An Enhancement Study on the SDSL Upstream Receiver

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Abstract
This paper provides a new approach to mitigate the crosstalk interference in the symmetric digital subscriber line (SDSL) upstream transmission. A vector channel equalizer has been proposed for the SDSL upstream receiver to enhance spectral compatibility for the SDSL services. This approach outperforms a conventional scalar equalizer, which used in the current SDSL systems, is about a 15dB gain in mean squared error (MSE). It significantly suppresses the crosstalk degradation and ensures the quality of service (QoS) on the SDSL transmission throughput. Moreover, the enhancement of the SDSL receiver can benefit on the extension of the SDSL deployment coverage range and also guarantees its promising data rates on increasing numbers of customer subscribers.

1. Introduction
Telephone access networks were originally constructed from twisted copper pairs carrying voice-band signals up to the 4 kHz frequency band. A combination of the existing copper infrastructure and digital subscriber line (DSL) transmission technologies became an emerging universal broadband access method to deliver the multimedia services to the customers [1]. However, there is a major threat to this vision of the future in the crosstalk, which is introduced by the adjacent channels. This crosstalk effect is especially bad near the central office, where the wireline binder groups are concentrated. Such degradation can severely reduce the transmission rate; sometimes even significantly polluting the copper network.

SDSL systems are modulated with 2B1Q, which is a baseband 4-level pulse amplitude modulation. These systems transmit the same bit rate in upstream and downstream directions in full duplex. Normally, the transceivers on the upstream end are co-located in the local exchange carrier (LEC) central office (CO). The upstream SDSL receivers suffer severely from its self-NEXT (near-end-crosstalk), which causes significant degradation on its data rates [2]. In this paper, we derive vector equalization for the SDSL upstream receiver, which can combat its crosstalk effectively. The SDSL upstream transmission system is proposed as a multiple input and multiple output (MIMO) channel model. Our simulation results have shown

more than a 15dB MSE gain compared with a conventional scalar decision feedback equalizer (DFE) that is being used in the current products.

In section 2, we review the effectiveness with NEXT. In section 3, we propose a MIMO version of SDSL channel model and its analysis. In section 4, we present some simulation results and discussions. The conclusion is in section 5.

2. SDSL Self-NEXT Limits and Reviews
Studies on the received signal-to-noise ratio (SNR) of 1168, 1552 and 2320 *kbps* SDSL were computed on effectiveness with common 24 self-NEXT disturbers [3]. In the SDSL transmission, the self-NEXT limits it to a 6 dB SNR margin with the channel probability of bit error being 10^{-7}. The simulation results were based on a 2B1Q SDSL receiver, which uses a scalar DFE with optimal minimum mean squared error (MMSE) tap values that has 12 baud-spaced forward filter taps and 64 feedback taps. The simulated SNR margin for different 26-AWG loop lengths has been shown in Fig. 1, (extracted from Ref. [3]).

The twisted pair channels (TPC) has been studied and modeled in a number of papers [4], [5]. It is assumed that the attenuation transfer characteristic $|H(f)|^2$, of the channel can be modeled by:

$$|H(f)|^2 = e^{-\alpha\sqrt{f}} \qquad (1)$$

where $\alpha = k\dfrac{l}{l_{ref}}$, l = length of the channel in ft, l_{ref}

= a reference length, k = a constant of the physical channel, and f = frequency in kHz. The *psd*, $P_{rec}(f)$ of the received signal is given by:

$$P_{rec}(f) = |H(f)|^2 \, P_{xmit}(f) \qquad (2)$$

where $P_{xmit}(f)$ is the two-side *psd* of the transmitted signal. In this paper, we target on the NEXT, which is the dominant factor on limiting the communication capabilities of the SDSL channel. The far-end-crosstalk (FEXT) has some minor effects on the SDSL throughput as well but is ignored here for the simplification purpose. In general, the FEXT can easily be counted into our

proposed model in the following section. Following with [6], the NEXT transfer function can be written as

$$H_{NEXT}(f) = j2\pi \cdot \int_0^d C_n(x,f)e^{-2\gamma(f)x}dx \quad (3)$$

where x is the distance from the disturbing source, d is the length of the twisted cable, and $C_n(x,f)$ is the NEXT unbalance function at distance x and frequency f.

The squared gain of the NEXT transfer function [7], $|H_{NEXT}(f)|^2$ can be modeled as

$$| H_{NEXT}(f) |^2 = \beta \cdot f^{1.5} \quad (4)$$

where β is a constant of the twisted pair cable, and varies from the cable to cable.

The SDSL transmission rate is directly proportional to its SNR, as the TPC Shannon capacity is a theoretical upper bound on the data rate that can be reliably transmitted [7], [8]. Our review on the TPC and NEXT has shown that the higher the SDSL transmission rate, the worse on the channel SNR. Meanwhile, the results of Fig. 1 also show that the crosstalk greatly degrades the SDSL transmission rate, thus limiting its deployment range. This kind of the degradation is especially bad on the upstream receivers at LEC side due to the concentration of the twisted pair binders group.
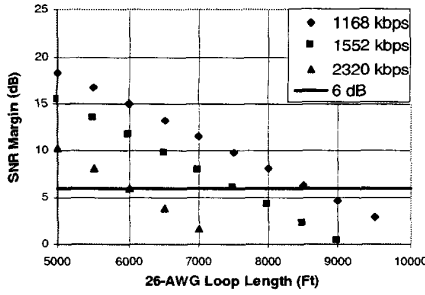

Fig. 1 Received SDSL SNR Margin with 24 Same-binder Self-NEXT

3. SDSL Receiver Enhancement and Analysis

A proposed MIMO SDSL upstream channel model has been introduced. We derive the vector equalization for the SDSL receiver, which can largely suppress the crosstalk degradation on the SDSL transmission throughput and greatly outperforms the current receiver design.

3.1. Proposed Channel Model

In a same binder group of a LEC at the CO side, the upstream SDSL transmission can be viewed as a multiple access channel. That is, an SDSL upstream receiver observes data from n different sources through m different linear coupling functions, resulting in an equivalent $n \times m$ MIMO channel model. The channel model upon that we design of the receiver is assumed to be linear, time-invariant

and sampled at the symbol rate. The proposed channel model is shown in Figure 2. The channel input x_k is a sequence of vectors whose components represent the symbol sequences for each of n SDSL transmitters, where k represents the discrete time index. r_k is the m receiving symbol sequence. The channel transfer function is H and background noise sequences are white Gaussian, expressed as n_k. We can define the multiaccess SDSL channel model in frequency domain as the following.

$$r = H \cdot x + n \quad (5)$$

where the channel transfer function matrix is

$$H = \begin{pmatrix} H_{11} & \cdots & H_{1n} \\ \cdots & \cdots & \cdots \\ H_{m1} & \cdots & H_{mn} \end{pmatrix} \quad (6)$$

In most of the cases, the SDSL services are co-located. The channel impulse response is easily traced with a training signal, due to relatively stable wire-line channel. Some previous works have been studied on detection method for MIMO channels in various other applications [9], [10]. In this paper, we focus on the vector least mean-squared (LMS) algorithm for adaptation with training applied to MIMO SDSL channel model.
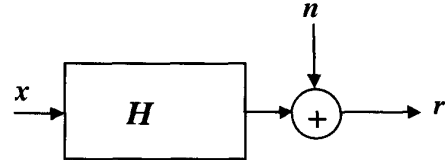

Fig. 2 MIMO SDSL Channel Model

3.2. Vector Equalization for SDSL Systems

A MIMO version of the least-mean square (LMS) approach is used to mitigate crosstalk on the SDSL system. The MIMO DFE [11] for the SDSL can be derived as following. It is a transversal filter with weight matrix $W_k^T = [WF_k^T, WB_k^T]$. There are $L+1$ matrix-valued taps on the feedforward described by the matrix $WF_k^T = [WF_{0,k} WF_{1,k}...WF_{L,k}]$ and I matrix-valued taps on the feedback section as

$WB_k^T = [WB_{1,k} WB_{2,k}...WB_{I,k}]$. Let

$R_k^T = [r_k^T r_{k-1}^T ...r_{k-(L+1)}^T]$ be a vector of SDSL equalizer inputs and $\bar{X}_k^T = [x_{k-1}^T x_{k-2}^T ...x_{k-I}^T]$ is the previously detected symbols, so that the SDSL equalizer output at time k is

$$y_k = WF_k^T R_k - WB_k^T \bar{X}_k .$$

The goal of the equalizer is to minimize the MSE cost function:

$$J = E[|| y_k - x_k ||^2] \quad (7)$$

where x_k is the desired SDSL signal. The complex gradient [12] of Eq. (7) with respect to W_k is:

$$\nabla J = 2E[V_k^* e_k^T] \qquad (8)$$

where $V_k = [R_k, \tilde{X}_k]$, and $e_k = y_k - x_k$ is the error between the equalizer output and the desired SDSL signal, respectively. With the stochastic approximation of the gradient in the steepest descent algorithm on Eq. (8), the vector LMS algorithm on the SDSL DFE weight-tap updating function is:

$$W_{k+1} = W_k - \mu V_k^* e_k^T \qquad (9)$$

where μ is the step size.

By substituting $e_k = W_k^T V_k - x_k$ into Eq. (9), then:

$$\nabla J = 2(\Phi W_k - P) \qquad (10)$$

where $\Phi = E[V_k^* V_k^T]$ and $P = E[V_k^* x_k^T]$. It follows that the optimal weight-tap is given by:

$$W_{opt} = \Phi^{-1} P \qquad (11)$$

and the minimum mean squared error is:

$$\xi_{min} = E[\| x_k \|^2] - tr(P^H W_{opt}) \qquad (12)$$

where P^H is conjugate transpose of P.

For the convergence of the vector LMS on the SDSL receiver, the vector LMS uses a time average to estimate an ensemble average, and the coefficient trajectories are random in nature. The rule on measuring performance is the rate of convergence of the average MSE. With the detailed approaches shown on [13], we can find the step size that maximizes the rate of decrease of the MSE is:

$$\mu_{opt.} = \frac{1}{nL\lambda} \qquad (13)$$

where n is the dimension of the vector, and λ is the eigenvalue of the diagonal matrix Φ. It is also known that the choice of the step size is a trade off between speed of convergence and excess asymptotic MSE.

4. Example and Discussion

Consider on any pairwise SDSL TPC crosstalk in a binder group. The proposed channel model as derived in section 3.1, which is shown in Fig. 2, with a channel transfer function as:

$$H(f) = \begin{bmatrix} 1 & H_{NEXT}(f) & 0 & H_{NEXT}(f) \\ 0 & H_{NEXT}(f) & 1 & H_{NEXT}(f) \end{bmatrix} \qquad (14)$$

where $H_{NEXT}(f)$ is the NEXT coupling path function as shown in Eq. (3). In a binder group, the SDSL channels are statistically independent and symmetric. We assume having the same pairewise coupling path function, $H_{NEXT}(f)$, for neighboring adjacent pairs. Also assume that the SDSL upstream and downstream transmitters are transmitted with the independent baseband PAM signal in a binder group. In

this example, the four transmitted signals are as $X_k = [x_{1up}, x_{1down}, x_{2up}, x_{2down}]^T$, where x_{iup} is the upstream transmitted signal and x_{idown} is the downstream transmitted signal, $i = 1,2$. The coupling path function $H_{NEXT}(f)$, is approximately 0.3 from Fig. (1) for 2320kbps SDSL service. That is

$$r_k = H(f) \cdot X_k = \begin{bmatrix} 1 & 0.3 & 0 & 0.3 \\ 0 & 0.3 & 1 & 0.3 \end{bmatrix} \cdot \begin{bmatrix} x_{1up} \\ x_{1down} \\ x_{2up} \\ x_{2down} \end{bmatrix} \qquad (15)$$

The Fig. 3(a) shows two scalar DFE receivers with the parallel conventional LMS algorithms. The Fig. 3(b) shows a MIMO DFE receiver employing the vector LMS algorithm.
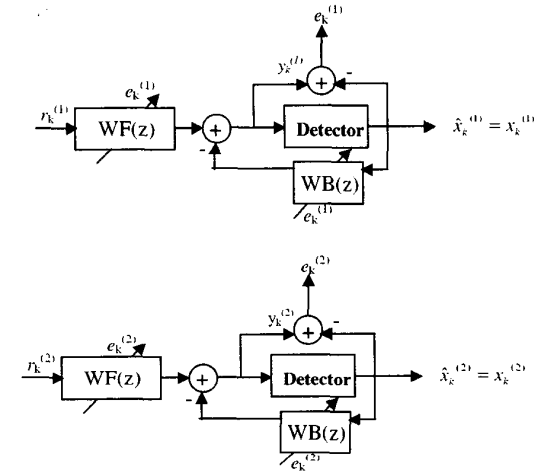

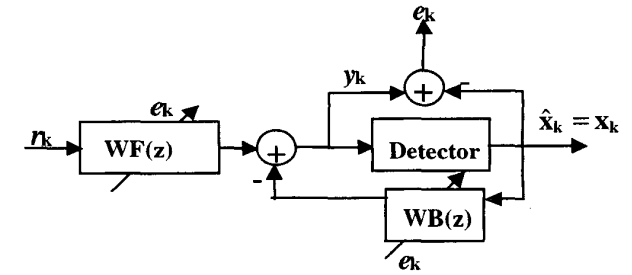**Fig. 3(a)** Conventional Scalar DFE Receiver

Fig. 3(b) Vector DFE Receiver

A key issue that needs to be emphasized here is that the LMS algorithm of the vector equalizer is not equivalent to the parallel independent scalar equalizers. The vector LMS algorithm exploits the crosstalk between users, whereas a bank of scalar LMS algorithms treats the crosstalk as background noise. It is better to exploit the

crosstalk than to treat it together with background noise. That is why the vector SDSL equalizer can significantly outperform the current scalar equalizer.

In Fig. 4, we show the simulation results of the MSE in dB on the 2320 kbps pairwise SDSL system at 7000 ft, with the equalizers chosen from Fig. 3(a) & (b). The step size was $\mu = 0.06$ for two of the scalar equalizer and the step size for the vector equalizer was chosen as in Eq. (13), with $\mu_{vector} = 0.036$. There was 20 forward taps and 84 feedback taps used for the vector equalization. It has been shown that the conventional SDSL receiver performs poorly on suppressing the crosstalk. The MSE for each user is about -15dB, which results in a total of −12dB. The vector SDSL receiver effectively mitigates the crosstalk and outperforms conventional equalizers more than 15 dB in MSE on the SDSL upstream transmission channel.

Based on this approach, the crosstalk for the SDSL services can be largely suppressed and the QoS on the SDSL transmission throughput has been ensured. With a reasonable prediction on this modified SDSL system for the deployment, its loop coverage range can be extended by more than 2000 feet and also increase the numbers of customer subscribers at a lower economic cost.
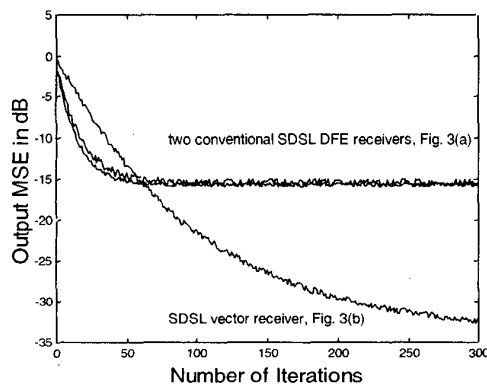

Fig. 4 Output MSE for the Scalar and Vector SDSL Receivers

5. Conclusion

The proposed vector DFE SDSL receiver can suppress the channel crosstalk significantly. This enhancement of the SDSL upstream receiver makes the capacity of the SDSL network utilized much better. With this modification on the SDSL receiver, the computational complexity is increased about 35% and its latency is approximately 10ms. Our goal on this study is to allow the SDSL network supporting the fast Internet access service with its sub-optimal capacity, and extends the SDSL deployment range to additional 2000 ft or more with QoS on customer promising throughput.

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