

A Multichannel Transceiver System for Asymmetric Digital Subscriber Line Service

Peter S. Chow*, Jerry C. Tu, and John M. Cioffi†
Information Systems Laboratory, Stanford University, Stanford, CA 94305

Abstract

We study the performance of a multichannel modulation technique for the contemplated subscriber line data service known as Asymmetric Digital Subscriber Lines (ADSL). We find that over all unloaded North-American subscriber lines in our test set, an unidirectional 1.536 Mbps data rate service (ADSL) from the end-office to the customer premises can be easily achieved on a single twisted pair at an error rate of 10^{-7} . In this study, the dominant line impairments include far-end crosstalk (FEXT) from other ADSL services, spill-over near-end crosstalk (NEXT) from Basic-rate Access ISDN, spill-over BA-ISDN signal, and additive white Gaussian noise (AWGN). We find that the proposed ADSL service can co-exist with existing baseband service on the same twisted pair; in fact, it is possible to reliably transmit data at a rate close to 5 Mbps over all loops within the Carrier Serving Area (CSA) using coded multichannel modulation with a sampling rate of 1 MHz.

1 Introduction

Asymmetric Digital Subscriber Lines (ADSL) service will support 1.536 Mbps data rate service on standard twisted-pair telephone lines, unidirectionally, from the Central Office to the customer premises with the intended application of compressed video distribution (see [1]). In this paper, our emphasis is on the description and performance of one type of transceiver technology that can be used to achieve reliable transmission of the ADSL service.

The term "asymmetric" in ADSL refers to high data rate in one direction only. ADSL is distinguished from the related High-Speed Digital Subscriber Lines (HDSL) service, as HDSL is bidirectional and will only be offered for the restricted set of loops within the so called Carrier Serving Area (CSA)¹. ADSL is also intended to be superimposed on the same single twisted pair that delivers Basic-rate Access ISDN service or possibly the plain-old telephone service (POTS), while HDSL is a substitute service for Basic-rate Access service or POTS.

In Section 2, we describe the loop plant characteristics that we choose as representative of the lossy end of the North-American copper loop plant. In Section 3 we briefly review the characteristics of a multichannel modulation

system that is intended for use with ADSL. In Section 4, we investigate achievable data rates both within and outside of the CSA and find that all loops will reliably support ADSL service with our specific version of the multichannel transceiver.

2 ADSL Loops and Signal Characteristics

2.1 Transmission Characteristics

Some of the key characteristics of the ADSL environment are as follows:

1. All loops are nonloaded.
2. All loops consist of 26-gauge or coarser cables (used alone or in combination with other gauge cables).
3. The maximum allowable loop length is 18 kft.
4. The 1.536 Mbps service must not occupy or interfere with the lower 100 kHz of the frequency band.
5. A low speed reverse channel is to be provided for signaling and control purposes.

2.2 Representative Lines

The twisted pair loops under study are shown in Figure 1. They are representative of "lossy" loops within and outside of the CSA [3]. We will find, as a general result, that channels outside the CSA perform significantly worse than those within the CSA. This is to be expected as channels outside of the CSA suffer much larger signal attenuation because they can be longer in length, smaller in size, and have more bridged taps.

Empirical studies indicate that crosstalk is likely to be the limiting impairment on two-way transmission at the ISDN frequencies of interest. It has been shown that the crosstalk phenomenon can be accurately modeled using only two terms, namely the near-end crosstalk (NEXT) and the far-end crosstalk (FEXT) [4]. In the ADSL environment, data is transmitted unidirectionally; thus, there will be no NEXT term in the frequencies of interest due to other ADSL services in the same wire bundle. (We have also assumed that there will be no T1, HDSL, or DDS systems in operation within the same wire bundle, for they would be extremely damaging to an ADSL system due to their large high frequency content.) Furthermore, since data is transmitted unidirectionally, there is

*Supported in part by a National Science Foundation Graduate Fellowship.

†Supported in part by a gift from Bell Communications Research and by University Technology Transfer Institute.

¹The CSA consists mainly of loops that are less than two miles in length (see Bellcore RFI 90-03 [2]).

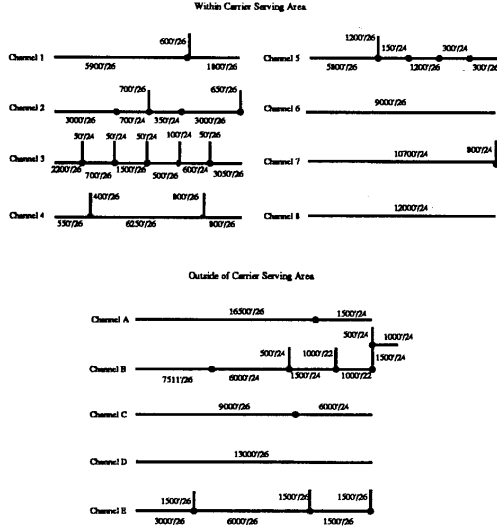


Figure 1: Loops under Study within the CSA and Outside of the CSA

no need for echo cancellation in ADSL frequencies at the customer end. However, there will be a significant amount of spill-over NEXT from bidirectional baseband services in the same wire bundle due to non-ideal filtering. This NEXT term can be modeled with a coupling function of the form:

$$|H_{NEXT}(f)|^2 = K_{NEXT} f^{\frac{3}{2}} \quad (1)$$

where f is frequency in Hz and K_{NEXT} is determined through empirical measurement. In our study, we will assume the scenario of 49-crosstalkers all due to Basic-rate Access ISDN service, where $K_{NEXT} \approx 10^{-13}$. The input power spectrum to this coupling function is the transmitted spectrum of the baseband service, which itself must also be treated as a source of noise as it will spill over to ADSL frequency. In addition to spill-over NEXT and spill-over BA-ISDN signal, FEXT also exists in the ADSL environment, and it can be modeled with a coupling transfer function of the form:

$$|H_{FEXT}(d, f)|^2 = K_{FEXT} d |C(f)|^2 f^2 \quad (2)$$

where $|C(f)|^2$ is the channel power spectral density function, d is the length of the cable in kft, f is frequency in Hz, and K_{FEXT} is determined through empirical measurement. In our study, we will mostly assume that $K_{FEXT} = 10^{-16}$; however, we will also investigate the effect of varying the level of K_{FEXT} at saturation power level in Section 4.2

In addition to crosstalk noise, we will also include an additive white Gaussian noise (AWGN) term in this study, which will be fixed at -140 dBm/Hz. Lastly, intersymbol interference (ISI) is inherent in ADSL loops since the transfer characteristics of the channels are non-ideal. We shall describe how ISI can be mitigated using a multicarrier approach in Section 3.

3 Multichannel Modulation for ADSL

Recently, Decision-Feedback Equalization (DFE) based single carrier systems [5] [6] [7] [8] as well as multicarrier systems [9] [10] [11] [12] have been proposed for ADSL and HDSL applications. In this study, we focus our attention on a multicarrier system, known as the Discrete Multitone (DMT) transceiver [13].

3.1 The Discrete Multitone System

The basic idea behind multicarrier modulation is the conversion of a data transmission channel with intersymbol interference (ISI), and possibly crosstalk and/or colored noise, into a set of parallel, independent, and ISI-free subchannels. A comprehensive tutorial of multicarrier modulation can be found in [11]. The specific modulation technique evaluated in this study is Discrete Multitone (DMT) modulation, which is based on frequency-division partitioning of the channel spectrum using the discrete Fourier transform, and it is an enhanced version of what appears in [13].

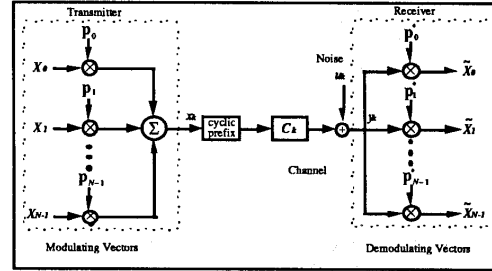


Figure 2: Basic Structure of Multicarrier Modulation

The general structure of multicarrier modulation is illustrated in Figure 2. Essentially, the modulator divides the channel into a fixed number of, say N , parallel, complex, independent subchannels. Different numbers of bits can then be assigned to different subchannels so that more data will be transmitted over those bands of the channel spectrum with larger gains, and less data will be transmitted over those bands of the channel spectrum with smaller gains, in order to optimize the overall data rate. In the case of the ADSL application, we simply assign zero bit to the subchannels within the lower 100 kHz of the frequency band to conform to the ADSL requirements. For the DMT system, the independent modulating vectors in Figure 2 are the Inverse Discrete Fourier Transform (IDFT) vectors, and the independent demodulating vectors are the Discrete Fourier Transform (DFT) vectors, given by the following pair of equations:

$$X_m = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_n e^{-j2\pi n m / N} \quad (3)$$

$$x_n = \frac{1}{\sqrt{N}} \sum_{m=0}^{N-1} X_m e^{j2\pi n m / N} \quad (4)$$

A major advantage of this transceiver structure is that the modulating/demodulating vectors can be computed very efficiently using the well known Fast Fourier Transform (FFT) algorithms.

3.2 Coset Code Concatenation

One attractive feature of multicarrier modulation is that since the independent subchannels are essentially memoryless, coset codes (trellis codes) can be concatenated to the modulation structure, and the coding gain of these powerful codes can be realized by the system. In the DMT system studied here, we will use a method of code concatenation described in [14] known as “coding down the block”, in an effort to achieve a good tradeoff between hardware complexity and decoding latency.

3.3 Channel Identification and Protocol

An accurate channel estimation is necessary in discrete multitone modulation, and this information must be available to both the transmitter and the receiver. The channel identification process takes place during the initial startup procedure. First, some predefined test patterns are transmitted from the Central Office, after receiving a request for transmission signal from the user, to verify the channel is indeed operational. Timing and synchronization are established at this time. Then a predefined pseudorandom training sequence is sent from the transmitter for spectral estimation. After frame synchronization is established, the DMT transceiver system is ready for actual data transmission. It should be stated that the information sent from the customer to the Central Office during this startup period cannot be in the lower 50 kHz of the frequency band; thus, it will not interfere with existing services on the loop. This requires the use of at least one subchannel in the opposite direction. Furthermore, this subchannel is silent in the forward direction, and it will also serve as a reverse channel for system control and monitoring functions during normal operation.

4 Performance in ADSL

4.1 DMT Transceiver Specification

The DMT transceiver that we study has a blocklength of 512 and a signaling rate of 1 MHz. These system parameters are only representative and can be changed easily. In particular, we note that a longer blocklength DMT (say 1024) or a higher signaling rate (for example, 2 MHz) would yield higher data rates at the cost of longer decoding delay and higher complexity. In [15], Aslanis and Cioffi showed that the capacity of loops inside the CSA for HDSL application will continue to increase until the signaling rate nears 600 kHz to 800 kHz. We will show that for ADSL, the capacity of loops will continue to increase with signaling rate well beyond 800 kHz, and we selected a signaling rate of 1 MHz in order to avoid radio frequency interference. On the other hand, our choice for blocklength of 512 reflects the current technology in terms of feasible computational complexity and cost.

4.2 Performance Results

First we used computer simulation to investigate the capacity of loops for ADSL as a function of sampling rate. In Figure 3, we show the achievable data rate through CSA channel 6; i.e., the 9 kft, 26 gauge cable, as a function of sampling rate for two different transmit power levels (20 mW for the solid line and 100 mW for the dashed line). Clearly, the capacity for this particular loop continues to increase with sampling rate well beyond 800 kHz; however, sampling at rates higher than 1 MHz will result in radio frequency interference.

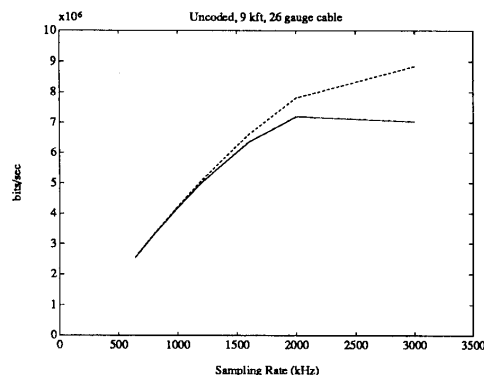


Figure 3: Loop Capacity for CSA Channel 6

We then used computer simulation to investigate the performance of a DMT transceiver in the ADSL environment as a function of transmitter power given that a sampling rate of 1 MHz and a blocklength of 512 are used. Using the DMT's frequency-specific bit allocation algorithm we can easily shape the transmitted spectrum for the ADSL environment in order to achieve the highest performance. We simulated power levels from 1 mW to 200 mW (0 dBm to 23 dBm) for both CSA loops and loops outside of CSA. The achievable data rates at Bit Error Rate of 10^{-7} are shown in Figures 4 and 5. We next investigated the performance of DMT with a concatenated trellis code. We assumed the coding gain achievable using a 8-dimensional 64-state trellis code with approximately 5 dB of gain. The resulting data rates are shown in Figures 6 and 7.

Our evaluation shows that all channels in our test set can support 1.536 Mbps data rate transmission in the ADSL environment using a DMT transceiver with reasonable transmit power. In fact, we can transmit data at well over twice the T1 rate over all CSA loops in our test set with at least a 6 dB noise margin, while using only 20 mW of transmit power with a coded DMT system.

We note that in all cases; i.e., coded and uncoded transmissions over loops within the CSA as well as those outside of the CSA, the achievable data rates will eventually saturate, due to the presence of far-end crosstalk, no matter how much more power we use at the transmitter. Furthermore, this saturation level can be explained and obtained from the following saturation capacity approximation, as-

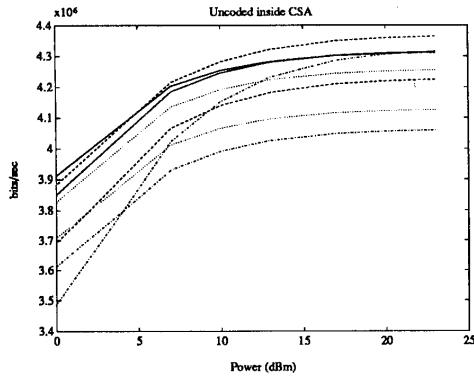


Figure 4: Uncoded Data Rates for CSA Channels as a Function of Transmitted Power

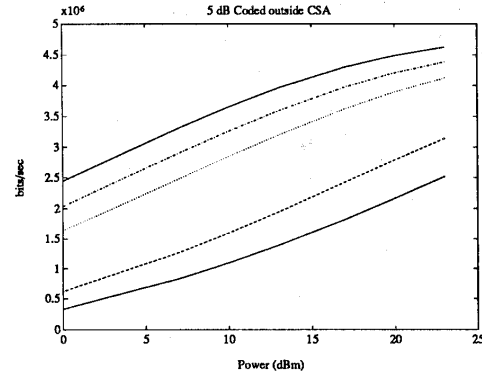


Figure 7: Coded Data Rates for Channels Outside of CSA as a Function of Transmitted Power

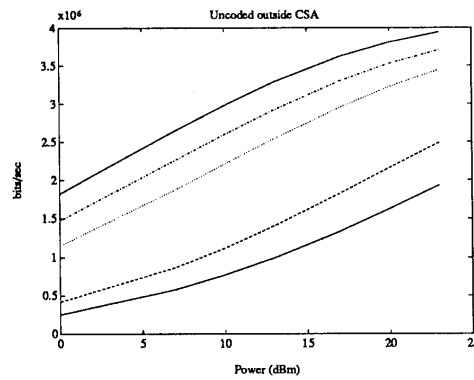


Figure 5: Uncoded Data Rates for Channels Outside of CSA as a Function of Transmitted Power

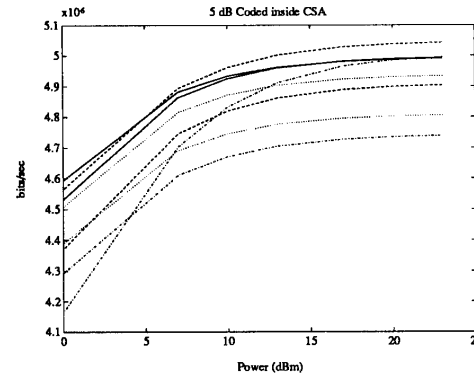


Figure 6: Coded Data Rates for CSA Channels as a Function of Transmitted Power

suming that FEXT is the only dominant source of line impairment:

$$C = \sum_{k=0}^{N-1} \frac{W}{2N} \log_2(1 + SNR_k) \quad (5)$$

$$\cong \int_{100kHz}^{500kHz} \log_2(1 + SNR(f)) df \quad (6)$$

$$= \int_{100kHz}^{500kHz} \log_2\left(1 + \frac{E_x |C(f)|^2}{E_x K_{FEXT} d |C(f)|^2 f^2}\right) df \quad (7)$$

$$= \int_{100kHz}^{500kHz} \log_2\left(1 + \frac{1}{K_{FEXT} d f^2}\right) df \quad (8)$$

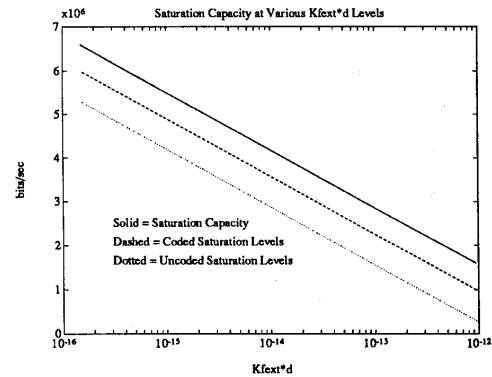


Figure 8: Data Rates at Saturation Power Level

We note here that this saturation level is independent of channel characteristics other than the channel length. Therefore, we can characterize the saturation level of any FEXT dominated channel as a function of $K_{FEXT} * d$. In

Figure 8, we plotted the achievable data rates as a function of $K_{FEXT} * d$ for the coded and the uncoded cases as well as the theoretical channel capacity calculated using Equation 8 above.

5 Conclusion

In this study, we evaluated the performance of a DMT transceiver system for ADSL channels. In particular, with the addition of a powerful 5dB trellis code, we found that all channels in our test set can support the 1.536 Mbps ADSL data rate with an error rate of 10^{-7} and a 6 dB operational margin while maintaining complete spectral compatibility with existing services. In fact, all subscriber lines within the CSA can support 3.088 Mbps data rate; i.e., twice the T1 rate, on a single twisted pair with an error rate of 10^{-7} and over 6 dB of operational margin using coded multichannel modulation with reasonable transmit power. However, the 3.088 Mbps data rate cannot be sustained over a single twisted pair for worst case subscriber lines outside of CSA even without any margin.

Based on these performance results, the computational efficiency of the DMT system, and the additional benefit that the DMT-based ADSL transceivers can be easily modified to accommodate other services such as HDSL [16] and VHDSL with only minor software changes, we conclude that the Discrete Multitone system represents an excellent design choice for the ADSL service.

References

- [1] A. Wong, C.T. Chen, D.J. Le Gall, F.C. Jeng, and K.M. Uz. MCPIC: A Video Coding Algorithm for Transmission and Storage Applications. *IEEE Communications Magazine*, 28(11):24–32, November 1990.
- [2] Bell Communications Research. High Bit-Rate Digital Subscriber Line (HDSL) Systems that Support DS1 Rate Access in the Copper Loop Plant. *Belcore Request for Information*, (RFI 90-03), March 1990.
- [3] K. Sistanizadeh. A Tentative CSA Loop Population for Preliminary Studies of HDSL Transmission Schemes. *T1E1.4 Technical Subcommittee Working Group Contribution*, September 24, 1990.
- [4] D.G. Messerschmitt. Design Issues in the ISDN U-Interface Transceiver. *IEEE Journal on Selected Areas in Communications*, pages 1281–1293, November 1986.
- [5] J.W. Lechleider. Digital Subscriber Line Terminals for Use with Correlated Line Codes. *IEEE Trans. on Communications*, 35(10):1029–1036, October 1987.
- [6] D.W. Lin. Wide-Band Digital Subscriber Access with Multidimensional Block Modulation and Decision-Feedback Equalization. *IEEE Journal on Selected Areas in Communications*, 7(6):996–1005, August 1989.
- [7] P. Crespo and D.W. Lin. Study of HDSL Transmission Employing Coded Modulation and Decision-Feedback Sequence Estimation. *1990 IEEE HDSL Workshop*, March 29, 1990. Parsippany, NJ.
- [8] V. Eyuboglu, G.D. Forney, G. Pottie, and L. Brown. Trellis Precoding for High Rate Transmission on Subscriber Lines. *1990 IEEE HDSL Workshop*, March 29, 1990. Parsippany, NJ.
- [9] I. Kalet. The Multitone Channel. *IEEE Trans. on Communications*, 37(2):119–124, February 1989.
- [10] N. Zervos and I. Kalet. Optimized Decision Feedback Equalization Versus Optimized Orthogonal Frequency Division Multiplexing for High Speed Data Transmission over the Local Cable Network. In *1989 International Conference on Communications*, Boston, June 1989.
- [11] J. Bingham. Multicarrier Modulation for Data Transmission : An Idea Whose Time Has Come. *IEEE Communications Magazine*, 28(5):5–14, May 1990.
- [12] J. Chow, J. Tu, and J.M. Cioffi. A computationally efficient adaptive transceiver for high-speed digital subscriber lines. In *1990 International Conference on Communications*, Atlanta, April 1990.
- [13] A. Ruiz, J.M. Cioffi, and S. Kasturia. Discrete Multiple Tone Modulation with Coset Coding for the Spectrally Shaped Channel. To appear.
- [14] J.C. Tu and J.M. Cioffi. On the Concatenation of Coset Codes with Multichannel Modulation Methods. In *1990 Global Telecommunications Conference*, San Diego, December 1990.
- [15] J.T. Aslanis and J.M. Cioffi. Achievable Information Rates on Digital Subscriber Loops: Limiting Information Rates with Crosstalk Noise. *IEEE Transactions on Communications*. To appear.
- [16] J.S. Chow, J.C. Tu, and J.M. Cioffi. A Discrete Multitone Transceiver System for HDSL Applications. *IEEE Journal on Selected Areas in Communications*. To appear, 1991.