

Digital Subscriber Line (HDSL and ADSL) Capacity of the Outside Loop Plant

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Abstract—The fundamental limits of the outside loop plant to carry high-speed digital (bi-directional HDSL and ADSL) data are reported. The paper focuses on the copper wire pairs, drop lengths, and interconnects that convey data over the “last mile” to almost all businesses and residences in the US. The two major customers, businesses and households, are classified, characterized, and categorized by the distance to the central office or the remote terminal. Their spectral capabilities are computed and their ultimate digital capabilities are reported. The crosstalk limitations inherent in the plant are also computed and verified against the loss of signal due the distance and spectral constraints. The signal to noise ratio can thus be estimated to ascertain the transmission quality through the plant. Accordingly, the paper reports on losses, bandwidths, and bit rates in the first half, and discusses the major bottlenecks in the second half.

I. INTRODUCTION

MULTIMEDIA SERVICES using the recent developments in video coding and compression techniques permit real time video telephony. The ability to deliver these services depends upon the limitations of the loop plant. The major inputs used in this study are the data bases portraying the make up of business and residential loops. The minimum signal to noise ratio is retained to evaluate the percentages of loops that support the new breed of HDSL and ADSL services envisioned in the future.

The trunk facilities in most telephone systems around the world have evolved systematically. The subscriber plant, on the other hand, being more dispersed, and driven by the demographic character of the region, tends to become a degraded star network emanating from the central office. This is particularly the case in the more established central cities where the growth in the number of residences was haphazard. This almost random growth has resulted in a highly diversified distribution of the physical loop plant and its topology.

Statistically, the attenuation characteristics of the copper cable prevail in limiting the spectral bandwidth in the loop plant. The objective of the investigation is to evaluate the ultimate capacity of providing high data rate services over existing unshielded twisted wire pairs in the loop plant. Our initial findings show that the bit-rates corresponding to the spectral band reported here include and extend beyond the current HDSL and ADSL applications.

At high data rates, two major effects are evident. First, the loss due to loop plant inconsistency becomes exaggerated, and second, the crosstalk coupling increases due to increased

bandwidth. These effects are also influenced by the bridged taps, drop wires, outside-plant (OP) interconnects, loading coils, distribution cabinets, and finally the customer premises wiring. The effects of these are discussed in the body of the paper. The object of the study is to evaluate the feasibility of providing additional high-speed data services over the unshielded twisted wire-pairs.

The platform for the study is a specifically fabricated computer-aided-analysis and design facility [1], [2]. The major inputs are the data bases portraying the OP for business loops and the residential loops. Spectral domain characteristics and crosstalk models supplement the study to evaluate the signal degradation on one hand, and the extent of the contaminating noise on the other hand. Between the two lies the estimate of the digital capacity of the OP. Results up to 5 MHz have been generated and reported for a possible array of services that new technologies may bring. These results are reported and discussed in Sections II and III.

II. SUBSCRIBER ENVIRONMENT FOR HDSL AND ADSL APPLICATIONS

The data base for HDSL and ADSL application is a subset of the 1983 Loop Survey data base. Results from two earlier surveys (1963 and 1973 Loop Surveys) also exist. The 1963 Survey resulted in the characterization of the OP for voice grade services [3]. The 1973 Survey was characterized twice. Results germane to the voice grade services were reported in 1978 [4]. However, results germane to the design and characterization of the digital subscriber line (DSL) were reported in 1982 [5]. The DSL, as it was perceived then, did not have a firm design and for this reason the spectral domain results were limited to about 250 kHz to cover the basic rate ISDN (BRISDN) services. Finally, the last and most recent of the Bell System Loop Surveys was characterized primarily for the evolving digital services ranging from BRISDN (144 kb/s) to possibly the H0 rate (384 kb/s) services. Results characterizing the OP to 400 kHz were reported in 1986 [6]. The current paper contains the characterization of loops (amenable to the current HDSL and ADSL applications) for frequencies up to 1 MHz. We also include the results up to 5 MHz to include most of the future services. Furthermore, characteristics of loops are presented by the type of service; general, business and residential for future designers to specifically target devices/services to certain segments of subscribers. At the next level of detail, we also classify the loop penetration data in nine distance bands (of all the 18 000' loops) in 2-kft increments.

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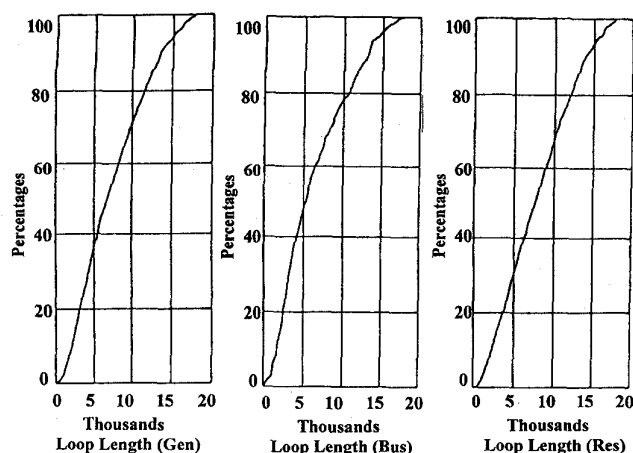


Fig. 1. Distribution of all the loop lengths in the database.

The general 1983 Loop Survey data base [6] with 2290 loops is reclassified into three major sections: general loops, business loops, and residential loops. Whereas all the loops were designed to carry voice traffic, a smaller fraction of shorter loops can carry digital (from ISDN rates to multi-megabits per second) data. The most dominant impairment is the presence of loading coil(s). Almost all loops longer than 18000 ft have loading coils and these coils make them unfit for consideration for any HDSL/ADSL application. Other loops with older aluminum alloys or with nonstandard gauge numbers (such as 14, 16, etc.) also are removed from consideration for HDSL applications. The fraction of loops with the nonstandard gauges is much less than 1% and these cables have not been characterized sufficiently to provide an accurate picture of their capabilities at very high rates. Thus 66.37% of the loops surveyed have the features and topology to carry the HDSL/ADSL rates. The distribution of loop lengths in the general, business, and residential loop databases are presented in Fig. 1.

A. Physical Characteristics

The physical characteristics of 1520 loops (i.e., 66.3% of all 2290 loops surveyed) are presented in Table I. We start out with this truncated population and then indicate the penetration based on the number of loops (i.e., 502 or the 1018 loops) in each of the two (business or residential) categories respectively.

About 33% of the 1520 loops of the OP loops serve businesses. The percentage of loops which serve business in the entire population of 2290 loops in the 1983 Loop Survey is estimated at 32%. The average length of the business loops is 6326 ft compared to 7865 ft for the residential loops because of the closer proximity of the businesses from the central offices and the centralized location of the central offices.

About 67% of the 1520 loops of the OP serve residences. The percentage of loops which serve residences in the entire population of 2290 loops in the 1983 Loop Survey is estimated at 68%. These results are consistent with the greater dispersion of the residences. A finer sub-classification for the special services loops was not attempted because of the limited number of loops for these services.

TABLE I
PHYSICAL CHARACTERISTICS OF THE OP FOR HDSL AND ADSL APPLICATIONS

	General Loops	Business Loops	Residential Loops
Number of Loops	1520	502	1018
Percentage Average	100%	33%	67%
Length	7354'	6326'	7865'
Loop Gauge Discontinuities	3.6	3.3	3.7
Bridged Tap (BT) Length	953'	477'	1186'
BT Gauge Discontinuities	1.37	1.03	1.52

B. Loss Characteristics

In this section the statistical distribution of the loss characteristics of all the loops in the three data bases (general, business, residential) are presented. The results are generated by the computer simulation of each set of loops and then the statistical summary is derived. The spectral band which is crucial for the HDSL or ADSL applications depends upon the code used. To make these results as general and useful as possible, we have investigated the loss over the spectral bands of interest for most HDSL and ADSL applications and for most of the common codes. Thus it becomes necessary for the user of these generic results to know where the spectral band of the particular interest lies. For example, if a 2B1Q code is used with 10% excess bandwidth, then the bandwidth of interest is from 0 to $((1 + 0.10) * 1544/2)/2$ or 424.6 kHz. On the other hand, if CAP-64 is to be used for T1 data using 5.5 customer bits per symbol (plus trellis coding) with 10% excess bandwidth, then the bandwidth of interest is from 0 to $(1 + 0.10) * 1544/5.5$ or 308.8 kHz. It is customary to start the lower band edge at about 10 kHz since very little spectral energy is actually present in most of the codes for both the HDSL and the ADSL applications.

1) *Cumulative Loss Distribution*: Three sets of curves are presented for the three (general, business, and residential) types of loops. However, the range between 100 kHz to 1 MHz is of immediate interest for the HDSL/ADSL application and the range between 1–5 MHz may have some interest in the future. Fig. 2(a) and 2(b) depict the cumulative loss distribution curves in the lower band (100–500 kHz and 500–1000 kHz respectively, with 100 kHz steps) for all loops. For higher band (1–5 MHz), the cumulative loss distribution is depicted in Fig. 2(c). Likewise, Fig. 3(a)–(c) depict the loss curves for business loops and Fig. 4(a)–(c) depict the curves for residential loops. In the upper band of frequencies ranging from 1–5 MHz, the cumulative loss becomes significantly higher and percentage of loops able to carry data at VHDSL (very high-speed digital subscriber line) rates can be interpolated from the data presented in these figures. If a simple signal loss criterion is used, then the penetration can be directly read from these curves.

2) *Multiple Interferer Crosstalk*: Any individual wire pair carrying data into the central office suffers from both near end

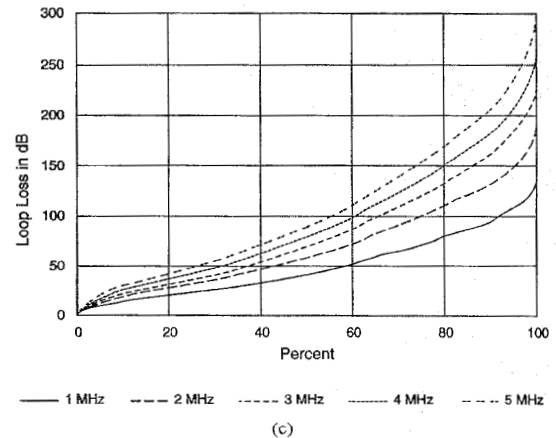
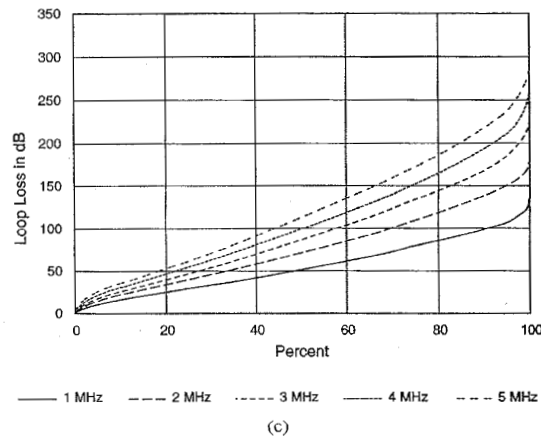
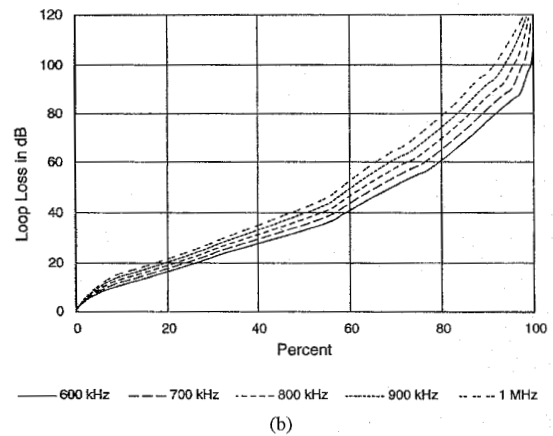
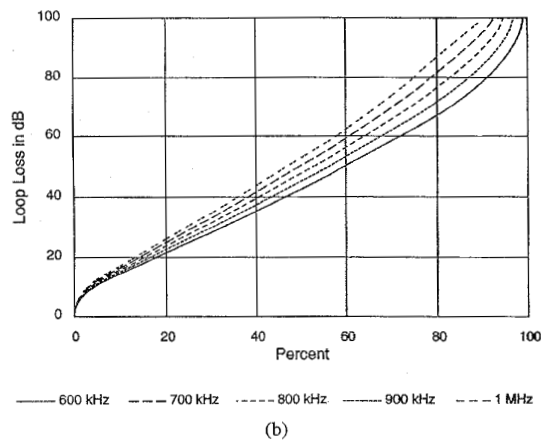
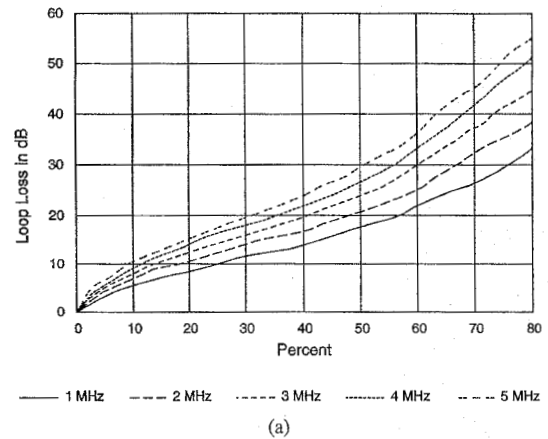
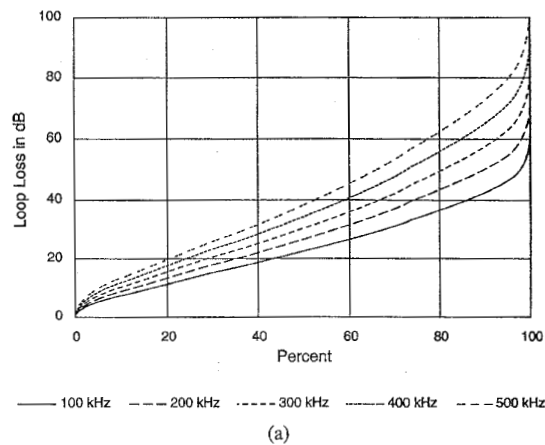
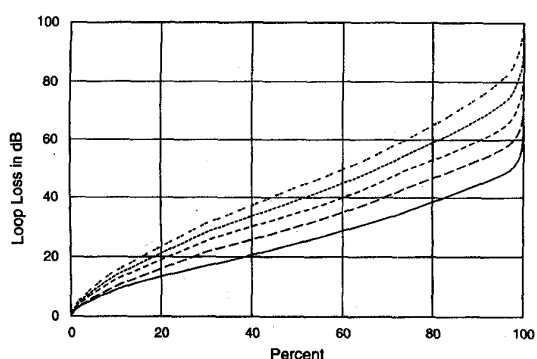


Fig. 2. (a) Cumulative loop loss of all loops at 100, 200, 300, 400, and 500 kHz. (b) Cumulative loop loss of all loops at 600, 700, 800, 900 kHz, and 1.0 MHz. (c) Cumulative loop loss of all loops at 1.0, 2.0, 3.0, 4.0, and 5.0 MHz.

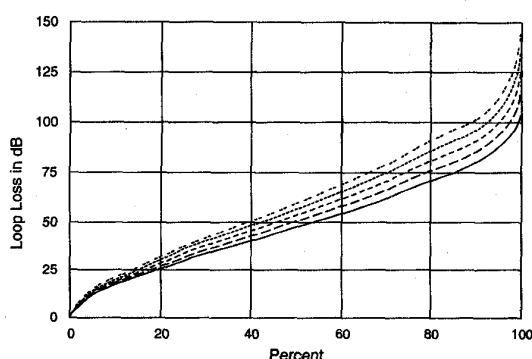
Fig. 3. (a) Cumulative loop loss of business loops at 100, 200, 300, 400, and 500 kHz. (b) Cumulative loop loss of business loops at 600, 700, 800, 900 kHz, and 1.0 MHz. (c) Cumulative loop loss of business loops at 1.0, 2.0, 3.0, 4.0, and 5.0 MHz.

crosstalk (NEXT) and far end crosstalk (FEXT). Both types of interference depend on the pair number bearing the disturbed signal and the vicinity from the disturbing source. The extent of twist in each of the two wire-pairs also influence the coupling between the two. The estimation of NEXT and FEXT becomes simplified by assuming the same power spectral density for the disturbing and the disturbed signals. For the

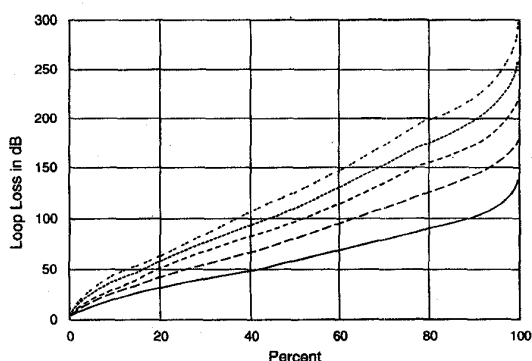
estimation of the interfering signal, the approach has been partially theoretical based on the coupling factor and partially experimental based on the measurements. The basic shape of the curve is derived from the coupling and signal strength along the cable length, and the constants are then evaluated to force the theoretical curve to overlap the experimentally observed curve.



(a)



(b)



(c)

Fig. 4. (a) Cumulative loop loss of residential loops at 100, 200, 300, 400, and 500 kHz. Cumulative loop loss of residential loops at 600, 700, 800, 900 kHz, and 1.0 MHz. (c) Cumulative loop loss of residential loops at 1.0, 2.0, 3.0, 4.0, and 5.0 MHz.

Two major conclusions are derived from the theoretical considerations. First, the single interferer NEXT coupling gain follows $f^{3/2}$ characteristic [7] when the cable length is sufficiently long. Second, the FEXT interference signal-to-noise ratio (in dB) decreases by 20 dB per decade with frequency and by 10 dB per decade by cable length. The role of FEXT is only slight in most of current HDSL/ADSL

applications and for this reason, this interference can be ignored even though it may become important for other VHDSL applications. The findings for NEXT (or self-NEXT in this case since the disturbing signal has the same power spectral density) can be expressed in terms of loss in dB as

$$\text{NEXT Power Sum Loss (dB)} = \text{Constant} - 15 \log f_{(\text{kHz})}. \quad (1)$$

The simple one-disturber model (above) is refined by Bellcore [8] and extended to a 22 AWG, 18 000' cable with 1, 10, and 49 disturbers. Above 20 kHz (the bandwidth of interest for the HDSL and ADSL applications), the loss with 49 disturbers is approximated as

$$\text{NEXT Power Sum Loss (dB)} = 83.6 - 14 \log f_{(\text{kHz})}. \quad (2)$$

At 80 kHz, the effect of 49 disturbers on a single wire-pair is computed as 57 dB. This value has been experimentally verified as a satisfactory limit for central offices self-NEXT with most gauges. When (1) and (2) are recombined to yield the Bellcore standard of 57 dB at 80 kHz, and account for the difference between the coefficient of $(\log f)$, the constant of 83.6 dB in (2) can be evaluated as a constant of 85.54 dB for (1). This constant (i.e., 85.54 dB) can also be alternatively represented as $2.7925\text{E-}09$ in the equation for the expected gain (G) of the squared NEXT crosstalk signal

$$G = 2.7925\text{E-}09 * f^{3/2} \quad (3)$$

since $2.7925\text{E-}09$ can be verified as $10^{-8.554}$.

We have used (1) twice. In the discussion of NEXT for the HDSL case, we have used this widely accepted Bellcore value of 57 dB at 80 kHz for interference and thus been able to compute the penetration by equating the attenuated signal strength due to line loss to approach this level of interference.

In the ADSL crosstalk computations, we have taken the interference for most reasonable combination of interferer (average white Gaussian noise, plus NEXT from T1, DSL, and HDSL) into consideration. To determine exactly where this NEXT starts to completely obliterate the signal at the central office, we have evaluated 60 dB as the near end crosstalk loss limit (i.e., $60 = 85.54 - 15 * \log 50$) at 50 kHz (which is taken as the limit of the bandwidth for upstream data). This computation is based upon the coupling constant for all interferers (at this 50 kHz frequency) as $2.7925\text{E-}09$ (computed to be consistent with the Bellcore standard). The NEXT loss is equated to the attenuation loss and the penetration is now evaluated. Inherent in this assumption is the fact that the upstream ADSL channel has a transmit energy consistent with the transmit energy of other signals in this band. Also inherent in this assumption is the fact that the ADSL downstream transmit level is consistent with the upstream transmit level. When these conditions are satisfied, then the penetration may be evaluated by determining the 60 dB loss (relative to the transmit level for ADSL).

3) *Symmetric Frequency Dependent Crosstalk Limits:* For the HDSL applications bidirectionality is essential, and in this case self-NEXT interference is the most important disturber. The crosstalk power [7] depends upon the well-documented 15

dB per decade rule in (1) consistent with the Bellcore BRISDN standard of 57 dB NEXT loss at 80 kHz. When the transmitted signal attenuates down to the crosstalk, there is no signal left to recover. In an extreme sense this becomes the limit of any signal transmission. In the practical applications, there is some comfortable margin (to be selected by the designer of that particular HDSL environment and the bit error rate requirement) that is retained above this extreme limit. As presented in Section II.C, the practical limit lies around 60–70% of this limit with well-designed equalizers, echo-cancellers, and possibly adaptive hybrids [9] for echo-reduction. In this section, we present this extreme limit by comparing the loss of the population of loops in the data bases with the symmetric frequency dependent NEXT-crosstalk limit.

Since the OP has a wide variety of subscriber loops, we have classified the data into nine (0–2, 0–4, 0–6, 0–8, 0–10, 0–12, 0–14, 0–16, and 0–18 kft) ranges. For the lower band, self-NEXT is computed at 100–1000 kHz at 100 kHz steps and the percentages of loops in each distance range that do not obliterate the signal are evaluated. Similar results are also generated for the 1–5 MHz band at 1 MHz steps.

Business loops: Results are depicted in Fig. 5(a) for the business loops. There are nine curves and each curve is for a distance range. There are 10 points on each curve to signify the 10 discrete frequencies in the lower (100–1000 kHz) band. The corresponding set of curves for the higher frequency band (1–5 MHz) is shown in Fig. 5(b). The percentages of loops drop significantly in the 1–5 MHz band.

These curves offer the spectral capacity of the OP for HDSL applications. For example, if 2B1Q needing 424.6 kHz is to be used for business loops with the HDSL mode, then an ordinate at this frequency, shows that 72% of 18 kft, 74% of 16 kft, 77% of 14 kft, 84% of 12 kft, 92% of 10 kft, 97% of 8 kft, and almost 100% of loops less than or equal to 6 kft will carry the data as an extreme case. Performance limitations for other systems, such as the dual duplex HDSL systems needing 212.3 kHz can be as easily read from Fig. 5.

Residential loops: Curves depicting corresponding results are depicted in Fig. 6(a) and (b) for residential loops. These two figures [Figs. 5(a) and 6(a) and then Figs. 5(b) and 6(b)] are plotted in complete conformity and results may be read from either sets of curves in the same way. For example, from Fig. 6(a), the 2B1Q data penetration (at 424.6 kHz) in the residential loops is 60%, 64%, 68%, 75%, 89%, 97%, and almost 100% of all loops in the 0–18, 0–16, 0–14, 0–12, 0–10, 0–8, and (0–6) kft distance ranges. The results for the general loop population can be derived as the weighted sum from the data for the (1018) residential loops and from the data for the (502) business loops. For this reason we do not have a dedicated section for the data for general loops.

4) Asymmetric (Frequency Independent) Crosstalk Limits: For the ADSL application, the composite interference from CO noise and crosstalk from other systems is the limitation. For most of the ADSL application, the more modern ESS-based CO's are quieter than the older crossbar central offices and the central-office noise is not considered as a serious limitation. However, the typical CO crosstalk pickup estimated from Section II.B.2 still remains at about 60 dB. When the

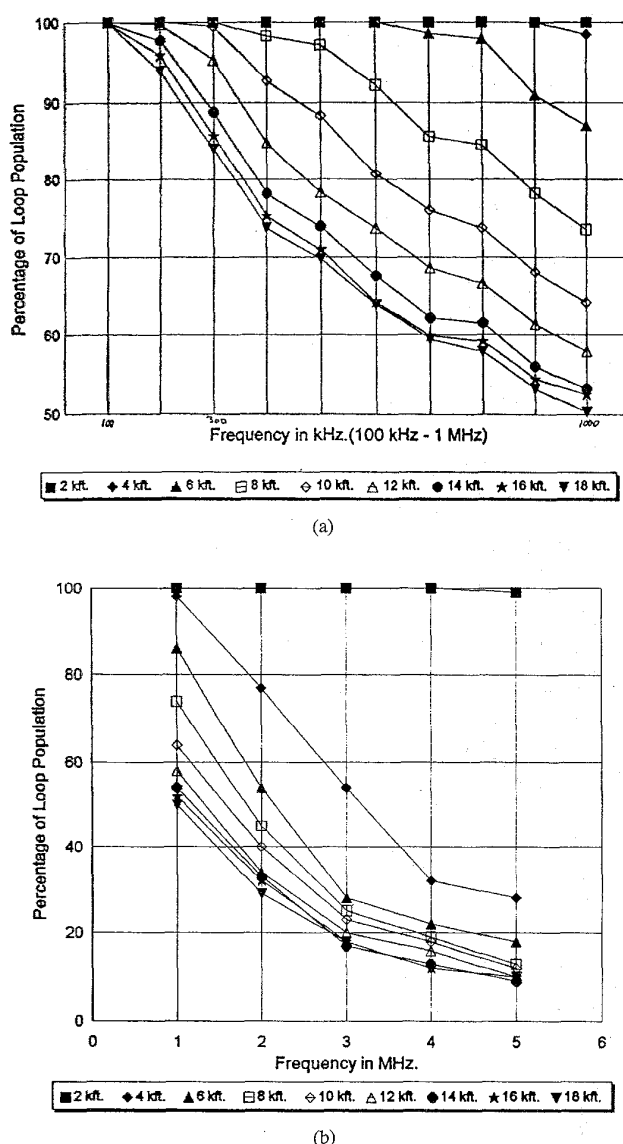
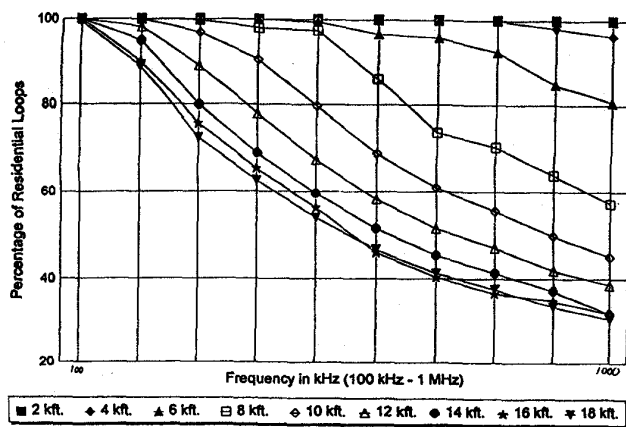


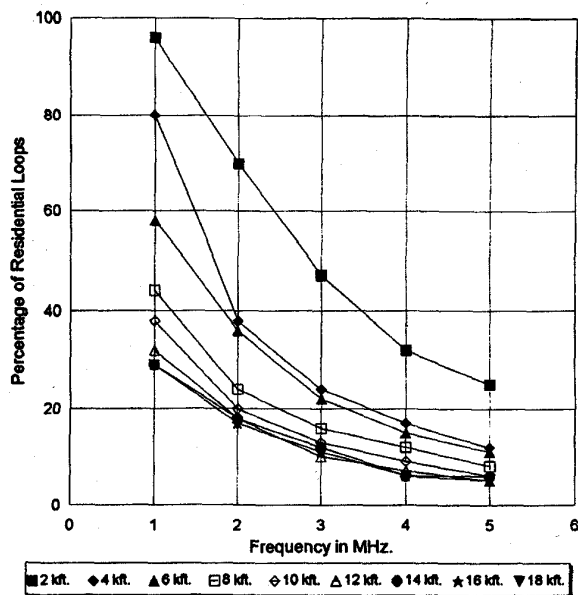
Fig. 5. (a) Penetration of business loops at different limits of loop length from 100 kHz through 1.0 MHz with symmetric X-talk limitation. (b) Penetration of business loops at different limits of loop length from 1.0–5.0 MHz with symmetric X-talk limitation.

extreme limit for the obliteration of the upstream signal is held at 60 dB, the penetration of the ADSL services may be expected to improve over the HDSL services where the self-NEXT is the dominant limitation. The curves indicating such penetration of the ADSL services are presented in the following sections.

Business loops: The percentages of business loops that offer a loss less than or equal to 60 dB in each of the nine distance (0–2, 0–4, 0–6, 0–8, 0–10, 0–12, 0–14, 0–16, 0–18 kft) ranges depicted in Fig. 7(a) for the spectral band of 100–1000 kHz are scanned at 100 kHz increments. Similar curves for the 1–5 MHz band are plotted in Fig. 7(b). These curves offer the spectral capacity of the OP for ADSL applications. For example, if 2B1Q needing 424.6 kHz is to be used for business loops with the ADSL mode, then an ordinate at this frequency,



(a)

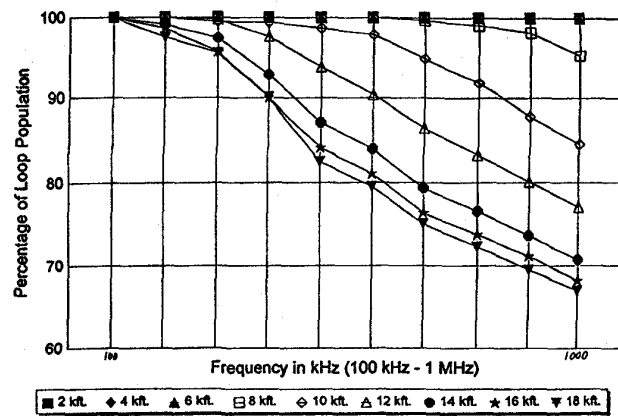


(b)

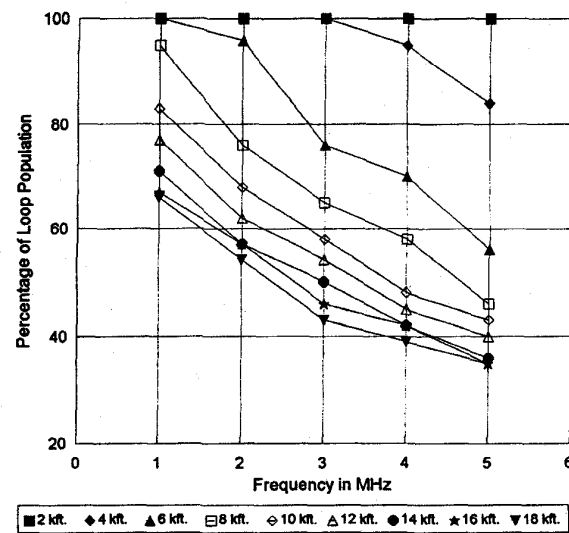
Fig. 6. (a) Penetration of residential loops at different limits of loop length from 100 kHz through 1.0 MHz with symmetric X-talk limitation. (b) Penetration of residential loops at different limits of loop length from 1.0–5.0 MHz with symmetric X-talk limitation.

shows that 87% of 18 kft, 88% of 16 kft, 96% of 14 kft, 96% of 12 kft, 98% of 10 kft, and almost all loops less than or equal to 8 kft will carry the data as an extreme case. Other performance limitations can be as easily read from Fig. 7(a) and (b).

Residential loops: Curves depicting the percentages of residential loops that meet the extreme loss (60 dB; see Section II.B.2) criterion for most of the current ADSL applications are depicted in Fig. 8(a) for the lower band 100 kHz to 1 MHz. For the higher bandwidth from 1–5 MHz the percentages are shown in Fig. 8(b). It is seen that the percentages of residential loops start to fall more rapidly than for the business loops. Longer loop lengths, more bridged taps and less stringent requirements on the residential loops are seen as the primary reasons for lower performance. These curves offer the spectral capacity of the OP for ADSL applications. For example, if 2B1Q needing $(1 + 0.10) * 1544/4$ or 424.6 kHz is to be used



(a)



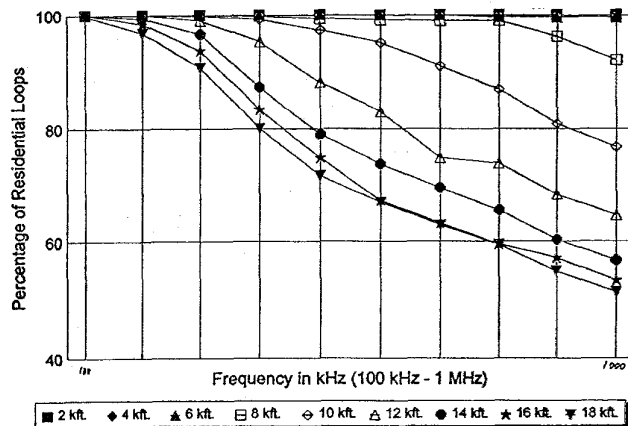
(b)

Fig. 7. (a) Penetration of business loops at different limits of loop length from 100 kHz through 1.0 MHz with asymmetric X-talk limitation. (b) Penetration of business loops at different limits of loop length from 1.0–5.0 MHz with asymmetric X-talk limitation.

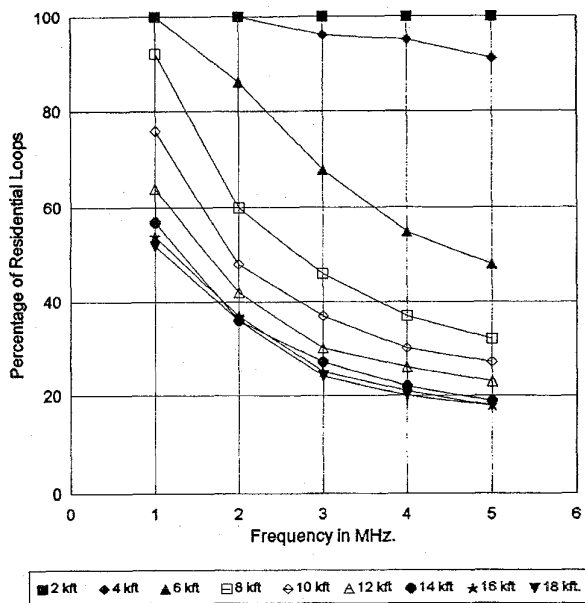
for residential loops with the ADSL (with a downstream rate of 1.544 Mb/s) mode, then an ordinate at this frequency in Fig. 8(a), shows that 77% of 18 kft, 82% of 16 kft, 86% of 14 kft, 93% of 12 kft, 96% of 10 kft, and almost (99–100%) of loops less than or equal to 8 kft will carry the data as an extreme case. On the other hand if the performance limitations for 6.34 Mb/s is to be evaluated, then the data from Fig. 8(b) needs to be read. The frequency of interest with 2B1Q becomes 1.698 MHz. An ordinate at this frequency shows that about 42% of loops in the 0 to 14 through 18 kft range, 47% of the 12 kft, 55% of 10 kft, 68% of 8 kft, 90% of 6 kft and 100% of the residential loops less the 4 kft will carry the data as an extreme case.

C. Spectral Limitations and Digital Capacity

The Shannon capacity of channels with colored noise is discussed in [10]. The relationship between bandwidth and capacity is quite fundamental, and is essentially independent



(a)



(b)

Fig. 8. (a) Penetration of residential loops at different limits of loop length from 100 kHz through 1.0 MHz with asymmetric X-talk limitation. (b) Penetration of residential loops at different limits of loop length from 1.0-1.0 MHz with asymmetric X-talk limitation.

of the gauge. In this paper, the theory has been applied to the case of 26, 24, 22, and 19 AWG cables assuming self-NEXT and 0 dB margin. These results are plotted in Fig. 9. The X axis depicts the available bandwidth. The lower curves give the maximum distance for each of the four gauges. The upper curve gives the Shannon capacity multiplier. For example, consider the top curve alone: a bandwidth of 400 kHz provides a capacity of about 3 (i.e., 0.4×7.2) Mb/s. In reality, our computer simulations and our experiments have shown that about 5 bps/Hz can be transmitted in this 400 kHz bandwidth using state-of-art digital transmission techniques. This leads to a practical achievable speed of about 2 Mb/s (i.e., 0.4×5). Now consider the lower curves. This 2 Mb/s rate can be achieved for a range up to 22 kft of 19 AWG, 15 kft of 22 AWG, 12 kft of 24 AWG, or 9 kft of 26 AWG. Our simulations

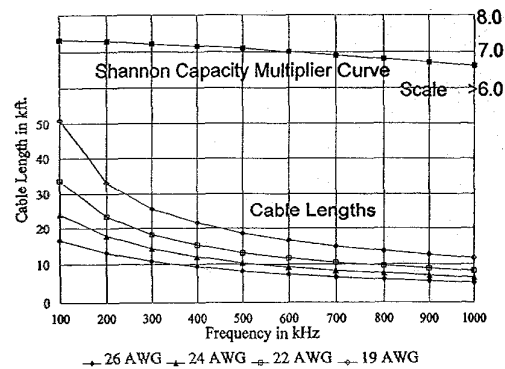


Fig. 9. Bandwidth and capacity limits of 26, 24, 22, and 19 AWG cables.

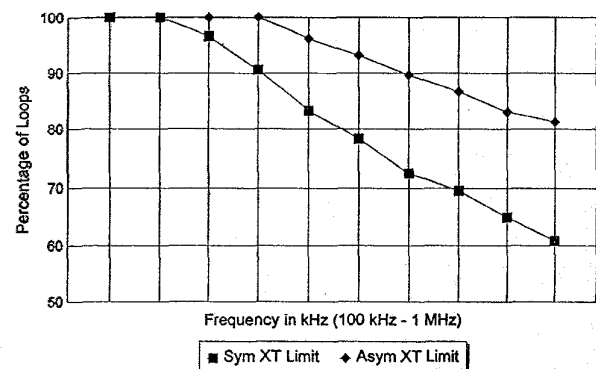


Fig. 10. Penetration of business loops with symmetric and asymmetric X-talk limitation with bridged taps stripped from loops.

and experiments of the achievable bandwidth efficiencies of about 5 bps/Hz has also been found to be close to optimum for other values of bandwidth at the current state of technology. For this reason, we contend that the limit of the outside plant can be estimated from the results presented in this paper for most of the DSL, HDSL, ADSL, and possibly for the VHDSL applications.

III. EFFECTS OF IMPAIRMENTS

A. Bridged Taps

Bridged taps are prevalent in many (US, Canadian, Australian, Japanese, and some Italian) loop plants. Taps do offer mismatch effects in certain bands of frequencies depending upon their length. The worst length of the tap offers a quarter wavelength resonance at the mid-band of the code carrying the data. The "frequency bumps" that they cause has been documented and in the analog domain compensated by "bump equalizers." The problem is solved effectively by decision feedback equalizers (DFE's) and their tapped delay line implementation. However, the increased loss due to their presence is an inherent limitation to the data traffic on the subscriber lines.

The physical stripping of bridge taps is an expensive and an error prone proposition for the Operating Companies. From the evolution of the DSL in the 1970's, the BOC's have resisted the idea of implementing any manual and labor-intensive alterations to the loop plant. For this reason, the investigation

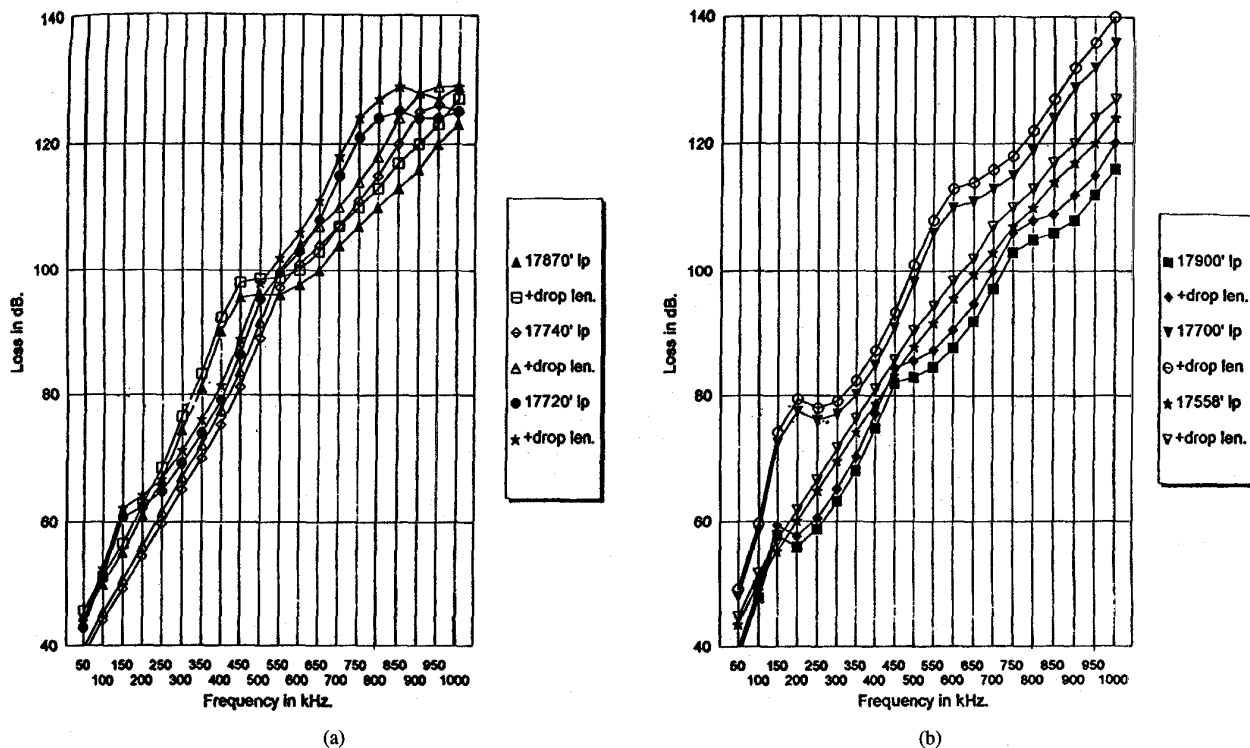


Fig. 11. (a) Effect of drop length on the loop loss of three loops between 17.5 and 18.0 kft. (b) Effect of drop length on the loop loss of three loops between 17.5 and 18.0 kft.

of the effects of bridge taps is limited to a subset of business loop in the 0–12 kft range.

To investigate the effects of taps, they were removed from all the loops in the 0–12 kft range from the business loop data base. The penetration of the loops for the HDSL (symmetric) and ADSL (asymmetric) applications is shown by the two curves in Fig 10. Corresponding figures (loops with taps intact) for comparison are shown in Figs. 5 and 7. Whereas for 308.8 kbaud data with CAP-64 application, 95% (Fig. 5) of the loops with taps will carry HDSL (symmetric case) data, the entire 100% of the loops without taps are expected to carry the same data. If the symbol rate is increased to about 1 Mbaud (for the 6.3 Mb/s HDSL), 57% of loops (Fig. 5) with taps will carry HDSL data, and 62% (Fig. 10) of loops without the taps will carry the data. In the former case the expense of physically altering the topology of all loops in the 0–12 kft band yields about 5% increased penetration. Even in the latter case, stripping the bridge taps increases the digital penetration by only five percent. For the ADSL case, the corresponding numbers are a 100% at the lower symbol rate (compare Figs. 7 and 10) and 77% (Fig. 7) versus 82% (Fig. 10) for the higher symbol rate. It is thus concluded that the expense of tap removal from the OP is not justifiable for the HDSL, ADSL and the VHDSL applications. We had made a similar argument for the DSL case [5] based on the eye opening and time domain simulations for the 1973 Loop Survey [4].

B. Digital Loop Carriers (DLC)

The effect of digital loop carriers is transparent for most applications. Interfacing and protocol conversion functions are

necessary. However, increased use of the DLC's has the effect of shortening the loop length since the DLC carries the data over the longer distance. The loop topology from the remote terminal (RT) to the customer premises is likely to be similar the loop topology from the CO to the CP. For this reason the increased use of DLC is seen as an impairment in the OP. Most crosstalk studies for DLC systems have indicated that crosstalk noise is far less than encountered in the OP subscriber environment. It is however recommended that the interfacing at the RT's is standardized and consistent with requirements of Section III.D.

C. Drop Lengths

The final connection from the curb-side to the actual residence (known as the drop length) varies between 50–600 ft and consists of 24 AWG cable. The median length is about 200 ft and has an effect of increasing the actual loop length by this distance with a 24 AWG cable. In a general sense, the effect of the drop length may be read in all the preceding figures by simply enhancing the loop length by about 200 ft. This approximation appears justifiable since the characteristics of the 24 AWG cable are close to those of the average loop characteristics and the effects of any impedance mismatches are minimal.

However, for the sake of completeness, we present the effect of drop length from two perspectives. First, the additional loss of the longest loops (i.e., loops in the 17.5–18.0 kft band) with the longest drop length (600 ft of 24 AWG) is reported. There are six loops in the general data base and the losses with and without the drop length are presented in Fig. 11(a) and (b). The

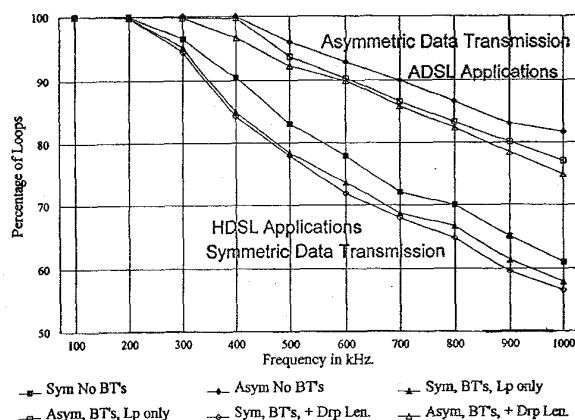


Fig. 12. Penetration of business loops for symmetric (HDSL) and asymmetric (ADSL) applications. The three curves in each application are for loops with bridged taps removed, loops with bridged taps in tact, and loops with bridged taps intact and with an additional 200' of #24 AWG drop length at the customer premises.

loops show an increased loss between 2–4.5 dB over the range of interest for the HDSL and the ADSL applications and its actual value should be estimated for any particular application and the code that is used.

Second, the penetration of the business loops under 12 kft for the HDSL/ADSL applications are reported. Business loops (with and without bridged taps) are added an average drop length of 200 ft of 24 AWG cable. The penetration of the loops under the three cases (business loops with taps, business loops with taps stripped, and business loops with taps and drop length added) is reported in Fig. 12. Two sets of curves are evident. Both set of curves, depict the effects of taps and taps and drop lengths both on the subscriber loops. Whereas, removing the taps may enhance the penetration at any frequency, by a maximum of about five percent, the added loss due to the drop length reduces the penetration by about a maximum of about 2–3%.

D. Other Impairments

Interconnects within the outside plant can offer serious mismatches in the spectral range of interest for the subscriber line data. When the mismatch is severe, the flow of data suffers immensely. This effect has been documented in many HDSL tests. Typically, in the Swiss HDSL CAP-64 tests [11], "twisted wire" connections between subscriber loops and the customer premises equipment were used and resulted in approximately 5–6 dB loss in the measured SNR. The suggested solution to such problems is to require soldered connections. This approach corrected the problem in the Swiss HDSL tests.

Distribution cabinets at RT's and CO can cause mismatch effects and also cause spurious crosstalk and EM pickup. In one of the recent HDSL tests, short lengths of nonstandard untwisted wire-pairs were used to connect the channel units to the CO end of the lines. This type of inter-cabinet wiring resulted in 3 dB loss in the cross-talk measurement. The suggested solution to such problems is to require standard

wiring and interconnects at the CO and subscriber terminations of the line.

Loading coils cause the most severe impairment for DSL data traffic. Loops with load coils are systematically eliminated from any DSL applications. This is not seen as a severe deterrent since loading coils generally exist in loops longer than 18 kft, where the natural loss limits also occur for any DSL data. The loops that indeed have loading coils, generally have the first loading coil at about 3000 ft from the central office and one every 6000 ft from there on. There is no elegant way for signal processing at either end of the loop to undo the damage sustained to the signal as it passes through a series of these load coils.

Home wiring is also a known cause for the degradation of high-speed data traffic to the desk top. Typically, low-quality nontwisted biquad is used for home wiring. Two balanced wire-pairs exist in the biquad and lack of proper care in choosing the balanced pair causes a serious crosstalk problem in delivering high-speed data for symmetric services such as HDSL. Because of the extensions cords, which act as bridged taps, the existing home wiring may also prove to be a harsh environment for asymmetric services such as ADSL. This issue is presently under intense study.

Within the office environment, unshielded twisted pairs are used. This type of wiring is not seen as a major bottleneck for DSL applications. Even the lowest quality cables, i.e., category 3, have a data transport capability that far exceeds the speeds that can be provided in the OP [12].

IV. CONCLUSIONS AND DISCUSSION OF RESULTS

The paper provides an insight into the balance between the signal loss in the loop plant and the noise within it. These two boundaries that define the subscriber digital line capacity at various frequencies have been plotted for frequencies to 5 MHz. The results are generic to the extent, that they provide the user these inherent limitations regardless of the code and the limitations of the line terminating units. Results presented offer the capabilities of the outside plant over the spectral band (100–1000 kHz) of interest to the current and proposed HDSL and ADSL designers. The data is also categorized in nine 2 kft bands to cover the entire range of DSL, HDSL, ADSL, and VHDSL applications. The extent of degradation due the seven bottlenecks, namely bridged taps, digital loop carriers, drop wires, OP interconnects, distribution cabinets, loading coils and customer premises wiring has been discussed and delineated.

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