IMPLEMENTATION OF NEAR OPTIMUM ELECTRICAL EQUALISATION AT 10 Gbit/s

H. F. Haunstein (1), K. Sticht (1),
A. Dittrich (2), M. Lorang (2), W. Sauer-Greff (2), R. Urbansky (2)

(1) Lucent Technologies Network Systems GmbH, D-90411, Nuremberg, Germany (hhaunstein@lucent.com)
(2) University of Kaiserslautern, D-67663 Kaiserslautern, Germany (sauer@eit.uni-kl.de)

The paper proposes modifications of the Maximum-Likelihood Sequence Estimator to implement a 10 Gbit/s Viterbi equaliser for nonlinear fibre channels. Performance comparisons for Viterbi, decision feedback and optimum threshold receivers are presented.

Introduction

In the last decades significant improvements of optical components and concepts extended the capacity of long-haul optical fibre transmission systems. Several linear and nonlinear effects like chromatic dispersion, Polarization Mode Dispersion (PMD) due to Differential Group Delay (DGD), chirp and EDFA noise in combination with direct detection result in systems corrupted by non-gaussian, signal dependent noise and nonlinear Intersymbol Interference (ISI) /1/. To compensate for ISI, several concepts have been proposed like dispersion compensation and optical PMD compensation /2/. Electrical equalisation for multi-Gigabit systems using threshold adaptation, Feed Forward Equalisation (FFE) and Decision Feedback Equalisation (DFE) have been discussed since several years and, by improvements in microelectronics, became more attractive as recently published /3,4/.

This paper presents a finite state model which approximates the nonlinear fibre transmission system and allows to state the Maximum Likelihood Sequence Estimator (MLSE) minimising the overall error probability. Bounds of error performance for fibre systems can be derived from the MLSE. Implementation considerations require a simplified pre-filter and a low resolution AD Converter (ADC). Also a generalized DFE for nonlinear channels without ADC is derived. Performance results for optimal threshold, DFE and MLSE receivers conclude the paper.

Channel model

In communications theory, optimal and suboptimal symbol and sequence estimation for minimum Bit Error Rate (BER) (Standard Receiver) in the presence of ISI and noise is well known. The implementation of an MLSE for binary symbols α ∈ A at symbol duration T requires an overall channel (including transmitter, fibre and photo detector receiver) with finite memory length of L symbols, which is fulfilled in fibre systems. In that case a state table S(α(µ)) with 2^L + 1 entries, addressed by the current and L passed symbols α(µ)=α(µ),...α(µ-L)), represents the channel model /5/, see Fig. 1. A Least Mean square algorithm estimates the table entries from the received electrical signal r(µT) /6/. To obtain a near time-continuous model output, corresponding to sampling phases 0≤φ<2π, the state concept extends to S(α(µ));ϕ], where the state table entries have to be replaced by chips (or oversampled waveform) of duration T/2. The chip state approach also allows for time efficient simulation, channel estimation and equalisation.

Maximum-Likelihood Sequence Estimator

The analogue front-end of an MLSE which minimises the error probability of the estimated sequence a consists of a bank of filters matched to the 2^L + 1 chips S(b(µ);ϕ]. For a linear channel one Matched Filter (MF) only is required /5/. Let w_b(µ) denote the MF outputs sampled at the symbol rate T. With the energy E_b(µ) of each of the chips, the ML sequence calculates to

\[ \hat{a} = \arg \max_{b \in A} \sum_{\mu} w_b(\mu) - \frac{1}{2} E_b(\mu) \]

where \( f[w_b(\mu),b(\mu)] \) are the metric increments along the state sequence \( [b(\mu)] \) related to the symbol sequence \( b \).

A trellis representation of the state model, i.e., the state diagram plotted along the time axis, is more convenient to solve (1), where the Viterbi Algorithm (VA) is a well known trellis-based strategy with a complexity of 2^L states. Also, the MLSE error bound can be calculated. Compared to the MF bound (without ISI) it characterises the ISI penalty.

From a practical point of view, it is highly desirable to replace the bank of matched filters by a simple noise limiting lowpass filter. Let w(µ) denote the sampled low pass output, let S(b) be the discrete time channel model including the lowpass filter and the sampling device, and suppose the noise samples are uncorrelated. Corresponding to (1) the Viterbi equaliser computes

\[ \hat{a} = \arg \max_{b \in A} \sum_{\mu} w(\mu) \cdot S[b(\mu)] - \frac{1}{2} (S[b(\mu)])^2. \]

Figure 1: Transmission Scheme
Low Resolution Quantization

Presently, a high resolution ADC at several Giga-samples per second is the most critical component in the Viterbi equaliser concept. Therefore, the q bit quantized VA input \( w_q(\mu) \) results in a quantization noise. However, the ADC may be included into the nonlinear channel model by using \( w_q(\mu) \) instead of \( w(\mu) \). Then, the metric increment \([f_{\mu}^w, b]\)
of (1) and (2) can be implemented by a lookup table with \( q+L+1 \) address bits. The Viterbi Equaliser (VE) hardware concept is based on block processing, similar to /1/.

Generalized DFE

For low complexity, threshold detection is preferred, cf. FFE and DFE receivers for linear ISI /5/. Since linear and nonlinear feed forward equalisation affects the noise adversely and extends the amount of nonlinearity, a pure FFE is less preferable. A generalized DFE for nonlinear channels without ADC results from (2). Suppose, the previous \( L \) estimated bits correspond to the channel state: \( \hat{a}(\mu|\mu)=\{\hat{a}(\mu-1),...\hat{a}(\mu-L)\} \). Using the state dependent threshold \( f[\hat{a}(\mu)]=2[S[1,\hat{a}(\mu)]+S[0,\hat{a}(\mu)]] \), the estimated bits are given by \( \hat{a}(\mu)=1 \) for \( w^q(\mu)>f[\hat{a}(\mu)] \), else \( \hat{a}(\mu)=0 \) /6/.

Results

A 10 Gbit/s scenario depicted in Fig.1, which includes PMD, chromatic dispersion and fibre nonlinearity, is used to assess different equalizers. Fig.2 shows the DGD spectrum for a span of 600 GHz. Sampling the spectrum equally spaced with 10 GHz, the received signal for each spectrum for a span of 600 GHz. Sampling the spectrum to assess different equalizers. Fig.2 shows the DGD PMD, chromatic dispersion and fibre nonlinearity, is used

Figure 2: DGD Spectrum of Simulated Fibre in Fig.1

Figure 3: BER of Quantized Input Viterbi Equaliser

Figure 4: Equaliser Performances

Conclusions

To simulate fibre systems for arbitrary long bit sequences, the state table model provides sufficient accuracy at significantly decreased numerical effort. For the investigated systems, an VE is close to the MLSE error bound and reduces the power penalty significantly. The modified DFE is a good compromise with acceptable performance for moderate DGD. However, for closed eye systems a VE, even with a low bit quantization, keeps within acceptable penalty, whereas other concepts fail.

References