On the Capacity of a Twisted-Wire Pair: Gaussian Model

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Abstract—**The performance of a twisted-pair channel is assumed to be dominated by near-end crosstalk (NEXT) from other pairs in the same cable. Both, intrabuilding local and central office loop channels may be modeled as NEXT-dominated channels. In this paper, the capacity of this type of channel is found, using a Gaussian model. It is shown that, the capacity is independent of the transmitted power spectral density. The results also indicate that present systems operate far below theoretical capacity. The capacity of a twisted-pair channel with both NEXT and white Gaussian noise present is also addressed.**

I. Introduction

There is at present much interest in the twisted-pair channel. This interest has arisen both in intrabuilding local (LAN) channels and in loops from the telephone company central office (LOOP). In both of these cases, models have been constructed for the channels [1]–[5] which assume a $\sqrt{f}$ degradation in the exponential of the channel attenuation characteristic. Similarly in both of these channels it is assumed that the dominant interference is due to near-end crosstalk (NEXT) [1]–[11] from other pairs in the same cable. For these channels it is usually assumed that the power spectral density of the interfering NEXT signal is equal to the transmitted spectral density (assuming all pairs have similar type signals) multiplied by a term proportional to $f^{3/2}$.

In this paper the channel capacity of a NEXT-dominated channel, under Gaussian assumptions and average power constraint, is found. This is an interesting channel model for the reasons described above. Numerical results are given for an ideal $\sqrt{f}$ channel transfer function, and also for a typical 24-gauge line. In [1], channel capacity was calculated for a NEXT-dominated channel using a different model at low frequencies. The NEXT-dominated results are then extended to include a channel with additive white Gaussian noise (AWGN), as well as NEXT interference. In a companion second paper [12], the more realistic problem of input signals which are peak constrained is approached.

In the next section, we discuss the standard twisted-pair channel model as well as the Gaussian assumption on the signals involved. In Section III we find the capacity of the NEXT-dominated channel including quantitative results. Section IV discusses the capacity of the same channel including AWGN. In Section V a different channel model is proposed for a LOOP channel. In the last section, results and conclusions are presented. In Appendix A, an argument for the use of the Gaussian model for the NEXT interference, is presented, and Appendix B contains a derivation of a lower bound on C_{NEXT} the NEXT dominated channel capacity.

II. The Channel Model (NEXT-Dominated)

The twisted-pair channel (see Fig. 1) has been investigated and modeled in a number of papers [1], [2], [4]–[7]. In some of these papers, it is assumed that the attenuation transfer characteristic $|H_c(f)|^2$, of the channel can be approximated by (Fig. 2)

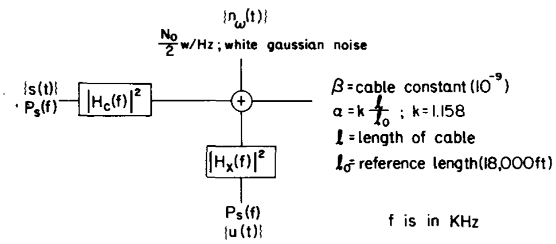

Fig. 1. Twisted-pair channel model.

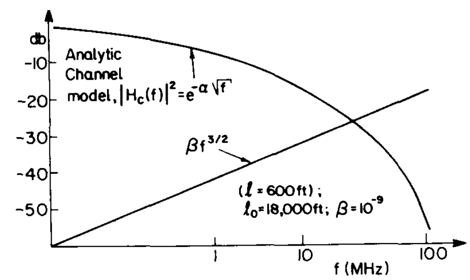

Fig. 2. $|H_c(f)|^2$ and $|H_x(f)|^2$ as functions of freq. (Mhz).

$$|H_0(f)|^2 = e^{-\alpha\sqrt{f}} \tag{1}$$

$$\alpha = k\frac{l}{l_c}$$

l = length of channel in ft

l_0 = a reference length (e.g., 18 000 feet)

k = a constant of the physical channel

f = frequency in kHz.

In a paper by Cox and Adams [1], discussion is made of another channel model at lower frequencies (in the range 10–200 kHz) involving f raised to a power different from one-half. In this paper, we work with two models. The first one uses (1). This is a good analytic model for an RC type line of short length, less than 1000 ft, but breaks down especially at lower frequencies for longer twisted-pair cable lengths. We also use a second model, based on measurements made on a typical 24-gauge line (without bridge taps).

The power spectral density (psd) $P(f)$ of the received signal is given by

$$P(f) = |H_c(f)|^2 P_s(f) \tag{2}$$

where $P_s(f)$ is the two-sided psd of the transmitted signal, $s(t)$.

The dominant factor limiting the communication capabilities of the channel is assumed to be near-end crosstalk (NEXT), usually caused by similar-type signals with the same psd, $P_s(f)$ as the desired signal. This interference, shown in Fig. 1, includes a crosstalk transfer

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function $|H_x(f)|^2$, multiplying $P_s(f)$, the psd of the interfering signals. $|H_x(f)|^2$ is given below [2], [9] (also see Fig. 2)

$$|H_x(f)|^2 = \beta f^{3/2} \tag{3}$$

where β is a constant of the cable, and varies from cable to cable.

As mentioned in the literature [1], [2], the NEXT interference is essentially influenced by only five to seven of the nearest pairs of wires. This causes a problem if we want to assume that the interfering crosstalk is statistically Gaussian since we cannot really use the central limit theorem to justify a Gaussian assumption on crosstalk. This point is addressed in Appendix A. Basing ourselves on the results of this Appendix *the Gaussian assumption is used throughout.*

In real channels another source of interference is, of course, the white noise (see Fig. 1) inherent in the system. For the local (LAN) channel it is assumed that the dominant interfering factor is NEXT, but certainly white noise creates a performance floor which cannot be overcome. Therefore, this noise is also included in the model and is addressed in Section IV.

In the next section, we calculate capacity assuming the NEXT-Only channel model.

III. Capacity for NEXT-Only Channel

If we assume the NEXT-Only model (Fig. 1) with no white noise present, it can easily be shown from [13], [14] that the channel capacity C_{NEXT} (assuming that the main signal and the NEXT may be represented as Gaussian interference) is given by

$$C_{\text{NEXT}} = \int_{f \in A} df \, \log_2 \left(1 + \frac{|H_c(f)|^2 P_s(f)}{|H_x(f)|^2 P_s(f)}\right)$$

$$= \int_{f \in A} df \, \log_2 \left[1 + \frac{|H_c(f)|^2}{|H_x(f)|^2}\right] \text{ bits/s} \tag{4}$$

where A is the frequency range in which $P_s(f) \neq 0$.

If we assume that $P_s(f) > 0$ over the entire frequency range, we have

$$C_{\text{NEXT}} = \int_0^\infty df \, \log_2 \left(1 + \frac{|H_c(f)|^2}{|H_x(f)|^2}\right) \text{ bits/s.} \tag{5}$$

As we see the capacity of the NEXT-Only channel is independent of the psd of the signal as long as $P_s(f) > 0$ for all frequencies. This is not unexpected since the psd of all the twisted-pair signals are the same.

If $P_s(f) = 0$ over a finite range, then the capacity will still not be affected by the shape of $P_s(f)$ but only by the frequency range of $P_s(f)$. $P_s(f)$ with unlimited bandwidth obviously maximizes C_{NEXT}.

Equation (5) will now be used to first find the channel capacity for the analytic model of (1) and afterwards for the capacity of the 24-gauge line.

Using equations (1) and (2), in (5), C_{NEXT} is given by

$$C_{\text{NEXT}} = \int_0^\infty df \, \log_2 \left(1 + \frac{e^{-\alpha\sqrt{f}}}{\beta f^{3/2}}\right) \text{ bits/s.} \tag{6}$$

This equation cannot be solved analytically in closed form. However it is possible to find a lower bound on C_{NEXT}. This is described in Appendix B.

Equation (6) for C_{NEXT} has been numerically integrated and plotted for the following parameters:

$$\alpha = 1.158 \frac{l}{l_0}; \quad \beta = 10^{-9}, \quad l = 6000 \text{ feet}; \quad l_0 = 18\,000 \text{ feet}.$$

(α is based on a 45 dB loss at 80 KHz, for an 18 000 ft cable.) C_{NEXT} as a function of cable length (from 150 to 18 000 ft) is shown in Fig. 3. C_{NEXT} decreases from a value of slightly less than 100 Mbps at about 700 ft, to 1.20 Mbps at 18 000 ft. A $T1$ channel of length 6000 feet has (under this model) a capacity of about 6 Mbps.

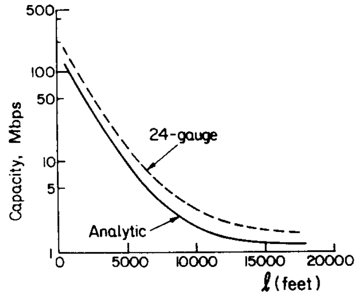

Fig. 3. Channel capacity as function of cable length (for analytic channel model and 24-gauge physical model).

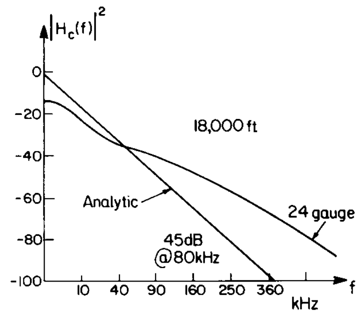

Fig. 4. Channel characteristics. Analytic and 24 gauge models-(18 000 ft.).

TABLE I
Channel Capacity (Mbps)

(cable length, ft.)	Analytic Model [eq. (1)] Capacity (Mbps)	24-gauge Model Capacity (Mbps)
600	120.3	176.9
6000	5.95	9.71
18000	1.19	1.56

C_{NEXT} has also been found for a channel transfer function based on measurements [15] of a 24-gauge line (with no bridge taps). This transfer function is shown alongside that of (1) in Fig. 4, for an 18 000 ft cable. The channel capacity, using this model, is typical of C_{NEXT} for real twisted-pair cables (of the gauge above).

The channel capacity C_{NEXT} based on this model is also shown in Fig. 3. C_{NEXT} for the 24-gauge model is actually greater than that of the analytic model of (1). This occurs because for the model based on the 24-gauge line measurements, $|H(f)|^2$ as function of f, does not decay as quickly as $e^{-\alpha\sqrt{f}}$.

In Table I, the results for both models are compared for lengths of 600 (LAN), 6000 ($T1$), and 18 000 (LOOP) feet.

These results indicate that current proposals for transmission over LAN (1–10 Mbps), and LOOP (160–350 Kbps) channels are far below the channel capacities of these channels, (using either model for comparison).

In Fig. 5, the percent of channel capacity, reached at a given frequency, (i.e., the upper bound in (5) is W and not infinity) in the integral of (5) is plotted, as a function of frequency. The curves shown are for an 18 000 ft cable. As can be seen in the figure, at 100 KHz almost 95% of the capacity of the $e^{-\alpha\sqrt{f}}$ model has already been achieved, while only 70 percent of capacity has been reached for the 24-gauge model at the same frequency. A larger percentage of the capacity of the 24-gauge model exists in the tail end of the channel characteristic. This indicates that on this type cable an effort should

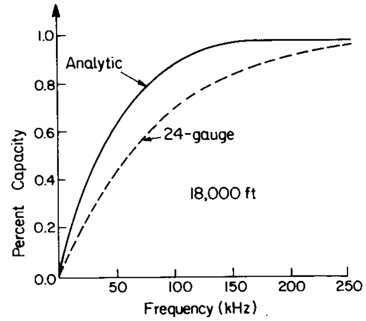

Fig. 5. Percentage capacity as function of bandwidth—analytic and 24-gauge models-(18 000 ft.).

be made to use a transmitted signal with relatively wide bandwidth.

IV. General Solution for Capacity of NEXT-Dominated Channel Plus AWGN

In this case, it is assumed that in addition to the NEXT interference described in Section III, additive white Gaussian noise, (AWGN) with spectral density, $N_o/2$ W/Hz, is also present (see Fig. 1). The capacity $C_{\text{NEXT-WGN}}$ of this channel is determined under the condition that the transmitted power P_s, is constrained, i.e.,

$$2\int_0^{+\infty} P_s(f)df \le P_s.$$

The equation for the capacity $C_{\text{NEXT-WGN}}$ is now

$$C_{\text{NEXT-WGN}} = \sup \int_0^{\infty} df \log_2 \left[1 + \frac{|H_c(f)|^2 P_s(f)}{|H_x(f)|^2 P_s(f) + N_o/2}\right] \text{ bits/s} \quad (7)$$

where the sup operation is carried out over all $P_s(f)$ satisfying the average power constraint

$$2\int_0^{+\infty} P_s(f)df \le P_s. \quad (8)$$

This is a classic calculus of variations problem in which we replace $P_s(f)$ by $P_x(f) + \epsilon\sigma(f)$ and then find the solution of the equation below (Euler–Lagrange technique)

$$\frac{\partial}{\partial \epsilon}\left[\int_0^{\infty} df \log_2 \left\{1 + \frac{|H_c(f)|^2[P_s(f) + \epsilon\sigma(f)]}{|H_x(f)|^2[P_s(f)+\epsilon\sigma(f)] + \frac{N_o}{2}}\right\} + \lambda \int_0^{\infty} [P_s(f) + \epsilon\sigma(f)]df\right] = 0 \quad (9)$$

where λ is the Lagrangian constant determined from (8).

Solving the equation above, we find that the solution reduces to

$$aP_s^2(f) + bP_s(f) + c = 0 \quad (10)$$

where

$$a = |H_x(f)|^2 \left[|H_x(f)|^2 + |H_c(f)|^2\right] \quad (11)$$

$$b = \frac{N_o}{2}\left[2|H_x(f)|^2 + |H_c(f)|^2\right]$$

and

$$c = \left(\frac{N_o}{2}\right)^2 - \frac{1}{\lambda}\frac{N_o}{2}|H_c(f)|^2.$$

Since $P_s(f) \ge 0$, we find that a solution exists only if $c \le 0$, in this case the solution is

$$P_{s_{\text{opt}}}(f) = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \text{ for } f < f_\Delta \quad (12)$$

where f_Δ is determined by (13) below.

The condition that $c \le 0$ reduces to

$$|H_c(f_\Delta)|^2 \ge \lambda \frac{N_o}{2}, \quad (13)$$

i.e., *$P_s(f)$ is band-limited to those frequencies for which the inequality of (13) above exists.*

In our model, the above implies that for $|H_c(f)|^2$ which decreases as a function of f, $P_s(f)$ is a baseband signal.

λ is determined from the equation

$$2\int_0^{f_\Delta} P_{s_{\text{opt}}}(f)df = P_s. \quad (14)$$

Capacity is achieved with a specific, band-limited signal as opposed to the NEXT-only case where capacity is achieved by any signal with spectral density greater than zero over the entire frequency range. The solution in the general case is complicated, but the bounds on $C_{\text{NEXT-WGN}}$ can be relatively simply found by considering the white-noise case only (i.e., no NEXT interference). Once the white-noise capacity C_{WGN} is known, then C_{WGN} and C_{NEXT} (found in the previous section) can be used to upper bound the capacity $C_{\text{NEXT-WGN}}$.

The solution for C_{WGN} is achieved using the classic water puring solution of information theory [13], [14]. (The LOOP cable consisting of twisted pairs with different transmitted signals may also, as a rough first-order approximation, be modeled as a WGN-Only channel).

The optimum $P_s(f)$ is given by [14]

$$P_s(f) = \begin{cases} \frac{1}{\lambda} - \frac{1}{|H_c(f)|^2}\frac{N_o}{2} & \text{for } f \le f'_\Delta \\ 0 & \text{otherwise} \end{cases} \quad (15)$$

where f'_Δ is determined from the equation below

$$|H(f'_\Delta)|^2 = \frac{\lambda' N_o}{2} \quad (16)$$

and λ is found using

$$2\int_0^{f'_\Delta} P_s(f)df = P_s. \quad (17)$$

The capacity C_{WGN} is given by [14]

$$C_{\text{WGN}} = \int_0^{f'_\Delta} df \log_2 \left[\frac{1}{\lambda}\frac{|H_c(f)|^2}{N_o/2}\right] \text{ nats/s.} \quad (18)$$

For example, using the twisted-pair channel (600 ft) described in (1), the capacity C_{WGN} of this channel as a function of P_s/N_o (dB–kHz) is found and shown in Fig. 6, along with the value of C_{NEXT} found by numerical integration of (6). The solid line forms the upper bound on the performance of a channel with both NEXT and AWGN interference.

As can be seen from Fig. 6, the twisted-pair channel (600 ft) using the analytic model of (1) is white noise dominated until P/N_o is in the range of 70 dB–kHz. Above that range it is the NEXT interference which dominates and the capacity is fixed at 120 Mbps.

The upper bound (C_{WGN} and C_{NEXT}) for the 18 000 foot channel is also shown in Fig. 6. In this case, the capacity is much lower, because the channel transfer function $|H_c(f)|^2$ decays exponentially as a function of l.

Summarizing the results of this section, we note that once white

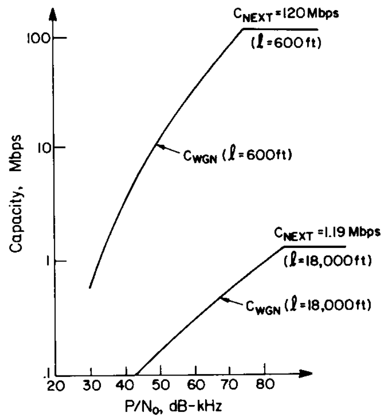

Fig. 6. Upper bounds on general channel capacity, $C_{\text{NEXT-WGN}}$—analytic channel model.

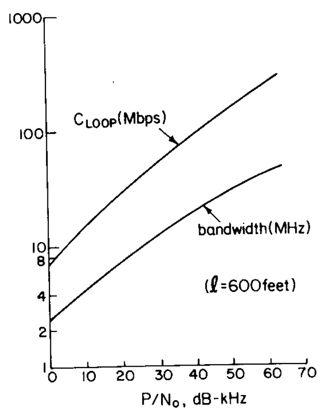

Fig. 7. Capacity C_{LOOP} and optimal bandwidth of channel with $f^{3/2}$ NEXT interference, as function of P/N_0—analytic channel model (600 ft).

noise is present there is an optimal transmitted spectral density and it is band-limited. In the NEXT-only channel any spectral density is optimal as long as it exists over the entire frequency range.

V. LOOP-Channel Model

The adjacent twisted pairs in the LOOP channel, may have different types of signals, e.g., voice or data of various rates. Therefore, the NEXT generating source in this case no longer has the same spectral density as the desired signal. It has been suggested that as a first order approximation the NEXT interfering signal may be modeled as white-noise ($N_o/2$ watts/Hz) passing through the crosstalk transfer function $|H_x(f)|^2$.

Using this model and in a procedure similar to those of previous sections the capacity C_{LOOP} of this channel can be found. C_{LOOP} is given by

$$C_{\text{LOOP}} = \int_0^{f_A} df \log_2 \left\{ \frac{1}{\lambda} \frac{|H_c(f)|^2/|H_x(f)|^2}{N_o/2} \right\} \frac{\text{bits}}{\text{s}} \quad (19)$$

where the optimal $P_s(f)$ and λ are determined by (15) and (17), respectively, with f'_Δ replaced by f_A.

C_{LOOP} for the analytic channel model, $|H_c(f)|^2$ of (1) is shown in Fig. 7 along with the optimum bandwidth, f_A.

VI. Discussion and Conclusions

The channel capacity for the twisted-pair channel for two different models has been found. In one model only NEXT interference is assumed to exist, and in the second model both NEXT and additive white Gaussian noise (AWGN) are present.

In the first (and more important case), it is shown that the channel capacity is independent of the transmitted power spectral density (psd) as long as the psd is nonzero over the entire frequency range. For the second model in which WGN is also present, the optimal psd is still band-limited and has a definite form but is complex.

For the NEXT-dominated channel described above, the capacity, as a function of cable length, was calculated for both analytic and 24-gauge channel models.

For the channel model based on measurements of a 24-gauge cable the capacities were 1.56 Mbps for an unloaded loop cable (18 000 ft), 9.7 Mbps for a $T1$ cable (6000 ft), and 177 Mbps for a LAN-type channel (600 ft). These capacities are much higher than present bit rates over these channels and indicate that more effort should be made in modem design for the twisted-pair cable.

The capacity of a channel with both NEXT and additive white Gaussian noise interference present was also considered. A simple joint upper bound was found for this capacity.

Our results are all based on the use of average power constraints and on an assumed Gaussian channel (the NEXT was assumed Gaussian). The real world situation may be more closely modeled by using peak-power constraints on the transmitted signal and on the interference, (if it is NEXT-dominated). The problem of finding capacity in this case is examined in a separate paper [12].

Appendix A

The Gaussian Model

The assumption that the signal $S(t)$ and the NEXT $u(t)$, are independent Gaussian processes possessing the same psd, $P_s(f)$ is used throughout the paper. In this Appendix, it is shown that the real capacity of the channel (without the Gaussian assumption) is lower bounded by the capacity under Gaussian assumptions. In cases where $u(t)$ is assumed Gaussian the capacity achieving probability law of $s(t)$ is also Gaussian.

Denote the capacity of the NEXT-WGN channel under average power constraints by C_a

$$C_a = \lim_{\tau \to \infty} \sup \frac{1}{\tau} I(s_o^\tau : r_o^\tau) \quad (A.1)$$

where s_o^τ and r_o^τ denote, respectively, the transmitted and received signal paths $s(t)$ and $r(t)$ for $o \le t \le \tau$, the $I(\cdot:\cdot)$ stands for the mutual information functional [14], and the supremum is taken over all M_s, the probability measures of $s(t)$ satisfying the average power constraints

$$\lim_{\tau \to \infty} E\left(\frac{1}{\tau} \int_0^\tau s^2(t)\, dt \right) \le P_s. \quad (A.2)$$

The NEXT signal $u(t)$, statistically independent of $s(t)$, is characterized by some *arbitrary* probability distribution law, M_u (which might be equal to or different from M_s), possessing the same psd $P_s(f)$ as the transmitted signal, $s(t)$. Assuming that $s(t)$ and $u(t)$ are stationary processes, induces no insignificant loss of generality due to the time invariant characteristic of the channel. The capacity achieving probability law M_s, is unknown and conventional bounding techniques are not straightforwardly applicable since the choice of M_s imposes second moment restrictions on M_μ, the probability law of the interfering signal [by forcing the psd of $u(t)$ to be $P_s(f)$].

Denote by C_a^* the capacity under a constraint of a given psd, $P_s(f)$.

$$C_a^* = \lim_{\tau \to \infty} \sup \frac{1}{\tau} I(s_o^\tau : r_o^\tau) \quad (A.3)$$

where the sup is taken over all probability measures M_s satisfying the average constraint (A.2) *and possessing a certain given psd, $P_s(f)$,* *with the average power*, $P_s = 2\int_0^{\infty} P_s(f)\,df$. It is obvious that

$$C_a \geq C_a^*. \tag{A.4}$$

Now, by results of Ihara [16], C_a^* is lower bounded by assuming the noise and the signal to be Gaussian with the same second-order statistics. Hence,

$$C_a \geq C_a^* \geq \int_0^{\infty} df\ \log_2\left[1 + \frac{P_s(f)|H_c(f)|^2}{P_s(f)|H_x(f)|^2 + N_o/2}\right]. \tag{A.5}$$

Since (A.5) is valid for any $P_s(f)$, it is also true for the $P_s(f)$ that maximizes the rhs of (A.5), which was analytically determined in Section IV and denoted by $P_{s_{opt}}(f)$ (see 12). Therefore, we conclude that

$$C_a \geq C_{\text{NEXT-WGN}} \tag{A.6}$$

where $C_{\text{NEXT-WGN}}$ is given by (7).

The capacity C_a defined in (A.1) is more general in the sense that M_u may be *arbitrarily* chosen to be equal or unequal to M_s and therefore by (A.6) the value $C_{\text{NEXT-WGN}}$ is a lower bound even in the general case where the statistics of $u(t)$ differ from those of $s(t)$ even though their psd remain equal. In cases where the NEXT $u(t)$ is actually a Gaussian signal the equal sign in (A.6) holds since capacity is achieved when M_s is Gaussian [14]. If $s(t)$ is not allowed to be a Gaussian process due to a peak power constraint while $u(t)$ is Gaussian, $C_{\text{NEXT-WGN}}$ turns into an upper bound on capacity, see details in [12].

Appendix B

Lower Bound on C_{NEXT}

It is possible to lower bound C_{NEXT} for the analytic channel model. If we rewrite (6) as

$$C_{\text{NEXT}} = \int_0^{\infty} df\ \text{Ln}\left(\frac{\beta f^{3/2} + e^{-\alpha\sqrt{f}}}{\beta f^{3/2}}\right)\frac{\text{nats}}{\text{s}}$$

$$\geq \int_0^{W} df\ \text{Ln}\left(\frac{\beta f^{3/2} + e^{-\alpha\sqrt{f}}}{\beta f^{3/2}}\right) \tag{B.1}$$

where W is a frequency to be chosen later, after some manipulation it can be shown that

$$C_{\text{NEXT}} \geq W\,\text{Ln}\frac{\beta+1}{\beta} - \frac{2}{3}\frac{\alpha}{1+\beta}W^{3/2} - \frac{3}{2}\frac{W}{\beta+1}(\text{Ln}\,W - 1)\frac{\text{nats}}{\text{s}} \tag{B.2}$$

where the right-hand side of the equation is a lower bound, $C_{\text{NEXT}_{lb}}$, on C_{NEXT}.

If f is given in kHz, β is usually a small number in the range of 10^{-9} [15], $C_{\text{NEXT}_{lb}}$ can be approximated as

$$C_{\text{NEXT}_{lb}} \approx W\,\text{Ln}\frac{1}{\beta} - \frac{2}{3}\alpha W^{3/2} - \frac{3}{2}W(\text{Ln}\,W - 1)\frac{\text{nats}}{\text{s}}. \tag{B.3}$$

$C_{\text{NEXT}_{lb}}$ can be maximized by setting its derivative with respect to W equal to zero. The solution for $\beta \ll 1$ is $1/\beta = W^{3/2}e^{\alpha W^{1/2}}$, from which the W which maximizes $C_{\text{NEXT}_{lb}}$ may be found. The solution of the equation above is the crossover point of the spectra $|H_c(f)|^2$ and $|H_x(f)|^2$ (see Fig. 2).

For a typical local LAN-type channel of length 600 ft, with values of α, β, and l_o equal to those used in Section III, W = 22 MHz and $C_{\text{NEXT}_{lb}}$ = 108.2 Mbps, as compared to 120 Mbps, as found in Section III. For 18 000 ft (the maximum length unloaded local loop), $C_{\text{NEXT}_{lb}}$ = 1.15 Mbps as compared to 1.20 Mbps (also found in Section III).

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