Channel Measurement Data Based Performance Evaluation of Coded Space-Time SC-MMSE MIMO Turbo Equalization

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Abstract— **Coded space-time soft cancellation minimum mean squared error filtering (CST SC-MMSE) based turbo equalization, which exploits transmit diversity and coding gains through two turbo iteration loops, horizontal and vertical iterations, has been introduced in [1] for uplink single carrier signaling. In this paper, performance of the CST SC-MMSE equalizer is evaluated in realistic scenarios using multi-dimensional channel measurement data. Measurement data consists of snapshots measured in different channel conditions in terms of spatial and temporal properties. It is shown that the CST SC-MMSE equalizer can achieve excellent performance even at the lower SNR range due to the vertical iterations between the decoders that can achieve a coding gain on top of the diversity gain. However, performance depends on channel conditions. The impact of the horizontal and vertical iterations is studied in different channel conditions.**

Index Terms— **channel measurement data, single carrier signaling, turbo equalization, turbo iterations,**

I. Introduction

Single carrier broadband signaling is subjected to severe inter-symbol-interference (ISI) due to multipath propagation. However, such hostility in propagation media can conversely be utilized to enhance performance by using an equalizer that can exploit the path diversity combining the path energies while efficiently compensating ISI distortion. A promising technique that can meet this requirement is turbo equalization, which has been intensively studied recently e.g. in [2]-[5]. One of the most credible complexity-reduced versions is soft cancellation minimum mean squared error filtering (SC-MMSE) -based turbo equalization [6],[7], and its modifications [8],[9],[10].

Besides the path diversity, transmit diversity as well as coding gain can be exploited by using coded space-time SC-MMSE (CST SC-MMSE) turbo equalization, proposed in [1]. It is shown in [1] that the CST SC-MMSE equalizer can achieve excellent performance due two turbo iteration loops: *horizontal* and *vertical* iterations.

Recently, importance as well as feasibility of the channel measurement data- based simulations in realistic performance evaluations has been recognized. Performance of the SC-MMSE MIMO turbo equalizer is evaluated using channel measurement data, e.g. in [11],[12],[13]. The main objective of this paper is to evaluate realistic performance of the CST SC-MMSE equalizer in different channel conditions. Impact of the horizontal and vertical iteration gains is studied as well. Furthermore, performance variations in the measurement route are examined by studying cumulative distribution functions (CDF) of the BER performance. CDFs are also used to make assessments for probabilities to achieve certain target BER. Single user as well as multiuser cases are considered.

This paper is organized as follows: Section II presents the system model of the CST SC-MMSE equalizer. In Section III, channel measurement data used for the simulations is presented. Performance of the CST SC-MMSE equalizer is evaluated in different channel conditions in Section IV. Conclusions are given in Section V.

II. SYSTEM MODEL FOR ST Coded SC-MMSE

A transmitter-receiver (Tx-Rx) block diagram of the ST SC-MMSE turbo equalizer is presented in Fig. 1. For the simplicity of the figure, number of transmit branches N is assumed to be 2. In the Tx, information bit stream is fed into 2 branches, where encoding E_i and interleaving Π_i are performed independently of i=1,2. There is another interleaver Π_0 between the first and second branches. The encoded symbols from the two Tx branches are transmitted simultaneously over the frequency selective fading channel.

The receiver, which is equipped with M antennas, consists of the common MIMO SC-MMSE part and N SfISfO decoder branches. In Fig. 1, there are two types of lines, solid and dashed, indicating different connections between the common SC-MMSE equalizer and SfISfO decoders. First, SC-MMSE iterations for equalization take place independently via the connection shown by the solid line. This process is referred to as *horizontal iteration.* After the *horizontal iteration*s, obtained log-likelihood ratios (LLR) are further propagated between the decoders via the interleaver Π_0 and the deinterleaver Π_0^{-1}. This process, indicated by dashed lines in Fig.1, is referred to as *vertical iteration.* Vertical iterations provide additional coding

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gain over diversity gain achieved by the horizontal iterations. Details for the algorithm can be found in [1].

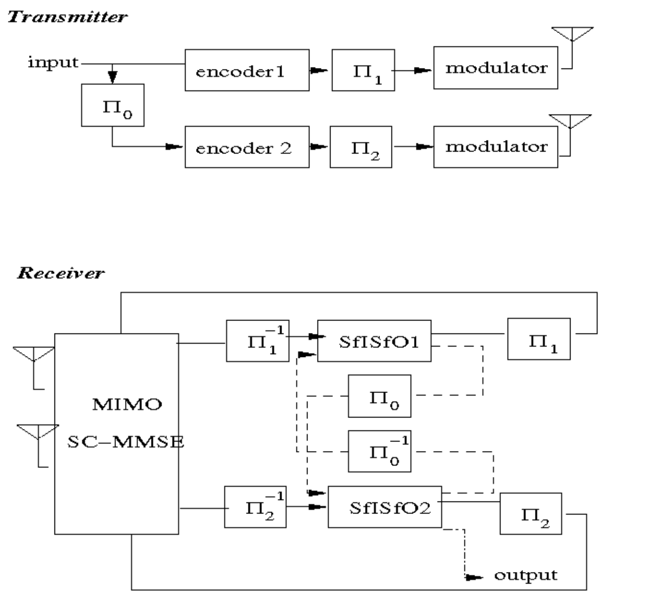

Fig.1. Transmitter-receiver block diagram of the CST SC-MMSE turbo equalizer.

III. MEASUREMENT DATA

The measurement data used for performance evaluations was collected in a courtyard at the campus of Ilmenau University of Technology and is released by MEDAV in [14]. Fig. 2 depicts the map and dimensions of the yard and the measurement route. The place was surrounded by 15m high buildings and some metal objects were located in the area, by which the area is multipath-rich. Thus, many signal reflections occurred. The transmitter antenna, an omnidirectional 16 element uniform circular array (UCA), located at the height of 2.1 m, moved along the route marked by a dashed line. An 8-element uniform linear array (ULA) was used as a receiver antenna, and it was fixed at a height of 1.67 m.

The measurement route is divided into 3 different regions: *static* non-line-of-sight (SNLOS), where Tx was held still, *dynamic* NLOS (DNLOS), where Tx moved at constant velocity, and line-of-sight (LOS), where Tx moved as well. The total number of the measurement snapshots is 108, of which 1:16 belong to SNLOS, 17:51 to DNLOS, and 52:108 to LOS regions. The regions have different propagation conditions, as noted in Fig.3 [12], which presents direction of arrival (RMS Rx azimuth) and direction of departure (RMS Tx azimuth) spreads.

The measurements were performed at 5.2 GHz carrier frequency with a bandwidth of 120 MHz. The measurement data was pre-processed to match the system requirements before using it in the simulations as described in detail in [13].

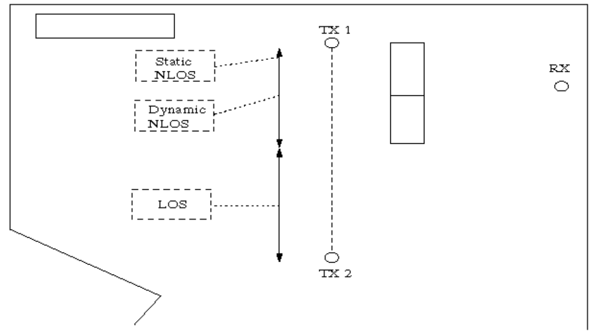

Fig. 2 The map of the MIMO measurement route.

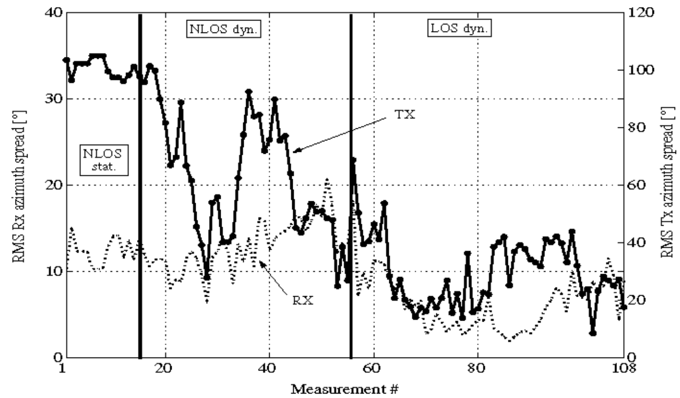

Fig. 3 RMS Rx and Tx azimuth spreads for the measurement route.

IV. PERFORMANCE RESULTS

Performance of the CST SC-MMSE equalizer is evaluated first in a single-user case. In the simulations, a ½ rate convolutional code with code polynomial [5 7] and constraint length of 3 was used. Binary Phase Shift Keying (BPSK) was the modulation format and the interleavers were random. The frame length was 2048. Numbers of transmitter antennas (N) and receiver antennas (M) were assumed to be 2. Symbol rate 20Msymb/s was assumed. The measurement data channel impulse responses were normalized so that in average, the energy in each of the Tx-Rx link is one within each snapshot. The length of the equalization window was 9 and only the most significant taps of the impulse response (the taps whose energy is maximum 10dB below the energy of the strongest tap) was taken into account. The scheduling of the horizontal and vertical iterations should make significant impact on performance, which is detailed in [1]. However, in this paper, the numbers for *horizontal* iterations (HI) was selected to be 4 and for *vertical* iterations (VI) 8.

First, averaged bit-error-rate (BER) versus signal-to-noise-ratio (SNR) is presented separately for SNLOS, DNLOS, and LOS regions in Fig. 4a, Fig.4b, and Fig.4c, respectively. SNR is defined per Tx-Rx antenna pair and, thus, it excludes the SNR gain from multiple Rx and Tx antennas. The curves resulted from the HI:s (solid lines) and VI:s (dashed lines) are shown. The curve with the last HI (-o-) is used as a reference in order to evaluate the gain obtained from the vertical iterations. It is found that within the simulated SNR range, the average horizontal iteration gain is minor especially in the LOS region. In the SNLOS and DNLOS regions, the HI-gain saturates after the 2^{nd} iteration and it is less than 1dB. Instead, the average vertical iteration gain is remarkable in all the regions. In the SNLOS and DNLOS regions, the VI gain saturates after the 4^{th} iteration, whereas in the LOS region after the 6^{th} iteration. Furthermore, the relative impact of vertical iterations is highest in the LOS region: the BER difference after the first VI and last VI is over 2 dB, whereas in the SNLOS and DNLOS regions the difference is around 1 dB. Fig. 4d presents the BER averaged over the whole measurement route. On average, the horizontal iteration gain is very minor but the impact of the first three vertical iterations is remarkable.

It is known from the literature [11],[12],[13], that the gain obtained from the horizontal iterations (i.e. normal SC-MMSE iterations) can be significant especially at higher SNR values. However, the vertical iteration gain is found to be superior even at the lower SNR range, which proves the efficiency of the novel receiver structure.

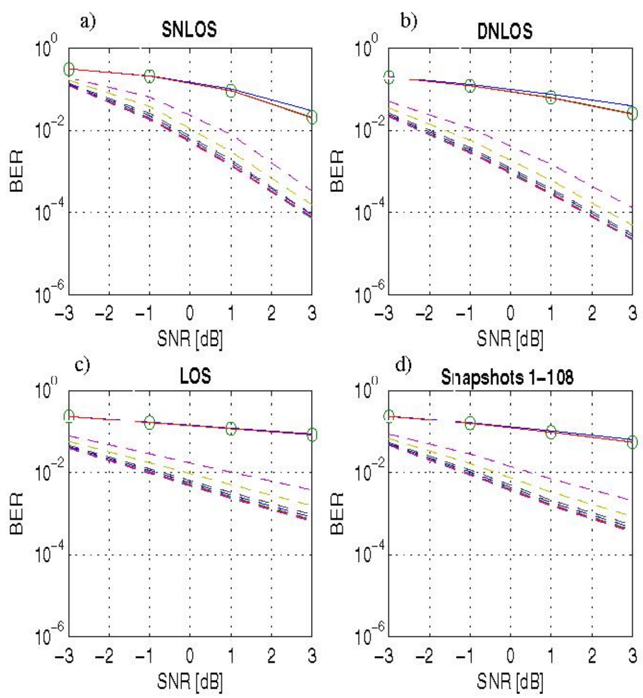

Fig.4. Averaged BER of the CST-SCMMSE turbo equalizer in SNLOS (a), DNLOS (b), and LOS (c) regions, as well as in the whole measurement route (d) with the HI:s (solid) and with VI:s (dashed). As a reference (-o-), performance obtained after the last horizontal iteration.

Next, performance dependency on the propagation conditions is studied more in detail by regarding the BER obtained after the last vertical iteration in the measurement snapshots as is shown in Fig. 5 (dashed line). As a reference, BER after the horizontal iterations (solid lines) is also shown. For clarity of the figure, BER curves are smoothed by averaging over two consecutive snapshots. SNR is fixed at 3 dB. It is noted that the performance tendency is largely affected by the propagation conditions shown in Fig. 3: In the SNLOS region, where Tx and Rx azimuth spreads are relatively wide and the curves are smooth, BER is relatively low and at the same level within the whole region. Instead in the DNLOS region, propagation conditions vary significantly, and hence also BER changes significantly. BER is highest in the LOS region, where the azimuth spreads are clearly narrower than in the other regions, as shown in Fig.3. The total gain obtained by vertical iterations is found remarkable high especially in the DNLOS region: There are several snapshots where no frame errors occurred in the simulations where 1000 frames were transmitted.

Observing Figs.4 and 5, it is clearly seen that in the LOS region, where azimuth spreads are small, the SC-MMSE performance is significantly deteriorated. This is primarily due to that fact that SC-MMSE's signal separability relies on the MMSE filtering, which, however, is limited to the rank of the channel matrix. Hence, within the simulated SNR range, the HI gain is negligible and BER is poor after performing only horizontal iterations in the LOS region. However, the VI gain is independent of spatial correlations, and thus, vertical iterations can improve overall performance significantly.

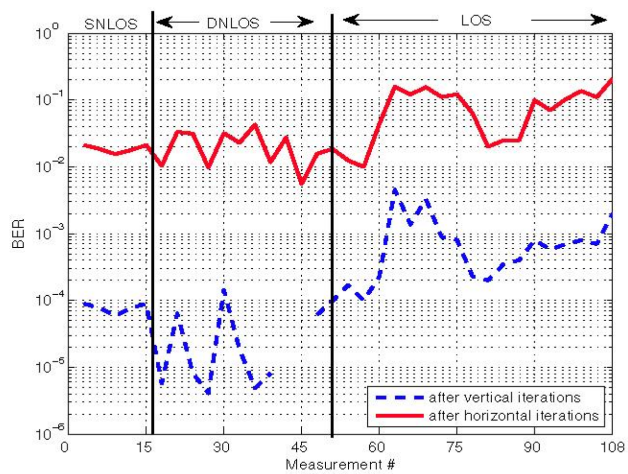

Fig.5. BER for the CST SC-MMSE after the last VI (dashed line) and after the last HI as the SNR=3dB.

In order to illustrate performance variations in the measurement route, cumulative distribution functions (CDF) for BER are studied. By CDFs it is also possible to make assessment of probabilities for achieving certain target BER along the route. Fig. 6 presents the CDFs for BER obtained after the last horizontal iteration (solid line) and after the last vertical iteration (dashed line). For the clarity of the figure, only SNR range [-1 1

3] dB is shown.

It is found that especially at lower SNRs, the CDF curves related to the horizontal iterations are steeper and clearly focused on the right part of the figure than the CDFs related to the vertical iterations. In other words, BER variations are minor when only horizontal iterations are performed, but the achieved BER is high in most of the cases even at the higher SNR range. Instead, when vertical iterations are performed, the performance variations are greater but the achieved BER is very low. At the SNR of 3dB, target BER $\leq 10^{-3}$ is achieved after the last VI with the probability of 0.95, whereas without the VIs the probability is around 0.05. As the SNR is 1 dB, that target BER is achieved with the probability of 0.7, and even at the SNR of -1 dB with the probability of 0.35. Instead, by performing only horizontal iterations it is not possible to achieve BER $\leq 10^{-3}$ at lower SNRs. Hence, also the target BER $\leq 10^{-4}$ is not achievable within the simulated SNRs. With vertical iterations, however, the target BER $\leq 10^{-4}$ is achieved with the probabilities of 0.15, 0.4, and 0.7 at the SNRs of -1dB, 1dB, and 3dB, respectively.

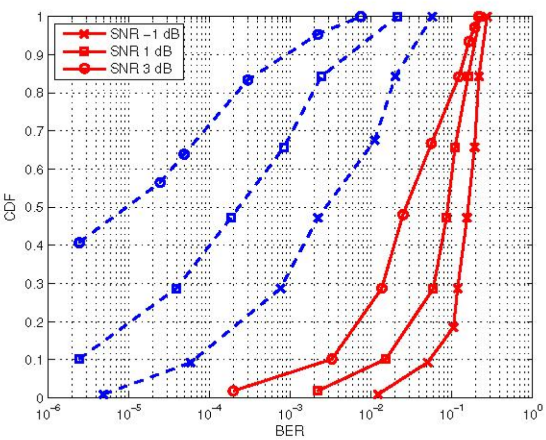

Fig.6. CDF for BER performance of the CST SC-MMSE equalizer after the last horizontal iteration (solid line) and after the last vertical iteration (dashed line) in the single user case.

Multiuser Case

Next, the performance of the CST SC-MMSE turbo equalizer is evaluated in the presence of two users. Both of the users are randomly located within the measurement route so that they occupy the snapshots at least once. The number of randomly chosen snapshots sets is 200. The simulation parameters are same as in the single user case.

First, the averaged BER is presented separately for the SNLOS, DNLOS, and LOS regions in Fig. 7a, Fig.7b, and Fig.7c, respectively, and for the whole measurement route in Fig.7d. Again, the BERs resulted from the HI:s are depicted with solid lines and the BERs from VI:s are shown by dashed lines. For the comparison, the converged BER obtained in the single user case is included (dash-dot line).

It is found that the within the simulated SNR range, the horizontal iteration gain is almost negligible in the SNLOS and LOS regions and minor also in the DNLOS region. The average vertical iteration gain is still remarkable in all the regions. In the SNLOS and DNLOS regions the vertical iteration gain saturates after the 5th iteration, whereas in the LOS region only three vertical iterations is required for the convergence. However, the converged performance is relatively poor in the LOS region even at the SNR of 5 dB: average BER is around 0.03, whereas in the SNLOS and DNLOS regions average BER is 0.003 with that SNR.

When comparing the converged BER with that obtained in the single user case, it is noted that the presence of two users causes loss of several decibels on the performance at higher simulated SNRs. Apparently, 2 receiver antennas is not enough in the presence of 2 users each equipped with 2 transmit antennas. The average loss is most remarkable in the LOS region. This is again due to SC-MMSE's inability of signal separability in rank-reduced scenarios.

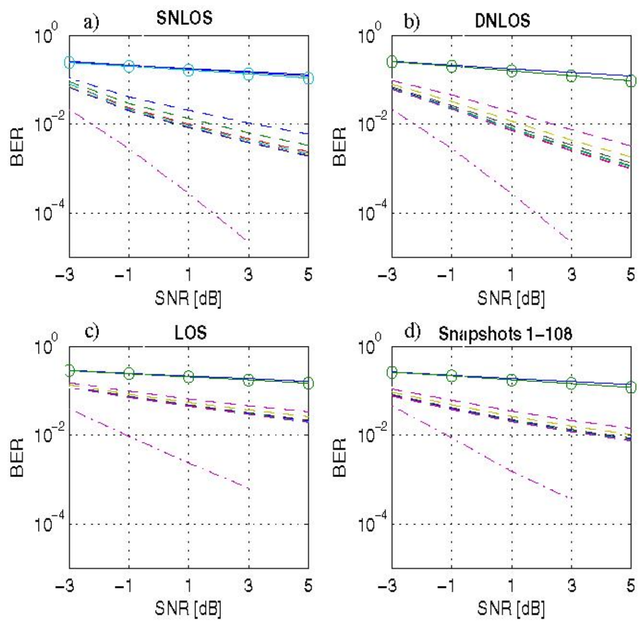

Fig.7. Averaged BER of the CST-SCMMSE MIMO turbo equalizer in SNLOS (a), DNLOS (b), and LOS (c) regions, as well as in the whole measurement route (d). Multiuser case.

Finally, the relative performance variations of the measurement route are examined by studying the CDFs of the BER. CDFs of the BER achieved after the last horizontal iteration (solid lines) and after the last vertical iteration (dashed lines) are shown in Fig. 8 for the SNR values [1 d**B,** 3 dB, 5 dB]. It is found that the superiority of the vertical iterations is emphasized in multiuser case: By performing only the horizontal iterations, probability for achieving BER$\leq 10^{-1}$ is around 0.2 even at the SNR of 5 dB, whereas by performing the vertical iterations that BER is obtained with the probability almost 1.0 even at the SNR of 1dB. The target BER$\leq 10^{-3}$, which can not be achieved by horizontal iterations at all, can be achieved by the vertical iterations with the probability of 0.8 as the SNR=5dB. Even at the SNRs of 3dB and 1dB, the probabilities are 0.6 and 0.3, respectively. Moreover, the probabilities for achieving the target BER$\leq 10^{-4}$ are 0.45 and 0.25 at the SNRs of 5dB and 3dB, respectively.

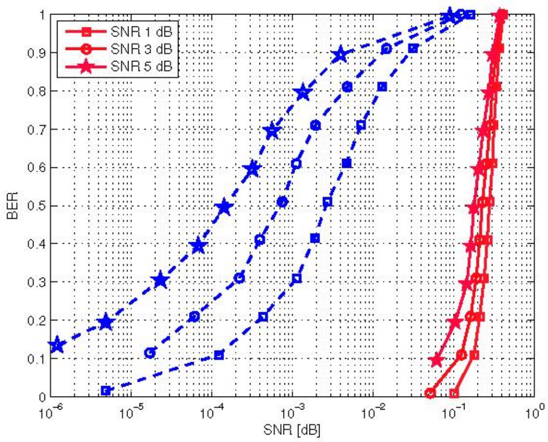

Fig.8. CDF for BER performance of the CST SC-MMSE turbo equalizer after the last horizontal iteration (solid line) and after the last vertical iteration (dashed line) in two-user case.

V. CONCLUSION

This paper has evaluated realistic performances for the CST MIMO turbo SC-MMSE equalizer, which exploits transmit diversity and coding gain through horizontal and vertical iteration loops. Performance of the CST SC-MMSE equalizer has been evaluated in different channel conditions in terms of Tx and Rx azimuth spreads using multi-dimensional channel sounding measurement data. The impact and efficiency of the horizontal and vertical iterations have been studied in different propagation conditions as well. Furthermore, CDFs have been used to examine performance variations in the measurement route and to assess probabilities for achieving certain target BER.

It has been shown that the performance of the CST SC-MMSE equalizer depends on the channel conditions in terms of Rx and Tx azimuth spreads: BER is high in the snapshots where azimuth spreads are small, and vice versa. Within the simulated SNR, the horizontal iteration gain has been found to be minor especially in the LOS region, where the spatial spreads at Tx and Rx sides are very small, which, hence, limits SC-MMSE's capability of separating the multiple transmit antennas and combining multipath components. The gain obtained by vertical iterations does not depend on the spatial properties and it has been shown to be significant in all the regions even at lower SNR range. Besides, the gain is several decibels. The superiority of the vertical iterations has been verified by CDF curves as well. It was found that within the simulated SNR range, the target BER$\leq 10^{-3}$ and BER$\leq 10^{-4}$ can be achieved only if vertical iterations are performed. These results are valid for single user as well as two-user cases.

Finally it should be emphasized that although the performance results presented in this paper are valid only in the measurement area where the snapshots were collected, similar tendencies can be expected in similar propagation environments.

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