A Study on Multiuser DSL Channel Capacity with Crosstalk Environment

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Abstract: This paper describes a new approach to enhance *Digital Subscriber Line* (DSL) (emphasizing DMT-ADSL) throughput with multiuser channel model. We have studied the spectral distribution of DSL interference and the capacity of a twisted pair channel in a same binder. The current single user DSL approach ignores the structure of the crosstalk interference and the underlying sources of the crosstalk environment. Our study has shown a significant improvement on multiuser DSL channel capacity, while treating the crosstalk as the sum of filtered coupling of other DSL signals onto the desired DSL receiver. With this circumstance, the DSL deployment restrictions may be relaxed and the DSL services can also extend the loop reach and/or increase the throughput at any given loop length. This study also has the potential implication and benefit for DSL spectral management.

1 Introduction

The sheer inertia of the worldwide installed copper base could take many years for access networks to migrate from copper to fiber. A combination of the existing copper infrastructure and digital subscriber line transmission technologies means that a new era of universal broadband access can now begin at a fraction of the cost and in a fraction of the time required for optical access networks. Even with fiber optical network, the DSL technologies will still exist in the last-mile access transmission [1]. Over the past ten years, DSL technologies have been developed and use larger parts of the available the *twisted copper pair* (TCP) channel bandwidth. Normally, xDSL use 1 to 15 MHz bandwidth. To be able to use this large bandwidth, the telephone lines interface in the *center office* (CO) and *customer premise end* (CPE) need to be exchanged when employing xDSL techniques.

Recently, an increasing number of people use the telephone access network for digital data communication. Even if the speed of an analog modem has increase to 54 kbps, it is still frustratingly slow for the next generation fast Internet multimedia services. The bottleneck when trying to reach higher bit rates is not the channel capacity of TCP, but rather high frequency digital signal interfaces between the lines a same binder. The telephone access networks were originally built for analog voice communication, carrying voice-band signals up to 4 kHz in the frequency bandwidth and not for digital data communication.

XDSL transceivers presently use advanced error correction coding to immunize the noise, such as impulse noise and background Gaussian noise. In a same binder, co-channel interference (crosstalk) occurs when a signal is transmitted on a DSL line in the same frequency range coupling onto a receiver on another DSL line. In currently deployed DSL channel models, crosstalk is modeled as a Gaussian distribution channel noise. It is lumped together with the twisted pair channel background AWGN to a single user receiver. This inaccurate DSL crosstalk model has grossly pessimistic on the DSL channel capacity performance.

The objective of this paper is to study the spectral compatibility issues for various DSL variants, in order to determine a more accurate DMT-ADSL channel model and implement with digital signal processing techniques that realize the true broadband potential of the existing copper access network. In the following sections of this paper, the spectral compatibility problem is covered in section 2. A new approach on DSL channel model for mitigation on crosstalk interference is presented in section 3. Proposed multiuser DSL channel capacity is addressed in section 4. A conclusion is in the final section.

2 Crosstalk in DSL Transmission

The primary impairment to sending digital information through the twisted-pair loop is crosstalk noise from similar digital services of adjacent loops. Now, DSL is treated as a single-user channel with crosstalk as loose Gaussian distribution [4]. Crosstalk to a receiver from a neighboring transmitter is called *near-end crosstalk* (NEXT), as shown in Fig. 1, and crosstalk to a receiver from a transmitter at the opposite end is called *far-end crosstalk* (FEXT), as shown in Fig. 2.

2.1 NEXT and FEXT Modeling

In the case of the NEXT model, it uses Unger's NEXT model [2], which states, as expected, 1% worst-case power sum crosstalk as a function of frequency [3]. NEXT is dependent on frequency as well as on the relative location of the pairs in the binder group. Thus, to find the crosstalk noise from a contributing circuit into another twisted pair in a 50-pair binder, the *power spectral density* (psd) on any line in the binder is modeled by

$$S_n = (\frac{N}{49})^6 \cdot 10^{-13} \cdot f^{1.5} \cdot S_{xtalk\_cont}(f), \qquad (2.1.1)$$

where N is the number of crosstalk-contributing circuits in the binder, S_{xtalk_cont} is the psd of crosstalk-contributing circuits.

FEXT is usually characterized in terms of 1% worst-power sum loss from all signals on other pairs in the binder group [3]. FEXT is less severe than NEXT because the FEXT noise is attenuated by traversing the full length of the cable.

2.2 Current Crosstalk Distribution Model

It has been determined that the time-domain crosstalk noise at the receiver is in a Gaussian distribution [4]. This statement is not true for single crosstalk interference because of the highly-frequency-dependent nature of the crosstalk. When summed over all frequencies from different contributors on different lines, the central limit theorem of statistics loosely applies to this statement. It has also been validated that this does hold for the case of practical interest [4]. The drawback of such an analysis may strongly depend on the size error between a Gaussian distribution and its true distribution. When background thermal noise is small, this error can actually be large with respect to such noise.

3. Multiuser DSL Channel Model

Multiuser detection is very successfully used in the wireless network to combat cochannel signals with employing frequency reuse where one or more secondary signals from nearby cells can interfere with the desired signal. It has also been studied in the VDSL system; together with the Home-Phone LANs (HPL) [5] and showing very little degradation from the HPL crosstalk with multiuser detection, while large degradation with a single-user detector.

This paper employs multiuser detection for the DMT-ADSL system to mitigate crosstalk from SDSL systems in the same binder. The goal of this paper is to apply this approach and algorithm to all DSL systems to suppress crosstalk between their services in a binder group. The ADSL multi-access channel model can be derived in Fig. 3, in a binder group with k pairs of wire lines. The transmitted ADSL signals are denoted as x_1 and the crosstalk data signals are x_k, where $K = 2,3,\ldots,k$, (can be various DSL signals in this proposal assuming all with the SDSL). The ADSL channel transfer function is represented as $H_c(f)$, and the attenuation characteristic of the ADSL channel is approximated by

$$|H_c(f)|^2 = e^{-\alpha\sqrt{f}}, \qquad (3.1)$$

where $\alpha = m\frac{l}{l_0}$, l = length of the channel in fleet, l_0 = a reference length, f in kHz, and m = a constant of the physical channel = 1.158, as in Ref. [6]. The spectral distribution of the NEXT interference coupling to the ADSL line channel is as in Eq. (2.1.1). A key issue, which differs from the Gaussian model, is that each crosstalking data signal undergoes filtering by a crosstalk coupling function before effectively being added at the channel output to the AWGN. With multiuser detection, our proposal will ensure the performance of telephone systems employing the ADSL loops in the presence of the SDSL crosstalk (as our example).

The best detector for the multiuser channel is a joint maximum-likelihood detector. This kind of detector is complex, but theoretically provides bounding of improvement from a multiuser detector. Based on ADSL and SDSL environment studies, a sub-optimal solution has been introduced to reduce the computational complexity.

4. Capacity Study on Multiuser DMT-ADSL

The maximum possible capacities for the individual users in multiuser transmission system help provide bounds and goals that guide the design. We have investigated a sophisticated and more convincing theoretic argument on the achievable performance bounds for the multiuse DMT-ADSL channel with the SDSL crosstalk noise in this section. It shows that data rate of the DMT-ADSL system, which is modeled as a multiuser channel together with the SDSL crosstalk, is higher than the data rate as the single-user channel that modeled the crosstalk as Gaussian noise with the same PSD.

4.1 Spectral Distribution on Multiuser DSL

The spectral distribution in a twisted pair channels (TPC) is not distributed linearly within the width of the frequency band. The reason is that the signal amplitude attenuates as the frequency increase and thus the useful spectrum of the TPC is located at low frequencies, as discussed in [7]. Based on previous studies, we can see that at higher frequencies, there is higher attenuation and higher NEXT crosstalk coupling, which results in smaller the *SNR* and the channel capacity per unit spectrum decreases in TPC. We derive these issues in the following and also address a comparison on channel capacity performance with our multiuser channel model to current single-user channel, treating crosstalk as Gaussian distribution.

For the DMT-ADSL system shown in Fig.5, basic information theory can be used to determine a maximum data rate between the set of channel inputs containing desired DMT-ADSL signal and crosstalk signals, $\{\mathbf{x}: (x_1, x_2,\ldots,x_k)\}$ and the channel output y, which is called mutual information [8]. This mutual information can be represented as

$$I(\mathbf{x};y) = H(\mathbf{x}) - H(\mathbf{x}/y) \qquad (4.1.1)$$

where $H(x)$ is called the entropy of the source **x** and defined as

$$H(\mathbf{x}) = -\sum_{i=1}^{k} p(x_i)\log_2 p(x_i) \text{ (bits/outcome)} \qquad (4.1.2)$$

and $H(x/y)$ is called the conditional entropy of **x**, which defined as

$$H(\mathbf{x}/y) = -\sum_{\mathbf{x}} p(x/y)\log_2 p(x/y) \qquad (4.1.3)$$

The mutual information can be viewed as the reduction in the uncertainty in **x**, on the average, if y is known. Hence, the mutual information is a function of the crosstalk signal contributions, which are often given and not necessarily alterable by optimization, for example using a coding scheme. Therefore, the Shannon's paper [9] is an assertion of the channel capacity on our study. Shannon asserted that there was a largest measure of information that a given noisy channel can carry with vanishing small error probability; it is called the channel capacity, which is

$$C = \max_{p(X)} I(X,O) \quad \text{(bits/channel used)} \qquad (4.1.4)$$

Therefore, C is the largest possible mutual information between the input source, X, and the output O. The capacity, C is the largest measure of information that can be learned about X through this channel. In the following, we derive the capacity for the conventional single-user and our proposed multiuser ADSL channel models.

We assume that the TCP channel can be characterized as a linear time-invariant system. In DMT system, we can divide the transmission bandwidth B of the channel onto K narrow frequency sub-channels (bins); each of width W Hz and assume that the channel, noise and the crosstalk characteristic vary slowly enough with frequency that they can be approximated as constant over each bin.

In the conventional single-user ADSL receiver, it is a fact that at higher frequencies, there is higher attenuation and higher *NEXT* results in smaller the *SNR* and the channel capacity per unit spectrum decreases. The reason is we sum all the crosstalk interferences and background noise (Gaussian distribution) to get the total Gaussian noise. Consider the case of two neighboring lines carrying an ADSL service (desired channel) and a SDSL service (crosstalk channel), under the Gaussian channel assumption, we can write the single-user ADSL receiver capacity as

$$C_{single-user} = \sup_{P_{desired}, P_{interference}} \int_0^{\infty} \log_2[1+\frac{|H_c(f)|^2 P_{desired}(f)}{N_o(f)+|H_{NEXT}(f)|^2 P_{interference}(f)}]df \quad (4.1.5)$$

The supermum is taken over all possible $P_{desired}(f)$ and $P_{interference}(f)$ satisfying:

$$P_{desired}(f) \geq 0, \qquad P_{interference}(f) \geq 0, \qquad \forall f \quad (4.1.6)$$

and the average power constraints for the two directions

$$2\int_0^{\infty} P_{desired}(f)df \leq P_{desired\_max},$$

$$2\int_0^{\infty} P_{interference}(f)df \leq P_{interference\_max} \quad (4.1.7)$$

The denominator of Eq. (4.1.5) is dominated usually by the lager NEXT, $|H_{NEXT}(f)|^2 P_{interference}(f)$. This NEXT is much lager than background noise, which usually in −140 *dBm/Hz*.

In our proposed multiuser ADSL receiver shown in Fig. 3, we use the best detector, which is joint ML detector. The JMLSE across all the channels, which include main desired channel and crosstalk channels, uses the single output available in a single ADSL receiver. It select over all possible crosstalk channel inputs and main desired channel inputs that particular set of inputs that minimizes the distance from the received single channel output. In another word, JMLSE decode the desired vector x_1, and possible the interfering signal vectors $\mathbf{x_K} = x_2,...,x_k$, based on received signal *R*. The signal component $\mathbf{H_K} \cdot \mathbf{x_K}$ is treated as an interfering signal matrix, which prevents the decoding of the desired signal x_1. Rather than treating this interfering signal as a background Gaussian noise, the JMLSE can significantly improve performance by jointly detecting the desired signal vector x_1 with crosstalk signals. Thus, we can write the ADSL channel capacity as

$$C_{multiuser} = \sup_{P_{desired}} \int_0^{\infty} \log_2[1+\frac{|H_c(f)|^2 P_{desired}(f)}{N_o(f)}]df \quad (4.1.8)$$

Obviously, we can conclude that Eq. (4.1.8) has much higher throughput that Eq. (4.1.5).

4.2 Examples on Capacity Analysis

As an example, assume that we are interested in the pairwise crosstalk interference from an adjacent neighboring the SDSL has *psd* of −38dBm/Hz to the desired DMT-ADSL system. Each DMT-ADSL tone has a bandwidth of 4.3125 kHz. The center frequency of the downstream DMT-ADSL is 690 kHz. The SDSL crosstalk coupling function to the ADSL channel can be calculated with $10^{-9}f^{1.5}$ [6]. A *psd* of −38 dBm/Hz SDSL transmitted energy will have a *psd* of −86.8 dBm/Hz at the ADSL receiver. As we know, the background white noise is −140 dBm/Hz in the commonly used case. The mutual information of a SDSL crosstalk on the ADSL circuit line is

$$I(x_2,y) = BW_{each\_tone}\log_2(1+10^{(psd\_awgn-psd\_coupling\_signal)/10})$$
$$= 4.3125kHz\log_2(1+10^{14-8.68}) = 78.5kbps.$$

This means, it is possible to sufficiently detect a 1552 kbps SDSL signal with 20 tones in the worst case with the right code. Moreover, though it is a pairwise result, this capacity is very closed to an ADSL line in a binder group with many wire lines together, because our study has also shown that the major dominant effect of the crosstalk is from an adjacent neighboring pair DSL service in the same binder group. Therefore, -86.8 dBm/Hz is quite closed to the total 50-pair crosstalk degradation in the binder, but only 2 or 3 dBm worse than that.

Assume that a maximum instantaneous data rate of 2320 kbps SDSL signal is coupling with an ADSL system; thus, the maximum mutual information from the SDSL signal into the ADSL line is limited to 2320 kbps. An ADSL signal has an average attenuation of about 43 dB in its downstream bandwidth, with *psd* of −40dB/Hz. Therefore, it should have a residual capacity of

$$I(x_1,y) = I(R,y) - 2320kbps$$
$$= 1.104MHz\log_2(1+10^{[-(40+43)-(-140)]/10}) = 21Mbps.$$

In theoretic bound, there is enough room for the ADSL signal to transmit much faster than the current limit. Though additional SDSL and other DSL signals would reduce this 21 Mbps rate a bit, it will always be possible to detect the ADSL signal even with some large impractical interference signal levels, which may never exist in DSL line channel.

Finally, if the SDSL crosstalk coupling were modeled as a white Gaussian noise with the same psd, the ADSL data rate then becomes

$$R_{ADSL} = 1.104MHz\log_2(1+10^{8.68-8}) = 330kbps,$$

which is almost a complete loss. Therefore, it is too pessimistic to model the crosstalk as a white Gaussian noise, as currently used.

5. Conclusion

In this paper, we examine the spectral distribution of the interference and capacity of a TCP channel in the same binder with DMT-ADSL service. Proposed multiuser DSL channel model has been introduced. This model has proved on enhancement of the DSL channel capacity and crosstalk mitigation. Based on this approach, the performance of the ADSL system throughput is greatly improved, and its service can be extended to about 2-*kft* compared with the current limit. Under these circumstances, the capacity of the network is utilized to a near sub-optimum solution.

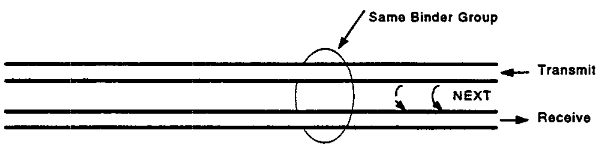

Fig. 1: near-end crosstalk (NEXT)

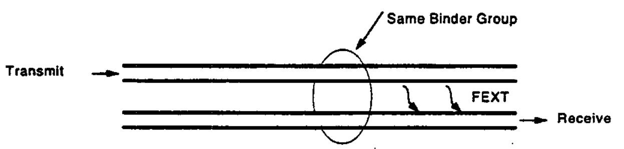

Fig. 2: far-end crosstalk (FEXT)

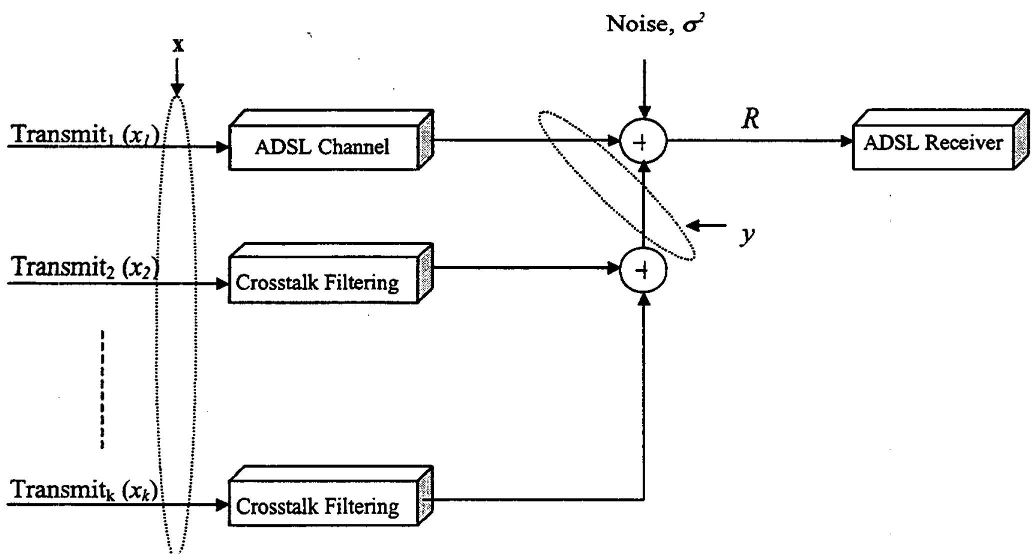

Fig. 3: ADSL Channel Model with *k-1* Crosstalk Signals

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