Theoretical and Practical Limits of Next-Generation High-Speed Digital Subscriber Loops

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***Abstract*—For the single-pair HDSL (HDSL2), the concept of having different upstream and downstream power spectral densities is highlighted. The signal-to-noise ratio (SNR) at the input of the central office HDSL terminal unit (HTU-C) can be enhanced by boosting the power output of the remote user HDSL terminal unit (HTU-R). Further improvement in performance can be achieved by reducing the HTU-C NEXT interference. Two techniques are proposed to reach this goal. The first approach is to reduce the HTU-C transmitter power in the downstream direction for shorter reach cables. The second approach is borrowed from the analog frequency-modulation preemphasis/deemphasis frequency tilting in the upstream direction. Combining the three techniques leads to at least 6-dB SNR margin improvement for the full reach carrier serving area loops.**

***Index Terms*—Digital subscriber loops, HDSL/HDSL2, preemphasis/deemphasis, spectrum modification.**

I. INTRODUCTION

THE first-generation high bit-rate digital subscriber loop HDSL uses two-pair cables, operating in full-duplex mode to support T1 rate of 1.544 Mb/s. The next-generation HDSL, known as HDSL2, will work on single-pair cables The HDSL2 is targeted to provide the T1 rate without repeaters over what is known as the carrier serving area (CSA) [3]. In this paper, a new approach to relax the theoretical limit of achievable HDSL2 bit rate is introduced by using asymmetric solutions to support symmetric transmission [1], [2]. Three different approaches to relax the theoretical limit of the channel capacity to combat near-end crosstalk (NEXT) are introduced. If the three techniques are combined, a 6-dB improvement in signal-to-noise ratio (SNR) is achieved The first technique is to boost the remote user HDSL terminal unit (HTU-R) transmitter power for the HTU-R units that are 7 kft or further from the central office. The second technique is to reduce the central office HDSL terminal unit (HTU-C) transmitter power on shorter-reach pairs, thus reducing NEXT to neighboring longer-reach pairs. Because NEXT is proportional to a power-law function in frequency, a third technique similar to the well-known frequency-modulation (FM) preemphasis/deemphasis (PDE) can be deployed. The PDE reduces the received NEXT at the HTU-C and help whiten the received NEXT spectrum, thus improving the receiver equalizer performance. The remainder of this paper is organized as follows. Section II summarizes the HDSL2 problem and the theoretical limit of the channel capacity under the limited latency constraint. Section III introduces PSD scaling techniques to improve the performance. The advantage of using the PDE technique for NEXT reduction is introduced in Section IV. Section V summarizes the simulation results for the three techniques.

II. HDSL2

The HDSL2 is a symmetric transmission environment because the upstream (link from the remote user to the central office) supports the same bit rate as the downstream (link from the central office to the remote user). The target reach for the HDSL2 is the set of CSA loops, which represent most of the subscribers' loop plant in the United States. For HDSL2, the agreed upon performance criteria include achieving T1 rate over all CSA pairs with at least 6-dB noise margin and at most 500-μs end-to-end delay. In this study, the 9-kft 26-gauge cable, namely loop number 6 of the standard CSA loops, is used as the benchmark. The theoretical limit of the channel capacity is calculated under the limited latency constraint T_{latency}. The limited latency restriction is modeled as extra noise from samples received beyond this time limit due to the extended impulse response of the channel. For channel with impulse response $h(t)$, a revised expression for the channel capacity, ignoring the correlation between the extra noise source and the signal, is given by [5]

$$C = \int_0^B \log_2 \left[1 + \frac{|H(f)|^2}{|X(f)|^2 + |H_e(f, T_{\text{latency}})|^2}\right] df \quad (1)$$

where $H(f)$ is the channel transfer function, $X(f)$ is the crosstalk transfer function, and $H_e(f, T_{\text{latency}})$ is the frequency response corresponding to $h_e(t, T_{\text{latency}})$, where

$$h_e(t, T_{\text{latency}}) = \begin{cases} 0, & 0 < t \le T_{\text{latency}} \\ h(t), & T_{\text{latency}} < t. \end{cases} \quad (2)$$

III. POWER CONTROL

The first step to relax the theoretical limit on the channel capacity is to unbalance the upstream and downstream power spectral densities (PSDs). A similar technique that jointly optimizes the upstream and downstream PSDs was also introduced in [6]. However, the techniques proposed in this paper are simpler to implement. The interference levels at the remote user end (HTU-R) are different from those at the central office (CO) (HTU-C) because of the difference in the number of users at the CO and the remote end. Because of that, simple power unbalancing of the upstream and downstream can be done without

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TABLE I
SIMPLE POWER CONTROL

line length	HTU-R noise margin	HTU-C noise margin	Action
$> 7kft$	$> 8dB$	$< 8dB$	Boost up-stream power
$< 5kft$	$> 10dB$	don't care	Reduce down-stream power
$< 3kft$	don't care	$> 10dB$	Reduce down-stream power

loss of performance. Thus, if the power is boosted only in the upstream direction for the HTU-R units 7 or more kft away from the CO, a higher noise margin should result in the received signal at the HTU-C. On lines up to 7 kft long, 6-dB noise margin can be achieved at 10^{-7} BER as shown in [7]. Another step to further improve HTU-C performance is to reduce the NEXT interference signal by reducing the transmitted power at the HTU-C on short-reach pairs. For example, the HTU-R margin for a 5-kft 26-gauge cable can be more than 15 dB. A simple algorithm for combining the two techniques is summarized in Table I. Further improvements in the noise margin can be achieved using the additional technique explained in the following section.

IV. PREEMPHASIS/DEEMPHASIS

The theoretical limit can be relaxed further by using nonlinear modification of the upstream and downstream PSDs. As explained earlier, the limiting impairment in HDSL2 is NEXT at the HTU-C end. As the NEXT channel is not flat in frequency, the receiver equalizer tries to whiten the NEXT noise. Fig. 1(a) shows the insertion loss for CSA loop 6 and for the simplified NEXT model which is proportional to $f^{1.5}$, where f is the frequency [8]. The monotonic increase in the NEXT channel PSD with frequency suggests that the well-known FM PDE algorithm can be used to improve the receiver SNR [9]. The effective NEXT channel changes as shown in Fig. 1(b). NEXT is reduced due to passing the NEXT signal through the attenuation filter H_d as shown in Fig. 2(a). Another effect of PDE of practical importance is the whitening effect of H_d over the received NEXT. This will improve the equalizer performance for a given complexity as shown by simulations. The following set of equations estimates the new NEXT channel PSD with deemphasis:

$$\begin{aligned}\mathrm{NEXT}_{\mathrm{HTU\text{-}C,\,PDE}} &= 2\int_0^B \mathrm{PSD}_{\mathrm{interferer}} |X_{\mathrm{HTU\text{-}C}}(f)|^2 |H_d(f)|^2\, df \\ &= 2\int_0^B S_2(f)\chi_{\mathrm{HTU\text{-}C}} f^{1.5} \frac{w_1^2}{w_1^2 + w^2}\, df, \qquad (3)\end{aligned}$$

where $X_{\mathrm{HTU\text{-}C}}(f)$ is the NEXT channel at the central office and $\chi_{\mathrm{HTU\text{-}C}}$ is the corresponding NEXT coupling coefficient. Choosing $f_1 = 300$ kHz and $f_2 = 800$ kHz and using bandwidth of 1 MHz leads to a PDE gain of

$$\begin{aligned}\mathrm{GAIN}_{\mathrm{HTU\text{-}C,\,PDE}} &= 10\log_{10}\frac{\mathrm{NEXT}_{\mathrm{HTU\text{-}C,\,PDE}}}{\mathrm{NEXT}_{\mathrm{HTU\text{-}C}}} \\ &= 6\ \mathrm{dB}. \qquad (4)\end{aligned}$$

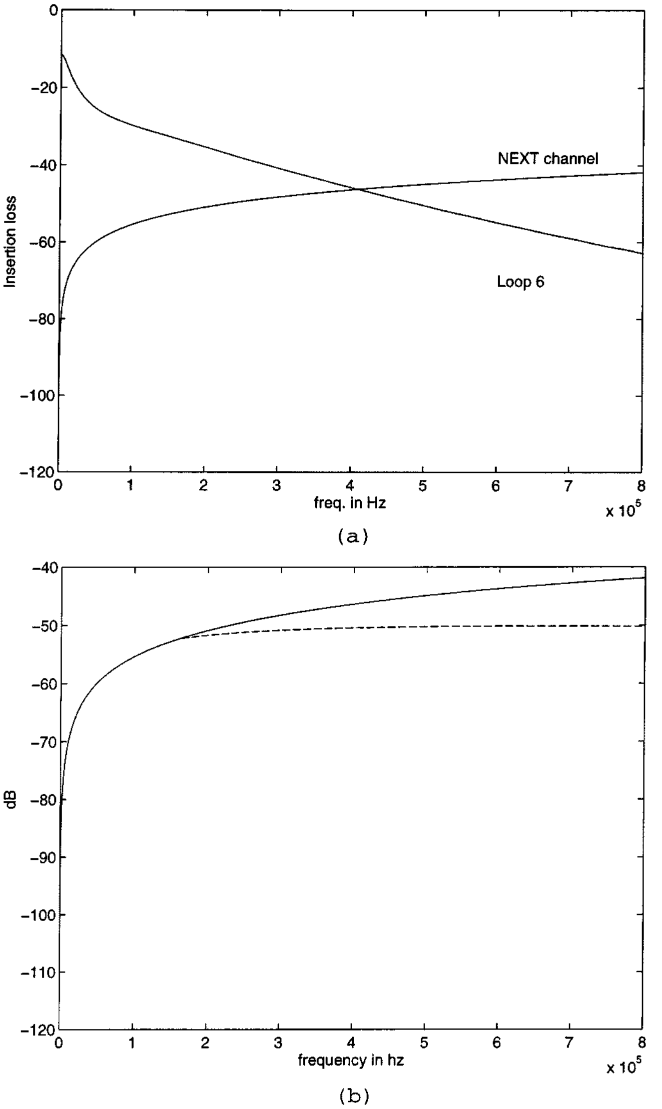

Fig. 1. (a) Channel insertion loss and the NEXT channel, and (b) NEXT channel with and without preemphasis (solid without deemphasis and dashed with deemphasis).

The 6-dB gain is expected from the upstream PDE alone. It is straightforward to conclude that the gain in NEXT power at the HTU-C side implies a loss at the HTU-R side. The loss is calculated to be only 2 dB. The channel capacity defined in (1) is now changed by substituting the new interference PSD as defined in (3). The new capacity expression is

$$\begin{aligned}C = \int_0^B &\log_2 \\ &\cdot\left[1 + \frac{|H(f)|^2}{|X_{\mathrm{HTU\text{-}C,\,PDE}}(f)|^2 + |H_e(f, T_{\mathrm{latency}})|^2}\right. df. \qquad (5)\end{aligned}$$

It is clear that the loss in SNR at the HTU-R side can be tolerated due to the small interference at the remote user's end, while significant gain can be achieved in the upstream direction. Fig. 3 shows the effect of using PDE on the theoretical limit of the channel capacity for latency of 500 μs.

V. SIMULATION RESULTS

In our simulations, we used uncoded carrierless AM/PM line code with 16-point constellation size (CAP-16) [10], and

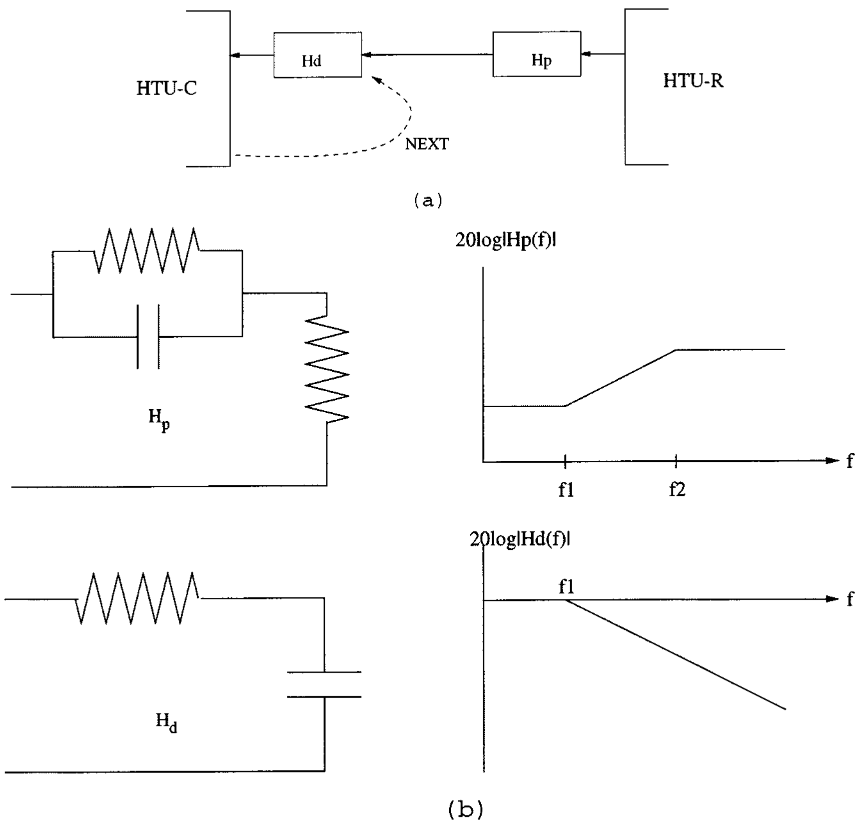

Fig. 2. (a) Preemphasis Deemphasis in the upstream direction, and (b) preemphasis and deemphasis filters and their frequency responses, slope is ±20 dB/decade

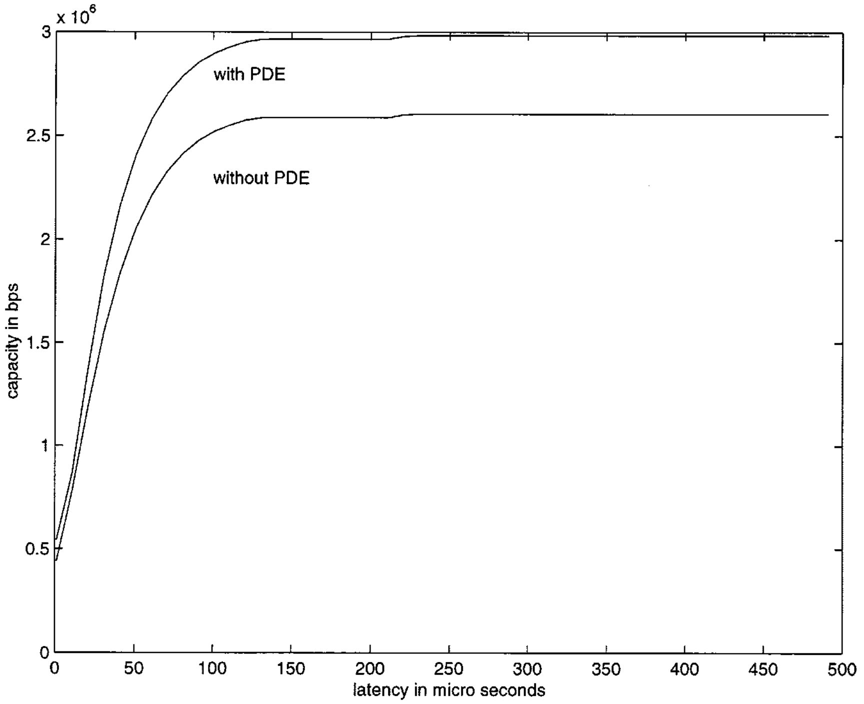

Fig. 3. The theoretical channel capacity with and without PDE

the NEXT model is 39 disturbers characterized by the Unger model [11]. The receiver equalizer used in the simulations is a DFE with fractionally-spaced feedforward filter followed by symbol-spaced feedback filter [12]. The upstream power is boosted and time-domain simulations for the DFE were carried out for different boosting levels. The results are summarized in Table II. Boosting the HTU-R upstream power by 3.5 dB leads to equal noise margins for upstream and downstream transmissions when the HTU-R by is degraded by three NEXT interferers. Simulations were carried out also for the

TABLE II
MARGIN FOR 10^{-7} BER

up-stream power boost	HTU-R margin: 3 disturbers	HTU-R margin: 7 disturbers	HTU-C margin: 39 disturbers
0dB	3.6dB	1.9dB	-1.7dB
1.0	2.9	1.0	-0.9
2.0	2.1	0.3	0dB
3.0	1.3	-0.7	0.9
4.0	0.5	-1.5	1.6

downstream power reduction. Margin improvement depends on the statistics of cable lengths. A 1-dB margin improvement is easily attained if 65% of the pairs are within the 5-kft reach. To integrate the system with PDE, the power boost limited to 1.4 dB to limit the effect on the HTU-R downstream performance. The overall HTU-C margin improvement becomes 6 dB when applying the three techniques together. This improvement is achieved as 1.2 dB due to HTU-R power boost alone, 1 dB due to HTU-C power reduction for shorter cable, and 3.8 dB with PDE alone. Use of different equalization techniques might lead to slightly different results, but the relative values of the HTU-C and HTU-R margins should be the same.

VI. CONCLUSIONS

The theoretical performance limit for the HDSL2 system is redefined under the limited latency constraint. The full CSA reach HDSL2 is attainable by unbalancing the power flow allocated to the upstream and downstream directions. Three techniques have been proposed in this paper. The first boosts the power in the upstream direction for HTU-R units beyond 7-kft reach. In the second technique, the NEXT received at the HTU-C is reduced by reducing downstream power for users that are 5 kft or less away from the central office. The third technique is to employ PDE only for upstream resulting in two effects. First, it further reduces the HTU-C NEXT as the received NEXT is attenuated by the deemphasis filter. Second, it reduces the required DFE processing by whitening the received noise. Combining the three techniques can produce 6-dB margin improvement for the full CSA reach pairs. This margin improvement, possible with a minimal increase in hardware, decreases the coding gain needed to achieve the required 6-dB margin for HDSL2 systems.

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