with soft information from the likelihood and the linearization method coincide. The TSA is furthermore a MVU estimator since the RMSE approaches the CRLB for all SNRs and for all positions. The WLS method performs worse: There is a certain gap between the CRLB and the RMSE. In Fig. 6(b) it can be observed that this gap depends on the position and, thus, on the GDOP: The larger the GDOP is, the larger is the gap. Hence, the gap between RMSE and CRLB in Fig. 6(a) is smaller for the second scenario (“S”) since the GDOP is smaller on average. For the two path channels, a similar behavior of the WLS method was observed. Therefore, only the results for the TSA are considered in the following due to its superior performance.

The third and fourth row of Fig. 6 show the simulation results for the two path channels with large and small excess delay, respectively. It was observed in Sec. IV-B that the likelihood method is generally accurate even for multipath channels. In contrast, the accuracy of the linearization method depends on the excess delay and the SNR. The smaller the excess delay, the higher is the nonlinearity of the problem and the less accurate is the linearization method. The accuracy increases with SNR. Hence, it is supposed that the likelihood method outperforms the linearization method. Only at very high SNR both methods are assumed to perform equally well. Surprisingly, the linearization and the likelihood method show approximately the same performance for all cases. The linearization method performs even slightly better in most cases. Only for very low SNR and a small excess delay the likelihood method outperforms the linearization method. The likelihood method seems to be more susceptible to the GDOP. Hence, the inaccuracy of the covariance matrices at low SNR barely influences the positioning accuracy. Actually, it seems that the absolute value of the weights in the weighting matrices $W$ and $W'$ is not crucial. Rather a correct ratio of the weights is relevant. Thus, rough soft information is sufficient as long as the ratio of the pseudo-range variances is accurate. This is fulfilled even for the inaccurate covariance matrices of the linearization method. Hence, it is suggested to apply the linearization method because of its lower computational complexity.

For the two path channel with large excess delay (Fig. 6(e)-6(f)) the RMSE with or without soft information is almost the same since the multipath components can already be separated by the estimator quite well. For a small excess delay (Fig. 6(g)-6(h)) the RMSE with soft information is much closer to the CRLB than without soft information. With respect to SNR a gain of approximately 7-10 dB is achieved (see Fig. 6(g)). Furthermore, positioning with soft information is less susceptible to the GDOP (see Fig. 6(h)). Thus, soft information is well suited to mitigate severe multipath propagation. The smaller the excess delay is, the more important it is to apply soft information for positioning.

The influence of the GDOP can be neglected for the scenario with small average GDOP. The curves labeled with “S” indicate that even for one-shot estimation without oversampling a positioning accuracy much smaller than the distance corresponding to the symbol duration, $d_s$, is achieved for all channel models.

For all simulations a LOS path has been assumed so far. Hence, the estimated TOA corresponds to distance between transmitter and receiver. However, in urban or indoor environments the LOS path is often blocked as already mentioned in Sec. II-A. Therefore, the influence of NLOS propagation is discussed here. In case of NLOS a modeling error is introduced that reduces the positioning accuracy significantly. The proposed soft channel parameter estimator does not take a priori information about the physical channel (e.g. probability of NLOS) into account and, hence, is not able to detect such a modeling error. The obtained soft information can only be used to mitigate multipath propagation. In order to mitigate NLOS effects further processing has to be done (e.g. [24]).

Nevertheless, multipath mitigation is an important issue. The multipath mitigation ability of the proposed soft channel parameter estimation has been presented for $M = 2$ paths due to clarity and simplicity reasons. The influence of the number of multipath components is as follows: The complexity of the soft channel parameter estimator increases with the number of multipath components. Furthermore, the reliability of the estimates decreases with $M$. Hence, the positioning accuracy deteriorates. If $M$ is large and the scatterers are closely spaced (dense multipath), the estimator becomes biased and the positioning accuracy saturates. In general, it is suggested to consider only the dominant paths if $M$ is large.

It was mentioned before that the TSA may diverge. Divergence occurred for large GDOP when the initial guess was far from the true position. This happened only rarely. The initial guess is determined by the WLS method which is very susceptible to the GDOP. Hence, the starting position may be far away from the true position for large GDOP.

As mentioned in Sec. II-B PSO does not assure global convergence. For both two path channels PSO sometimes converges prematurely. In most of these cases it converges to a boundary of the search space, such that the premature convergence can be detected (outage). In Fig. 7 the outage rates are shown for both path channels: The dashed lines (i) and (iii) denote the probability that the delay estimation fails for one RO and the solid lines (ii) and (iv) denote the

\[^9\text{The outliers due to divergence were not considered in the calculation of the RMSE.}\]