Near-End Crosstalk Cancellation in xDSL Systems

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Abstract

An algorithm for reducing the computational load in near-end crosstalk (NEXT) cancellation is proposed. The algorithm first detects the major NEXT sources by taking the crosscorrelation of the adjacent transmitted signals with the received signal. A fast method for estimating the crosscorrelation is utilized to speed up the detection process. Upon detection, each NEXT source is cancelled by an adaptive filter. The detection and cancellation are done simultaneously as the algorithm progresses. This helps the smaller NEXT signals to be detected as the larger NEXT signals are cancelled out.

1 Introduction

Digital subscriber line (DSL) technology exploits the existing copper loop plant to transfer data at Mb/s rates for high-speed Internet and other digital transmission services. In this technology, the DSL signal travels on a twisted pair loop from the central office to the subscriber. Many, sometimes thousands, twisted pairs are bundled together in a single cable.

Telephone loops were designed and built to carry voice services, and at these frequencies crosstalk is insignificant. However, at higher frequencies crosstalk becomes a major impairment. Considering the bundle as a multi-input/multi-output channel [1], the near-end crosstalk (NEXT) signals for a particular line can be cancelled by using an adaptive filter for each adjacent transmitted signal. This method can be very expensive if the bundle has a large number of twisted pairs.

The worst-case crosstalk scenario used in simulations is often too pessimistic, and using a crosstalk canceller in each line would be wasteful if little or no crosstalk is present on the line. A better option would be to first detect the crosstalk present on a line and then add an adaptive filter to cancel each of the crosstalk sources detected.

By taking the crosscorrelation of the adjacent transmitted signals with the received signal, the crosstalk signals can be detected and then effectively identified [2].

This paper aims to increase the speed of crosstalk detection by using a fast algorithm for estimating the crosscorrelation between the received signal and the transmitted signal. Upon detection, each NEXT source is cancelled by an adaptive filter. The detection and cancellation are carried out simultaneously. This enables the smaller NEXT signals to be detected for cancellation as the larger NEXT signals are cancelled out. The output of the NEXT cancellers are combined to cancel the detected NEXT signals.

The paper is organized as follows. Section 2 describes NEXT detection using the fast algorithm for estimating the crosscorrelation. Section 3 presents the NEXT cancellation algorithm which detects and cancels the NEXT signals. Simulation results are presented and discussed in Section 4.

2 NEXT Detection

The echo-cancelled signal received on a single twisted pair can be expressed as

$$y(m) = r(m) + n(m) + \sum_i h_i(m) * d_i(m) \quad (1)$$

where $y(m)$ is the noisy observation, $r(m)$ is the received message signal, $n(m)$ is the additive background noise, $d_i(m)$ is the signal transmitted on pair i, and $h_i(t)$ is the time-domain crosstalk coupling function between pair i and the considered pair.

For the purpose of crosstalk detection, we assume that the echo at the hybrid is already cancelled by the echo canceller before the crosstalk detection is performed. In most cases, the impulse response of the channel can be readily estimated [2]; hence the received signal can be removed, leaving behind only the

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crosstalk signals. With the received signal and the transmitted signal echo removed, the remaining signal $y(m)$ can be expressed as

$$y(m) = n(m) + \sum_i h_i(m) * d_i(m) \qquad (2)$$

Assuming $y(m)$ and $d_i(m)$ are widesense stationary the crosscorrelation is defined as

$$R_{yd_i}(l) = E[y(m+l)d_i(m)] \qquad (3)$$

Assuming that the signals transmitted from the different users are statistically independent with zero mean, and that the noise is uncorrelated with all the other signals, (3) can be written as

$$R_{yd_i}(l) = h_i(m+l) * R_{d_i}(m) \qquad (4)$$

Taking the ideal case where the transmitted signals d_i are uncorrelated and have an energy ε_i, i.e., $R_{d_i}(k) = \varepsilon_i \delta(k)$, we have

$$R_{yd_i}(l) = \varepsilon_i h_i(l) \qquad (5)$$

This shows that if the signals d_i are uncorrelated, the crosscorrelation is proportional to the impulse response of the crosstalk coupling function.

Using the crosscorrelation, $R_{yd_i}(l)$, the strength of the crosstalk signal can be obtained as

$$\tau = \frac{1}{L} \sum_{l=0}^{L} |R_{yd_i}(l)| \qquad (6)$$

Note that τ is also a measure of the average magnitude of the impulse response of the crosstalk coupling function where L is the length of the crosscorrelation. The crosscorrelation R_{yd_i} is approximated as

$$R_{yd_i}(l) = \frac{1}{N} \sum_{m=1}^{N} y(m+l)d_i(m) \qquad (7)$$

where N is the number of data samples.

To speed up the crosscorrelation estimate, we use a fast and efficient algorithm for estimating R_{yd_i} based on the sign algorithm [3]-[5], which assumes a zero-mean, stationary Gaussian process.

Assuming that $d_i(m)$ is a zero-mean, stationary Gaussian process, we can further simplify (7) to

$$R_{yd_i}(l) = \frac{1}{N} \sum_{m=1}^{N} y(m+l)\ \mathrm{sign}(d_i(m)) \qquad (8)$$

where

$$\mathrm{sign}(x) = \begin{bmatrix} -1 & \text{for } x < 0 \\ 1 & \text{for } x \geq 0 \end{bmatrix}$$

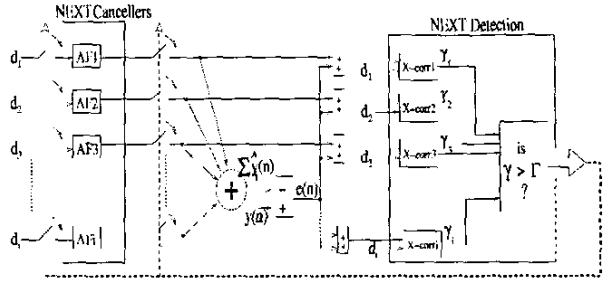

Figure 1: **NEXT adaptive canceller.**

3 Adaptive NEXT Cancellation

The adaptation algorithm is present for every line that receives the signal. It is best deployed in areas where the number of twisted pairs in a bundle is high, like in a central office.

The algorithm consists of two parts. The NEXT detection comprises the first part and its cancellation comprises the second. Using the crosscorrelation technique, the NEXT signals are detected by the first unit. For each NEXT signal detected, a normalized least mean-square (NLMS) [6] adaptive filter is assigned to cancel it. The NLMS algorithm can be described by the following three basic equations:

1. *Filter output*:

$$\hat{y}_i(n) = w_i^H(n)d_i(n) \qquad (9)$$

2. *Estimation error*:

$$e(n) = y(n) - \sum_i \hat{y}_i(n) \qquad (10)$$

3. *Tap-weight adaptation*:

$$w_i(n+1) = w_i(n) + \frac{\mu}{||d_i(n)||} d_i(n)e^*(n) \qquad (11)$$

In the above equations, i is the index of the line identified to be causing the NEXT, $w_i(n)$ are the adaptive filter coefficients, $y_i(n)$ the estimated NEXT signal from the ith adaptive filter, and μ is the adaptation constant.

To enhance the detection of a particular NEXT signal, the other detected NEXT signals are first removed before performing the crosscorrelation for that signal. A block diagram of the adaptive canceller is shown in Fig. 1.

To decide whether a particular crosstalk signal is large enough to require cancellation by an adaptive filter, a threshold value Γ can be set such that for

$$\gamma_i = \frac{\max|R_{yd_i}(l)|}{\sum_{l=0}^{L} |R_{yd_i}(l)|} > \Gamma \qquad (12)$$

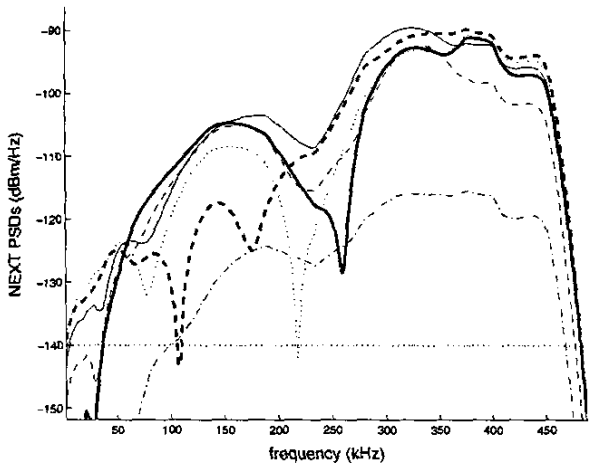

Figure 2: **Simulated NEXT PSD for HDSL2.**

the crosstalk signal is considered large enough to require cancellation.

As the larger NEXT signals are cancelled out, the ratio γ_i given in (12) becomes larger for the smaller NEXT signals and hence allows the smaller NEXT signals to be detected.

The adaptive filter can be an LMS or an NLMS type. Since the reference signal to the adaptive filter is taken after the scrambler, it has a low eigenvalue spread, and thus provides a good convergence rate for LMS-type adaptive filters.

4 Simulation Results

The crosstalk data was computed by simulating a bundle consisting of 7 twisted pairs of gauge 26 AWG and length 7600 feet. HDLS2 was simulated on each of the pairs, as specified in the T1E1.4 draft for the HDSL2 standard [7].

It was assumed that each of the twisted pairs generates a crosstalk of certain magnitude on a particular line. Fig. 2 shows the power spectral densities (PSDs) of the simulated NEXT signals and the associated noise floor. The transmitted data symbols from all the lines are made available to each line for the purpose of crosstalk detection and cancellation. For NEXT detection, the length L of the crosscorrelation $R_{yd_i}(l)$ was fixed at 200. The crosscorrelation update was done using the relation

$$R_{yd_i}(l,k) = \lambda R_{yd_i}(l,k-1) + (1-\lambda) Y(k)^T D_i(k) \quad (13)$$

where λ is the forgetting factor, $Y(k)$ is a column vector of the received signal $y(n)$ and $D_i(k)$ is the column vector of the transmitted symbols from line i. Assuming that the sampling rate is twice the symbol rate,

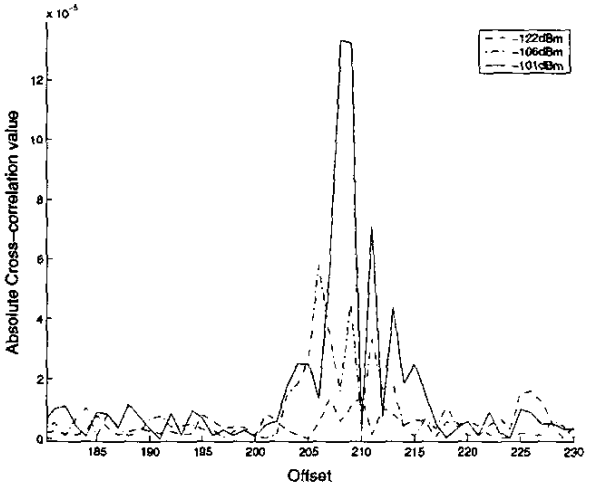

Figure 3: **NEXT crosscorrelation using the standard method.**

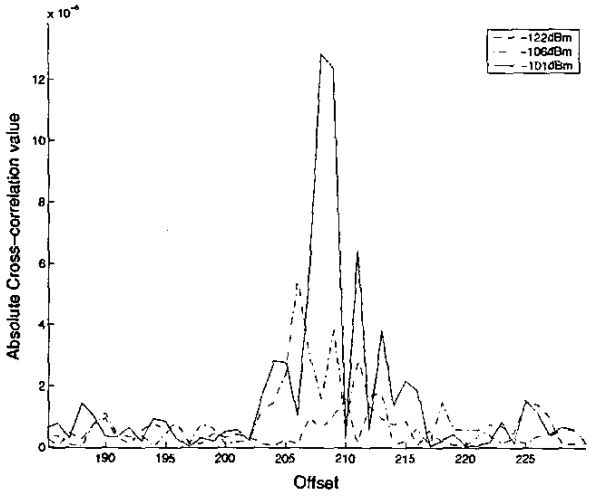

Figure 4: **NEXT crosscorrelation using the sign algorithm.**

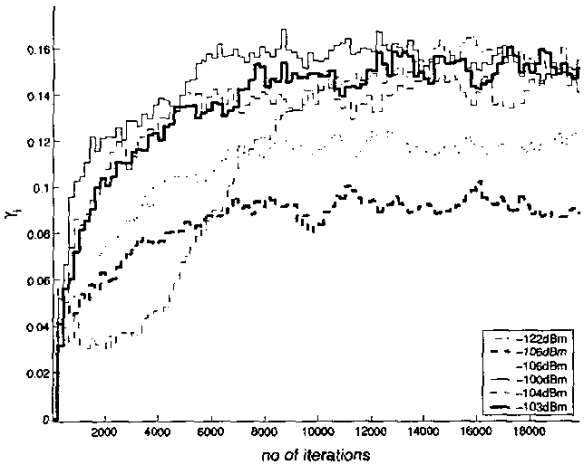

Figure 5: **Value of γ_i for each of the NEXT signals.**

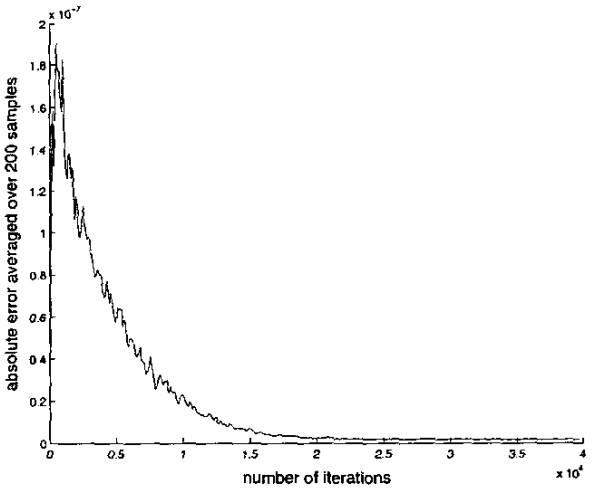

Figure 6: **Plot of the error versus no of iterations.**

the received signal in $Y(k)$ is a downsampled version of the received signal $y(n)$. The update was done every 200 symbols and since $y(n)$ was sampled at twice the symbol rate, the update in (13) occurs at every 400 samples of $y(n)$.

The crosscorrelation $R_{yd_i}(l)$ calculated by using the sign algorithm in (8) can be compared with the crosscorrelation obtained by using (7). Figs. 3 and 4 show a comparison between the two methods for three NEXT signals of different magnitude. As seen from the figures, the plots are quite similar. When extended to the case where the transmitted signals $d_1, d_2, \cdots, d_i, \cdots$ are not totally uncorrelated nor truely Gaussian, the system still performs reasonably well.

The adaptive NEXT canceller shown in Fig. 1 performs the NEXT detection and accordingly assigns a NEXT canceller for each NEXT signal detected. The detection of the other undetected NEXT signals is performed with the known NEXT signals removed from the received signal. This allows the smaller NEXT signals present to be detected and cancelled. Fig. 5 shows a plot of the values of the ratio γ_i in (12) for estimating the amount of NEXT present in the received signal from the other lines. It can be seen from the figure, that the ratio improves as the larger NEXT signals are detected and cancelled. A value of 0.05 was used for the threshold Γ.

The duration of the impulse response of the crosstalk coupling function is usually less than 20 μs. The adaptive filter used for cancelling the crosstalk had 40 taps. Fig. 6 shows a plot of the absolute value of the error signal, where each displayed point represents the absolute sum of 200 error signal values.

The convergence rate of the adaptive filter can be increased further by using the error signal $e(n)$ to adjust the adaptation constant [8]. During the NEXT detection and cancellation process, the adaptive cancellers can resort to partial updating of the filter coefficients [9] if the number of NEXT signals to be cancelled is high. By combining the adaptive filter outputs to cancel the NEXT signals, a smaller mean residual error is achieved compared to what can be achieved with successive cancellation [2]. The convergence rate is also much faster [10].

5 Conclusions

The NEXT detection process circumvents the necessity of having adaptive NEXT cancellers for each and every line. In addition, the crosscorrelation in (8) used for the detection process can be computed by additions only. This makes it effective, computationally simple, and well suited for hardware implementation.

NEXT detection before cancellation results in significant savings in computation, especially in bundles with a large number of twisted pairs. This is because crosstalk originates mainly from the adjacent twisted pairs,[1] which constitute a small percentage, if the total number of twisted pairs in the bundle is large.

During the NEXT detection process, the larger NEXT signals are detected first; this allows all the computational effort to be focused on cancelling the larger NEXT signals first and then on cancelling the smaller NEXT signals, as the larger ones are cancelled out.

[1] in some bundles the twisted pairs are inter-twined so as to reduce the crosstalk dominance by a few twisted pairs and distribute it more evenly among all the pairs [11]. In this case the advantage of the detection process is reduced.

As more and more of the smaller crosstalk signals are detected for cancellation, the adaptive filters can resort to partial update of the filter coefficients [9] thereby further reducing the computational load. By setting the appropriate threshold value Γ and adjusting the number of taps of the NEXT cancellers, the degree of NEXT cancellation required can be controlled.

Acknowledgements

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