Proceedings of the 6th Nordic Signal Processing Symposium - NORSIG 2004
June 9 - 11, 2004
Espoo, Finland

REDUCING IMPULSIVE NOISE IN DSL SYSTEMS - ROBUSTNESS AND DELAY

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ABSTRACT

A canonical piece-wise-linear filter (CPWL) realization is proposed as part of the scheme for non linear time - domain equalization (TEQ) aiming impulsive noise interference reduction in xDSL transmission systems. The resulting structure is discussed in the context of a VDSL system using Reed-Solomon (RS) coding and interleaver to prevent impulsive noise effects. Also, a recently introduced impulsive noise model is used in order to evaluate the new methodology. The results are compared evaluating the performance of the new structure with different impulsive noise sample and different interleavers deep. The delay , for a free error system, in the new design and the linear design are compared to show the improvement obtained using the CPWL structure.

1. INTRODUCTION

Digital subscriber line (DSL) transmission is today one of the fastest growing technologies [1]. Since twisted-pair wires in the telephone network are unshielded and many wires are tightly bundled in thick cables, there are a number of interferences that must be considered. For the particular cases of ADSL and VDSL, crosstalk (NEXT, FEXT), radio frequency interference (RFI) and impulsive noise are the main disturbances to be contemplated. Some basic ideas can be applied to mitigate IN in multicarrier modulation. In [20] a variety of error control techniques are discussed. They are focused on enhancing the RS code performance.

Of particular interest in this work are the characteristics and alternatives to reduce impulse noise (IN) interference effects in VDSL systems. IN in access networks has been extensively studied over a number of years. Large surveys have also been performed by many telephone companies, [2, 3, 4]. Due to the non-stationary behavior and large variety of sources, no complete statistical IN model exists. Despite of that, recent proposed models [5] seems to reflect the most harmful effects on the DSL interface.

The concept to combat IN effects is closely related to non-gaussian detection that is a classical subject [6] for the single user channel case. Non-gaussian signal detection for CDMA multiuser channels is a subject of increasing interest [7] [10] [12]. Following these ideas, improved detection can be obtained if an specific nonlinearity is introduced before linear detection is performed.

We propose here a kind of nonlinear filter [8] that is amenable to previous linear TEQ designs (i.e., only the training algorithm needs to be changed) whose objective is twofold: to reduce the intersymbol interference in an IN context, if compared to a classical MMSE TEQ design, and to change the statistics at the receiver input in order to improve detection performance. Since coding and interleaving are at hand to prevent IN effects, the robust nonlinear TEQ is a complementary alternative to obtain a different trade-off between delay and performance. Interleaving delay is the main concern for real time DSL application .

The paper presentation is the following. A brief a description of the DSL system environment of interest is presented in Section 2, where all signals and perturbations involved are modeled. In addition, some special attention is given to the most recent IN models available in the literature. The description of a scheme suitable for IN reduction, that use a CPWL filter as basic building block modifying a conventional MMSE time-domain equalizer (TEQ), is included in Section 3. In Section 4, a discussion of specific aspects and simulations are presented. Finally, some conclusions are presented in Section 5.

2. VDSL SYSTEMS AND IMPULSIVE NOISE MODELS

VDSL systems use DMT modulation, i.e. a multicarrier scheme [1]. The number of bits allocated to each carrier are a function of the corresponding subchannel signal-to-noise ratio and are modulated with QAM techniques.

We use $b_i = (1/2)\log_2(1 + SNR_i\gamma_{coding}/\Gamma\gamma_{margin})$ to define bit allocation, where $SNR_i = \xi H_i^2/\sigma_{i_{TOTAL}}^2$ is the SNR per tone, ξ is the energy per symbol, $\sigma_{i_{TOTAL}}$ is

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the total noise that includes AWGN and NEXT and FEXT interferences, H_i is the subchannel loss, γ_{coding} is the coding gain, Γ is the gap, γ_{margin} is the noise margin. If the cyclic prefix v is large enough, the DMT system is equivalent to N sub-channels $Y_k = X_k H_k + n_k$, where H_k is the channel transfer function for tone k. The ratio $N/(N+v)$ define the system efficiency. To avoid a large cyclic prefix, a channel shortening equalizer (TEQ) is used before the FFT.

On the other hand, IN in access networks has been extensively studied over a number of years. IN modelling is an area of growing interest, but is characterized by the lack of an unified result. Among the most popular IN models are [11] and [5]. Since the Gaussian mixture model of [11] has parameters not easy to test, a more complete model seems to be required. In [5] a set of IN models were discussed. The main parameters of this model are: i) the inter-arrival time generator that is modeled using a Poisson distribution, given by $f(t) = \lambda e^{-\lambda t}$, where λ (Hz) is the parameter associated, ii) the impulse width that has a Log-Normal distribution, given by $f(t) = \frac{1}{2\pi S_1 t} e^{\frac{1}{2\pi S_1^2} ln^2(\frac{t}{t_1})}$, and iii) the pulse amplitude modeled with a Weibull distribution, given by $x = \frac{\alpha b}{2} y^{\alpha-1} e^{-by^{-\alpha}}$.

2.1. Coding and interleaver

The impulsive noise have amplitude levels 30 dB bigger than NEXT interference [21] and its duration can reach $500\mu s$. If we consider a FDD VDSL System ($200\mu s$ DMT symbol duration), the IN can affect up to 3 DMT symbols . In addition to the specific gap γ used in the bit allocation algorithm, the strategies to combat IN include forward error correcting codes (FEC) and interleaving.

Usually Reed-Salomon (RS) (n, k) codes are used in VDSL systems. This codes introduce $n-k$ parity bytes which help to correct up to $(n-k)/2$ symbols. Interleaving is used to protect bursts of errors by spreading the errors over a number of RS codewords. The use of interleavers improves system robustness against IN and other interferences. However, its use introduce also transmission delay, that is not suitable for real-time applications. The delay is a function of the data rate and burst error correction capability.

With the purpose to reduce the IN effects, i.e., obtain reduced deep interleavers and also improved system performance, a new non-linear TEQ design is introduced in the following section.

3. NONLINEAR TEQ BASED ON CPWL FILTERING

Basic ideas to perform detection in a non-gaussian environment in single, or even multiuser applications can be summarized in the introduction of a controlled nonlinearity that copes with the harmful effects of IN, in a complementary form to the usual linear (ML) detection scheme [10] [7] [9].

One example of this is the transformation model introduced in [10] where, in a CDMA application context, a tuned clipper previous to a linear estimator is proposed. A different approach was used in [7] where nonlinear regression is performed using the M-estimation based regression concept for CDMA, or even DSL applications [9]. An additional example, also in CDMA, was the proposal of [12], where a neural network preprocessing was introduced in order to reduce non-gaussian noise effects. These are only some examples of the many research efforts being addressed to this purpose.

The key idea presented here is to modify a basic TEQ design in order to obtain a more robust behavior of the detection scheme. This modification has two purposes: to introduce a robust TEQ design and to change the noise statistics at the output in order to obtain an improved system performance.

The proposed robust TEQ will replace linear FIR filter by a canonical piece-wise-linear filter (CPWL) [14] [15]. The CPWL approach is an approximate representation of a nonlinear function, essentially composed of a FIR filter followed by an static nonlinearity. It replaces the global nonlinear function by a set of linear subfunctions which are defined in properly partitioned sub-regions of the original nonlinear function domain. For the linear part, it is possible to consider an N_w-order FIR realization given by

$$v(k) = \sum_{i=0}^{N_w} w_i x(k-i) = \boldsymbol{w}^T \boldsymbol{x}(k) \tag{1}$$

where $\boldsymbol{w} = [w_0 \ \cdots \ w_{N_w}]^T$. The static nonlinear function allows to describe the output of the nonlinear filter as $y(k) = f(v(k)) : \boldsymbol{R} \longrightarrow \boldsymbol{R}$. The partition related to the CPWL approximation is defined by $v = \beta_j$. Thus, the β_j divide the output domain, where $\beta_1 \leq \beta_2 \leq \cdots \leq \beta_M$. Using the basis function of [15],

$$\Lambda_i(v(k)) = \frac{1}{2}\left(v(k) - \beta_i + |v(k) - \beta_i|\right) \tag{2}$$

the CPWL has the special form given by

$$f(v(k)) = \boldsymbol{c}^T \boldsymbol{\Lambda}(v) \tag{3}$$

where $\boldsymbol{c} = \begin{bmatrix} a & c_1 & c_2 & \ldots. & c_M \end{bmatrix}^T$, and

$$\boldsymbol{\Lambda}(v) = \begin{bmatrix} 1 \\ \frac{1}{2}\left(v(k) - \beta_1 + |v(k) - \beta_1|\right) \\ \frac{1}{2}\left(v(k) - \beta_2 + |v(k) - \beta_2|\right) \\ \vdots \\ \frac{1}{2}\left(v(k) - \beta_M + |v(k) - \beta_M|\right) \end{bmatrix} \tag{4}$$

A typical implementation is illustrated in Figure 1. In

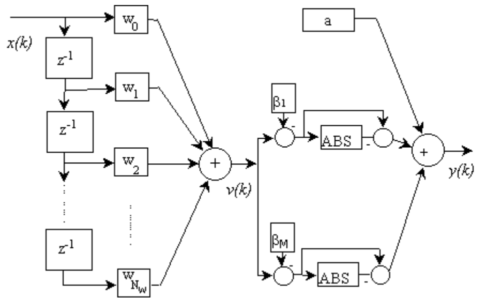

Fig. 1. The proposed CPWL adaptive filter.

order to change the statistics at the TEQ output, when IN is present, the choice of the β_j is the tool at hand [12], [9]. A simple rule for the selection of these parameters will be presented in the following section. The standard approach to derive a LMS-based algorithm, for robust CPWL TEQ is to use the squared estimation error as an estimative of the mean-square error, i.e.

$$J(e(k)) = e^2(k) = d^2(k) - 2d(k)y(k) + y^2(k)$$

where, $d(k)$ is the TIR output and the adaptive filter output is given by $y(k) = \boldsymbol{c}^T \boldsymbol{\Lambda}\left(\boldsymbol{w}^T \boldsymbol{x}(k)\right)$. An LMS-based algorithm can be used to minimize the objective function using

$$\boldsymbol{w}(k+1) = \boldsymbol{w}(k) - \mu_w e(k)\hat{\boldsymbol{g}}_h(k) \quad (5)$$

$$\boldsymbol{c}(k+1) = \boldsymbol{c}(k) - \mu_c e(k)\hat{\boldsymbol{g}}_c(k) \quad (6)$$

for $k = 0, 1, \cdots$, where $e(k)\hat{\boldsymbol{g}}_c(k)$ and $e(k)\hat{\boldsymbol{g}}_w(k)$ represent estimates of the gradient vector of the objective function with respect to the filter coefficients $\boldsymbol{c}$ and $\boldsymbol{w}$, respectively. In particular, these vectors are

$$\hat{\boldsymbol{g}}_c(k) = \boldsymbol{\Lambda}^T(v) \qquad \hat{\boldsymbol{g}}_w(k) = \left(\boldsymbol{c}^T \frac{\partial \boldsymbol{\Lambda}(v)}{\partial v}\right) \boldsymbol{x}(k)$$

where $\left[\frac{\partial \boldsymbol{\Lambda}(v)}{\partial v}\right]_1 = 0$, $\left[\frac{\partial \boldsymbol{\Lambda}(v)}{\partial v}\right]_{j+1} = \frac{1}{2}(1 + \text{sign}(v - \beta_j))$ for $j = 1, \cdots, M$. Some properties of this algorithm can be found in [15].

As a second refined methodology, aiming to improve the modelling capabilities of the CPWL model as a nonlinear TEQ, some specific constraints on $\boldsymbol{c}$ can be introduced (i.e., smoothness, saturation, etc.) [9] [10].

4. APPLICATION AND DISCUSSION

A complete VDSL receiver was simulated to compare the performance of the MMSE TEQ and the proposed CPWL-based robust TEQ. Different RS coding structures and interleaver's deep were evaluated under impulsive noise samples. The objective is to obtain a system robust under impulsive noise. In this simulation the deep and the FEC coding

IN	Duration (DMT Symbols)	Power
I	1	Low
II	2	Low
III	2	High
IV	3	High

Table 1. IN samples

		MMSE TEQ		CPWL TEQ	
IN	FEC	m	Delay	m	Delay
I	RS(144,128)	2	16 ms	2	16 ms
II	RS(144,128)	3	24 ms	2	16 ms
III	RS(63,57)	3	24 ms	2	16 ms
IV	RS(63,57)	4	32 ms	3	24 ms

Table 2. Delay both TEQ structures under different IN samples.

are designed in order to obtain a free error system [17]. A block interleaver format the encoded data in a rectangular array of m rows and n columns, where each row constitute a code word of length n. The time delay due to the interleaver is calculated using $Delay = (m * n) * T_{DMT}$ where T_{DMT} ($25\mu s$)is the system data rate. Additive Gaussian white noise and NEXT from other VDSL services, were included. IN was modelled using the previously discussed model [5], with the following typical parameters: $\lambda = 0.16$ Hz, $s_1 = 1.15$, $t_1 = 18.1$, $\alpha = 0.263$ and $b = 4.77$. The simulation was made using 4 different samples of IN that correspond to different IN duration and different power. Table 1 summarizes the IN characteristics. Related to the CPWL-based TEQ, the number of partitions β_j was chosen equal to 10, and the width of the partitions was chosen to allow a better approximation of an smooth (asymmetric) saturation characteristic, i.e. widest partitions were chosen close to the origin. The best performance was reached using $\mu_w = 0.001$ for MMSE TEQ and $\mu_C = 0.0005$ for nonlinear TEQ adaptation algorithm.

Table 2 shows results obtained with different IN samples, different duration and power, using RS codes and interleaver with different deep. The IN samples are scaled in amplitude in order to generate interferences with high power and lower power if it is compared with the other interferences (AWGN, NEXT). In this table the delay and overhead produced by the interleaver and the FEC code are also shown. For severe interference (III and IV) is necessary to use short RS codes with more overhead. When the IN is shorter and low power, the performance of both TEQ are similar. But, Using the $CPWL$ structure, asumming a free error service [17], the interleaver's deep is shorter than the conventional structure under severe IN . This results can help to improve the performance the VDSL in real time applications with a good safety margin under impulsive noise and other interferences.

5. CONCLUSIONS

A novel nonlinear TEQ was presented aiming to reduce IN effects in VDSL systems. The proposed TEQ is essentially formed by a linear filter and an static nonlinearity trained with the IN environment. The free parameters in this static nonlinearity are useful to change the TEQ output signal statistics, aiming to improve the basic detection performance of the VDSL system. The results presented, using computer simulations, allow to verify the expected improved performance of the system in terms of delay and overhead. The new design can be applied combined with bit erasure techniques [18] reducing even more the system delay.

ACKNOWLEDGMENT

Supported by the Programme ALβAN, European Union Programme of High Level Scholarships for Latin America. Identification Number:**E03D19254AR**

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