QUANTIFYING THE REPEATABILITY OF WIRELESS CHANNELS BY QUANTIZED CHANNEL STATE INFORMATION

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ABSTRACT

Repeatability is the prerequisite for scientific evaluation of wireless measurements. However, in real-world scenarios, the channel always slightly changes with time as, for example, trees move in the wind. In this paper, we propose a methodology that uses quantized channel state information and a technique similar to non-substractive SNR-dithering to quantify the repeatablility of wireless channels. Thereby, we introduce a new metric that allows for a comparison of different setups and scenarios in terms of repeatability. In a measurement campaign, we compare (1) a directional link to (2) an outdoor to indoor urban scenario with a fixed receiver and (3) the same scenario with the receiver moving in a circle, thereby experiencing the same high speed channel again and again.

1. INTRODUCTION

"Being able to repeat experiments is considered a hallmark of the scientific method, used to confirm or refute hypotheses and previously obtained results" [1]. The authors of [2] provide a broad overview of topics arising in the context of repeatable experiments in the field of wireless research. Such experiments include but are not limited to comparing different transmit modes at different values of Signal-to-Noise Ratio (SNR) [3,4], the experimental evaluation of MIMO handsets [5], the experimental evaluation of the coexistence of different mobile standards [6], experimental evaluation of multiuser beamforming [7] and certain channel sounding techniques [8,9].

Repeatability[1] of wireless transmissions requires the channel to be time invariant over repetitions. Time invariant channels are commonly referred to as static. Even if the receiver might not be fixed at a certain position, time invariant channels are realizable by sampling of periodic movements at the same point within the fundamental period. System theory names this *lifting* of time periodic systems [11–13].

In order to analyze the repeatability of wireless channels and especially, to compare different scenarios in terms of channel repeatability, we consider the approach illustrated in Figure 1.

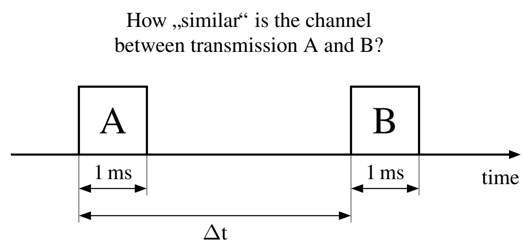

Fig. 1. Motivation.

We compare the Channel State Information (CSI) obtained through the transmission of a single 3GPP Long Term Evolution (LTE) downlink [14] subframe A to the CSI obtained through the transmission of an equal subframe B. Thereby, full CSI is given by the combination of the estimated channel matrix $\widehat{\mathbf{H}}$ and the estimated noise power $\widehat{\sigma}_z^2$ while the Channel Quality Indicator (CQI) reflects CSI in a quantized way. The actual type of CSI that is available depends on the application and the implementation of the LTE receiver. In contrast to lifting, within our LTE system, we do not sample at one point. The LTE subframes we measure extend over 1 ms. Thus, we investigate time invariance of the channel quality captured by the change of the CSI.

Contribution and outline

In this contribution, we propose a new metric to quantify the repeatability of wireless channels based on the CQI and introduce a technique similar to non-subtractive dithering [15] to overcome the quantized nature of the CQI. After introducing this new metric in Section 2, we use it in a measurement

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[1] repeatability…"The closeness of agreement between independent results obtained with the same method on identical test material, under the same conditions (same operator, same apparatus, same laboratory and after short intervals of time)" [10]

campaign described in Section 3, where we compare different scenarios in terms of repeatability of channels. The results are compared to a metric that uses full CSI. Finally, we conclude our findings in Section 4 and highlight further research questions.

2. THE $\mathrm{CQI}_{\neq}$ METRIC

In LTE, the CQI is used to report CSI to the transmitter in order to adapt the transmit signal to the actual channel state. In the Vienna LTE Link Level Simulator [16, 17], the LTE implementation of this work, the CQI is calculated by first mapping the actual channel state to the equivalent AWGN channel and then determing the CQI for the equivalent AWGN channel [18]. This mapping, as well as the quantized characteristics of the CQI, is illustrated in Figure 2.

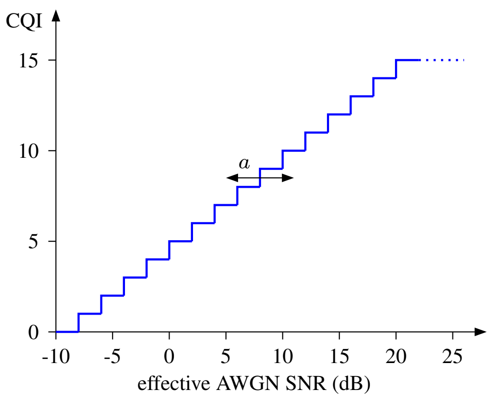


Fig. 2. Schematic relation between the CQI and the SNR for a frequency-flat AWGN channel.

Plotted over received SNR, the actual slope and the SNR step size depend on the actual channel charateristics and the receiver implementation. In order to capture channel fluctuations between two transmissions based on the CQI we introduce the $\mathrm{CQI}_{\neq}$ metric

$$\mathrm{CQI}_{\neq} = \begin{cases} 0, & \mathrm{CQI}_{\mathrm{A}} = \mathrm{CQI}_{\mathrm{B}} \\ 1, & \mathrm{CQI}_{\mathrm{A}} \neq \mathrm{CQI}_{\mathrm{B}} \end{cases}. \quad (1)$$

Due to the quantized characteristics of the CQI, the sensitivity of this metric depends on the actual effective AWGN SNR and therefore on the characteristics of the underlying channel and the noise power.

In order to overcome CQI quantization we propose a method similar to non-subtractive dithering. Thereby, we vary the estimated noise power $\widehat{\sigma}_z^2$ passed to the CQI calculation within a certain range of a factor a. This scaling of the noise power corresponds to a shift of the CQI characteristics in Figure 2. In this work, we randomize a uniformly distributed within a range of -1.5 dB...1.5 dB [19]. The whole procedure to calculate the $\mathrm{CQI}_{\neq}$ metric is illustrated in Figure 3. There-

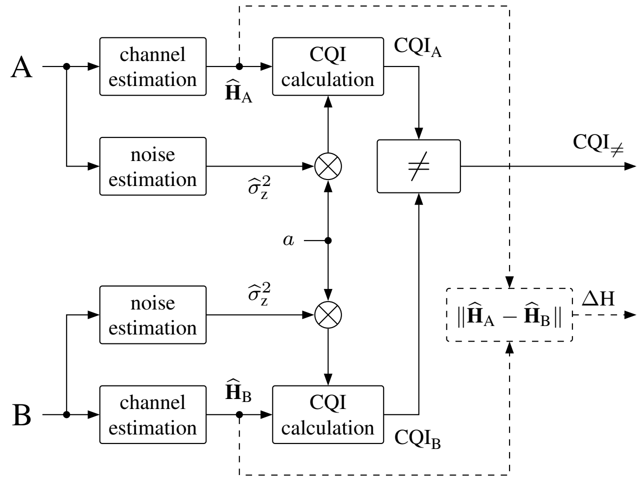


Fig. 3. Calculation of the $\mathrm{CQI}_{\neq}$ metric.

by, for each set of channel estimates $\widehat{\mathbf{H}}_{\mathrm{A}}$ and $\widehat{\mathbf{H}}_{\mathrm{B}}$, the calculation of $\mathrm{CQI}_{\neq}$ is repeated for every value of a. The results are then averaged over all measurements with the same time interval Δt between two consecutive transmissions. Note, that the actual SNR is left unchanged and therefore the impact of noise is independent of a.

3. MEASUREMENTS

In a measurement campaign, we use the proposed $\mathrm{CQI}_{\neq}$ metric to compare different scenarios in terms of repeatability of wireless channels. These measurements were performed at TU Wien in downtown Vienna by the Vienna MIMO testbed [20]. Thereby, we compared a directional link, a fixed indoor receiver and a fast moving indoor receiver. On the transmitter side, we use for all scenarios the same off-the-shelf sector antenna located on a rooftop location, see Figure 4.

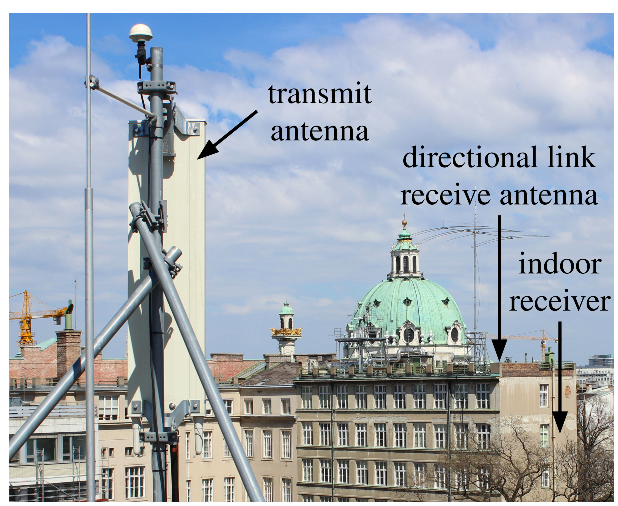


Fig. 4. Measurement setup.

3.1. Directional link

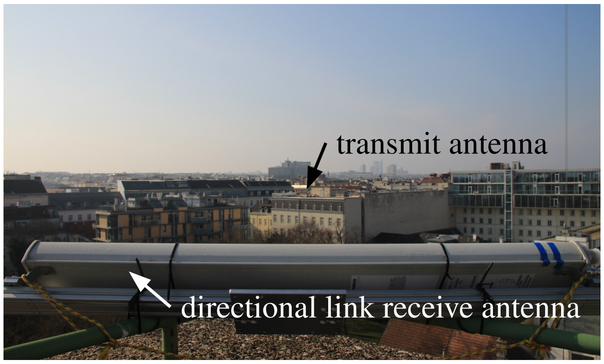


Fig. 5. Setup for the directional link measurement in downtown Vienna, Austria. The receive antenna is mounted on a rooftop opposite the building the transmitter is located.

In order to generate a static baseline scenario where slowly time-varying reflections from the surrounding area are suppressed, we setup an outdoor-to-outdoor directional link. Therefore, at the receiver side, we use an antenna similar to the transmit antenna but mounted 90° rotated and tilted upwards as shown in Figure 5. Reflections from the surrounding buildings are suppressed due to the rather small horizontal beamwidth of about 10° while reflections from the ground are suppressed by the uptilt of the antenna. The $CQI_{\neq}$ metrics retrieved from this measurement plotted in Figure 6 are independent of the time interval between consecutive transmissions and reflect the properties of a directional link. Simulations show, that the fluctuations in the results are due to noise only.

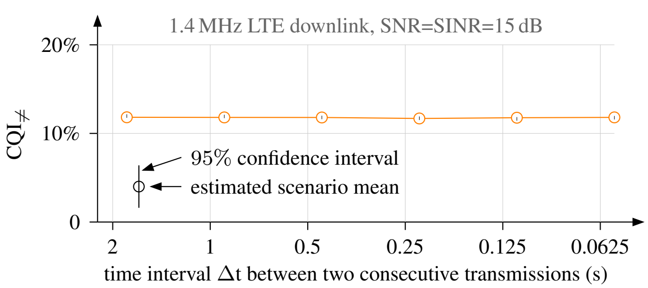


Fig. 6. Results for the directional link.

3.2. Fixed receiver

In this scenario, we measure the outdoor-to-indoor scenario of the fast moving receiver scenario described in Section 3.3 but without actually moving the receive antenna. Thereby, the receiver is located in an unpopulated office building opposite the building the transmit antenna is mounted on. In between, there is a courtyard with several trees. The measurements were performed in the evening on December 24th, 2015, at a wind speed of 10 km/h.

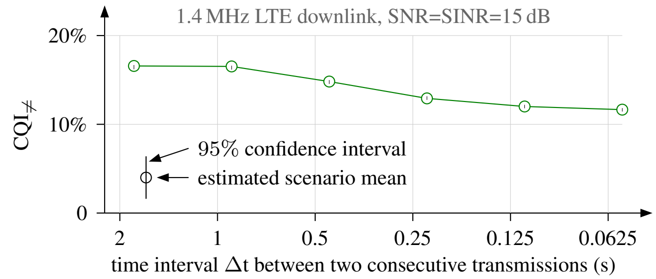


Fig. 7. Results for the fixed receiver.

For small Δt, we see results similar to the results for the directional link. With increasing time between two consecutive transmissions, the channel fluctuations increase caused by a slowly changing environment, e.g. trees moving in the wind.

3.3. Fast moving receiver

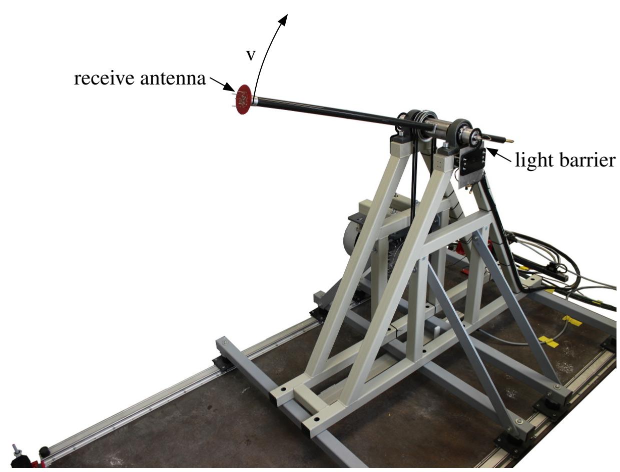
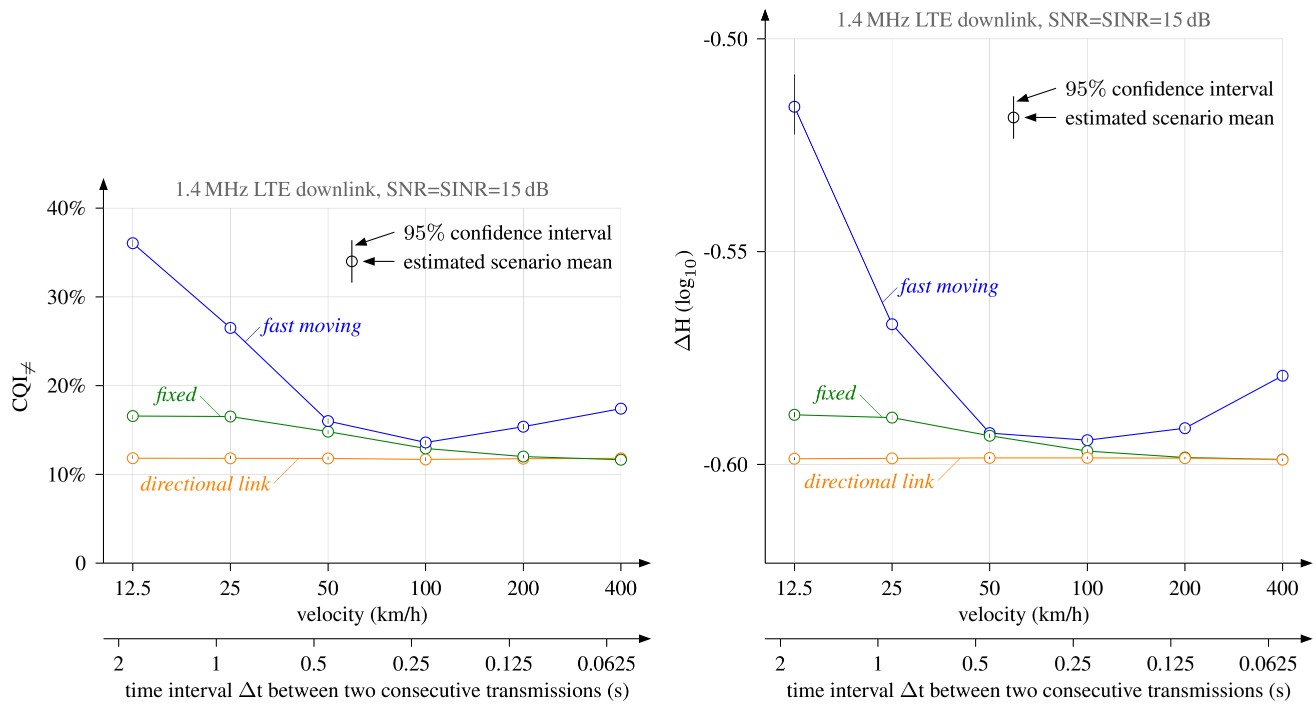


Fig. 8. The rotary unit, located indoors, generates time-variant channels by rotating the receive antenna around a central pivot.

The rotary unit [21–25] shown in Figure 8 generates repeatable time-variant channels by rotating the receive antenna around a central pivot. The received signals are then fed through the rod and rotary joints mounted inside the axis to the receiver hardware. A light barrier mounted on the axis captures the start of each turn and triggers the signal transmission. Thereby, the actual velocity and therefore the roundtrip time of the antenna determines the minimum time interval between two consecutive transmissions over the same channel. For the maximum velocity of 400 km/h this time interval is ≈56 ms. In order to compare the fast moving receiver to the other scenarios, the time intervals for these measurements were chosen such that they correspond to the velocities in the measurement of the fast moving receiver.



(a) (b)

Fig. 9. Results in terms of (a) $\mathrm{CQI}_{\neq}$ and (b) $\Delta\mathrm{H}$. The axis were scaled such that they allow for a qualitative comparison.

A comparison of the results for the fast moving receiver and the results for the other scenarios is given by Figure 9a. We observe, that for velocities above 50 km/h, our fast moving receiver is able to accurately reproduce a fast fading channel. Simulations with equal channels and different thermal noise show that the slight increase in the $\mathrm{CQI}_{\neq}$ metric at very high velocities is only the result of an increase in channel diversity. On the other hand, for velocities below 50 km/h, the variable-frequency drive powering the AC motor is not able to move the receive antenna at a constant velocity anymore, thus the channel cannot be repeated precisely anymore.

3.4. Channel distance metric

Finally, we compare the measurement results in terms of the $\mathrm{CQI}_{\neq}$ metric to results obtained through evaluation of unquantized channel information. We therefore define the channel distance as the relative average distance between two channel estimates in terms of the Frobenius norm[2]

$$\Delta\mathrm{H} = \frac{\|\widehat{\mathbf{H}}_\mathrm{A} - \widehat{\mathbf{H}}_\mathrm{B}\|_\mathrm{F}}{\sqrt{\|\widehat{\mathbf{H}}_\mathrm{A}\|_\mathrm{F} \cdot \|\widehat{\mathbf{H}}_\mathrm{B}\|_\mathrm{F}}}. \qquad (2)$$

Thereby, $\Delta\mathrm{H}$ considers differences in the magnitude as well as differences in the phase of the channel estimates. This means in turn, that in contrast to the $\mathrm{CQI}_{\neq}$ metric, this metric is only applicable on measurements performed with phase synchronized equipment or if knowledge of the actual phase difference between the transmitter and the receiver is available. We use the latter approach by simultaneously measuring a reference phase over the directional link and phase-shift the channel estimates obtained from the receive antennas under investigation by this reference phase. Comparing the results plotted in Figure 9b to the results in terms of the $\mathrm{CQI}_{\neq}$ metric in Figure 9a, we find a qualitative accordance between the results based on full CSI and the results in terms of the $\mathrm{CQI}_{\neq}$ metric that is based on quantized CSI.

[2] $\|\mathbf{H}\|_\mathrm{F} := \sqrt{\mathrm{trace}(\mathbf{H}^H\mathbf{H})}$

4. DISCUSSION AND CONCLUSIONS

The proposed $\mathrm{CQI}_{\neq}$ metric together with the underlying methodology allows to quantify the repeatability of wireless channels based on quantized channel state information. Performance bounds of the proposed method along with the optimal SNR-based dithering are still subject to future research and investigating the influence of interference. The replacement of SNR dithering with dithering through statistical dispersion of receiver hardware, for example, imperfections from off-the-shelf cell phones, is currently under research. The conducted measurement campaign verifies the applicability of the proposed method.

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