A NEW ALGORITHM FOR T/2-SOFT DECISION FEEDBACK BLIND EQUALIZER

VLADIMIR R. KRSTIC
Institute "Mihajlo Pupin"
Volgina 15, 11000 Belgarde
ZORAN PETROVIC
School of Electrical Engineering
Avenue of king Alexander 73, Belgrade
SERBIA AND MONTENEGRO
vladak@kondor.imp.bg.ac.yu http://www.imp.bg.ac.yu
zrpetrov@etf.bg.ac.yu http://www.etf.bg.ac.yu

Abstract – T/2 soft DFE is based on idea of transforming a classical DFE to a cascade of uncoupled linear devices. The crucial component of this cascade is a white filter, which supplies the linear T/2 FSE with uncorrelated samples. The adaptive whiting of input sequence is controlled by a stochastic gradient algorithm based on Joint Entropy Maximization (JEM-W) criteria which introduces soft decision properties at the very beginning of blind equalization. Soft decisions probably smooth the error surface and allow the algorithm to escape from local minima.

Keywords – Blind equalizer, white filter, fractionally spaced FIR filter, performance index, soft decision feedback

1 Introduction

The classical adaptive equalizers based on minimum mean square error (MMSE) criteria use the training with an ideal reference to acquire quick and reliable parameters adjustment. The sending of a training sequence is costly and sometimes is not applicable. Generally, any interrupt of transmission of payload bits because of sending a training sequence decreases an effective throughput. Besides that, there are systems where such training may not be possible or desirable, e.g., some broadband access systems [1].

These drawbacks of a classical training can be overcome using blind (unsupervised) equalization techniques. Instead of ideal reference, equalizer now has knowledge of statistical properties of the data signal sent by transmitter. One of the best known and the simplest blind algorithms is the Godard [2], which has been originally designed for a linear T-spaced FIR filter. Besides algorithms dedicated to linear FIR filters, there are solutions of blind equalizers using decision feedback techniques, which are the subject of the most recent investigations. These solutions can be very efficient on channels where the intersymbol interference (ISI) is dominantly caused by severe attenuation distortions or channels with multipath effects. The idea of using DFE as a basic framework for blind equalization is to find suboptimal solutions with a better cost-performance ratio than optimal but complex solutions based on Bayes estimation theory [3].

J.Labat, O.Macchi, and C.Laot [4] designed the blind equalizer which "…skips the training period" using a linearized and decoupled DFE structure where the feedback part of DFE is transformed into the all-pole white filter (WF) preceding the feedforward T-FIR filter. The task of a white filter is to supply the Godard T-FIR filter with uncorrelated samples so that its correlation matrix becomes well conditioned. The idea of the described transformation of DFE is to help the Godard equalizer at the start of acquisition mode to open eye diagram and increase convergence speed. Another key point of this solution is the setting of white filter coefficients that are what the feedback part of the classical DFE (optimal in MMSE sense) needs in the tracking mode. The solution [4] will be referred to in this paper as a linearized DFE (LDFE).

On the other hand, Y.H. Kim and S.Shamsunder [5] developed a new class of soft decision blind algorithms where the theoretical framework is based on joint entropy maximisation. Using this approach they naturally introduced a soft decision device into decision feedback structure so one can choose different nonlinear functions for decision device and get relatively simple stochastic gradient algorithms for decision feedback part of DFE. The soft decisions probably smooth the error surface and allow the algorithm to escape from local minima. This class of algorithms is known as JEM algorithms.

The new blind soft DFE presented in this paper integrates the key features of LDFE structure and JEM algorithms. The LDFE is realised with a fractionally spaced (FS) FIR filter instead of TS so the new soft DFE yields the well known advantages of FSE as they are suppressing timing phase sensitivity and noise enhancement. Besides this, the results of most recent investigations indicate that the Godard-FSE converges globally under some milder conditions than T-FIR filter [6]. Another important feature of this solution is activation of soft decision algorithm at the start of acquisition mode. This is realized by introduction of a new version of JEM algorithm (JEM-W) for white filter adjustment.

This paper is divided into five sections. The structure of T/2 soft DFE is described in Section 2. A new version of JEM algorithm for a white filter, JEM-W is derived in Section 3. The running control and performance index are described in Section 4. The results of computer simulations are presented in Section 5. The comparative performance tests are carried out for LDFE and T/2 soft DFE solutions using QPSK, QAM-16 and QAM-32 signal constellations.

2 T/2 soft DFE structure

T/2 soft DFE design follows the basic idea of decoupling and swapping places of the main components of the DFE [4]. When the T/2 soft DFE reaches the steady state then it is the classical DFE with a FS passband feedforward equalizer (FSE-T/2) placed upstream and feedback part (RF-T) and hard decision device placed downstream. The complex gain control is divided into the real automatic gain control and the carrier phase tracking second order loop [7]. At the start of equalization the FSE-T/2 and RF-T swap places and the RF-T becomes a recursive part of the all-pole WF preceding FSE-T/2. This order of linear transformers, especially, WF and FSE-T/2, is crucial for the blind equalization and this regime is called acquisition mode. It is important to emphasize that when this cascade reaches the steady state (tracking mode) the order of linear transformers becomes irrelevant and the whole equalizer can be described as a linear equalizer [4]. The structure of T/2 blind DFE is shown in Fig. 1a.

The function of WF is to supply FSE-T/2 with uncorrelated samples. The input and output sampling rates of WF are equal and amount to 2/T samples per second. This equality of sampling rates defines the structure of WF which is realized by two parallel TS white filters, one whiting odd and the other even samples. The realization of WF is shown in Fig. 1b.

When the blind equalizer reaches the defined performance index (MSE level) the T/2 soft DFE switches back into decision feedback structure. Since there are two TS white filters it is clear that only one of them, i.e. coefficients of its recursive part, will be translated into the feedback part of the DFE. The selection criterion of this transformation is coupled with selection of the reference tap of FSE-T/2. It means that the selected TS white filter is the one (odd or even) which supplies the reference tap with uncorrelated samples.

The performance index algorithm measures the MSE at the output equalizer and compares it with a defined threshold to switch DFE from acquisition to tracking mode and vice versa. The described T/2 soft DFE uses a slightly modified solution of performance index algorithm presented in [4]. This algorithm is not the subject of this paper.

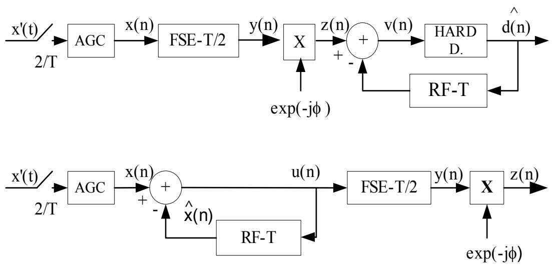

Fig. 1a. Structures of classical and linearized DFE

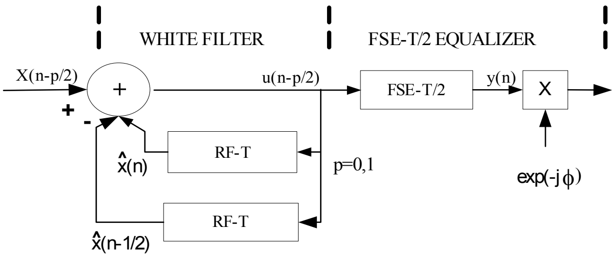

Fig. 1b. The white filter for T/2 FSE

3 JEM-DFE algorithms

The generic structure of JEM-DFE is illustrated in Fig. 2. A function g(.), used for soft decision device, should be a strictly monotone, differentiable function with a zero memory. The key point of this JEM-DFE is introduction of this nonlinear function into the adaptive algorithm so that the output sequence of estimated symbols {r(n)} has the maximum joint entropy.

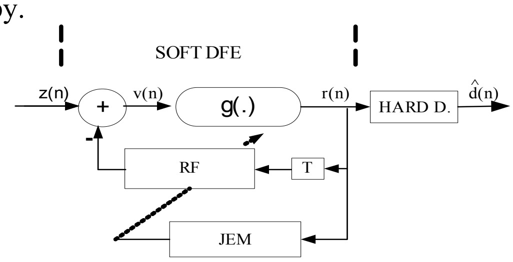

Fig.2, Block diagram of the basic soft DFE structure

Using this framework a new class of JEM algorithms is derived in [5]. Also, after simple approximations, some of these algorithms become identical with already known algorithms. Two of them are of interest for this work and will be repeated here.

The basic JEM algorithm is derived by introducing a hyperbolic tangent function $g(x)=\alpha\tanh(\beta x)$ into gradient descent

$$\text{JEM-1: } b^{n+1}(k) = b^{n}(k) - \mu\, r(n)\, r(n-k) \quad (1)$$

where $b^n(k)$ is k-th coefficient of RF at $t=nT$ and μ is a step size.

Using the Taylor series approximation for r(t) and r(t-k) in (1) and taking only the first term with $\alpha=3$ and $\beta=1/3$ JEM-3 algorithm is possible

$$\text{JEM-3: } b^{n+1}(k) = b^{n}(k) - \mu\, v(n)\, v(n-k) \quad (2)$$

This algorithm is exactly the same as the adaptive decorrelation algorithm used for the white filter in [4].

JEM-4 is derived in the same way as JEM-1 but using the cubic nonlinearity, $g(x) = \alpha x + \beta x^3$,

$$\text{JEM-4: } b^{n+1}(k) = b^{n}(k) + v(n)\, \{1 - 3\beta/\alpha\, v^2(n)\}\, r(n-k) \quad (3)$$

In the special case for $\alpha=3$ and $\beta=1$ this algorithm coincides with CMA-DFE algorithm.

The computer simulations results presented in [5] and herein references indicate that introducing soft decisions into DFE possibly smoothes the error surface and allows the algorithm to easily escape from local minima. This suggests the use of soft decision at the very beginning of blind equalization. This idea was the motive to propose a new JEM algorithm for WF.

A new decorrelation algorithm for white filtering, is JEM type and it is also derived from (1). Its current value of the joint entropy is approximated using Taylor series expansion and taking the two first terms

$$r(n)\, r(n-k) \approx \alpha^2\beta^2 v(n)\, v(n-k) - \alpha^2\beta^4/3\, v^3(n)\, y(n-k)$$
$$= \alpha^2\beta^2 v(n)\, \{1 - \beta^2/3\, v^2(n)\}\, v(n-k) \quad (4)$$

$$\text{JEM-W: } b^{n+1}(k)=b^{n}(k)-\mu v(n)\{1-\beta^2/3\, v^2(n)\}v(n-k) \quad (5)$$

One can see from (3) and (5) that the algorithms JEM-4 and JEM-W are similar because they use practically the same current value of error term. This common feature is important at the moment of switching structure: the JEM-W is activated at the start of acquisition mode and JEM-4 continues to update WF's coefficients after its transformation into decision feedback part of DFE. Using these two same type algorithms T/2 soft DFE probably reaches the smooth error surface which removes the local minima.

From the point of implementation of algorithms (3) and (5) it is impractical to manage parameters α and β separately. Because of that, the new common parameter BETA for both algorithms is introduced. In the special case for $\alpha\beta=9$ the parameter BETA is $\text{BETA}=3\beta/\alpha=\beta^2/3$. The BETA makes rounding of nonlinear functions, which is critical for soft DFE blind activation mode and also for steady state MSE. The optimisation and selection of BETA is carried out in Section 5.

4 Performance index monitoring

As emphasized above, the equalizer has two basic modes of operation: the acquisition and tracking mode. On the other hand, the acquisition mode, which is crucial for equalizer's activation, has two phases of operation one of which is a blind acquisition and another soft decision acquisition. Using this terminology the activation of the T/2 soft DFE can be summarized as it is done in the following Table 1,

Table 1

T/2 soft DFE STRUCTURE	PHASE of operation and ALGORITHM
1. LDFE	Blind acquisition
White filter	JEM-W
FSE-T/2	Godard
2. SOFT DFE	Soft DFE acquisition
FSE-T/2	Passband LMS
Decision feedback	JEM-4
3. DD DFE	Classical LMS

The described activation is controlled by the performance index monitor. Using in advance defined checkpoints, it makes switching of the structure and algorithms. As a measure of performance index of the running equalizer we use the estimated MSE of its output, denoted here as M. The MSE estimation is not the problem for the classical (trained) equalizers because they have an ideal reference or very good estimates of data symbols. On the other hand, blind equalizers have no reference for error counting what implies a new design of MSE estimator that should be suited to our T/2 soft DFE .

The basic recursive formula for MSE estimation is given by

$$M(k) = \lambda M(k-1) + (1-\lambda)|e(k)|^2 \quad (6)$$

where e (k) is the current value of error and λ is a so called "forgetting factor" that is slightly less than one, e.g., λ=0.99. In the blind phase of acquisition the error counting is refereed to the Godard factor R2 [2], which represents the statistical properties of transmitting signal. In that specific case formula (6) becomes

$$M_G(k) = M_G(k-1) + (1-\lambda)(\sqrt{|y(k)|^2} - \sqrt{R_2})^2 \quad (7)$$

where y(k) is the output of FSE/T2.

When the estimated MSE becomes less than an in advance defined threshold MSE_{SW-1} and the LDFE structure switches to the soft DFE, the MSE counting proceeds with a changed correction term. Now the soft DFE structure, Fig. 2, starts to generate estimated values of symbols $\hat{d}(k)$ (true output) so the error signal becomes decision directed type, $e(k) = (\hat{d}(k)-v(k))$. The formula (6) assumes now the final form

$$M_{DD}(k) = \lambda M_{DD}(k-1) + (1-\lambda)(|\hat{d}(k)-v(k)|^2) \quad (8)$$

Using MSE estimates given by (7) and (8) the , performance index monitor makes control of T/2 soft DFE according to the following rule:

$M_G(k_0) \geq M_{SW-1}$, blind phase for $k>k_0$, or (9)
$M_{DD}(k_0) < M_{SW-1}$, soft decision or tracking mode $k>k_0$
where $M_G(k_0-1) = M_{DD}(k_0-1)$ for any k_0.

Simulations carried out for different signal constellation sand voice-band channels have shown that the threshold MSE_{SW-1} must be chosen carefully to guarantee reliable switching of structure from LDFE to soft DFE and reverse. Especially, the performance index monitor must not allow the possibility of uncontrolled switching between two structures caused by a poor estimate of MSE in the blind phase. Generally, if the threshold level is higher than desired, the equalizer can switch to soft DFE before an eye diagram is opened enough and in that case the activation fails. On the other hand, if the threshold level is lower than desired the equalizer can stay permanently in a blind mode because the estimated MSE in the blind phase of acquisition, given by (7), has a minimum value for different signal constellations.

The T/2 soft DFE has to pass two thresholds during its activation, the first one MSE_{SW-1} and the second MSE_{SW-2}, where MSE_{SW-2} is less than MSE_{SW-1}. As described above, the threshold MSE_{SW-2} controls swapping of JEM-4 by a classical LMS algorithm when the equalizer enters the tracking mode. The carried out simulations have shown that choice of MSE_{SW-2} is not as critical as that of MSE_{SW-1} because the equalizer can permanently stay in soft DFE phase.

5 Computer simulations

T/2 soft DFE is tested with a software simulator designed for voice-band modem ITU-T V.32 [7]. This simulator is modified by changing classical trained equalizer with different solutions of blind equalizers. T/2 soft DFE simulations are carried out for QPSK, QAM16 and QAM32 signal constellations. The applied non-minimum phase voice-band channels are selected according to EIA methodology [7]. The attenuation and group delay characteristics which are used to synthesize channels with different levels of linear distortions are depicted in Fig 3.:

-channel 2 (EIA-B2) with modest attenuation and group delay,
-channel 3 (EIA-C2) with severe attenuation,
-channel 4 (EIA-B4) with severe group delay distortions.

The most important parameters of designed blind DFE are:

-T/2 FSE is 21 lengths in T intervals,
- feedback part is 6 lengths in T intervals,
- referent coefficient C_{ref} (k) = [Re, Im], is $C_{ref}(20)$=[1.7,0.0],
- R_2 statistics parameter for QPSK, QAM16 and QAM32 has the following values $R_{2,QPSK}$=10.0, $R_{2,QAM16}$=13.2 and $R_{2,QAM32}$=13.2, [2].

The carried out simulations are grouped into two basic tests:

-TEST 1, where the optimal values of BETA are fixed,
-TEST 2, comparative tests for T/2 hard DFE and T/2 soft DFE. The T/2 hard DFE is FS variant of the original solution of blind DFE presented in [4].

TEST 1: Taking into account a large number of simulations we checked an assumption about the existence of optimal values of parameter BETA in JEM-4 and JEM-W algorithms for different signal constellations and severity of channel degradation. This optimality is measured by steady state MSE while the BETA was taking values from range the {0.01, 0.20}. The simulations carried out on channel 2 have shown that the performances of T/2 soft DFE are practically independent of BETA. This result is expected because of a low level of ISI, so that the white filtering is not relevant in this case. On the other hand, the results with channels 3 and 4 have clearly indicated that the influence of BETA is critical. The optimal values of BETA for different signal constellations are

$BETA_{QPSK}$≈0.05, $BETA_{QAM16}$≈0.08 and $BETA_{QAM32}$≈0.08. The equal values of $BETA_{OPT}$ for QAM16 and QAM32 are caused by the same R_2 statistics of these signals, i.e., $R_{2,QAM32}=R_{2,QAM16}$. At the same time $BETA_{OPT}$ is 0.05 for signal QPSK which has $R_{2,QPSK}$=10.0. The steady state MSE for different values of BETA for channel 3 are shown in Fig 4a. In the case of channel 4, which is selected to represent voice-band channels with severe group delay distortions, it is shown that the MSE has not a unique minimum.

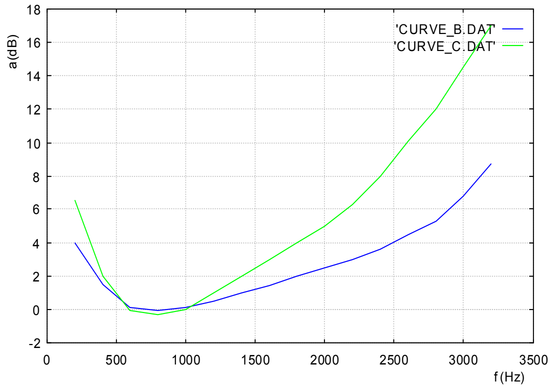

Fig. 3a. Channel attenuation curves: B-modest, C-severe

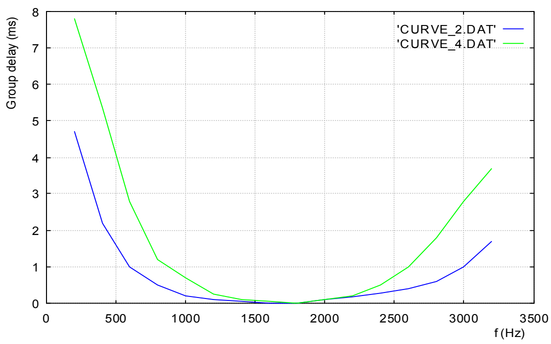

Fig. 3b. Channel group delay curves: 2-modest, 4-severe

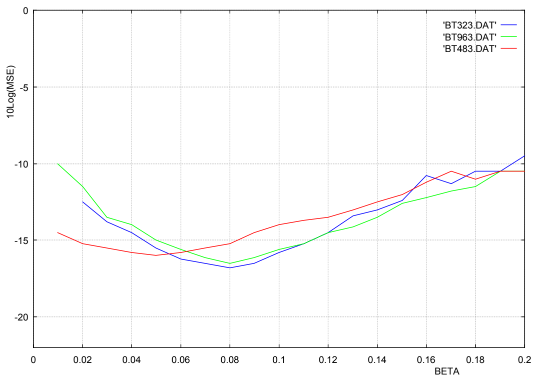

Fig. 4a. MSE versus BETA for channel 3
BT323=QAM32, BT963=QAM16, BT483=QPSK

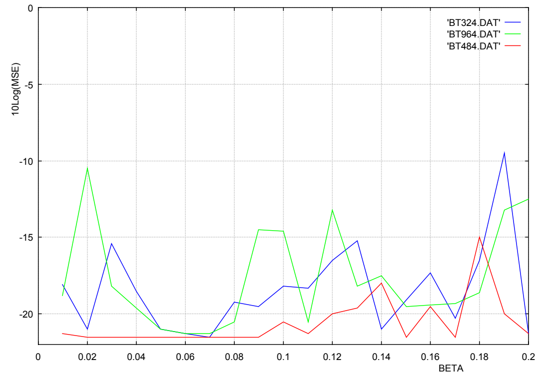

Fig. 4b. MSE versus BETA for channel 4
BT324=QAM32, BT964=QAM16, BT484=QPSK

One can see in the Fig 4b. a common region of $BETA_{OPT}$ where the equalizer reaches the minimum MSE for all of three signal constellations. This region surrounding BETA≈0.07 also coincides with $BETA_{opt}$ for channel 3. Besides this common region (minimum), there are a number of local minimums which are caused by non-minimum phase channel. It is reasonable to hope that $BETA_{opt}$ which can be fixed for channels with severe attenuation (channel 3) will also provide for desired parameters setting for all other channels (channel 4).

All these results of simulations considering rounding effects of nonlinear functions on MMSE are preliminary and will be the subject of a future study.

TEST2: These comparative simulations are carried out for two solutions of decision feedback blind equalizers: T/2 hard DFE and T/2 soft DFE. The last is optimized with the values of $BETA_{opt}$ fixed in TEST1. Fig 5a. presents the convergence curves for channel 3. The T/2 soft DFE has a lower MSE than T/2 hard DFE for about 1.8 dB and also a little better speed of convergence. This advantage of T/2 soft DFE over hard one becomes higher for channel 4, Fig 5b.,c.

The curves of convergence for QPSK have revealed that T/2 hard DFE has reached local minima and has not been able to escape from it when DFE was switching to the decision directed mode, Fig 5c. On the other hand, T/2 soft DFE has softly passed this switching and reached the same steady state MSE as QAM32. It is important to note that the efficiency of a soft DFE in the case of voice-band channels with phase distortions was the first time presented in [3]. It was a suboptimum equalizer, known as the estimated feedback, based on Bayes estimation theory.

6 Conclusion

This paper presents a new solution of blind soft DFE based on the idea of cascading and reversing the places of linear transformers, which are components of classical DFE, to defeat a difficult start of blind equalization. The key transformers, whiting filter and feedforward part are designed to support T/2 FS equalization. The adjustment of white filter and feedback part, during the acquisition mode is realised using joint entropy maximisation algorithms, JEM-4 and JEM-W. These two soft decision algorithms provide a "soft" switching from acquisition to tracking mode and reverse. This means, they probably smooth the error surface and allow the equalizer to easily escape from local minima. This efficiency and steady state performance superiority of T/2 soft DFE in comparison with hard decision solution is illustrated by a number results for different signal constellations.

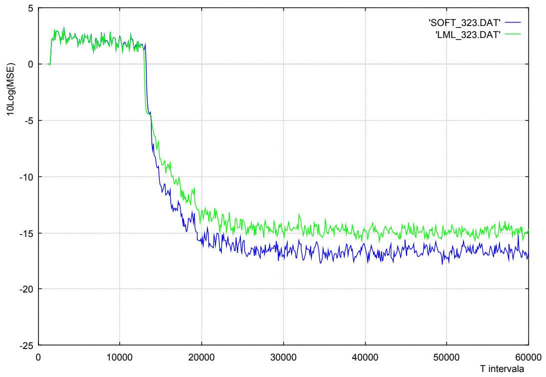

Fig. 5a. Channel 3, QAM32: MSE for T/2 soft DFE and LDFE

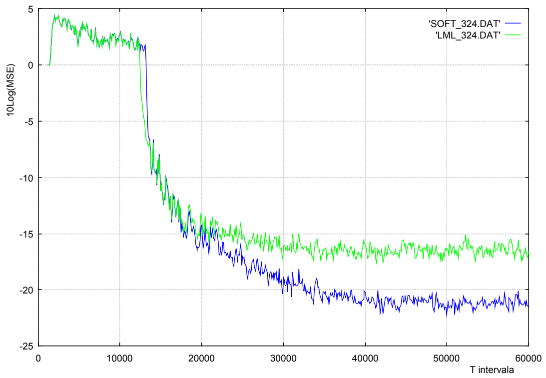

Fig. 5b. Channel 4, QAM32: MSE for T/2 soft DFE and LDFE

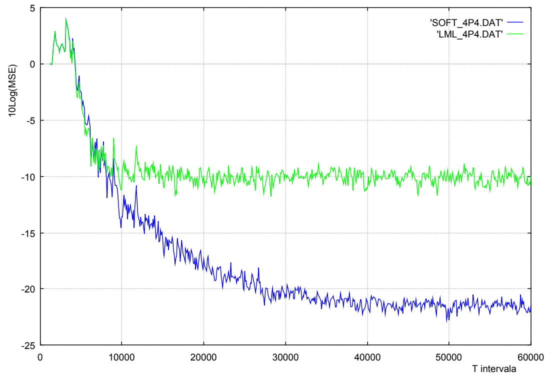

Fig. 5c. Channel 4, QPSK: MSE for T/2 soft DFE and LDFE

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