A New Reduced Complexity Turbo-Detector for Highly Selective Long Delay Spread ISI Channels: A Solution for 4G Mobile Systems ?

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Abstract- In this paper, we investigate a new turbo-detector scheme. The data detection part of the iterative receiver is based on variants of full-states SOVE and SOVA Interference InterSymbols (ISI) decoders. Those variants employ reduced-state techniques combined with generalized per-survivor processing. They offer a very good trade-off between performance and complexity even with long delay channels. Monte-Carlo simulation results in various severe propagation environments show that the proposed sub-optimal turbo-detector is usually 1,8 to 3 dB away from the optimal BCJR-based one with a significant computational complexity reduction. Hence it appears as a possible candidate for future mobile radio communications with high bit rate transmission.

Indexing terms: Turbo-detection, Generalized Per-Survivor Processing, Soft-Output Viterbi Algorithm

1. Introduction

Since their first presentation in 1993 [1], turbo-codes have generated quite intensive investigations among communication theorists and practitioners. By extending the basic concept of turbo-codes, a very promising turbo principle has recently emerged as a way of exchanging randomized soft information between concatenated functions involved in a digital receiver. Turbo-detection, first introduced in [2][3], is an exciting application of the turbo principle for efficiently fighting against InterSymbol Interference (ISI).

Two interesting issues can be drawn from the past studies on that subject. The first issue concerns the mismatched channel estimation, which degrades the performance by 2.9 dB, no matter the modulation employed. By designing an additional parallel iterative re-estimation process embedded in the turbo-detector structure, it has been shown in [5] that the initial channel estimate can be dramatically refined, together with coded data detection, as iterations advance. The second major drawback of the turbo-detection scheme lies in the quickly prohibitive complexity of the inner soft-in soft-out (SISO) ISI decoder, which, as well known, grows exponentially with modulation order and ISI channel constraint length. While retaining the general architecture, a natural trend for reducing the turbo-detection computational complexity consists in replacing conventional BCJR ISI decoders [3][4] (log and min-log versions) by efficient sub-optimal ones [5][6][7][8].

This paper aims at presenting robust and sophisticated reduced-state trellis-based SISO ISI decoders. It is organized as follows. In section 2, the equivalent discrete-time transmission model considered here is briefly recalled. Section 3 is devoted to the description of two sub-optimal SISO ISI decoding algorithms, used as basic inner tools in the novel reduced-complexity turbo-detector, described in section 4. A performance analysis follows in section 5. Finally, section 6 ends with concluding remarks.

2. Transmission model

The equivalent discrete-time base-band communication model considered here is depicted on Figure 1. A data sequence $\{\underline{u}_1,\ldots,\underline{u}_{\tau_o}\}$ with $\underline{u}_n=\lfloor u_1,\ldots,u_{k_o}\rfloor$ is encoded by a error-control code C_o. Coded sequence $\{\underline{c}_1,\ldots,\underline{c}_{\tau_o}\}$ with $\underline{c}_n=\lfloor c_1,\ldots,c_{n_o}\rfloor$ enters a bit-level pseudo-random interleaver Π. Coded interleaved sequence is then split into N bursts $\{\underline{a}_1,\ldots,\underline{a}_\tau\}$ of τ bit-labeled symbols $\underline{a}_n=\lfloor a_1,\ldots,a_q\rfloor$ in some finite alphabet A of cardinality $Q=2^q$. Each burst is sent to a Q-ary signal mapper Ψ which produces a corresponding complex-valued burst $\{z_1,\ldots,z_\tau\}$. The channel ISI is modeled as a transverse filter made of K symbol-spaced complex coefficients $\underline{h}=[h_0,\ldots,h_{K-1}]$. At reception, the discrete-time channel outputs are given by:

$$y_n=\sum_{i=0}^{K-1}h_i z_{n-i}+\zeta_n$$

where ζ_n are uncorrelated circularly symmetric zero-mean complex Gaussian noise samples of variance $2\sigma^2$.

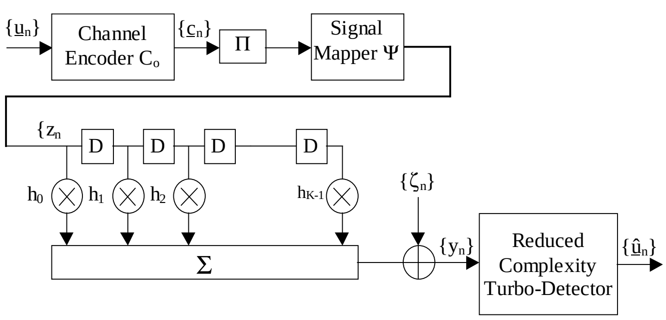

Figure 1: Equivalent discrete-time transmission model

3. Generalized reduced-state SISO ISI decoders

An ISI channel of constraint length K can be regarded as a time-varying Markov source whose state and transition time progression is visualized by a regular trellis diagram T. Let V and B denote the vertex and branch space of T. Let also V_n and B_n denote the vertex and branch space at depth and section n on the trellis time axis. Note that when the trellis is regular, any trellis section B_n is sufficient to describe the Markov process evolution. Moreover, at any depth n, vertex space V_n can be identified to one unique finite state space of cardinality Q^{K-1} made of all possible states:

$$s = (s_1, \ldots, s_{K-1}) \text{ with } s_i \in A.$$

To any input sequence $\{\underline{a}_1, \ldots, \underline{a}_\tau\}$ specifying one single path in the trellis, the Markov process associates an output complex-valued sequence $\{z_1, \ldots, z_\tau\}$. If, at time instant n, the input sequence terminates with the sub-string $\{\underline{a}_{n-K+1}, \ldots, \underline{a}_n\}$, the corresponding path ends at state:

$$s = (\underline{a}_{n-K+1}, \ldots, \underline{a}_n) \quad \underline{a}_i \in A$$

For a positive integer L ≤ K, called reduced constraint length, we now define sub-states as the restriction of trellis full states to the L-1 most recent symbols:

$$s = (s_1, \ldots, s_{L-1})$$

and say that the trellis path associated with the input sequence $\{\underline{a}_1, \ldots, \underline{a}_n\}$ terminates in sub-state s at depth n if:

$$(s_1, \ldots, s_{L-1}) = (\underline{a}_{n-L+1}, \ldots, \underline{a}_n).$$

Let V_n and B_n denote sub-state and branch spaces of the resulting sub-trellis T at any depth or section n. Clearly, state complexity is exponentially reduced to $Q^{L-1} << Q^{K-1}$.

In the packet-oriented BCJR algorithm, a posterior probabilities (APP) on input and output symbols are expressed as functions of probability density functions (pdf) on states and transitions of the considered Markov process, given the observed sequence. These pdf's are themselves computed by using forward and backward recursions [4]. When the full trellis representing the Markov process evolution is considered, branch metric expression only depends on the considered transition and on the departure state it is connected with. On the contrary, when a reduced-state strategy is introduced, a part of the branch metric expression involves past estimates of past modulation symbols which are not contained in trellis sub-states. The per-survivor processing (PSP) precisely consists in reading such estimates on survivors previously stored at each sub-state in a traceback matrix. To better fight against the resulting well-known error propagation effect, we call *generalized per-survivor processing* (GPSP) the concept of retaining more than one survivor (say Ω>1) per sub-state [9].

We now describe two *forward-only* ISI decoding algorithms, both based on the powerful combination of reduced-state and GPSP techniques. Those algorithms only differ in the fashion they compute soft outputs. One is SOVE-like [3][7], whereas the other is much more a generalization of the SOVA algorithm [10]. A *two-way* version, which mimics the BCJR algorithm, also exists. However, this version is much more complex in computational and storage requirements and, hence, will not be detailed in that paper.

Each branch $b \in B_n$ carries three fields: a departure sub-state $b^- \in V_{n-1}$, a termination sub-state $b^+ \in V_n$, and a branch label $b^\nabla = [b_1^\nabla, \ldots, b_q^\nabla]$ modeling a bit-labeled input symbol entering the rate-1 convolutional ISI code at time instant n.

For the generalized SOVE-like SISO algorithm, let us assume that, at any section $n \in [1, \tau]$, to each departure sub-state $s' \in V_{n-1}$, are attached:

- an ordered list $\{\mu_{n-1,\omega}(s'), \omega \in [1, \Omega]\}$ of the Ω best accumulated sub-state metrics ;
- an ordered list $\{\hat{\underline{a}}_{i=n-\theta-1}^{n-1}{}^{s'}_{\omega}, \ \omega \in [1, \Omega]\}$ of the Ω corresponding survivor paths $\hat{\underline{a}}_{i=n-\theta-1}^{n-1}{}^{s'}_{\omega} = \{\hat{\underline{a}}_{n-\theta-1}{}^{s'}_{\omega}, \ldots, \hat{\underline{a}}_{n-1}{}^{s'}_{\omega}\}$ terminating in sub-state $s' \in V_{n-1}$.

The SOVA-like SISO algorithm also requires:

- an ordered list $\{\hat{\underline{L}}_{i=n-\theta-1}^{n-1}{}^{s'}_{\omega}, \ \omega \in [1, \Omega]\}$ of the Ω bit-wise unsigned soft sequences associated with survivors $\hat{\underline{L}}_{i=n-\theta-1}^{n-1}{}^{s'}_{\omega} = \{\hat{\underline{L}}_{n-\theta-1}{}^{s'}_{\omega}, \ldots, \hat{\underline{L}}_{n-1}{}^{s'}_{\omega}\}$.

The SOVE and SOVA-like algorithms perform a forward recursion, and for each termination sub-state $s \in V_n$, compute, for all transitions $b \in B_n$ such that $b^+ = s$ and for all ranks $\omega \in [1, \Omega]$, the $\Omega \times 2^q$ new accumulated sub-state metrics:

$$\mu_{n,*}(s) = \mu_{n-1,\omega}(s') + \xi_{n,\omega}(b).$$

Those metrics are then classified by increasing order (the smallest the first rank). This forward recursion is carried out with the boundary conditions:

$$\mu_{0,1}(0) = 0 \ \mu_{0,\omega}(0) = \infty \ \forall \omega > 1 \quad \mu_{0,\omega}(s) = \infty \ \forall s \neq 0, \forall \omega \in [1, \Omega]$$

The branch metric is expressed as:

$$\xi_{n,\omega}(b) = \frac{1}{2\sigma^2} \left\| y_n - \hat{h}_0 z_n{}^{b}_{\omega} - \sum_{i=1}^{L-1} \hat{h}_i z_{n-i}{}^{b^-}_{\omega} - \sum_{i=L}^{K-1} \hat{h}_i \hat{z}_{n-i}{}^{b^-}_{\omega} \right\|^2 - \ln \Pr(b)$$

In the first term of the above expression, the complex-valued symbol $z_n{}^{b}_{\omega}$ results from simple re-mapping of the branch label b^∇. The complex symbol sequence $\{z_{n-L+1}{}^{b^-}_{\omega}, \ldots, z_{n-1}{}^{b^-}_{\omega}\}$ is simply deduced from sub-state b^- of rank ω, whereas the estimated symbol sequence $\{\hat{z}_{n-K+1}{}^{b^-}_{\omega}, \ldots, \hat{z}_{n-L}{}^{b^-}_{\omega}\}$ is obtained by tracebacking the survivor path which terminates at sub-state b^- of rank ω, and re-mapping labels on branches composing it. Survivor paths are stored in a generalized traceback sliding window of depth θ.

The log a prior probability on branch b is formally identified to the log a prior probability on its carried label b^∇, so that:

$$\ln \Pr(b) = \ln \Pr(\underline{a}_n = b^\nabla)$$

Assuming perfect independence between log a prior probability on symbol bits $a_{n,j}$ after re-interleaving of log extrinsic probability ratio sequence coming from outer decoder, we have:

$$\ln \Pr(b) = \sum_{j=1}^{q} \ln \Pr(a_{n,j} = b_j^\nabla)$$

Since it is always possible to isolate the a prior contribution of bit $a_{n,j}$ in the branch metric expression, we define:

$$\xi_{n,\omega}^{e,j}(b) = \frac{1}{2\sigma^2} \left\| y_n - \sum_{i=0}^{L-1} \hat{h}_i z_{n-i}{}^{b^-}_{\omega} - \sum_{i=L}^{K-1} \hat{h}_i \hat{z}_{n-i}{}^{b^-}_{\omega} \right\|^2 - \sum_{\substack{l=1 \\ l \neq j}}^{q} \ln \Pr(a_{n,l} = b_l^\nabla)$$

The past survivors paths $\hat{\underline{a}}_{i=n-\theta-1}^{n-1}{}^{s'}_{\omega}$, $\forall \omega \in [1, \Omega]$, are extended according to existing transitions $s' : \underline{a}_n \mapsto s$. The $\Omega \times 2^q$ new potential survivors $\hat{\underline{a}}_{i=n-\theta}^{n}{}^{s}_{*}$ are sorted in compliance with the rank of their associated metrics $\mu_{n,*}(s)$, but only the best ones (in metric sense) will be actually used for next section step. In parallel, the generalized SOVA-like SISO algorithm updates in a similar way the bit-wise unsigned soft sequences $\underline{\hat{L}}_{i=n-\theta-1}^{n-1}\,{}^{s'}_{\omega}$ associated with the new potential survivors. Again, the $\Omega\times 2^{q}$ new potential $\underline{\hat{L}}_{i=n-\theta}^{n}\,{}^{s}_{*}$ are temporary stored and sorted in compliance with the rank of classified sub-state metrics $\mu_{n,*}(s)$.

At time n, the generalized SOVE-like algorithm computes log extrinsic probability ratio on bit $a_{n-\theta,j}$ as:

$$\lambda^{e}\left(a_{n-\theta,j}\right)=\min_{1\le\omega\le\Omega}\left\{\min_{b\in B_n,\hat{a}_{n-\theta,j}\,{}^{b^-}_{\omega}=0}\left\{\mu_{n-1,\omega}\left(b^{-}\right)+\xi^{e,j}_{n,\omega}\left(b\right)\right\}\right\}-\min_{1\le\omega\le\Omega}\left\{\min_{b\in B_n,\hat{a}_{n-\theta,j}\,{}^{b^-}_{\omega}=1}\left\{\mu_{n-1,\omega}\left(b^{-}\right)+\xi^{e,j}_{n,\omega}\left(b\right)\right\}\right\}$$

or, more practically, as:

$$\lambda^{e}\left(a_{n-\theta,j}\right)=\lambda\left(a_{n-\theta,j}\right)-\lambda^{p}\left(a_{n-\theta,j}\right)$$

where $\lambda\left(a_{n-\theta,j}\right)$ the log a posterior probability ratio on bit $a_{n-\theta,j}$ defined as:

$$\lambda\left(a_{n-\theta,j}\right)=\min_{1\le\omega\le\Omega}\left\{\min_{b\in B_n,\hat{a}_{n-\theta,j}\,{}^{b^-}_{\omega}=0}\left\{\mu_{n-1,\omega}\left(b^{-}\right)+\xi_{n,\omega}\left(b\right)\right\}\right\}-\min_{1\le\omega\le\Omega}\left\{\min_{b\in B_n,\hat{a}_{n-\theta,j}\,{}^{b^-}_{\omega}=1}\left\{\mu_{n-1,\omega}\left(b^{-}\right)+\xi_{n,\omega}\left(b\right)\right\}\right\}$$

and $\lambda^{p}\left(a_{n-\theta,j}\right)$ the log a prior probability ratio coming from outer decoder:

$$\lambda^{p}\left(a_{n,j}\right)=\ln\frac{\Pr\left(a_{n,j}=1\right)}{\Pr\left(a_{n,j}=0\right)}$$

The generalized SOVA-like algorithm proceeds in a slightly different way. At time n, estimated bit-wise unsigned soft values $\hat{L}_{n,j}\,{}^{s}_{\omega}$ corresponding to the most recent symbol of the survivor $\underline{\hat{a}}_{i=n-\theta}^{n}\,{}^{s}_{\omega}$ are initialized to infinite value. Bit-wise soft values composing the sequence $\underline{\hat{L}}_{i=n-\theta}^{n}\,{}^{s}_{\omega}$ are updated from depth $i=n-1$ down to depth $i=n-\delta$ according to:

$$\hat{L}_{i,j}\,{}^{s}_{\omega}=f\left(\hat{L}_{i,j}\,{}^{s}_{\omega},\Delta_{n,j}\,{}^{s}_{\omega}\right)$$

where $f(.)$ is an updating function, and where:

$$\Delta_{n,j}\,{}^{s}_{\omega}=\mu_{n,\varpi_{i,j}}(s)-\mu_{n,\omega}(s)$$

with:

$$\varpi_{i,j}=\min\left\{l\ge\Omega+1,\ \hat{a}_{i,j}\,{}^{s}_{l}\ne\hat{a}_{i,j}\,{}^{s}_{\omega}\right\}$$

Following [10], the updating function can be simply approximated by:

$$f\left(\hat{L}_{i,j}\,{}^{s}_{\omega},\Delta_{n,j}\,{}^{s}_{\omega}\right)=\min\left(\hat{L}_{i,j}\,{}^{s}_{\omega},\Delta_{n,j}\,{}^{s}_{\omega}\right)$$

As soon as $n\ge\theta$, the algorithm delivers bit-wise signed soft decisions on bit $a_{n-\theta,j}$. Signed bit-wise soft values:

$$\lambda\left(a_{n-\theta,j}\right)=\left(2\times\hat{a}_{n-\theta,j}\,{}^{s_{best}}_{1}-1\right)\times\hat{L}_{n-\theta,j}\,{}^{s_{best}}_{1}$$

are calculated using the survivor path of first rank $\underline{\hat{a}}_{i=n-\theta}^{n}\,{}^{s_{best}}_{1}$ and the corresponding bit-wise unsigned soft sequence $\underline{\hat{L}}_{i=n-\theta}^{n}\,{}^{s_{best}}_{1}$, which both terminate, at section n, into trellis sub-state s_{best} defined as:

$$s_{best}=\arg\min\left\{\mu_{n,1}(s),\ s\in V_n\right\}.$$

Finally, useful approximated log extrinsic probability ratios on bits $a_{n-\theta,j}$ are computed bit-wise subtracting log a prior probability ratios $\lambda^{p}\left(a_{n-\theta,j}\right)$ coming from outer decoder to produce signed soft values:

$$\lambda^{e}\left(a_{n-\theta,j}\right)=\lambda\left(a_{n-\theta,j}\right)-\lambda^{p}\left(a_{n-\theta,j}\right)$$

We enclose this algorithmic description with few concluding remarks. In both generalized algorithms, all estimated paths (hard and soft, if any) need to be stored on the depth θ of a sliding window, within which they are updated. As a consequence, all depth indices related to this window are considered modulo θ. In the generalized SOVE-like algorithm, θ=K-1 to ensure that at a time, any symbol has passed all taps of the discrete-time ISI channel model. In the generalized SOVA-like algorithm, θ=5×(K-1) just like in a conventional Viterbi algorithm. δ parameter acts as the actual soft-deciding updating depth, but is usually taken identical to θ. The bottleneck of both generalized algorithms clearly lies in the path selection procedure. In [9], an analysis of several sorting methods is presented. In case where $\Omega\times 2^{q}$ is greater than 32, a quicksort algorithm should be used for the purpose of optimizing the execution speed.

4. The new turbo-detector

The inputs and outputs of the reduced-state SISO ISI decoder and of the outer SISO (BCJR) decoder are depicted on Figures 2 and 3 respectively.

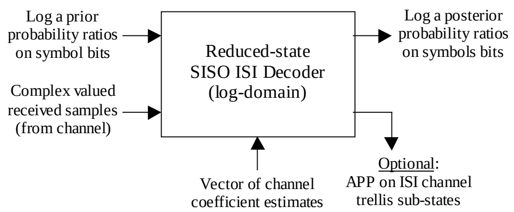

Figure 2: Reduced-state trellis-based SISO ISI decoder

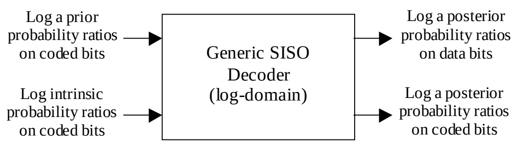

Figure 3: Outer SISO decoder

At first iteration, for each burst, the SISO ISI decoder produces a sequence of log extrinsic probability ratios on each bit of each modulation symbol, given the received burst and the current vector of estimated channel coefficients. No a prior information is yet available. After burst re-multiplexing and de-interleaving, the global sequence becomes a sequence of log intrinsic probability ratios for the outer SISO decoder. The latter evaluates the sequence of log extrinsic probability ratios on coded bits, which after re-interleaving and burst de-multiplexing, is passed to the SISO ISI decoder as a sequence of log a prior probability ratios on bits of modulation symbols for the next iteration. A recapitulative diagram is shown on Figure 4.

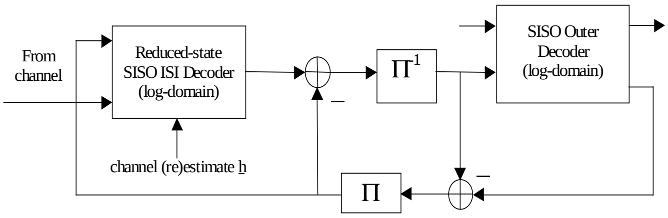

Figure 4: New proposed reduced-complexity turbo-detector

5. Performance analysis

The considered communication model is made of an outer recursive systematic convolutional code C of rate ½ and generator polynomials $(1,1+D+D^2+D^4/1+D+D^4)$. The employed bit-level interleaver Π is pseudo-random of depth 4096 bits. Interleaved convolutionally encoded bits are segmented into N=16 bursts of τ=128 QPSK symbols each. K-1 tail symbols are added to each burst before transmission. At the receiver side, the channel impulse response is supposed to be perfectly known.

To evaluate the robustness of the proposed reduced complexity turbo-detector, computer simulations have been realized on three severe long delay spread static ISI channels:

- Channel A is the 5-tap ISI channel given in [11]:

$$\underline{h}_A = \{0.227, 0.460, 0.688, 0.460, 0.227\}$$

- Channel B is the worst 6-tap ISI channel given in [11]:

$$\underline{h}_B = \{0.23, 0.42, 0.52, 0.52, 0.42, 0.23\}$$

- Channel C a static ISI channel of constraint length K=10, with all taps equally distributed:

$$\underline{h}_C = \{1/\sqrt{10},\ldots,1/\sqrt{10}\}$$

Figure 5 shows the performance in terms of Bit Error Rate (BER) of the turbo-detector on channel B and compares it with the optimal BCJR-based turbo-detector. For this simulation, the generalized reduced-state ISI decoder has been chosen SOVA-like with parameters L=3, Ω=4, θ=δ=40. We point out that at iteration 1, the BER remains relatively high. However, after few additional iterations, low BER can be achieved thanks to a powerful turbo-effect. At iteration 3, the optimal turbo-detector outperforms the reduced complexity version by 2.8 dB. However, in this simulation scenario, the sub-trellis on which the reduced-state ISI decoder proceeds has only 16 states to compare with the full ISI trellis state complexity of 4^5=1024 ! Taking into account the Ω parameter value, the difference in terms of computational complexity is roughly of an order 16.

Figure 6 illustrates the influence of Ω in the generalized SOVA-like version (channel B). As expected, increasing Ω leads to more accurate soft outputs (sign and magnitude), and consequently to a better overall performance of the iterative process. Note that this severe ISI configuration makes the SISO DDFSE [5][6] clearly too much sensitive to error propagation, highlighting the benefit of the GPSP technique. Contrary to a widely spread cut-and-dried opinion, we do not believe that iterative decoding can help to recover the theoretical information loss due to inner ISI decoding sub-optimality. However, Figure 7 clearly proves that, at similar computational complexity, and assuming transmission on channel A, using sub-optimal ISI decoders (generalized SOVE-like, L=3, Ω=2 and generalized SOVA-like, L=3, Ω=2, θ=δ=30) in an iterative scenario (4 iterations) can lead to a far better performance than performing one single iteration with an optimal ISI decoding (neglecting repetitive outer decoding and de/re-interleaving). Moreover, we point out that the SOVA-like algorithm produces a slightly better soft-output quality than the SOVE-like algorithm.

To conclude, we also show on figure 8 the performance of the proposed turbo-detector on channel C. For this last case, we employ the generalized reduced-state SOVE-like ISI decoder with parameters L=3, Ω=2. Of course, it was not possible to simulate the optimal case since the BCJR-based ISI decoder would require a trellis with 4^9=262144 states. On the contrary, our reduced complexity turbo-detector again proceeds on a far smaller 16-state trellis.

6. Conclusion

A modified turbo-detector employing generalized reduced-state SISO ISI decoders has been presented. This new sub-optimum advanced receiver should be used as soon as the optimal BCJR-based turbo-detection is discarded for prohibitive complexity reasons. An adequate choice of the multiple parameters of the scheme enables to trigger the turbo-effect even for the most severe long delay spread ISI channels. Therefore, this turbo-detector appears as a promising candidate for future mobile radio communications with high bit rate transmission, namely the future 4G TDMA systems operating in millimeter waves frequency band.

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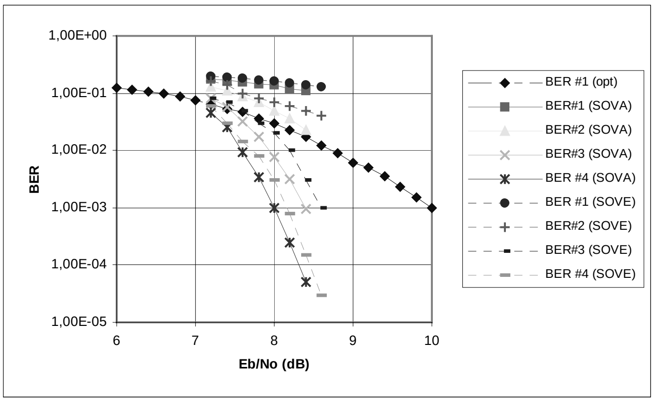

Figure 7: Reduced-state turbo-detectors versus optimal conventional receiver (no feedback) on static 5-tap ISI channel A

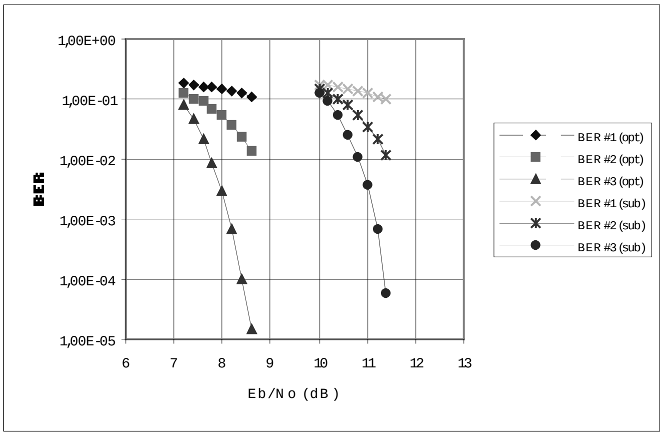

Figure 5: BJCR versus generalized reduced-state SOVA-like ISI decoders (Ω=4) on worst static 6-tap ISI channel B

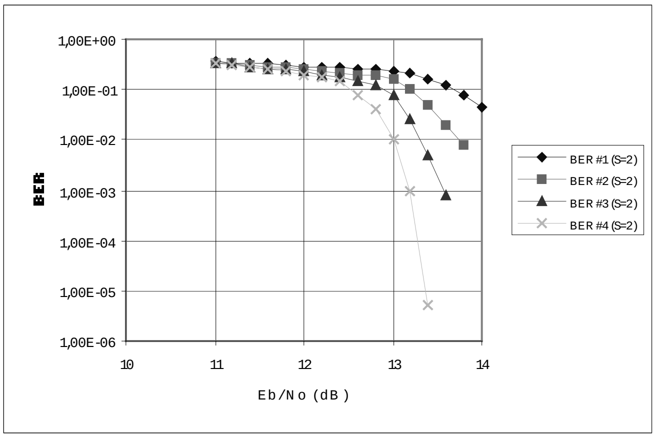

Figure 8: Turbo-detection performance using the generalized reduced-state SOVE-like ISI decoder on EQ static 10-tap ISI channel C

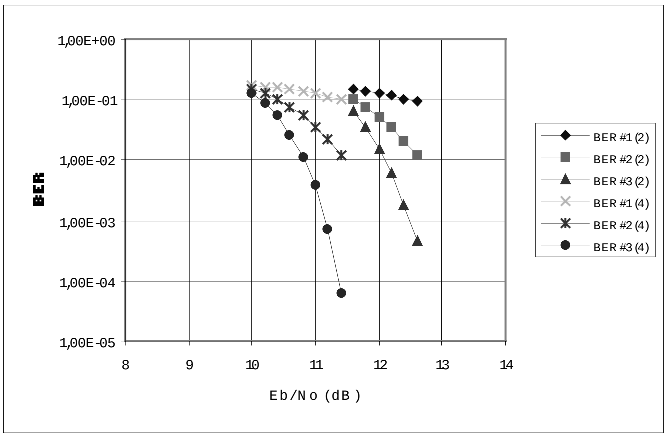

Figure 6: Influence of Ω parameter (=2 and 4 respectively) in the generalized reduced-state SOVA-like ISI decoder on worst static 6-tap ISI channel B