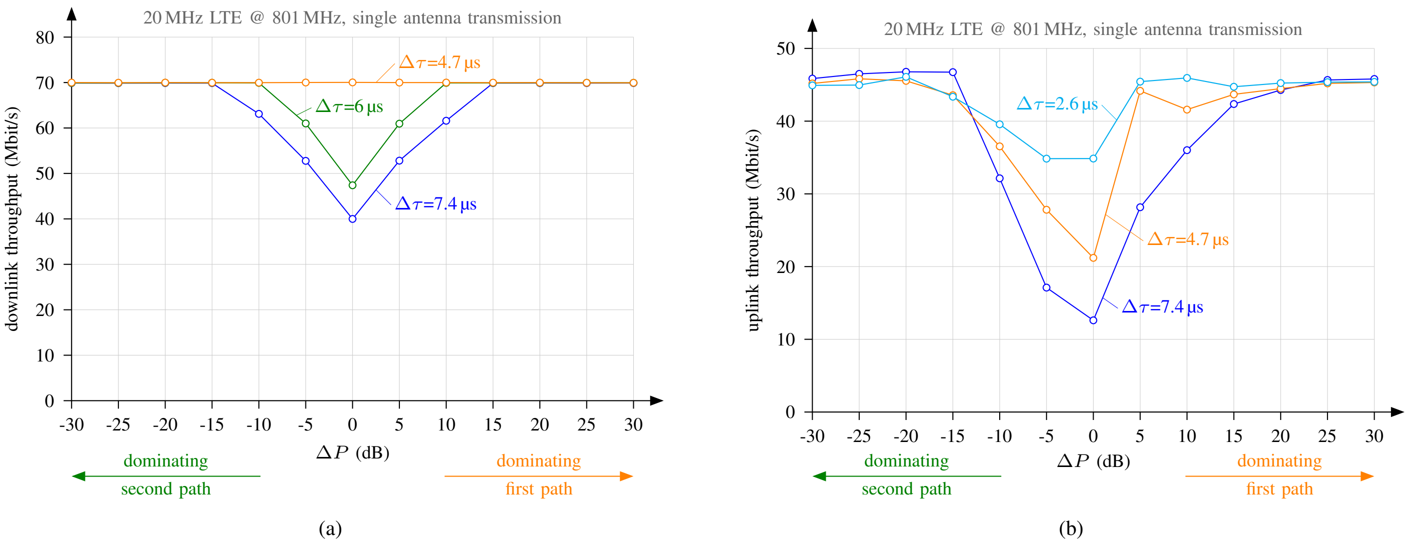

Fig. 6. Throughput over path power difference and relative path delay.

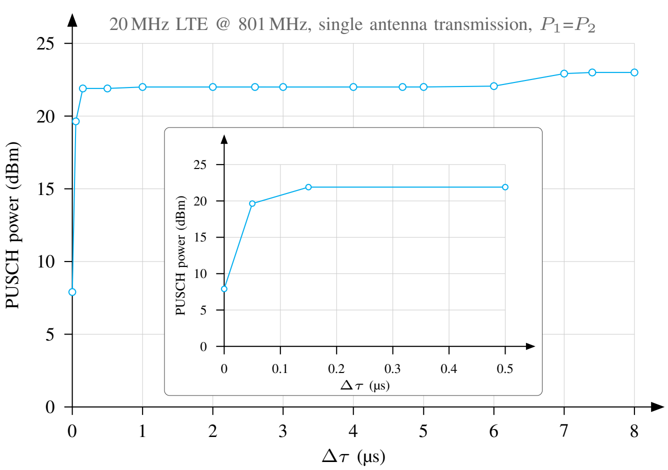

Fig. 7. PUSCH power over relative path delay.

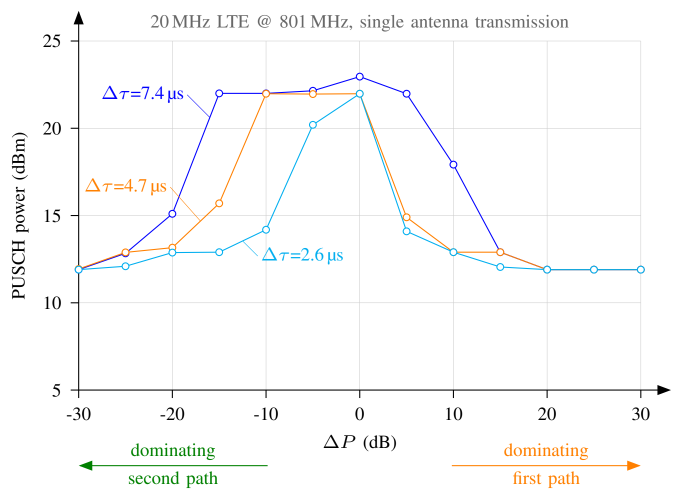

Fig. 8. PUSCH power over path power difference and relative path delay.

CP duration, we observe increased PUSCH power in the region $\Delta P = -15\,\mathrm{dB}\ldots 0\,\mathrm{dB}$ where the second path is equal or stronger than the first path. We kept pathloss and RB usage constant in our experiment, therefore this cannot have caused the observed PUSCH power increase. The increase is caused by the BTS that uses closed-loop power control to achieve a specific target signal-to-interference-plus-noise ratio, indicating an increased interference level at the BTS. In our setup, the interference can only be caused by inter-symbol-interference (ISI) due to insufficient CP [11] or non-optimal time-synchronization. In this case, an increase of transmit signal power at the UE will directly cause the same increase of interference. The BTS, in order to reach the target signal-to-interference ratio (SIR) level, signals the UE to increase transmit power. As signal power and interference are interdependent, this cannot improve the SIR; only the UE transmit power increases.

V. Analysis of Uplink Time-Synchronization

Both effects observed in the UL, decreased throughput and increased PUSCH power, indicate that the BTS experiences ISI even for relative path delays smaller than the CP duration. The cause for this ISI may be the way the BTS performs time-synchronization. This assumption is supported by analysis of the TA commands. Even though we are not able to measure the total round-trip delay of our setup in order to compare it to the reported values of the TA commands, we can compare the TA values for the TPC to the values reported for single-path channels. Figure 9 shows the reported TA values of a TPC with equally strong paths and the TA values for the case when only one of the two paths is active. The plotted values are averaged over approximately 20 s and $N = 5$ different values of excess delay τ_0. The spread of the reported TA values for one measurement point is approximately $T_{\mathrm{TA}} \approx 0.52\,\mu\mathrm{s}$. Over

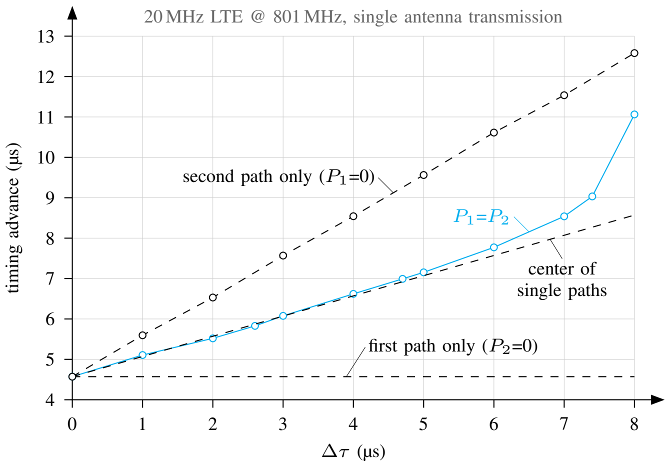

Fig. 9. Reported TA for UL transmissions over the TPC.

a wide range of relative path delays $\Delta\tau$, the TA for the TPC corresponds to approximately the center point of the TAs for the two separately measured paths. This result implies that the BTS synchronizes to the center of the impulse response and the ISI experienced by the BTS is caused by the first path as it arrives too early. Still, without knowledge of the absolute propagation delay, it is not visible if the BTS under test adds a fixed offset to the estimated TA value. For ISI-free reception, the BTS should time-synchronize to the first path as the CP is capable of suppressing ISI due to delayed paths within the length of the CP only. This kind of time-synchronization also explains the non-symmetric characteristics of the UL throughput (Figure 6b) and the PUSCH power (Figure 8). Furthermore, this kind of time-synchronization explains the UL throughput plotted in Figure 4. Due to the quantization of the TA, the ISI decreases with increasing excess delay and sharply increases to the maximum value when the TA is increased to the next step.

VI. Conclusions

From the results obtained, we can conclude that in the DL, the used UE can cope with the TPC for relative path delays smaller than the CP length. That is different for UL transmissions over the TPC. We can see that throughput degraded and PUSCH power increased even for relative path delays smaller than the CP length. For this case, the performance degradation is limited to regions $\Delta P = -15\,\mathrm{dB}\ldots0\,\mathrm{dB}$ where the second path is equal or stronger than the first path. Both effects, the reduced throughput and the increased PUSCH power that causes the cell to shrink, severely degrade the quality of LTE networks. We can deduct several implications from these results on vehicular repeater scenarios. First, the repeater path is required to stay substantially above the direct path, e.g., 15 dB. That requires either a sufficient shielding of the vehicular cabin, e.g., high window penetration loss, or a high repeater gain. The repeater gain can only persist constant if the repeater operates below its maximum output power. That might not be possible near a BTS. Therefore, also the track side deployment needs to be considered, see [12]. Second, the excess delay in a vehicular scenario will continuously change depending on the distance between the vehicle and BTS. This alone causes a change in performance due to the quantization of time-synchronization in LTE. Therefore, drive tests in real world scenarios are not suitable for a fair comparison of different repeater configurations. Third, any reduction of the digital processing delay of the ITR improves the performance. However, in order to reach maximum UL performance in sub CP cases, the design of the time-synchronization at the BTS must not cause any ISI.

Acknowledgments

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