Turbo Equalization and Iterative (Turbo) Estimation Techniques for Packet Data Transmission

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Abstract: *In this paper we introduce a combined iterative estimation-equalization technique and study its performance/complexity trade-off for packet data transmission systems GPRS/EGPRS. It was found that iterative estimation is more beneficial in GPRS environment, showing 1dB gain after the fist estimation update, while only a slight improvement is observed after further turbo equalization rounds. On the other hand, the turbo equalization seems to be a preferable solution for EGPRS, providing 2-3dB gain for the price of receiver complexity.*

Keywords: iterative estimation, turbo-equalization.

1. INTRODUCTION

A general problem of reliable data transmission over channels with intersymbol interference (ISI) includes joint estimation, detection and decoding, and as a whole it is non-tractable because of tremendous complexity involved. A suboptimal method to solve this problem is to split the processing into tractable sub-blocks, and then iteratively exchange locally processed information among sub-blocks. For example, decoding of celebrated turbo codes is based on iterative information update among relatively simple decoders [1]. The same principle applied for channel equalization lead to turbo equalization (TE) scheme [2] that recently has gained a lot of interest [3,4]. This technique performs iterative ISI removal, where iterations proceed between a detector and a channel decoder relaying on channel estimates that usually are obtained based on a known training sequence.

However, in practice channel estimates may have rather poor quality that in turn deteriorates the efficiency of equalization. This fact motivated us to include a decision-directed adaptive channel estimation in the iteration process similar to TE.

In this paper we considered a combination of iterative equalization and estimation techniques and presented a simple method of updating channel estimate that includes decoder outputs into the iteration process. Then, we studied different iterative estimation-equalization scenarios for packet data transmission. In particular, we considered General Packet Radio System (GPRS), which provides packet data services in GSM environment via GMSK modulation. Another considered system is Enhanced GPRS (EGPRS), where GPRS data rates will be enhanced by 8PSK modulation used instead of binary GMSK modulation [5].

The paper is organized as follows. In Section 2 we introduce notation and overview of conventional receivers. In Section 3 we present a method of iterative channel estimation and propose a combined iterative estimation - equalization scheme. Trade-off between performance gain and receiver complexity in (E)GPRS under different scenarios is addressed in Section 4, with conclusions following in Section 5.

2. CONVENTIONAL RECEIVER

Let's consider a transmission of binary data u_i in blocks $\mathbf{u}=(u_0, u_1, ...u_{K-1})^T$, $\mathbf{u} \in \mathbb{Z}^K$ over a channel with a memory L in the presence of white Gaussian noise $\mathbf{w}$, i.e $w_n = \mathcal{N}(0, \sigma^2)$. We assume that channel impulse response (CIR) is unknown and characterized by complex channel taps $\mathbf{h}_L=(h_0, h_1,..., h_L)^T$. Data $\mathbf{u}$ are protected by a code, such that $\mathbf{c} = \Xi\mathbf{u}$, $\mathbf{c} \in \mathbb{Z}^N$. To assist channel estimation a known training sequence $\mathbf{m}$ is inserted in each coded block $\mathbf{c}$. The training sequence $\mathbf{m}$ consists of $L + P$ symbols, with L preamble and P midamble symbols; $\mathbf{m}=(m_0, m_1,..., m_{(P+L-1)})^T$. The resulting data block $\mathbf{a}$ of length N_b is arranged into sub-blocks, i.e. $\mathbf{a} = \left[\mathbf{c}_1^T \mathbf{m}^T \mathbf{c}_2^T\right]^T$, where $\mathbf{c}_i = (c_0^{(i)}, c_1^{(i)}, ...c_{\frac{N}{2}-1}^{(i)})^T$, $N_b = (N + L + P)$. Finally a data block $\mathbf{a}$ is mapped into M-ary symbols and transmitted with normalized symbol energy E_s=1.

According to maximum likelihood (ML) criteria, the optimal receiver is to find

$$\hat{\mathbf{u}} = \arg\max_{\mathbf{h},\mathbf{u}} p(\mathbf{r}|\mathbf{h}, \mathbf{a}) = \arg\max_{\mathbf{h},\mathbf{u}} p(\mathbf{r}|\mathbf{h}, \mathbf{m}, \Xi\mathbf{u}) \quad (1)$$

The optimal solution of (1) is prohibitively complex, and in practice the problem (1) is split into several ones, which are then considered separately. Separating channel equalization (detection) and decoding, and taking into account that the training sequence is known, a suboptimal solution for (1) may be presented as

$$\hat{\mathbf{a}} = \arg\max_{\mathbf{h},\mathbf{a}} p(\mathbf{r}|\mathbf{h}, \mathbf{a}) \Longrightarrow \hat{\mathbf{c}} = \arg\max_{\mathbf{h},\mathbf{c}} p(\mathbf{r}|\mathbf{h}, \mathbf{c}) \quad (2)$$

$$\hat{\mathbf{u}} = \arg\max_{\mathbf{u}} p(\hat{\mathbf{c}}|\mathbf{u}) \quad (3)$$

The optimal solution requires a search over all possible $\mathbf{c}$ and $\mathbf{h}$ that is impractical for realistic values of L, N. A typical suboptimal solution of (2) is to separate channel estimation and equalization, that leads to

$$\hat{\mathbf{h}} = \arg\max_{\mathbf{h}} p(\mathbf{r} \mid \mathbf{m}, \mathbf{h}) \quad (4)$$

$$\hat{\mathbf{c}} = \arg\max_{\mathbf{c}} p(\mathbf{r} \mid \hat{\mathbf{h}}, \mathbf{c}) \quad (5)$$

In particular, assuming a linear channel with time-invariant CIR during a transmitted block, a received block can be presented as

$$\mathbf{r} = \mathbf{A}\mathbf{h} + \mathbf{w} = \left[\mathbf{r}_{c_1}^T \mathbf{r}_m^T \mathbf{r}_{c_2}^T\right]^T$$

where $\mathbf{A}$ is $N_b \times (L+1)$ block matrix formed by data $\mathbf{c}_i$ and training sequence $\mathbf{m}$; $\mathbf{A}=\left[\mathbf{A}_1^T \mathbf{M}^T \mathbf{A}_2^T\right]^T$.

In a conventional receiver the channel estimation is made based on received symbols $\mathbf{r}_m = \mathbf{M}\mathbf{h} + \mathbf{w}$, and the ML channel estimate [7]

$$\hat{\mathbf{h}}_{ML}=\arg\max_{\mathbf{h}} p(\mathbf{r}_m|\mathbf{M}, \mathbf{h})=\mathbf{C}(\hat{\mathbf{h}}_{ML})\mathbf{M}^H\mathbf{r}_m, \quad (6)$$

where $\mathbf{C}(\hat{\mathbf{h}}_{ML}) = (\mathbf{M}^H\mathbf{M})^{-1}$ is a covariance matrix of the estimate.

Given $\hat{\mathbf{h}}$, one of equalization algorithms is applied to remove ISI and obtain $\hat{\mathbf{c}}$. Finally, a decoder recovers transmitted information $\hat{\mathbf{u}}$.

3. ITERATIVE DATA PROCESSING

3.1. Turbo equalization

In many cases the complexity of (2) remains unacceptable, and different forms of decision feedback equalizers (DFE) are used in practice to reduce the number of equalizer states. Another solution that is related to DFE is the method of turbo equalization [1]. This method is based on iterations between detection and decoding stages and tries to find a solution $\hat{\mathbf{u}}$ over a combined trellis formed by a multipath channel and encoder, i.e.

$$\hat{\mathbf{u}}=\arg\max_{\mathbf{u}} p(\mathbf{r}|\hat{\mathbf{h}}, \mathbf{m}, \Xi(\mathbf{u}))=\arg\max_{\mathbf{u}} p(\mathbf{r}|\hat{\mathbf{h}}, \mathbf{a}).$$

The equalizer provides soft decisions $\lambda^E(\hat{c}_n)$ on detected symbols $\hat{c}_n$, where $\lambda^E(\hat{c}_n)$ is some reliability information associated with the detected symbol $\hat{c}_n$ usually presented in a log-likelihood ratio form. Then soft decisions are deinterleaved and are fed into soft-in-soft-out (SISO) decoder. The decoder outputs soft decisions $\lambda^D(\hat{u}_n)$, $\lambda^D(\check{c}_n)$ both for information $\hat{\mathbf{u}}$ and coded $\check{\mathbf{c}}$ symbols. In case of turbo equalization the input (intrinsic) information should be removed from soft decisions to form so-called extrinsic information from decoder $\lambda_{ex}^D(\check{c}_n)$. Values $\lambda_{ex}^D(\check{c}_n)$ are interleaved and fed back into the equalizer as *a priori* information that usually allows the equalizer to make more reliable decisions than at the previous round. Updated equalizer outputs are used again in the SISO decoder and iterations are repeated as needed.

3.2. Iterative (turbo) estimation

In the turbo equalization scheme the iteration proceeds between the signal detector and channel decoder assuming a known channel state during iterations. In many cases the accuracy of channel estimates based only on a relatively short training sequence $\mathbf{m}$ is not enough, and that in turn may cause a significant degradation in the receiver performance, which cannot be fully compensated by the turbo equalization. This fact motivated us to use a decision-directed adaptive channel estimation method during the iteration process similar to [6]. The idea is to feed back decoded symbols to the channel estimator and update previous channel estimates assuming that the whole burst is now known by the receiver (Fig. 1). Hence, the receiver uses decoded data symbols $\hat{\mathbf{u}}$ and a known training sequence $\mathbf{m}$ to calculate a new channel estimate. In other words, the receiver iteratively updates channel estimates based on an "extended" training sequence. In particular, decoded data $\hat{\mathbf{u}}$ are once more encoded and combined with the training sequence $\mathbf{m}$, forming a new "extended" training sequence $\hat{\mathbf{a}}$ of length $N_b = P + L + N$. If we would use all available data $\mathbf{a}$ as the known training sequence, then in AWGN channel the ML channel estimate is

$$\widehat{\mathbf{h}}^{extend} = \mathbf{C}(\widehat{\mathbf{h}}^{extend})\mathbf{A}^H\mathbf{r} \quad (7)$$

where the covariance matrix of the new "extended" estimate is

$$\mathbf{C}(\widehat{\mathbf{h}}^{extend}) = (\mathbf{A}^H\mathbf{A})^{-1}$$
$$= (\mathbf{A}_1{}^H\mathbf{A}_1 + \mathbf{M}^H\mathbf{M} + \mathbf{A}_2{}^H\mathbf{A}_2)^{-1} \quad (8)$$

To avoid computation demanded calculation of matrix inverse in (8), we can use some adaptive algorithm to update channel estimates. In this paper we applied stochastic adaptation of estimates based on the LMS algorithm [7]

$$\widehat{\mathbf{h}}^{(k+1)} = \widehat{\mathbf{h}}^{(k)} - \mu(\hat{\mathbf{A}}^{(k)})^H(\hat{\mathbf{A}}^{(k)}\widehat{\mathbf{h}}^{(k)} - \mathbf{r}) \quad (9)$$

where $\widehat{\mathbf{h}}^{(k)}$ is an estimate from kth iteration, $\hat{\mathbf{A}}^{(k)}$ is an estimated data matrix containing all (data + training) symbols known at kth iteration, $\mathbf{r}$ is a received vector and μ is a step size of the iterative algorithm. At the initial round the channel estimate could be based on some conventional method, e.g.(6).

3.3. Combined turbo estimation-equalization

Iteratively updating channel estimate and decoded symbols (turbo-estimation) on one hand, and detected and decoded symbols (turbo-equalization) on the other hand, we actually try to find a solution for the general problem (1).

The suggested algorithm may be described as follows:

<u>Initialization</u> (conventional receiver):

1. Make an initial channel estimate based on the known training sequence. The initial channel estimate could be based on some conventional method, e.g. one-shot estimate,

$\widehat{\mathbf{h}}^{(0)} = (\mathbf{M}^H\mathbf{M})^{-1}\mathbf{M}^H\mathbf{r}_m$

2. Given a channel estimate $\hat{\mathbf{h}}$, detect a sequence $\hat{\mathbf{c}}^{(0)}$, e.g.

$\hat{\mathbf{c}}^{(0)} = \arg\min_{\mathbf{c}} \left\| \mathbf{r}_c - \mathbf{A}\hat{\mathbf{h}}^{(0)} \right\|^2$

3. Decode detected symbols

$\hat{\mathbf{u}}^{(0)} = \arg\min_{\mathbf{u}} \left\| \hat{\mathbf{c}}^{(0)} - \Xi(\mathbf{u}) \right\|^2 = \Omega(\hat{\mathbf{c}}^{(0)})$

Iterations (iterative receiver)

4. Based on decoded symbols make re-encoding operation, $\check{\mathbf{c}}^{(k)} = \Xi\Omega(\hat{\mathbf{c}}^{(k)})$ for the kth iteration.

5. Rebuild matrix $\check{\mathbf{A}}_i^{(k)}$ $(i = 1, 2)$ based on the updated $\check{\mathbf{c}}_i^{(k)}$ ($\hat{\mathbf{c}}_i^{(k)}$ for uncoded data).

6. Update channel estimate using some adaptation rule, e.g. the LMS:

$\widehat{\mathbf{h}^{(k+1)}} = \hat{\mathbf{h}}^{(k)} - \mu(\check{\mathbf{A}}^{(k)})^H(\check{\mathbf{A}}^{(k)}\hat{\mathbf{h}}^{(k)} - \mathbf{r})$

7. Given channel estimate $\widehat{\mathbf{h}}^{(k+1)}$, update detected sequence $\hat{\mathbf{c}}^{(k+1)}$ as

$\hat{\mathbf{c}}^{(k+1)} = \arg\min_{\mathbf{c}} \left\| \mathbf{r}_c - \mathbf{A}\widehat{\mathbf{h}}^{(k+1)} \right\|^2$

In case of turbo-equalization the extrinsic information from decoder $\lambda_{ex}^D(\check{c}_n)$ is to be used for the sequence update.

8. Update decoded symbols $\hat{\mathbf{u}}^{(k+1)} = \Omega(\hat{\mathbf{c}}^{(k+1)})$. In case of turbo-equalization the decoder is to provide the soft outputs $\lambda^D(\check{c}_n)$ (it also applies to the step 3).

9. Iterate between steps 4-8 (turbo-estimation) or/and between steps 7-8 (turbo-equalization) as needed.

4. PERFORMANCE EVALUATION

To find an efficient way to perform iterations described above it is necessary to study trade-off between receiver complexity and performance gain provided by different iteration scenarios. Turbo equalization method is based on soft decision decoder outputs that itself significantly (2-4 times) increases decoder complexity. On the other hand, iterative estimation method in the form presented above does not require soft decisions and hence, modifications of the decoder. A simple channel update based on an adaptation rule allows us to avoid complex calculations associated with matrix inverse.

As a practical testbed we considered performance of different iterative receivers for GPRS/EGPRS in typical mobile radio channels. In this paper we present simulation results for CS1 (GPRS) and MCS5 (EGPRS) coding schemes that employ $\frac{1}{2}$-rate convolutional codes [8]. Rectangular interleaving over 4 bursts is used in all cases. We used the estimator (6) with the LMS adaptation rule (9) and equalizers with 5 and 6-taps. Quality of service in packet data transmission is characterized by block error rate (BLER), but bit error rate (BER) is also shown at performance figures.

We evaluated performance of different iterative scenarios in typical urban, bad urban and hilly terrain channels with speed v=3 (TU3), 50 (BU50) and 100km/h (HT100), respectively.

The performance figures are presented for:

(a) the conventional receiver (Fig.2-5, solid lines);

(b) separately after turbo equalization (Fig.2,4), and after iterative channel estimate update (dashed lines at Fig.3 and Fig.5);

(c) after turbo equalization iterations, where the channel estimate is no more changed (Fig.3, dash-dotted lines).

Performance gain obtained from iterative data processing is summarized in Table 1. Here we present results obtained from only turbo-estimation and turbo equalization after 2 and 4 iterations, where 1st iteration corresponds to the conventional receiver. In case of the combined turbo estimation-equalization we used only one turbo round for each operation. For example, in case of GPRS the gain achieved after one channel estimate update is around 1dB at BLER=10^{-2}, and the turbo equalization is able to provide only 0.2 dB extra gain on top of that (Fig.3). The iterative estimation used alone shows also the same improvement in EGPRS environment (Fig.5). However, now the turbo equalization provides 2-3 dB gain (Fig.4) and that may justify the increase of decoder complexity to provide soft decisions.

Table 1. Performance improvement from iterative methods at BLER=10^{-2}

Coding scheme	Code rate	Modulation	TEqu 2it/4it	TEst 2it/4it
CS1	0.5	GMSK	0.2/0.3	1.0/1.1
MCS5	0.53	8PSK	2.2/3.2	1.0/1.1

Coding scheme	Code rate	Modulation	TEst & TEqu one round each
CS1	0.5	GMSK	1.1
MCS5	0.53	8PSK	2.4

5. CONCLUSIONS

In this paper we studied the trade-off between receiver complexity and performance gain provided by different receivers utilizing turbo equalization and the suggested iterative channel estimation technique. It was found that turbo-estimation is beneficial mainly in GPRS environment, where more complex turbo equalization practically does not improve performance. At the same time in EGPRS case the turbo equalization seems to be an attractive solution showing more than 2dB gain.

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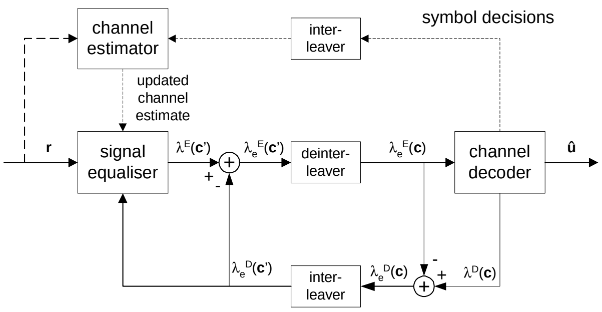

Fig.1. Block diagram receiver with iterative estimation-equalization.

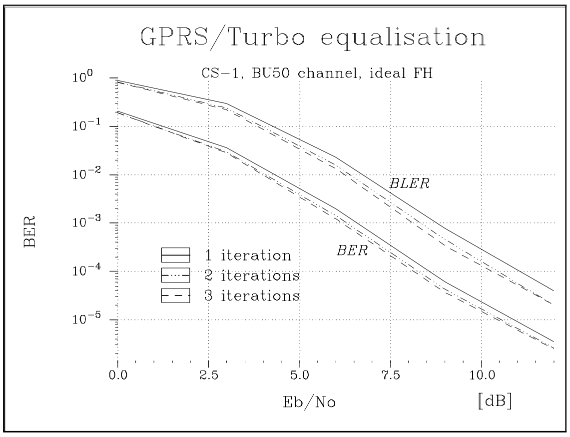

Fig.2. Performance of turbo-equalization in GPRS.

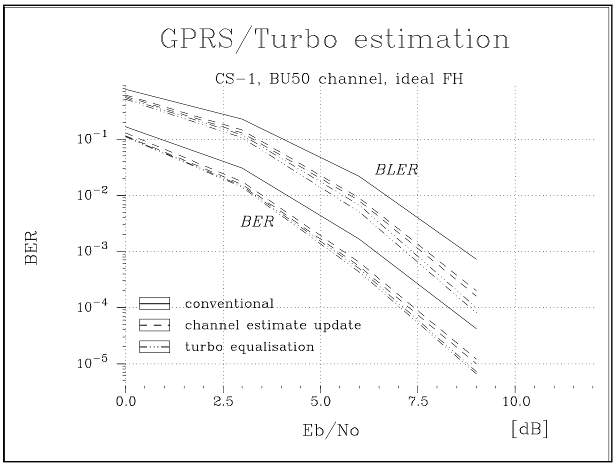

Fig.3. Iterative (turbo) estimation in GPRS.

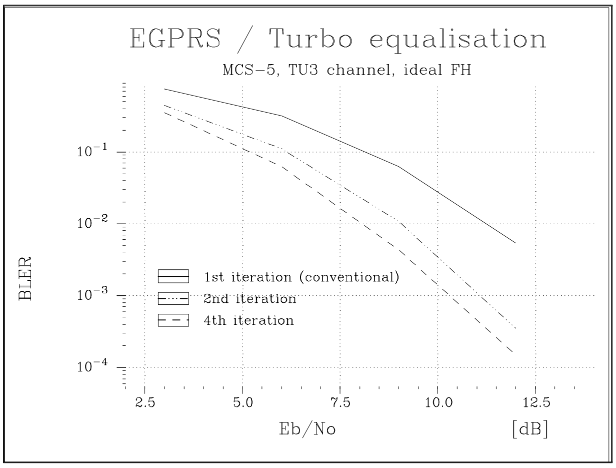

Fig.4. Performance of turbo-equalization in EGPRS.

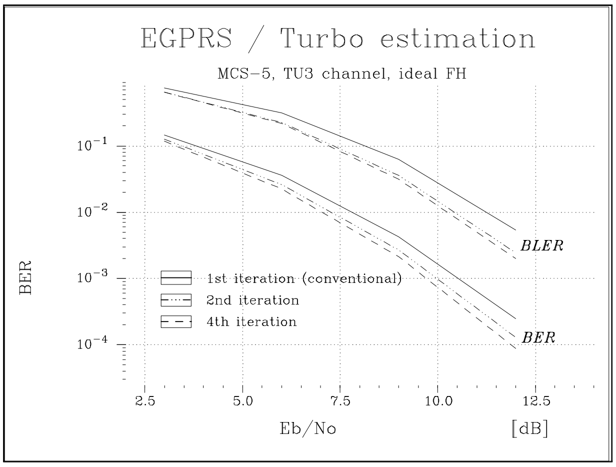

Fig.5. Iterative (turbo) estimation in EGPRS.