Performance Evaluation of a Multichannel Transceiver System for ADSL and VHDSL Services

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***Abstract*—We study the performance of a multichannel modulation method for two contemplated subscriber line data services known as asymmetric digital subscriber lines (ADSL) and very high-speed digital subscriber lines (VHDSL). In the ADSL case, we find that over all unloaded North American subscriber lines in our test set, an unidirectional 1.536 Mb/s data rate service from the end office to the customer premises is possible on a single twisted pair at an error rate of 10^{-7} with at least a 6 dB margin using coded multichannel modulation with sufficient transmit power. Furthermore, we find that the proposed ADSL service can co-exist with basic-rate access ISDN (or voiceband analog services) on the same twisted pair with our proposed system. In the VHDSL case, data rates in excess of 100 Mb/s can be transmitted reliably, at an error rate of 10^{-7}, using uncoded multichannel modulation on a single twisted pair over a relatively short distance (≤ 150 feet) with a sufficiently high sampling rate (≈ 24 MHz) and transmit power. In this study, the dominant line impairments in the ADSL environment include intersymbol interference (ISI), far-end crosstalk (FEXT) from other ADSL services, spill-over near-end crosstalk (NEXT) from baseband services in the same wire bundle, spill-over far-end baseband signal on the same twisted pair due to imperfect filtering, and additive white Gaussian noise (AWGN) from such sources as electronic and thermal noises. In the VHDSL environment, ISI, FEXT and NEXT from other VHDSL services in the same wire bundle, as well as AWGN, are included. Finally, we show that a cost-effective multichannel transceiver design that has been suggested for high-speed digital subscriber lines (HDSL) service will also work well for the proposed ADSL and VHDSL services with only minimal modifications.**

I. Introduction

With the advent of high-speed digital subscriber lines (HDSL) technology in recent years, a number of new high-speed transport concepts have been proposed in the communications industry. Among these newly proposed transport concepts, asymmetric digital subscriber lines (ADSL) and very high-speed digital subscriber lines (VHDSL) are two of the most promising future data transmission services in today's market. In this paper, our emphasis is on the description and performance evaluation of one type of HDSL transceiver technology that can be used to achieve reliable data transmission for both ADSL and VHDSL services.

The proposed ADSL service will support a 1.536 Mb/s data rate on standard twisted-pair telephone lines, unidirectionally, from the Central Office to the customer premises. The term "asymmetric" in ADSL refers to a high data rate in one direction only, as ADSL is distinguished from HDSL, the latter of which is bidirectional and will only be offered for the restricted set of loops within the so-called carrier serving area (CSA)[1]. Furthermore, HDSL is intended for conventional T1 or DS1 data rate services, while ADSL is a consumer service with the intended application being the transmission of compressed TV-quality video (see [2]) with distribution over almost the entire loop plant, including those outside of the CSA. Lastly, ADSL is also currently being considered, for economical reasons, 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 will be a substitute service for basic-rate access ISDN or POTS.

Because of the asymmetry in the transmission system for ADSL, near-end crosstalk (NEXT) from one ADSL service to another cannot occur, and we will show that in the ADSL environment, the dominant line impairments are intersymbol interference (ISI), far-end crosstalk (FEXT) from other ADSL services, spill-over near-end crosstalk (NEXT) from baseband services, spill-over far-end baseband signal on the same twisted pair, and additive white Gaussian noise (AWGN) from such sources as electronic and thermal noises. The absence of near-end crosstalk due to other ADSL services in the same wire bundle significantly improves the data transport capability of the twisted pair and allows 1.536 Mb/s transmission on all loops in our test set with adequate margin when a sufficiently powerful transceiver is used.

VHDSL, on the other hand, is a high-speed data transport concept that serves as a component of the eventual

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

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migration to fiber within the loop plant. VHDSL considers full-duplex transmission of data at rates significantly higher than the HDSL rate but over only that segment of the loop plant located between the pedestal and the customer premises, and it presumes a high-speed media (such as fiber) from the end office to the pedestal. Data rates of interest include those sufficiently high to sustain computer network applications, such as 8, 10, and 16 Mb/s, the T3 rate of 44.736 Mb/s, the OC-1 rate of 51.84 Mb/s, the FDDI rate of 100 Mb/s, and the OC-3 rate of 155.52 Mb/s.

Typical VHDSL channels are short drops (≤ 150 feet) of unshielded twisted pair (26 gauge or better) from the pedestal to the customer premises. There are usually two such pairs into the average customer premises, and these two pairs can crosstalk into one another if both are used. ISI on such channels is not as severe as those encountered in HDSL or ADSL but is still significant at the data rates of interest, and we find near-end crosstalk (NEXT) to be more limiting than far-end crosstalk (FEXT) when both pairs are used.

In this paper, we focus on multichannel modulation and show that it is an excellent method for delivering reliable high data rates to the customer, both in terms of performance and cost, for ADSL and VHDSL. In Section II, we describe the loop plant characteristics for both the ADSL and the VHDSL environments. We also describe the provisions made for possible co-existence of ADSL with other analog and digital baseband data services and the inclusion of a reverse channel capability in ADSL. In Section III, we briefly review the characteristics of a multichannel modulation system that is intended for use with ADSL as well as VHDSL. In particular, we use discrete Fourier transform in the transceiver design with the goal of maximizing performance and minimizing computational requirements. In Section IV, we investigate achievable data rates both within and outside of the CSA for ADSL and find that all loops in our test set will reliably support ADSL service with at least a 6 dB margin using our specific version of coded multichannel transceiver. In Section V, we investigate achievable data rates for VHDSL with varying system parameters, and we find that with a very high signaling rate (24 MHz) and sufficient transmit power, we can reliably transmit over 100 Mb/s through VHDSL lines even without an additional trellis code. Finally, we summarize our findings in Section VI.

II. LOOPS AND SIGNAL CHARACTERISTICS

A. *ADSL Transmission Characteristics*

The proposed ADSL service is closely related to HDSL; however, unlike HDSL, ADSL provides *unidirectional* high data rate service to consumers within the carrier serving area (CSA) and possibly outside of the CSA. At the present time, there are no established design rules for ADSL, though several key characteristics of the ADSL environment have been identified as follows [3]:

1) All loops are nonloaded.

2) All loops consist of 26 gauge or coarser cables, either used alone or in combination with other gauge cables.

3) The maximum allowable loop length, including bridged taps, is 18 kft.

4) A reverse channel with a maximum data rate of 9.6 kb/s is to be provided for control purposes.

In addition, it would be economically advantageous if the ADSL service can be superimposed on the same line that delivers basic-rate access ISDN or analog baseband services, e.g., POTS. For this reason, though it is not a formal design rule for ADSL, we will evaluate a multicarrier system that delivers the unidirectional 1.536 Mb/s data rate without occupying or interfering the lower 50 kHz of the frequency spectrum. Furthermore, an important design objective for the authors is that the existing HDSL transceivers should be easily modified to handle ADSL service, e.g., via simple software changes, so that minimal design impact is to be incurred while implementing ADSL as a subset of HDSL.

B. *Representative Loops in the ADSL Environment*

The set of loops under study is shown in Fig. 1. They are representative of "lossy" loops within and outside of the CSA [4], [5]. The impulse response and power spectral density[2] characteristics for these channels have been determined with data in [6], using a modified version of the LINEMOD program[3]. A pole-zero model is added to the response of each loop to eliminate the dc component and to simulate the effects of the transformer coupling that exists at both ends of the twisted pair. This pole-zero model consists of a double-zero at dc and a double-pole that makes the power gain of the transformer equals to −6 dB at 300 Hz.

We will find, as a general result, that channels outside of 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 are longer in length. Cable attenuation characteristics of various channels in the frequency domain are illustrated in Fig. 2, which compares the power spectral densities of loops outside of CSA to one of the "worst-case" CSA channels (channel 6). We should point out that these power spectral densities are calculated based on source-to-load loss. Therefore, power spectral densities of the same loops calculated based on insertion loss should be scaled 6 dB higher uniformly across the entire frequency band, assuming that the source and load impedances are matched. We will use these power spectral densities based on source-to-load loss in our computer analysis for achievable throughput of our proposed system, which implies that we have tacitly included a 6 dB noise margin

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[2] We define the "power spectral density" of a channel as the magnitude squared of the Fourier transform of the channel impulse response.

[3] We thank Prof. D. G. Messerschmitt of the University of California at Berkeley for making the source code of this program available to us.

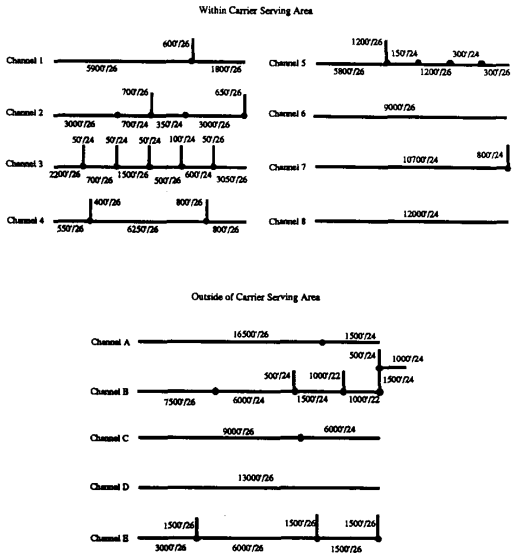

Fig. 1. ADSL loops under study within and outside of the CSA.

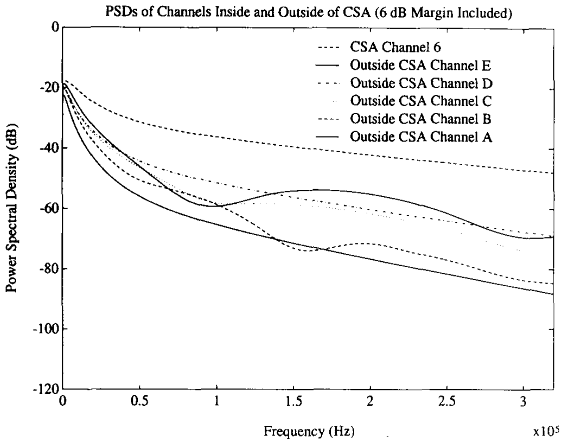

Fig. 2. Power spectral densities of representative ADSL loops under study.

(as is now required in HDSL applications) in any environment where the dominant source of noise does not depend on the channel characteristics. This is the case for HDSL, where the channel-independent near-end crosstalk is the dominant source of noise [7], and we will show in Section V-B that this is also true in the VHDSL environment. In the case of ADSL, however, the dominant source of impairment in most of our test loops turns out to be the channel-dependent far-end crosstalk, which is proportional to the channel transfer function. Thus, the factor of 6 dB margin does not apply. We will describe the various channel impairments for both ADSL and VHDSL in more detail in Sections II-C and II-F, respectively, and we will evaluate the consequences of including a 6 dB noise margin explicitly on the ADSL system in Section IV-B.

C. ADSL Line Impairments

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) [8]. The NEXT and FEXT terms are identified in Fig. 3. In the ADSL environment, data is transmitted unidirectionally. Therefore 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 or HDSL 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.) However, there will be a significant amount of spill-over NEXT from bidirectional baseband services in the same wire bundle due to nonideal filtering. This NEXT term can be modeled with a coupling function of the form [8]:

$$|H_{\mathrm{NEXT}}(f)|^2 = K_{\mathrm{NEXT}} f^{3/2} \qquad (1)$$

where f is frequency in Hz and K_{NEXT} is determined through empirical measurement. In our study, we will assume the worst-case scenario of 49 crosstalkers all due to basic-rate access ISDN service, where $K_{\mathrm{NEXT}} \approx 10^{-13}$ [9], [10]. The input power spectrum to this coupling function is the transmitted spectrum of the baseband service. For basic-rate access ISDN service over AT&T DSL's, square pulses are passed through a second-order lowpass filter with the 3 dB point at 40 kHz and at least a 50 dB/decade rolloff after 50 kHz [11]. The actual signal voltages used are ±2.5 volts and $\pm\frac{5}{6}$ volt, leading to an average power of approximately 25 mW with a 135 Ω load impedance. We will use this transmit spectrum and power level for BA-ISDN in our computer evaluation, though this is not the worst-case transmit spectrum. In particular, if sinc pulses are used instead of square pulses, we would have a flat instead of sinc squared spectrum.

In addition to spill-over NEXT, FEXT also exists in the ADSL environment, and it can be modeled with a coupling transfer function of the form [12]:

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

where $|C(f)|^2$ is the channel power spectral density function as plotted in Fig. 2, 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 $K_{\mathrm{FEXT}} \approx 10^{-16}$ [13]–[15], though we will also investigate the effect of varying the level of K_{FEXT} at saturation power level in Section IV-B.

In addition to crosstalk noise, there are several other impairments that will degrade the performance of any system operating over twisted copper pairs at ADSL rates. Because we have assumed that the ADSL service is superimposed on the same wire that delivers baseband BA-ISDN, the spill-over far-end signal from BA-ISDN on the same wire will be received along with the ADSL signal,

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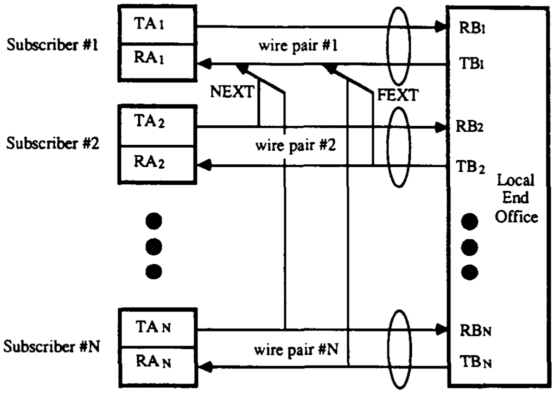

Fig. 3. Near-end and far-end crosstalk.

and this spill-over "signal" must be treated as noise by the ADSL receiver. Electronic noise, including quantization noise from the A/D converter, and thermal noise in the analog portion of the receiver can be modeled as additive white Gaussian noise (AWGN). We will assume a fixed level of AWGN at -140 dBm/Hz in our study, which represents a fairly conservative estimate [5]. Inductive noise at 60 Hz and its harmonics generally do not cause a problem at ADSL rates [1]; therefore, it will be ignored in our study. Residual echo noise is also negligible since there will be no echo due to ADSL at the receiver end as data is transmitted unidirectionally, and residual echo from baseband service is assumed to be sufficiently cancelled and filtered out. Impulse noise caused by switching transients, lightning, and electrical machinery is less well understood, and usually an operational margin of 6–12 dB is placed on a system to handle such infrequent but high-peak noise. We shall not include impulse noise in our model. However, the block processing nature of our multicarrier system is advantageous when dealing with this type of short but intense noise, since the noise energy contained in the impulse is effectively spread over the entire block and the blocklength used is typically in the order of several hundred times that of the duration of the impulse (see [7]). Impulse noise of long duration, on the other hand, is hopefully eliminated by the high-pass filter in ADSL. Lastly, intersymbol interference (ISI) is inherent in ADSL loops since the transfer characteristics of the channels are nonideal. We shall describe how ISI can be mitigated using a multicarrier approach in Section III.

D. VHDSL Transmission Characteristics

The proposed VHDSL service is an enhancement [16] of the presently developing HDSL service. VHDSL provides reliable, bidirectional data transmission at rates of 10 Mb/s or higher over only relatively short distances. Loops intended for use with VHDSL service are those that are located between the pedestal and the customer premises. These are generally no more than 150 feet in length and no smaller than 26 gauge in size. As in the case of ADSL, VHDSL is a new transport concept with no established design rules yet. Some of the target data rates that may be desirable for VHDSL applications include:

- Current Ethernet standard rate = 10 Mb/s
- DS-3 (digital signal, level 3) = T3 rate = 44.736 Mb/s
- OC-1 (optical carrier, level 1) = 51.84 Mb/s
- FDDI rate = 100 Mb/s
- OC-3 (optical carrier, level 3) = 155.52 Mb/s

E. Representative Loop in the VHDSL Environment

In this study, we only consider the worst-case VHDSL loop, i.e., 150 feet of 26 gauge wire. Furthermore, we assume that PIC cables operating at 70°F with matched source and load resistances of 110 Ω are used and that within this short 150 feet line there are no bridged taps or wire gauge changes. As in ADSL loops, a transformer is added to both ends of the cable to eliminate the dc component in the frequency response. Again, the effects of the transformer coupling is simulated by a pole-zero model that consists of a double-zero at dc and a double-pole that makes the power gain of the tranformer equal to -6 dB at 300 Hz. Using the modified version of LINEMOD with data in [6], we can determine the impulse response and power spectral density characteristics for this channel. We found that the maximum useful bandwidth of this worst-case loop is around 12 MHz (see Fig. 4). Thus, a maximum signaling rate of 24 MHz will be used in this study.

F. VHDSL Line Impairments

As in the case of ADSL, NEXT, and FEXT are two of the most serious line impairments encountered in VHDSL. The coupling function for NEXT is given by (1) in Section II-C. In [9], Lin estimated that $K_{\text{NEXT}} \approx 10^{-13}$ for the 49-crosstalker case from data in a Bellcore Technical Reference [10]. In the case of VHDSL, however, the twisted pairs are most likely unbundled. Therefore, instead of 49-crosstalkers, there will usually be a maximum of only one crosstalker, as existing customer lines often contain two twisted pairs into each customer premises. We will assume that $K_{\text{NEXT}} \approx \frac{1}{50} \times 10^{-13} = 2 \times 10^{-15}$ for our test loop. Note that if we assume there are normally only 6 dominant crosstalkers in a 50-pair bundle, then the VHDSL K_{NEXT} with one crosstalker should be closer to $\frac{1}{6} \times 10^{-13}$. We will investigate the effect of varying the level of K_{NEXT} in Section V-B. The coupling function for FEXT is given by (2) in Section II-C. As in the case of K_{NEXT}, K_{FEXT} is determined through empirical measurement [13]–[15]. In this study, we will assume that $K_{\text{FEXT}} \times d \approx \frac{1}{50} \times 0.15 \times 10^{-16} = 3 \times 10^{-19}$ for the test loop, since there will only be one far-end crosstalker instead of 49 and $d = 150$ ft $= 0.15$ kft. The performance of DMT for K_{FEXT} varying over several orders of magnitude are discussed in Section V-B. Besides NEXT and FEXT, the transmitted data may also be corrupted by interaction crosstalk and apparatus crosstalk at VHDSL fre-

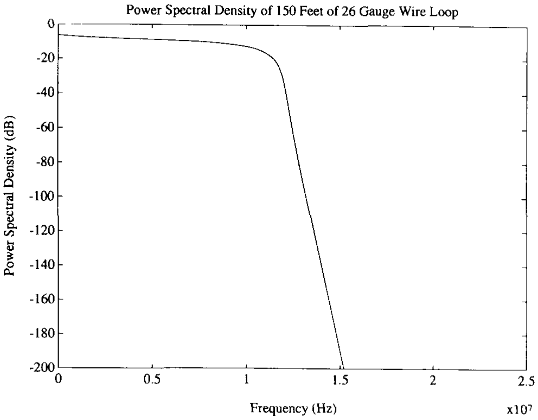

Fig. 4. Power spectral density for 150 feet of 26 gauge copper twisted pair loop.

quencies. However, the specific effects of interaction crosstalk, which is the coupling between two pairs involving other pairs, and apparatus crosstalk, which takes place at terminals, splices, and cross-connects, are not well understood [17]. Therefore, they will not be included here.

In addition to various forms of crosstalk, there are several other potential impairments that will degrade the performance of a VHDSL system. Residual echo noise does exist in VHDSL loops, and it is typically modeled as additive white Gaussian noise (AWGN). Assuming an input signal power of around 20 mW, a typical VHDSL loop will attenuate the signal by approximately 10 dB, resulting in a total received signal power of 3 dBm. With an excellent echo canceller that can reduce the echo to a level of 40 dB below the received signal, we expect a total noise power of around -37 dBm across a two-sided bandwidth of 24 MHz, yielding a noise power spectral density of approximately -110 dBm/Hz. Therefore, we will fix the level of AWGN due to residual echo at a constant level of -110 dBm/Hz throughout this study. Other sources of AWGN noise, such as electronic noise and thermal noise, are less damaging. We will assume a fixed level of electronic noise at -140 dBm/Hz in our study [5], which represents a fairly conservative estimate and can be ignored since it is much lower than the AWGN level of the residual echo noise. The effects of inductive noise and impulse noise in VHDSL are similar to those in ADSL, and lastly, ISI can be mitigated by using a multicarrier modulation approach described in Section III.

III. MULTICHANNEL MODULATION

Recently, various multicarrier systems [18]–[21] have been proposed to transmit data reliably in the presence of severe intersymbol interference (ISI) for digital subscriber line applications. In this study, we focus on a specific implementation of multicarrier modulation, known as the discrete multitone (DMT) modulation [21].

A. The Discrete Multitone System

The fundamental concept of 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. In [20], Bingham gives a comprehensive tutorial on the various multicarrier modulation methods, and the specific modulation technique evaluated in this study is known as the discrete multitone (DMT) modulation. DMT modulation 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 [21]. We shall not attempt a detailed description of the DMT modulation in this section, but rather we refer readers to the companion paper [7] by J. S. Chow and two of the co-authors of this paper on the performance evaluation of the DMT system for high-speed digital subscriber lines (HDSL) in this same issue.

B. Trellis Code Concatenation

One attractive feature of multicarrier modulation is that since the independent subchannels are 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 [22] and [23], Forney characterized most of the known good codes for bandlimited channels as coset codes. In the DMT system studied here, we will use a method of code concatenation described in [24] known as "coding down the block," in an effort to achieve a good tradeoff between hardware complexity and decoding latency. This method was also inherent in [25] and in a recently filed patent application by Decker of Telebit [26]. In this method, a single encoder/decoder pair is used and several coded symbols from the encoder are concatenated together to form the multidimensional transmit vector that is to be processed by the multicarrier modulator. Each orthogonal dimension of the transmit vector is assigned to succeeding subchannels of the multicarrier system until all subchannels are used. The details of the coset code concatenation procedure are given in [24].

C. Channel Identification and Protocol

An accurate estimate of the channel response is necessary in discrete multitone modulation, and this information must be available to both the transmitter and the receiver in order for the bit allocation algorithm and the pole-cancelling filter to function properly. The channel identification process takes place during the initial startup procedure. We will now briefly summarize the general protocol used by the DMT for ADSL and VHDSL services.

After receiving a request for transmission signal from one subscriber, predefined test patterns are transmitted to verify that the channel is indeed operational. Timing and synchronization are established at this time. Then a predefined pseudorandom training sequence is sent from the

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