Adaptive NLMS Partial Crosstalk Cancellation in Digital Subscriber Lines

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Abstract-Crosstalk is a major limitation to achieving high data-rates in next generation VDSL systems. Whilst crosstalk cancellation can be applied to completely remove crosstalk, it is often too complex for application in typical VDSL binders, which can contain up to hundreds of lines. A practical alternative, known as partial cancellation limits the cancellation to crosstalkers that cause severe interference to the other lines within the binder. In real VDSL systems, the crosstalk environment changes rapidly as new lines come online; old lines go offline, and the crosstalk channels change with fluctuations in ambient temperature. Therefore, adaptive crosstalk cancellers are often required. In this paper, we propose a new detection guided adaptive NLMS method for Adaptive Partial Crosstalk Cancellation that detects significant crosstalkers and tracks variations in their crosstalk channels. This exploits the sparse and column-wise diagonal dominant properties of the crosstalk channel matrix and leads to fast convergence, accurate crosstalk channel tracking, with a lower update complexity. The end result is an adaptive Partial Crosstalk Cancellation algorithm that has lower run-time complexity than prior state-of-the-art whilst yielding comparatively high data-rates and reliable service.

I. Introduction

Until the promise of a full Fiber Network is fulfilled, Digital Subscriber Lines (DSL) will continue to be an attractive means of providing broadband communication. The twisted line pairs within a DSL cable binder however throw large amounts of electromagnetic coupling between the neighbouring lines. This initiates crosstalk in the adjacent pairs and is a major source of performance degradation as it limits the data rate and the reach at which DSL service is provided [1]. In practice, two main types of crosstalk can cause problems, namely, Near End Crosstalk (NEXT) and Far End Crosstalk (FEXT). NEXT appears at the same end of the binder as the transmission and reception takes place in the same frequency band. FEXT propagates through the binder cable and hence the crosstalk effect can be visible on the other side. NEXT can be avoided using disjoint frequency bands for upstream and downstream communication or Frequency Division Duplexing (FDD). This FDD solution however is not generally applicable to FEXT. One approach to suppressing FEXT in downstream VDSL (Central Office to Customer) is through crosstalk pre-compensation techniques which are jointly applied at co-located transmitters while the channel information is made available at the transmitter end. In upstream VDSL communication, we may, however jointly apply multiuser crosstalk cancellation to the co-located receiver modems at the Central Office (CO) [2]. The application of crosstalk cancellation for upstream VDSL is the main thrust of the paper.

This paper proceeds as follows. Section II explains the typical VDSL scenario with the crosstalk cancellation environment which we have assumed for our simulations. Section III explains the motivation for using the Normalized Least Mean Squared approach for estimating the crosstalk cancellation matrix in DSL. Section IV proposes the algorithm which we have called 'The Normalized Least Mean Squared Adaptive Partial Cancellation (NLMS-APC) Algorithm' for Crosstalk Cancellation in upstream DSL. Section V compares the performance of the proposed algorithm with Standard NLMS crosstalk cancellation techniques for white noise and spatially colored noise environments. Lastly, Section VI concludes mentioning some advantages and disadvantages.

II. VDSL System Scenario

A typical scenario of a VDSL System with crosstalk cancellation is as shown in figure 1.1. Here, the subscript k denotes the k^{th} tone. The input $X_{k,t} = [x_{k,t}^{1} \cdots x_{k,t}^{N}]^{T}$ represents the vector of symbols transmitted by the N customers at the symbol interval t.

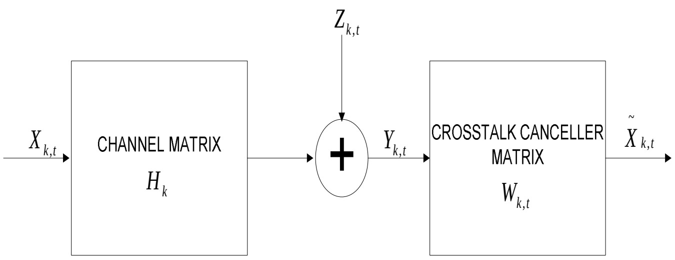

Figure 1.1: Crosstalk cancellation system

We assume that each of the transmitted symbol sequences, $x^{m}_{k,t}$, $m = 1,2,3….N$, are digitally white and are independent. We represent the transmission media on the k^{th} tone by a square crosstalk channel matrix H_k, where diagonal element $h_k^{n,n}$, is the direct channel gain from transmitter n to receiver n, whilst the off-diagonal element $h_k^{n,m}$, is the crosstalk channel gain from transmitter m to receiver n. The system is said to be corrupted by noise viz. radio frequency interference (RFI), thermal noise and alien crosstalk which are incorporated in the noise vector $Z_{k,t} = [z^1_{k,t} \cdots z^N_{k,t}]^T$

$Y_{k,t}$ is the vector of received symbols on tone k at time t, and is related to the transmitted symbol vector $X_{k,t}$ by:

$$\mathrm{Y}_{k,t} = \mathrm{H}_k \, \mathrm{X}_{k,t} + \mathrm{Z}_{k,t}$$

In upstream VDSL transmission, the diagonal element of any column of the channel matrix H_k has a much larger gain than the off-diagonal elements of that column

$$\left|h_k^{n,n}\right| >> \left|h_k^{m,n}\right|, \ \forall m.$$

This property is known as column-wise diagonal dominance (CWDD) [9].

III. Motivation of Adaptive NLMS Crosstalk Cancellation

Recently the Decision Feedback Canceller (DFC) has attracted considerable interest for FEXT cancellation in Upstream VDSL. However, the DFC tends to increase in complexity as the number of active users in the binder increases especially when some form of coding technique is used [9]. Moreover, error propagation can be a significant disadvantage to DFC as the accuracy of the next symbol decoded, depends upon the decoding of the previous symbol being error-free. In addition, DFC ([5], [6]) shows good performance only when the noise is white. Spatially colored noise may occur when the binder includes other noise interference inducing services like T1/HDSL running parallel to VDSL. Under these circumstances, a pre-whitening operation is necessary to whiten the colored noise which further increases the receiver complexity [7].

Note: Implementation of the DFC assumes the availability of an (accurate) estimate of the cross-talk channel matrix H_k. In practice, such an estimate is obtained through an initial transmission of a known 'training' sequence.

In this paper, we consider a Normalized Least Mean Square (NLMS) adaptive approach for providing crosstalk cancellation via the estimation of a suitable Crosstalk cancellation matrix. The main attraction of this approach is that, comparatively, it has low complexity and requires no additional processing if the noise is colored or the noise statistics are varied. A potential drawback is the relatively slow convergence rate of the NLMS algorithm, particularly in systems with a *large* number of estimation parameters. The crosstalk canceller in a multi-user, 4096 tone-VDSL system is such a system. This can lead to the need for relatively long initial training sequences to enable the adaptive crosstalk canceller to converge with sufficient accuracy.

In this paper, we propose a scheme to enhance the convergence rate of the adaptive NLMS FEXT canceller for upstream VDSL. This is based on the following. In some systems, the parametric system being estimated is sparse, that is, it consists of only a relatively small number of significant parameters. For such systems, an approach to combat the NLMS slow convergence issue is to employ a parameter detection stage. This stage identifies the significant parameters and the adaptive NLMS algorithm then focuses its adaptive estimation on those. Such a detection-guided NLMS approach was proposed in [3], [4] for estimation of the impulse response of sparsely time dispersive communication channels. Importantly, in the upstream VDSL application the desired crosstalk canceller matrix W_k is typically sparse. This follows from the crosstalk matrix H_k, being CWDD together with $W_k \approx H_k^{-1}$. This motivates us to present a detection guided NLMS based Adaptive Partial Cancellation (NLMS-APC) algorithm for the crosstalk cancellation in VDSL lines on each tone in the upstream frequency band.

IV. Proposed NLMS-APC Algorithm for VDSL

At a particular symbol interval t, the processed vector output from the crosstalk canceller is:

$$\tilde{X}_{k,t} = W_{k,t} Y_{k,t} \qquad (1)$$

The corresponding error for the 'm^{th}' user is

$$E_{k,t,m} = X_{k,t}(m) - \tilde{X}_{k,t}(m) \qquad (2)$$

We consider that for each time sample t within tone k the m^{th} row of the crosstalk cancellation matrix $W_{k,t}$ is estimated with the modified NLMS equation:

$$W_{k,t+1}(m,:) = B_{k,t,m} W_{k,t}(m,:) + \frac{\mu B_{k,t,m} E_{k,t,m} Y_{k,t}}{Y^T_{k,t} B_{k,t,m} Y_{k,t} + \varepsilon} \qquad (3)$$

Where $B_{k,t,m}$ is a diagonal matrix with $B_{k,t,m}(j,\ j) = 1$ if $W_{k,t}(m,\ j)$ is detected to be significant, otherwise $B_{k,t,m}(j,\ j) = 0$.

μ is the step size parameter and ε is a small constant to avoid divide-by zero instabilities.

Note: The corresponding Standard (non-modified) NLMS Adaptive cancellation algorithm, considers all the coefficients as significant; hence $B_{k,t,m}(j,\ j) = 1$ for all j = 1, 2,…,N

Through the extension of work in [3], [4], we obtain the following activity criterion. The j^{th} coefficient of $W_{k,t}(m,:)$ is classified as being active if:

$$\frac{N_{k,t,m}{}^{2}(j)}{D_{k,t,m}} > \frac{G_{k,t}(j)\log(T_t)}{T_t}; \qquad (4)$$

where,

$$N_{k,t,m}(j) = \gamma N_{k,t-1,m}(j) + [E_{k,t,m} + W_{k,t}(m,j)Y_{k,t}(j)]Y_{k,t}(j)$$

$$D_{k,t,m} = \gamma D_{k,t-1,m} + E^{2}{}_{k,t,m}$$

$$G_{k,t}(j) = \gamma G_{k,t-1}(j) + Y_{k,t}{}^{2}(j)$$

$$T_t = \gamma T_{t-1} + 1$$

The forgetting factor, γ, is typically set to 0.99 or 0.999 (similar to the corresponding parameter in the recursive least squares algorithm). Note: The above significant coefficient detection criterion is based on minimization of structurally consistent least squares cost functions as discussed in [3], [4]

V. PERFORMANCE

Within our simulations, we design a channel matrix for a given number of users N ($2 \leq N \leq 64$). It is assumed that each cable in a binder is surrounded by a number n (n<<N) of nearest neighbors. We create a sparse and CWDD crosstalk channel matrix based on assigning crosstalk signals to the nearest neighbors of the VDSL cable with the direct channel gain, $h_k^{m,m}$, of each user being 100 times greater than the crosstalking channels of the *n* nearest neighbors.

4-ary Quadrature Phase Shift Keying (QPSK) Modulated symbols are transmitted for each user with -40dBm/Hz transmitter power (T_p) on the same tone (bandwidth=4.3125 kHz). Noise statistics were considered to be either white or colored and the noise power was varied in the range of -116dBm/Hz<N_p<-56dBm/Hz. The convergence factor μ is chosen to be such that 0.001< μ < 0.1 and the constant ε is chosen such that 0.0001 < ε < 0.01.

A. *In presence of high noise power*

This section provides a snapshot of the extensive study mentioned above. In particular, we compare the steady state error and convergence rate performance of the proposed Detection guided NLMS Adaptive Partial Cancellation (NLMS-APC) algorithm with the Standard NLMS Adaptive Cancellation (Std. NLMS-AC) algorithm. The following results plot one user's squared symbol estimation error, $E^{2}_{k,t,m}$ against the number of time samples

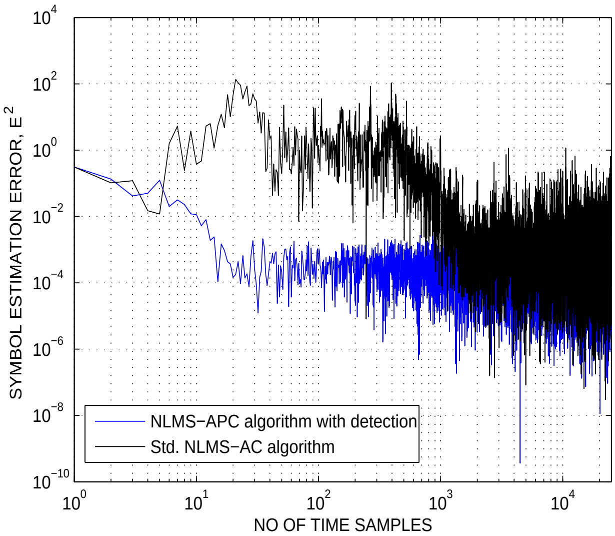

Figure 1.3: Convergence and S.S.E performance of proposed NLMS-APC algorithm and Std. NLMS-AC algorithm for high white noise with power, N_p = -56dBm/Hz (N = 19, μ = 0.1, ε =0.01, γ = 0.999, n = 6).

Figure 1.3 compares the performance of the proposed NLMS-APC with the Std. NLMS-AC algorithms for white noise with relatively high noise power level. The proposed NLMS-APC algorithm converges more rapidly than the std. NLMS-AC algorithm. This implies that the proposed canceller requires shorter training sequences and hence provides better data efficiency. Importantly, this convergence advantage of the NLMS-APC algorithm comes with essentially no loss in steady state performance. Furthermore, the overall complexity (measured by the average multiplications per sample interval) of our proposed NLMS-APC algorithm is typically less than that of the std. NLMS-AC algorithm. Note: The results are similar for all users.

Finally, the popular Decision Feedback Crosstalk Canceller method requires complex receiver structures if the noise is spatially coloured, due to the needed pre-whitening operation at the receiver [7]. In contrast, we can see from figure 1.3 and 1.4 that the performance of the proposed NLMS-APC algorithm in presence of colored noise is very similar to white noise case.

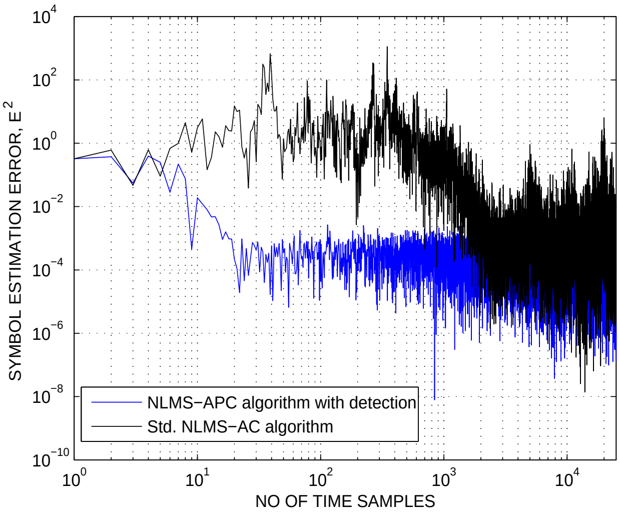

Figure 1.4: Convergence rate and S.S.E performance of proposed NLMS-APC algorithm and std. NLMS-AC algorithm for highly coloured noise with power, N_p = -56dBm/Hz (N = 19, μ = 0.1, ε =0.01, γ = 0.999, n= 6).

B. *In presence of low noise power*

Simulations were carried out at noise power of -116dBm/Hz keeping the transmitter power to -40dBm/Hz.

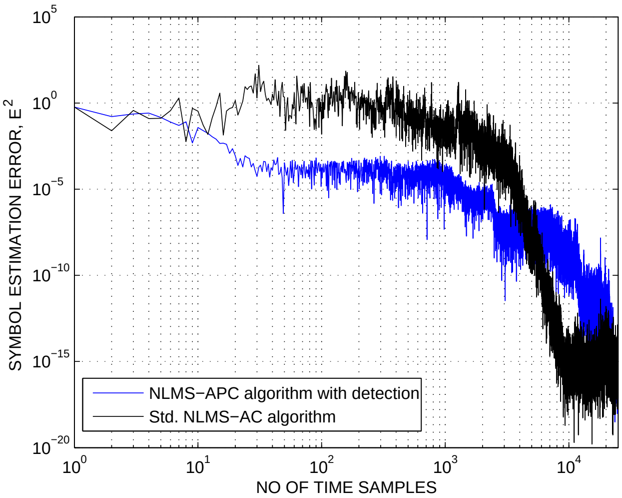

Figure 1.5: Convergence rate and S. S. E performance of proposed NLMS-APC algorithm and Std. NLMS-AC algorithm for low noise power, N_p = -116dBm/Hz (N = 19, μ = 0.1, ε =0.01, γ = 0.999, n = 6)

Figure 1.5 compares the performance of the Std NLMS algorithm with the proposed NLMS-APC. It can be seen that the proposed NLMS algorithm converges at a faster rate than the standard NLMS technique but the standard NLMS algorithm reaches a lower steady state error as compared to the proposed NLMS-APC. This is due to incapability of the proposed algorithm to detect the very small active coefficients. Note, due to the 'smallness' of such coefficients, the additional symbol estimation error converges on the insignificant level.

C. Computational Complexity

Similar to the work in [10], we can say that, the proposed NLMS-APC algorithm requires 6N+2n+4 multiplications per sample interval (MPSI) while the std. NLMS algorithm requires 3N+2 MPSI where N is the number of users and n is the number of crosstalk active neighbors to each user. It is clear that for N>>n>1 the proposed algorithm involves essentially twice the computational complexity (MPSI) as that of the standard NLMS algorithm.

VI. Conclusions

In this paper, we have proposed an efficient Adaptive Partial Cancellation algorithm based on the Normalised Least Mean Square Algorithm for the multi-user VDSL system. The proposed NLMS-APC algorithm aims to detect and estimate the most significant coefficients within the crosstalk canceller so as to enhance the convergence speed and subsequently keep the length of the training sequences to a minimum. Importantly, the computational cost of the proposed NLMS canceller is significantly lower than the popular Decision Feedback Crosstalk Canceller, (slightly greater than std. NLMS) and does not require complex receiver structures for coloured noise.

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