

EXIT Chart Analysis of Turbo DeCodulation

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Abstract— Turbo DeCodulation is the combination of iterative demodulation and iterative source-channel decoding to a single multiple Turbo process. The receiver structures of bit-interleaved coded modulation with iterative decoding (BICM-ID), iterative source-channel decoding (ISCD), and iterative source coded modulation (ISCM) are merged to one novel Turbo system, in which in two iterative loops reliability information is exchanged between the three single components, demodulator, channel decoder, and (softbit) source decoder. Simulations show quality improvements compared to the different previously known systems, which use iterative processing only for two components of the receiver. We propose the enhancement to Turbo DeCodulation⁺ by an additional link for a direct supply of reliabilities from the softbit source decoder to the demodulator. We will demonstrate that using three-dimensional EXIT charts a convergence analysis of Turbo DeCodulation similar to single Turbo processes is possible.

I. INTRODUCTION

With the discovery of Turbo codes [1],[2],[3] channel coding close to the Shannon limit becomes possible with moderate computational complexity. In the past years the Turbo principle of exchanging *extrinsic* information between separate channel decoders has been adapted to other components of the receiver. In our case a receiver consists of demodulator, channel decoder, and source decoder.

In [4],[5] *bit-interleaved coded modulation with iterative decoding* (BICM-ID) is presented, in which the channel decoder exchanges *extrinsic* reliabilities with the demodulator. This technique for *iterative demodulation* is based on non-iterative *bit-interleaved coded modulation* (BICM) [6],[7], the standard transmission scheme for higher order modulations in today's wireless communication systems, e.g., WLAN, due to its simplicity and flexibility and its robustness against fading.

To exploit the residual redundancy in the source coded parameters such as scale factors or predictor coefficients for speech, audio, and video signals in a Turbo process, *iterative source-channel decoding* (ISCD) has been developed in [8],[9],[10]. The *a priori* knowledge on the residual redundancy, e.g., non-uniform probability distribution or auto-correlation, is utilized for *error concealment* by a derivative of a *softbit source decoder* (SBSD) [11], which exchanges *extrinsic* reliabilities with a channel decoder.

In *iterative source coded modulation* (ISCM) [12] no channel coding is needed at all and the *extrinsic* reliabilities are exchanged between the demodulator and the SBSBD.

The *Turbo DeCodulation* scheme [13] described in Section II is a multiple Turbo process, in which the *extrinsic* reliabilities are exchanged between all three receiver components, *demodulator*, *channel decoder*, and (*softbit*) *source decoder*. The term *Turbo DeCodulation* is chosen according to the short-term *codulation* [14] for the, in our case, source and channel coded modulation. *Turbo DeCodulation* can be either interpreted as serial concatenation of BICM-ID and ISCD via a common channel code or as integration of a single channel code into ISCM.

In Section III we present the novel enhancement for systematic channel codes to *Turbo DeCodulation*⁺. Here, *extrinsic* reliabilities are additionally supplied directly from the SBSBD to the demodulator. The simulation results in Section IV show a further improvement with respect to *Turbo DeCodulation* with a negligible additional computational complexity.

Section V contains a novel EXIT chart analysis [15] of the two versions of *Turbo DeCodulation*. With three components processing *extrinsic* reliabilities the classic two-dimensional EXIT chart is not sufficient anymore. However, with three-dimensional EXIT charts the convergence behavior of *Turbo DeCodulation* can be very well analyzed.

II. THE TURBO DECODULATION SYSTEM

In Fig. 1 the baseband model of the proposed *Turbo DeCodulation* system is depicted. The *inner* iterative loop corresponds to a BICM-ID system [4],[5], while the *outer* iterative loop is similar to an ISCD system [8],[9],[10].

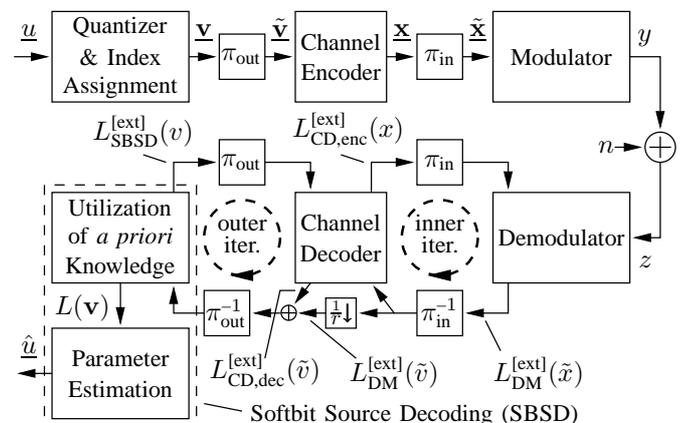


Fig. 1. Baseband model of Turbo DeCodulation.

At time instant τ , a source encoder determines a frame \underline{u}_τ of K_S source codec parameters $u_{\kappa,\tau}$ with $\kappa=1, \dots, K_S$ denoting the position in the frame. The single elements $u_{\kappa,\tau}$ of \underline{u}_τ are assumed to be statistically independent from each other. Each

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value $u_{\kappa,\tau}$ is individually mapped to a quantizer reproduction level $\bar{u}_{\kappa}^{(\xi)}$, $\xi = 1, \dots, 2^{M_{\kappa}}$. To each quantizer reproduction level $\bar{u}_{\kappa}^{(\xi)}$ selected at time instant τ a unique bit pattern $\mathbf{v}_{\kappa,\tau}$ of M_{κ} bits is assigned according to the index assignment Γ , $\mathbf{v}_{\kappa,\tau} = \Gamma(\bar{u}_{\kappa}^{(\xi)})$. For simplicity we assume $M_{\kappa} = M$ for all κ . The single bits of a bit pattern $\mathbf{v}_{\kappa,\tau}$ are indicated by $v_{\kappa,\tau}^{(m)}$, $m = 1, \dots, M$. The frame of bit patterns is denoted by $\underline{\mathbf{v}}_{\tau}$.

The first and outer bit interleaver π_{out} scrambles the incoming frame $\underline{\mathbf{v}}_{\tau}$ of data bits to $\tilde{\underline{\mathbf{v}}}_{\tau}$ in a deterministic manner. Notice, bit interleaving as well as channel encoding need not to be limited to the present set $\underline{\mathbf{v}}_{\tau}$ of bit patterns resp. $\tilde{\underline{\mathbf{v}}}_{\tau}$. Both routines can also be realized for a time sequence of $\Lambda+1$ consecutive sets, e.g., $\underline{\mathbf{v}}_{\tau-\Lambda}, \dots, \underline{\mathbf{v}}_{\tau}$, if a delay of (in maximum) Λ time instants is tolerable in a practical application. However, to simplify matters, in the following we consider only a single time instant τ .

For channel encoding of a frame $\tilde{\underline{\mathbf{v}}}_{\tau}$ of bits $v_{n,\tau}$, $n = 1 \dots N$, we use a standard terminated *recursive systematic convolutional* (RSC) code of constraint length $J+1$ and a code rate (close to) $r = 1/2$. In general, any channel code can be used as long as the respective decoder is able to provide the required *extrinsic probabilities*. For termination of the RSC code J tail bits are appended to the frame $\tilde{\underline{\mathbf{v}}}_{\tau}$. The resulting codeword is denoted by $\underline{\mathbf{x}}_{\tau}$ with systematic bits $x_{n,\tau}^{(1)}$ and parity bits $x_{n,\tau}^{(2)}$ and $n = 1, \dots, N+J$.

The second and inner bit-interleaver π_{in} permutes this codeword $\underline{\mathbf{x}}_{\tau}$ to $\tilde{\underline{\mathbf{x}}}_{\tau}$. Besides ensuring uncorrelated *extrinsic* information just as the outer interleaver, this inner interleaver is additionally responsible for breaking up burst errors on the transmission link.

The interleaved codeword $\tilde{\underline{\mathbf{x}}}_{\tau}$ is divided into bit patterns $\tilde{\mathbf{x}}_{k,\tau}$, $k = 1, \dots, K_C$, with I single bits $\tilde{x}_{k,\tau}^{(i)}$, $i = 1, \dots, I$. In case the last bit pattern $\tilde{\mathbf{x}}_{K_C,\tau}$ is not completely filled the remaining positions are padded by zeros. The modulator maps each pattern $\tilde{\mathbf{x}}_{k,\tau}$ according to a mapping rule μ to a complex modulated symbol $y_{k,\tau}$ out of the *signal constellation set* \mathcal{Y} , $y_{k,\tau} = \mu(\tilde{\mathbf{x}}_{k,\tau})$. The respective inverse relation is denoted by μ^{-1} , with $\tilde{x}_{k,\tau}^{(i)} = \mu^{-1}(y_{k,\tau})^{(i)}$. The modulated symbols are normalized to an average energy of $\mathbb{E}\{\|y_{k,\tau}\|^2\} = 1$.

On the channel complex additive white Gaussian noise (AWGN) $n_{k,\tau} = n'_{k,\tau} + jn''_{k,\tau}$ with a known power spectral density of $\sigma_n^2 = N_0$ ($\sigma_{n'}^2 = \sigma_{n''}^2 = N_0/2$) is applied, i.e., $z_{k,\tau} = y_{k,\tau} + n_{k,\tau}$.

The received symbols $z_{k,\tau}$ are evaluated in a multiple Turbo process, which exchanges *extrinsic* reliabilities between demodulator (DM) and channel decoder (CD) in the *inner* iterations, and between channel decoder and *softbit source decoder* (SBSD) in the *outer* iterations. Such reliability information can either be evaluated in terms of probabilities $P(\cdot)$ or in so-called *log-likelihood* ratios, or short *L-values* [2], $L(\cdot)$.

The *Turbo DeCodulation* receiver is described in detail in [13]. For the equations for the computation of the *extrinsic* probabilities or their respective L-values in each component we refer to the literature, i.e., for the demodulator to [4],[5], for the channel decoder to [16],[17], and for

the *softbit source decoder* (including parameter estimation with the minimum mean squared error serving as fidelity criterion) to [8],[9],[10],[11]. Note, the channel decoder in a *Turbo DeCodulation* system needs to compute *extrinsic* reliabilities for decoded bits $x_{n,\tau}$ as well as for the encoded bits $v_{n,\tau}$. In case of a systematic channel code, the channel decoder of a conventional system would implicitly forward the *extrinsic* reliabilities of the demodulator for systematic bits to the SBSBD. However, for consistency, i.e., all receiver components provide only their respective *extrinsic* reliabilities, the considered channel decoder generates $L_{\text{CD,dec}}^{[\text{ext}]}(\tilde{v})$ and the $L_{\text{DM}}^{[\text{ext}]}(\tilde{v})$ are added afterwards. The extraction of the *extrinsic* reliabilities for the systematic bits $L_{\text{DM}}^{[\text{ext}]}(\tilde{v})$ out of the stream of $L_{\text{DM}}^{[\text{ext}]}(x)$ can be seen as a down-sampling “ $\frac{1}{2}\downarrow$ ”. For the examined $r = 1/2$ RSC code, e.g., this down-sampling by a factor of 2 would be denoted by “ $2\downarrow$ ”.

III. THE TURBO DECODULATION⁺ SYSTEM

In contrast to conventional non-iterative systems or systems like BICM-ID and ISCD with a single iterative loop the demodulator of the *Turbo DeCodulation* receiver can profit from *extrinsic* reliabilities $L_{\text{SBSBD}}^{[\text{ext}]}(v)$ generated by the SBSBD if systematic channel coding is used. This requires a kind of up-sampling “ $\frac{1}{2}\uparrow$ ”, i.e., “ $2\uparrow$ ” for the considered $r = 1/2$ RSC code, of the stream $L_{\text{SBSBD}}^{[\text{ext}]}(\tilde{v})$, in which we set $L_{\text{SBSBD}}^{[\text{ext}]}(x) = 0$ for the non-systematic bits and $L_{\text{SBSBD}}^{[\text{ext}]}(x) = L_{\text{SBSBD}}^{[\text{ext}]}(\tilde{v})$ for the systematic bits. The $L_{\text{SBSBD}}^{[\text{ext}]}(x)$ are added to the $L_{\text{CD,enc}}^{[\text{ext}]}(x)$. These modifications are depicted in the gray shaded area in Fig. 2. We denote this enhancement by *Turbo DeCodulation*⁺.

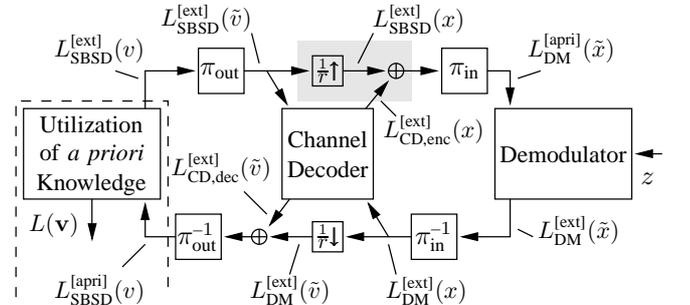


Fig. 2. Receiver of the Turbo DeCodulation⁺ system.

IV. SIMULATION RESULTS

The capabilities of the proposed *Turbo DeCodulation* scheme shall be demonstrated by simulation. Instead of using any specific speech, audio, or video encoder, we model $K_S = 500$ statistically independent source codec parameters u by K_S independent 1st order Gauss-Markov processes with auto-correlation $\rho = 0.8$, a typical value for some parameters of source codecs. Each parameter $u_{\kappa,\tau}$ is scalarly quantized by a Lloyd-Max quantizer using $M = 3$ bits/parameter. The index assignment Γ is either *natural binary* (if SBSBD stand-alone) or *EXIT optimized* [18] (if SBSBD in the loop). The bit-interleaved frame $\tilde{\underline{\mathbf{v}}}_{\tau}$ is channel encoded using a memory $J = 2$, terminated RSC code with generator polynomial $\mathbf{G} = (1, \frac{1}{1+D+D^2})$. The modulator maps $I = 3$ bits to one

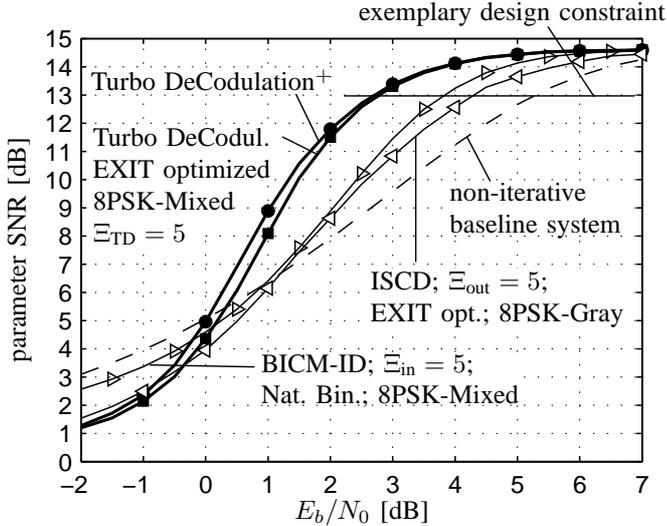


Fig. 3. Parameter SNR Simulation Results

channel symbol by either 8PSK-Gray (if demodulator stand-alone) or 8PSK-Mixed mapping [4] (if demodulator in the loop). In [5] other mappings are presented, which exhibit a better asymptotic performance than 8PSK-Mixed. However, with the SBSD providing good *extrinsic* information to the channel decoder already at relatively low E_b/N_0 , the 8PSK-Mixed mapping is the better choice for the given settings, due to its waterfall region being at a likewise low E_b/N_0 [4],[5].

At the *Turbo DeCodulation* receiver Ξ_{outer} outer iterations and Ξ_{in} inner iterations are performed. For the order of inner and outer iterations there exist lots of possibilities. For simplicity we set $\Xi_{\text{TD}} = \Xi_{\text{in}} = \Xi_{\text{out}}$ and restrict ourselves to the case in which demodulator, channel decoder and SBSD are executed sequentially in this order. This results in single *inner* and *outer* iterations being performed alternately. Except for the first and the last iteration, this can be seen as both iterative loops being executed in parallel, i.e., the channel decoder feeding both loops simultaneously.

The *parameter signal-to-noise ratio* (SNR) between the originally generated parameters $u_{\kappa,\tau}$ and the reconstructed estimates $\hat{u}_{\kappa,\tau}$ is used for quality evaluation. The simulation results are depicted in Fig. 3.

The dashed line is the result for a non-iterative ($\Xi_{\text{TD}} = 1$) baseline system which uses *natural binary* index assignment Γ and standard 8PSK-Gray mapping μ . The solid line marked “◁” uses ISCD with $\Xi_{\text{out}} = 5$ iterations and *EXIT optimized* index assignment [18]. Since the demodulator is not part of the iterative process ($\Xi_{\text{in}} = 1$), still the, for this case, optimum 8PSK-Gray mapping is applied. Due to the relatively weak memory 2 channel code the performance gain of ISCD is only $\Delta_{E_b/N_0} = 1.0$ dB, if a reference parameter SNR of 13 dB is assumed as exemplary design constraint. At this parameter SNR BICM-ID with 8PSK-Mixed mapping (solid curve “▷”) allows an improvement of $\Delta_{E_b/N_0} = 1.6$ dB. In the *inner* loop $\Xi_{\text{in}} = 5$ iterations are executed ($\Xi_{\text{out}} = 1$) and the standard *natural binary* index assignment is used.

At the baseline parameter SNR the performance gain of the combined *Turbo DeCodulation* system (solid curve “■”) compared to the non-iterative system is approximately (for the given settings) with $\Delta_{E_b/N_0} = 2.5$ dB the sum of the gains by the ISCD and BICM-ID systems used for comparison.

For *Turbo DeCodulation* 8PSK-Mixed mapping and *EXIT optimized* index assignment are applied and $\Xi_{\text{TD}} = 5$ iterations are carried out.

Identical settings are used for the *Turbo DeCodulation+* system (solid curve “●”). At the reference parameter SNR of 13 dB only a slight improvement of $\Delta_{E_b/N_0} = 0.1$ dB compared to *Turbo DeCodulation* can be observed. For medium parameter SNR (3...11 dB) this gain increases to $\Delta_{E_b/N_0} = 0.3$ dB. Note, the additional computational complexity of *Turbo DeCodulation+* with respect to *Turbo DeCodulation* is negligible.

V. EXIT CHART ANALYSIS

In this section the convergence behavior of *Turbo DeCodulation* and *Turbo DeCodulation+* is analyzed using EXIT charts [15]. With the three different receiver components generating four different *extrinsic* reliabilities this analysis is much more complex than in the classic case. Three-dimensional EXIT charts [19] are required. In contrast to [19] the EXIT characteristics of the components differ significantly due to the demodulator and the SBSD being part of the Turbo process. At first, we will present the EXIT characteristics of the three components.

A. EXIT characteristics

The EXIT characteristic of the SBSD with EXIT optimized index assignment is depicted in Fig. 4. On the two horizontal axes the *a priori* mutual information from the channel decoder ($\mathcal{I}_{\text{SBSD|CD}}^{\text{[apri]}}$) and the demodulator ($\mathcal{I}_{\text{SBSD|DM}}^{\text{[apri]}}$) is shown. On the vertical axis the generated *extrinsic* mutual information $\mathcal{I}_{\text{SBSD}}^{\text{[ext]}}$ is plotted. In the plane $\mathcal{I}_{\text{SBSD|DM}}^{\text{[apri]}} = 0$ the EXIT characteristic for the classic ISCD system can be found. If no *extrinsic* reliabilities are forwarded from the demodulator to the SBSD, i.e., no down-sampling ($L_{\text{DM}}^{\text{[ext]}}(\tilde{v}) = 0$), we get the lower, light gray surface. However, in the considered systems the SBSD uses the $L_{\text{DM}}^{\text{[ext]}}(\tilde{v})$ and we obtain the upper, dark gray surface. This surface can be generated either by simulation with two *a priori* reliabilities or by interpolation using the known EXIT characteristic for the ISCD case. For a binary erasure channel (BEC) the combined *a priori* mutual information $\mathcal{I}_{\text{SBSD},\Sigma}^{\text{[apri]}}$ to be used in the ISCD EXIT characteristic is [20]

$$\mathcal{I}_{\text{SBSD},\Sigma}^{\text{[apri]}} = \mathcal{I}_{\text{SBSD|CD}}^{\text{[apri]}} + \mathcal{I}_{\text{SBSD|DM}}^{\text{[apri]}} - \mathcal{I}_{\text{SBSD|CD}}^{\text{[apri]}} \cdot \mathcal{I}_{\text{SBSD|DM}}^{\text{[apri]}}. \quad (1)$$

In [21] it was shown that the BEC channel is a good approximation for the AWGN channel in the context of EXIT characteristics. A not depicted comparison between simulated and interpolated results confirms this.

As visible in Fig. 5, the EXIT characteristics for demodulation of 8PSK-Mixed mapping differ for *Turbo DeCodulation* (left, light gray surface) and *Turbo DeCodulation+* (right, dark gray surface), since with *Turbo DeCodulation+* the demodulator also gets *extrinsic* reliabilities from the SBSD.

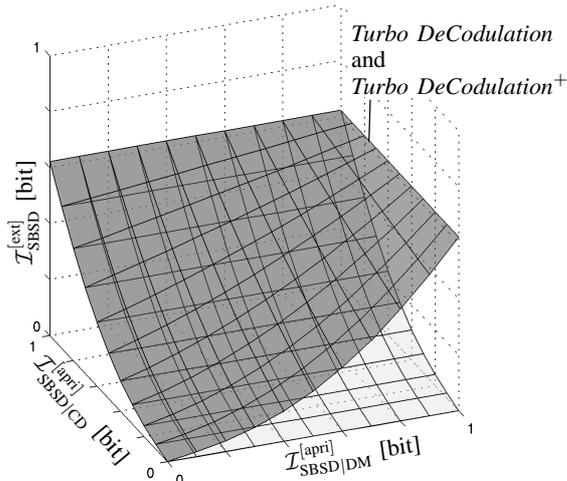


Fig. 4. EXIT characteristics for the softbit source decoder; EXIT optimized index assignment, 3 bit Lloyd-Max quantization

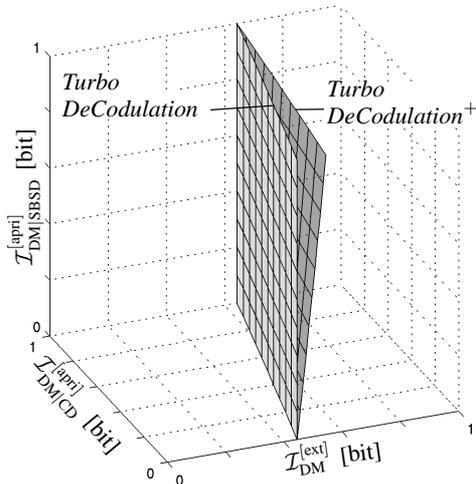


Fig. 5. EXIT characteristics for the demodulator; 8PSK-Mixed mapping, $E_b/N_0=2$ dB, AWGN.

However, with the considered $r = 1/2$ RSC coded, we have $L_{\text{SBSD}}^{[\text{ext}]}(x) \neq 0$ only for the systematic half of the bits. Thus, for interpolation we have to use

$$\mathcal{I}_{\text{DM},\Sigma}^{[\text{apri}]} = \mathcal{I}_{\text{DM}|CD}^{[\text{apri}]} + 0.5 \cdot \mathcal{I}_{\text{DM}|SBSD}^{[\text{apri}]} - \mathcal{I}_{\text{DM}|CD}^{[\text{apri}]} \cdot 0.5 \cdot \mathcal{I}_{\text{DM}|SBSD}^{[\text{apri}]} \quad (2)$$

In Fig. 6 the EXIT characteristic for the encoded bits $L_{\text{CD,enc}}^{[\text{ext}]}$ of the channel decoder is depicted. The EXIT characteristic for the decoded bits diverges only slightly and is not shown. In contrast to Fig. 4 and [19], the surface is not symmetric with respect to $\mathcal{I}_{\text{CD}|DM}^{[\text{apri}]}$ and $\mathcal{I}_{\text{CD}|SBSD}^{[\text{apri}]}$, because the two *a priori* mutual information refer to different inputs, i.e., encoded and decoded bits.

B. Decoding Trajectories

Figs. 7 and 8 show the EXIT charts including the trajectories at $E_b/N_0 = 2$ dB for Turbo DeCodulation and Turbo DeCodulation+ respectively. The EXIT characteristic of the SBSD is omitted, because it would conceal the trajectory. For the channel decoder the EXIT characteristic for the encoded bits (Fig. 6) is used. Thus, the EXIT charts reflects the

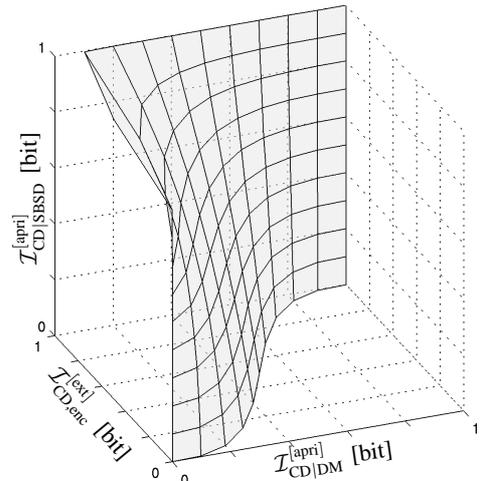


Fig. 6. EXIT characteristic for the channel decoder (encoded bits $\mathcal{I}_{\text{CD,enc}}^{[\text{ext}]}$); RSC code, $r = 1/2$, memory 2, generator polynomial $G = (1, \frac{1}{1+D+D^2})$.

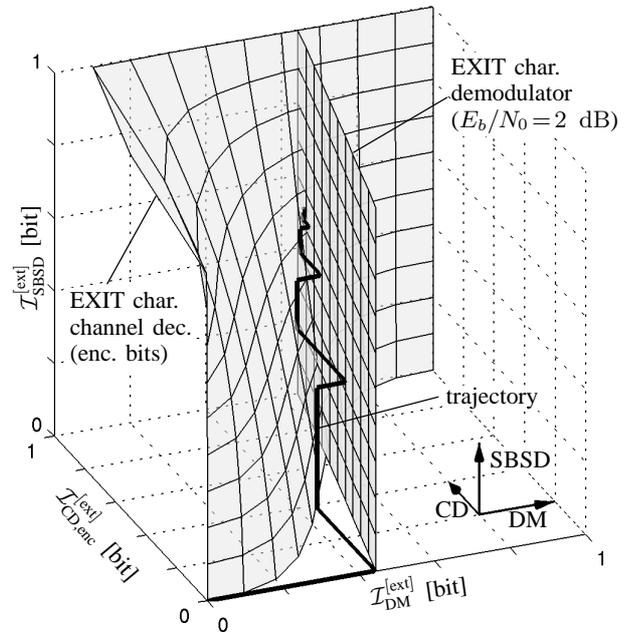


Fig. 7. EXIT chart for Turbo DeCodulation, $E_b/N_0 = 2$ dB.

exchange of *extrinsic* mutual information in the *inner* iteration loop. The trajectory proceeds in all three dimensions, to the right for demodulator, to the back for the channel decoder, and upwards for the SBSD. The corners of the trajectories very well coincide with the visible EXIT characteristics.

In Fig. 9 the trajectories for Turbo DeCodulation and Turbo DeCodulation+ as well as for BICM-ID and ISCD are compared. The end points of the trajectories are projected onto the planes of the cube for an easier comparison. As visible Turbo DeCodulation+ slightly outperforms Turbo DeCodulation as a result of the inclined EXIT characteristic of the demodulator with Turbo DeCodulation+ (cmp. Fig. 5). The trajectory of BICM-ID matches the EXIT characteristics of channel decoder and demodulator in the bottom plane ($\mathcal{I}_{\text{SBSD}}^{[\text{ext}]} = 0$ bit) of Figs. 7 and 8. Especially with respect to $\mathcal{I}_{\text{CD,enc}}^{[\text{ext}]}$ the trajectories of the two versions of Turbo DeCodulation can proceed much further

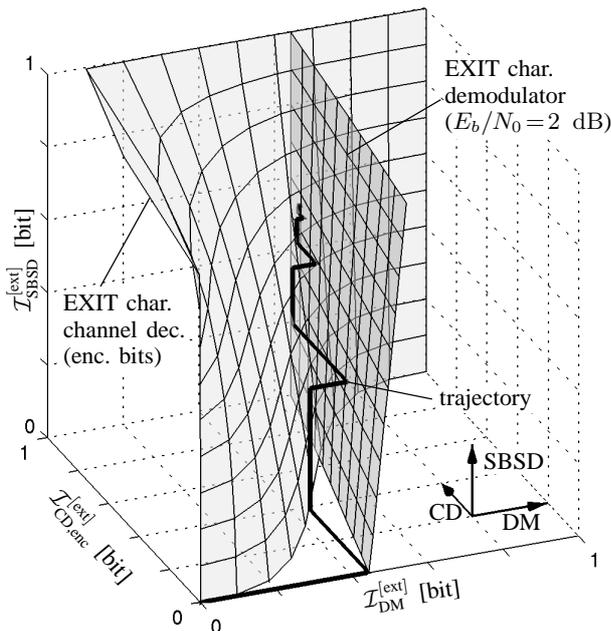


Fig. 8. EXIT chart for *Turbo DeCodulation+*, $E_b/N_0 = 2$ dB.

than the BICM-ID trajectory since the gap is much wider at $I_{\text{SBS D}}^{[\text{ext}]} > 0.4$ bit compared to the bottom plane ($I_{\text{SBS D}}^{[\text{ext}]} = 0$ bit). Note, BICM-ID also uses *a priori* knowledge in the SBS D, but only once before the final parameter estimation. Thus, only in the final iteration the BICM-ID trajectory advances in the upward direction. In the first iteration the ISCD produces a higher $I_{\text{DM}}^{[\text{ext}]}$ than the other systems because it uses 8PSK-Gray mapping, which optimal for the non-iterative case of a single iteration. However, without updating the demodulation, the ISCD trajectory cannot advance any further to the right.

VI. CONCLUSION

We presented an EXIT chart analysis of *Turbo DeCodulation*, which uses iterative processing for all three components of the considered receiver. This combination of iterative source-channel decoding and iterative demodulation results in a multiple Turbo process with exchanging *extrinsic* reliabilities in two separate loops. In comparison to a non-iterative system as well as previously developed systems with a single iterative loop, i.e., ISCD and BICM-ID, simulations demonstrated significant quality gains by *Turbo DeCodulation*. We presented a further enhancement for systematic channel codes, denoted as *Turbo DeCodulation+*, in which additionally *extrinsic* reliabilities from the SBS D are fed back to the demodulator. The three receiver components require a three-dimensional EXIT charts. With these EXIT charts the convergence behavior can be analyzed and predicted as in conventional Turbo processes.

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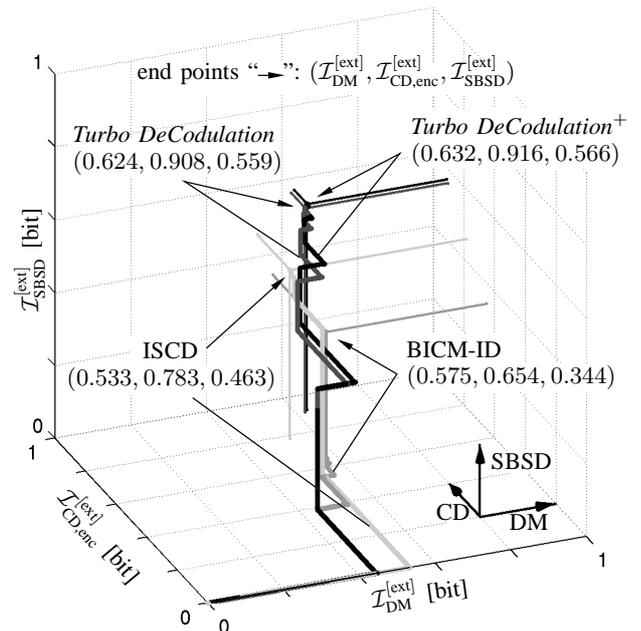


Fig. 9. Comparison of trajectories, $E_b/N_0 = 2$ dB.

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