Development of Equal Level Far-End Crosstalk (ELFEXT) and Return Loss Specifications for Gigabit Ethernet Operation On Category 5 Copper Cabling

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ABSTRACT

1000BASE-T, a Gigabit Ethernet Physical layer specification for 1000 Mb/s, is designed to operate on 4-pair 100 ohm Category 5 balanced copper cabling as specified in ANSI/TIA/EIA-568-A. During the development of 1000BASE-T it was recognized that the 1000BASE-T link segment transmission parameters of equal level Far-End crosstalk (ELFEXT) loss and return loss needed to be added to the transmission parameters of attenuation and Near-End crosstalk (NEXT) as specified in ANSI/TIA/EIA-568-A for Category 5 cabling. This paper provides a description of the development of these parameters.

The 1000BASE-T link segment transmission parameters include insertion loss, NEXT loss, ELFEXT loss, return loss, link delay, and characteristic impedance. The link segment transmission parameter limits are specified to ensure 1000BASE-T operation on a Category 5 link segment of at least 100 meters constructed of cable and connecting hardware that meet the minimum requirements of the Category 5 specification, i.e., the components are worst case.

Category 5 cabling as specified in ANSI/TIA/EIA-568-A consists of cable, connecting hardware, and recommended topology[1] (Figure 2). The transmission characteristics of the ANSI/TIA/EIA-568-A cabling channel are specified for NEXT loss and attenuation.

Validation of 1000BASE-T operation on Category 5 was performed with simulation software that used the cabling measurements of NEXT loss, FEXT loss, and insertion loss as input, and then output the signal-to-noise margin based on the design constraints. Link segments using minimally compliant components were constructed and measured. Some of the measured data, falling short of worst case, were scaled to touch the limit line.

BACKGROUND

Ethernet standards are developed by the 802.3 working group of the IEEE LAN-MAN Standards Committee. In the spring of 1997, a task force called 802.3ab was formed to work on a copper cabling solution for Gigabit Ethernet. The 802.3ab Gigabit Ethernet copper solution, now termed 1000BASE-T, is specified to operate on 4-pair, 100 ohm Category 5 balanced copper cabling as defined in ANSI/TIA/EIA-568-A.

A 1000BASE-T Link segment consists of 4-Pair 100 ohm Category 5 Cabling as illustrated in Figure 1. Each of the 4-Pairs is a full duplex channel supporting an effective data rate of 250 Mb/s simultaneously in both directions achieving an aggregate data rate of 1000 Mb/s. Five-level Pulse Amplitude Modulation (PAM5) is employed for transmission over each wire pair. The PAM5 baseband signaling of 125 Mbaud is used on each of the wire-pairs to constrain the width of the transmit signal spectrum below 80 MHz.

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[1] Category 5 cabling channels as specified in ANSI/TIA/EIA-568-A exclude the equipment connectors and may include a transition point. The building cable is referred to as horizontal cable.

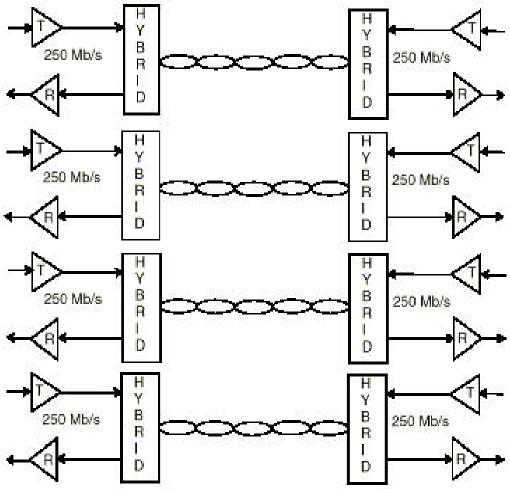


Figure 1

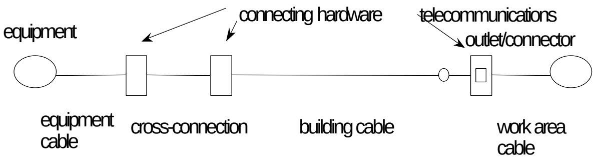


Figure 2

Full-duplex bi-directional transmission.

Full-duplex bi-directional transmission consists of transmitting and receiving data simultaneously in both directions on each of the four wire pairs. Hybrid circuits are needed to enable bi-directional transmission over single wire pairs. Bi-directional transmission allows FEXT to combine with NEXT and echo at the receiver (Figure 3).

Cancellation in a Digital Signal Processor (DSP). The most significant impairments in a 4-pair Category 5 transmission system are those caused by Echo (combined effect of the cabling return loss and the hybrid function), NEXT and FEXT. Since the sources of all these impairments are known to the receiver (transmitted symbol sequence, received symbol sequence), it is possible to employ Digital Signal Processing (DSP) cancellation techniques to mitigate the effect of these impairments on the receiver.

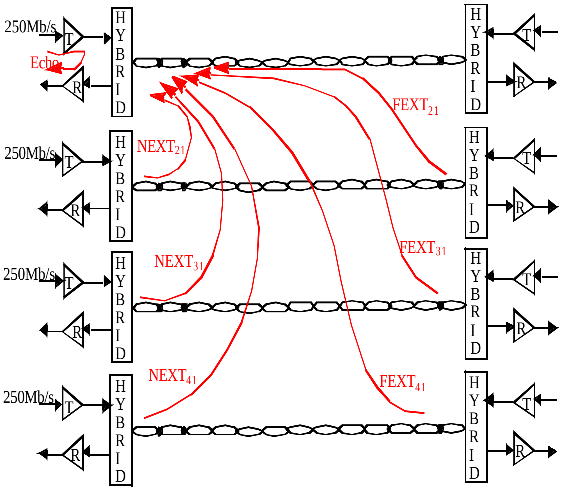


Figure 3

The characteristics of the impairment signals are learned in order to implement the necessary cancellation. A pulse is transmitted while the receive signal is monitored. The receive signal is sampled and a digital filter with a finite impulse response is constructed with the negative of these sampled values as the coefficients. The filter impulse response is constructed to have a pulse response that is the exact opposite of the pulse response of the received impairment and therefore, adding the output of this filter to the received signal will result in the necessary cancellation. In practice, the difficulty in cancellation is determining the coefficients in the presence of transmission from the far end.

ELFEXT

Development of Cable FEXT limits based on Cable NEXT limits.

ANSI/TIA/EIA 568-A standard specifies the NEXT loss and the attenuation limits for Category 5 cables and connectors that comprise a worst case Category 5 channel up to a frequency of 100 MHz. The FEXT loss requirements are not specified but can be derived from the NEXT limits. This is because both NEXT and FEXT are mathematically related to the coupling function between two pairs over the length of cable. This section provides a methodology for deriving the worst case FEXT limits and substantiates the results based on empirical data. Additional theoretical information on ELFEXT simulation is provided in Annex C.

Figure 4 below illustrates the coupling between two pairs for a cable of length (l) composed of (n) sections, where each section represents an incremental cable length (Δx). The equation for the coupling function (δ_k)[1] depends on the capacitance unbalance (Cu) and the mutual inductance unbalance (M) for each section of cable. (δ_k) is the coupling function for NEXT or FEXT. In the case of NEXT, the coupling function (δ_k) is the sum of the capacitance unbalance and the mutual inductance unbalance terms. In the case of FEXT, the coupling function δ_k is the difference between the capacitance unbalance and the mutual inductance unbalance terms.

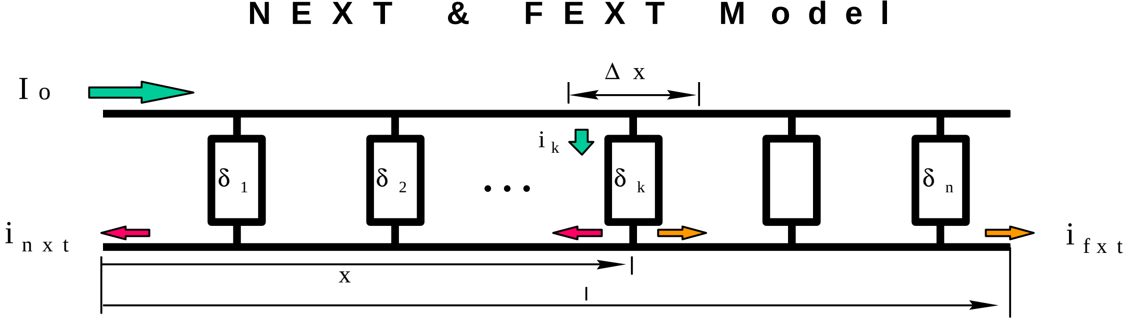


Figure 4

$$\delta_k = \frac{i_k}{I_o} = \frac{Cu_k Z_o}{8} \pm \frac{M_k}{2 Z_0} \qquad \text{(eq 7)}$$

The coupling current at section (k) divides in two and travels toward the near end (inxt) and toward the far end (ifxt). For NEXT, the current starts at the near end of the disturbing pair, travels a distance x, is coupled into the disturbed pair at section (k), and travels back to the near end of the disturbed pair. The total distance traveled is (2x). The coupling current (inxt) experiences an attenuation and phase delay of ($e^{-2\gamma x}$) relative to the input signal. The equations for NEXT, based on Figure 4, are:

$$NEXT = 10 \log \left[\sum_k \left| \frac{i_{nxt}}{I_o} \right|^2 \right] \qquad \text{(eq 1)}$$

$$NEXT = 10 \log \left[\sum_k \left| \frac{\delta_k e^{-2\gamma x}}{2} \right|^2 \right] \qquad \text{(eq 2)}$$

In a similar manner, for FEXT, the current starts at the near end of the disturbing pair, travels a distance x, is coupled into the disturbed pair at section (k), and travels toward to the far end of the disturbed pair. The total distance traveled is (l). The coupling current (ifxt) experiences an attenuation and phase delay of ($e^{-\gamma l}$) relative to the input signal. The equations for FEXT, based on Figure 4, are:

$$FEXT = 10 \log \left[\sum_k \left| \frac{i_{fxt}}{I_o} \right|^2 \right] \qquad \text{(eq 3)}$$

$$FEXT = 10 \log \left[\sum_k \left| \frac{\delta_k e^{-\gamma \ell}}{2} \right|^2 \right] \qquad \text{(eq 4)}$$

$$FEXT = 10 \log \left[\sum \left| \frac{\delta_k}{2} \right|^2 \right] + 10 \log \left[\left| e^{-\gamma \ell} \right|^2 \right] \qquad \text{(eq 5)}$$

$$FEXT = ELFEXT + Attenuation \qquad \text{(eq 6)}$$

A Mathcad model was developed for an n-section transmission line, which incorporates the above equations 1 thru 7 . The attenuation equation for the cable was taken per TIA/EIA 568-A and the propagation delay was taken per TIA/EIA 568-A1. The coupling function (δ_k) was varied until the corresponding NEXT limit of 32.3 dB was reached at 100 MHz.

The coupling function for FEXT is the difference between the capacitance unbalance and the mutual inductance unbalance terms in the equation for (δ_k). To obtain the worst case FEXT, it is assumed that one or the other term is dominant, in which case the same function (δ_k) can be used to derive both NEXT and FEXT. The result of these calculations is illustrated graphically in Figure 5.

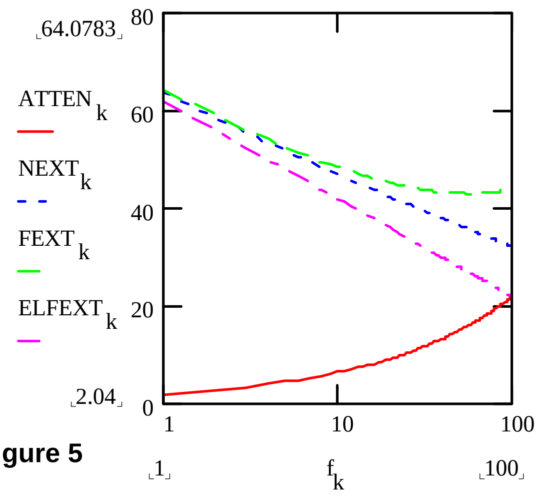


Figure 5

From Figure 5 above it is evident that at low frequencies (less than 4 MHz) the NEXT and the FEXT limits in dB are roughly equal. At high frequencies, FEXT is much less than NEXT because of the signal attenuation over 100 meters of cable.

ELFEXT is defined as the difference between FEXT and attenuation in dB as developed in equations 3 through 6. ELFEXT is a function only of the couplings between cable pairs. Unlike NEXT, which is mostly affected by unbalance couplings close to the end of the cable, ELFEXT is equally affected by unbalance couplings anywhere along the cable. In the above analysis, a uniform coupling function was assumed. However, the same analysis can be performed using any desired coupling function.

ELFEXT follows a 20 dB per decade slope as a function of frequency whereas NEXT follows a 15 dB per decade slope. The value of ELFEXT at 100 MHz for worst case Category 5 cable is 22 dB and FEXT is 44 dB. The modeling results agree closely with FEXT measurements taken on a worst case cable, as illustrated in Figure 6.

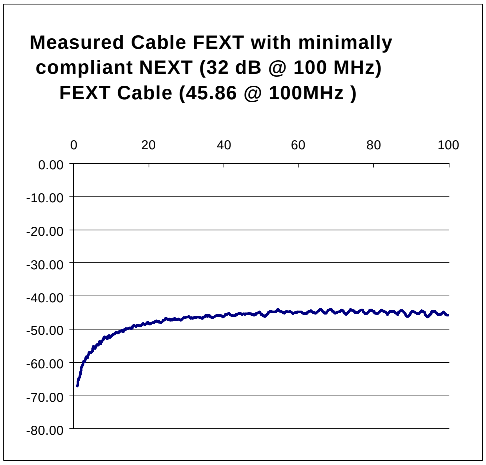


Figure 6

<u>Development of Connector FEXT contribution to the link.</u> The objective in this section is to characterize the connecting hardware FEXT contribution to the overall link crosstalk performance. With an understanding of the connector FEXT contributions, and the cable, the worst case cabling performance can be determined by calculation using worst case component specifications and cabling configurations i.e., numbers of connectors and cables.

Modeling and measurements determined the FEXT contribution of the connecting hardware to the link segment. The measurement configurations shown in Figure 12-Annex B were constructed of cable with crosstalk loss >65 dB in order to isolate the connecting hardware contribution. The number of connectors were varied as well as the distances.

The configurations 1-3 illustrated in Figure 12-Annex B were measured in sequence in order to determine the incremental connector FEXT contribution. Simulation results show good agreement to the measurement (Figure 13). Measurements and simulation show expected slope of 20 dB per decade. Values at 100MHz are provided in Table 1.

Table 1

Configuration (4 connector)	Measured FEXT (dB) @100Mhz	Calculated FEXT (dB) @100MHz	Measured ELFEXT (dB) @100Mhz	Calculated ELFEXT (dB) @100MHz
Concatenated 4 ft and 35 ft	18.73	18.74	15.79	16.12

Development of Channel ELFEXT limits based on Cable ELFEXT and Connector ELFEXT. Comparisons were made between vector summation and a power summation of the cable and connecting hardware contributions, and the simulated link segment. The graph of Figure 14-Annex B shows good agreement between a voltage summation and the simulated ELFEXT of the link segment.

Based on the analysis, a link limit was calculated using a voltage summation of minimally compliant cable and connecting hardware.

$$ELFEXT_{cabling(f)} \geq -20\log\left(10^{-\frac{ELFEXT_{cable}}{20}} + 10^{-\frac{FEXT_{connector}}{20}}\right) \text{ dB}$$

(eq 8)

1000BASE-T (Draft 4) specifies that the worst pair ELFEXT loss between any two duplex channels (any two pairs) shall be greater than:

$$ELFEXT_{loss(f)} \geq 17 - 20\log(f/100) \text{ dB}$$

(eq 9)

Where f is the frequency over the range of 1 MHz to 100 MHz.

1000BASE-T (Draft 4) also specifies a power sum ELFEXT (PSELFEXT) limit in order to simplify a multiple disturber ELFEXT field test. The PSELFEXT between a duplex channel (a pair) and the three adjacent disturbers shall be:

$$PSELFEXT_{loss(f)} \geq 14.4 - 20\log(f/100) \text{ dB}$$

(eq 10)

Where f is the frequency over the range of 1 MHz to 100 MHz.

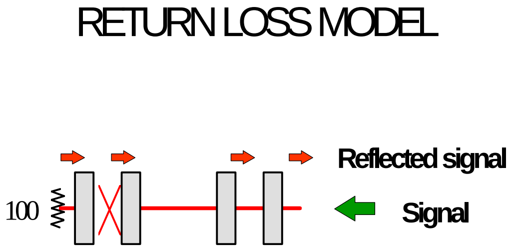
Return Loss

Development of Link Return Loss Limit Based on Component Values. The objective of this section is to characterize the connecting hardware return loss contribution to the overall link performance. With an understanding of the connector contributions, the worst case cabling performance can be calculated based on worst case component specifications and the cabling configurations, i.e., numbers of connectors and cables.

Modeling and measurements determined the return loss contribution of the connecting hardware. The measurement configurations are shown in Figure 8-Annex A, and Figure 9-Annex A .

Return Loss is a measure of the reflected signal energy in dB. The return loss is affected by the impedance mismatch between the cabling and the far end termination and between the various components comprising a channel, including horizontal cables, patch cables and connectors. The impedance matching between cables and connectors are particularly important at higher frequencies.

The model for return loss is illustrated in Figure 7. It consists of a series of concatenated transmission lines where each component is modeled by its own transmission matrix [T_k]. The Return Loss is determined from the resultant transmission matrix using the equations shown in Figure 7.



$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \prod_k [T_k] \qquad Z_{in} = \frac{A + \frac{B}{100}}{C + \frac{D}{100}} \qquad RL = -20\log\left(\frac{Z_{in} - 100}{Z_{in} + 100}\right)$$

(eq 11)

Figure 7

Return Loss Modeling Results. A Mathcad model was developed for modeling a worst case channel including up to four connectors. The worst case return loss occurs for a short length channel where the magnitude of the far end reflections are the greatest. Figure 11-Annex A illustrates the modeling results for the channel configuration shown in Figure 9-Annex A for manufacturer 2.

The predicted return loss trace in Figure 11-Annex A closely matches the measured data (Figure 10-Annex A). The peaks occur at the same frequencies of approximately 50 MHz and 90 MHz. The modeling results were generated using connecting hardware having 15.6 dB return loss (practical worst case) and a mismatch of 10 ohms between the patch cable and the horizontal cable impedance.

The graph also illustrates another transmission parameter, labeled as Roughk. This transmission parameter is the insertion loss deviation (ILD) of the channel, also called roughness. Insertion loss deviation is quite pronounced at higher frequencies. Insertion loss deviation is a new parameter under study by the TIA TR 41.8.1 working group. Insertion loss deviation needs to be taken into account in the overall channel budget for insertion loss. It can also be considered as excess noise and can contribute to jitter in digital systems.

The return loss limit for 1000BASE-T is shown as the lower dotted line in Figure 10-Annex A. The return loss for a 1000BASE-T (DRAFT 4) link is specified as:

$$\text{Return\_Loss}(f) \left\{ \begin{array}{ll} 15 & (1\text{-}20\ \text{MHz}) \\ \\ 15-10\log_{10}(f/20) & (20\text{-}100\ \text{MHz}) \end{array} \right\} (\text{dB})$$

where f is the frequency in MHz. The reference impedance shall be 100 ohms.

The return loss specifications for an “Enhanced Category 5 Cabling” (currently balloting in TIA/EIA) is a 2 dB improvement over the specifications of ANSI/TIA/EIA-568-A. This limit is shown as the upper dotted line in Figure 10-Annex B. The improvement in return loss can be achieved using the “Enhanced Category 5“ connecting hardware and cable.

CONCLUSION

The transmission parameters of ELFEXT loss and Return Loss have been developed to characterize cabling as specified in ANSI/TIA/EIA-568-A in order to validate 1000BASE-T operation on Category 5 cabling. Two-connector topologies minimally compliant with TIA/EIA-568-A are expected to meet these limits. Other Category 5 topologies can be implemented as long as they meet the ELFEXT loss and return loss limits.

“Enhanced Category 5 Cabling” (currently balloting in TIA/EIA) will sufficiently characterize the cabling components to ensure a compliant four-connector topology.

Annex A: Return Loss Test Configurations and Measurements

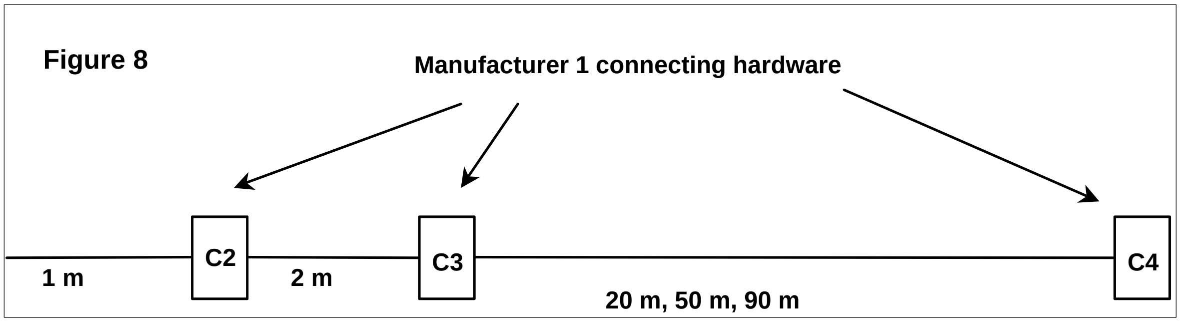


Figure 8

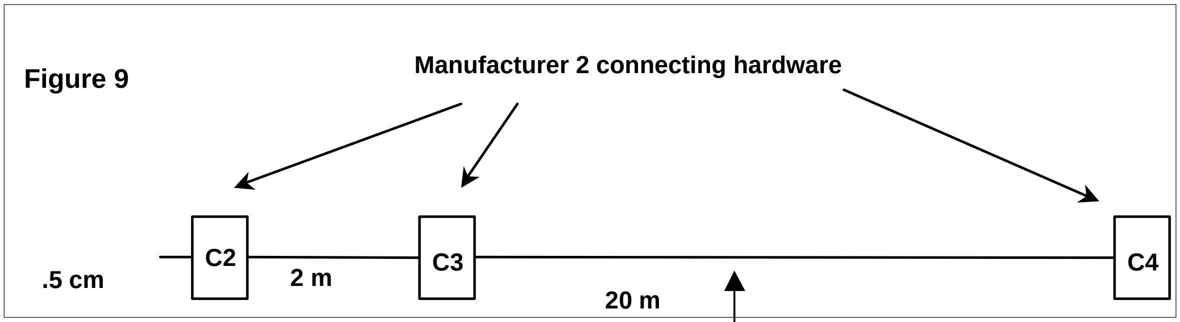


Figure 9

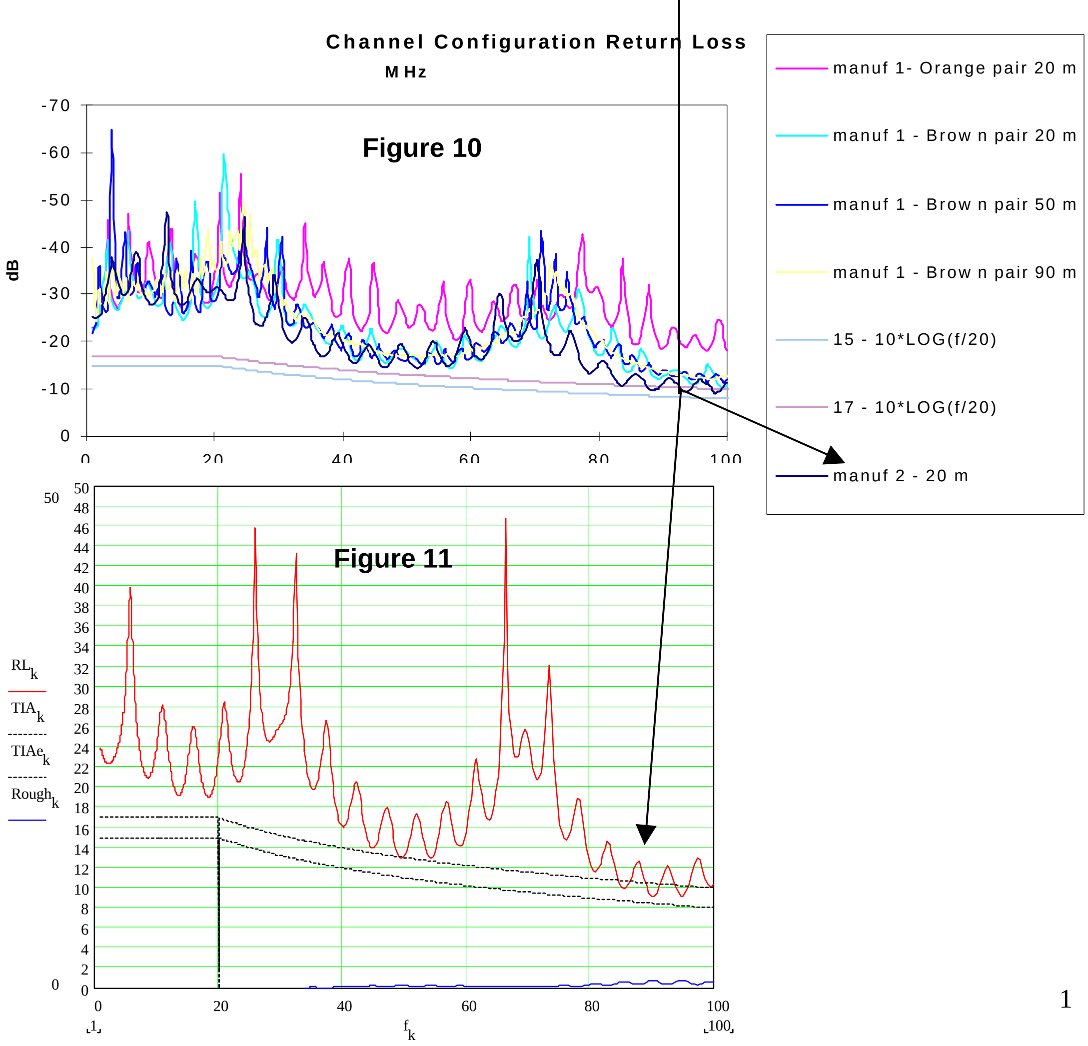


Figure 10

Figure 11

Annex B: ELFEXT Configuration and Measurements

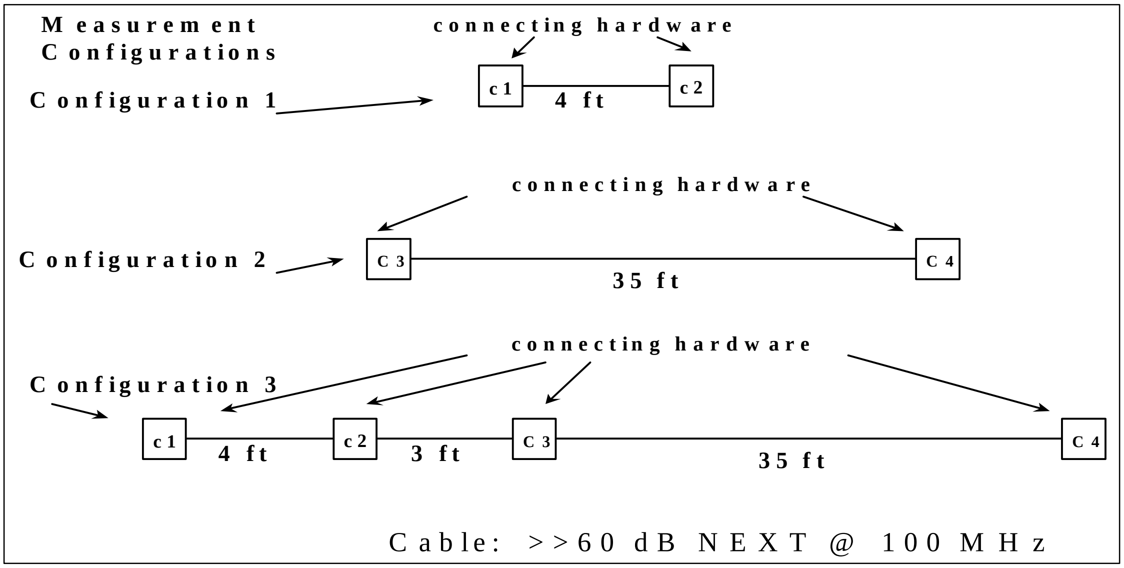


Figure 12

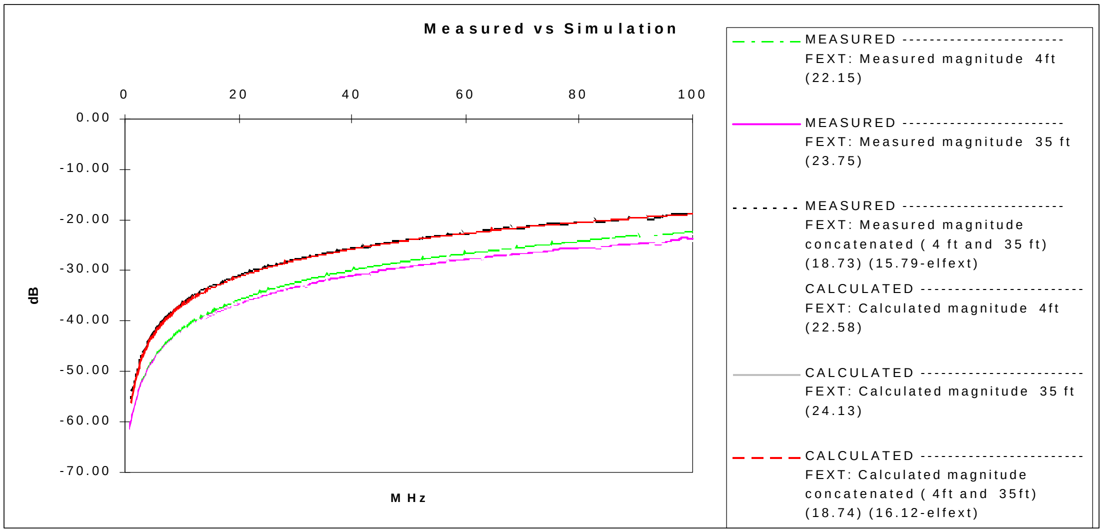


Figure 13

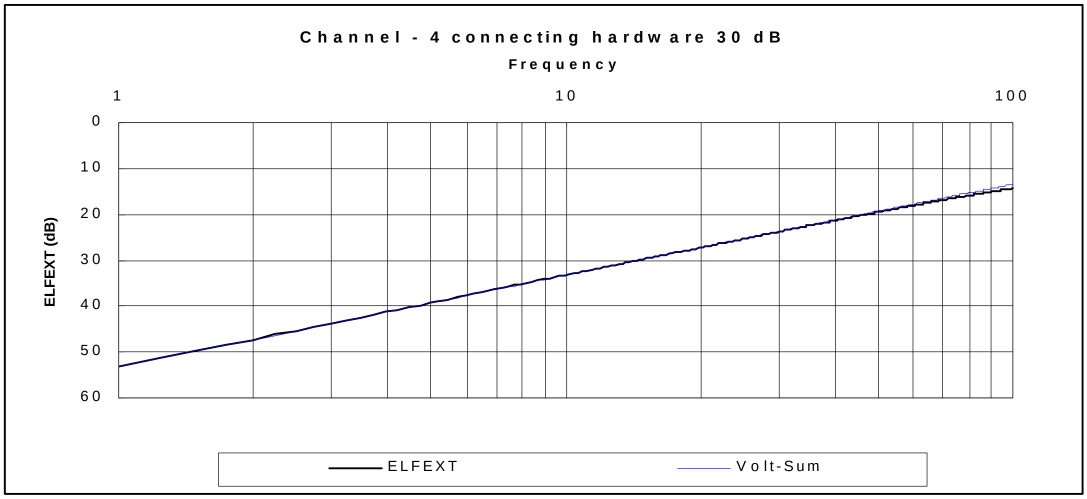


Figure 14

ANNEX C: ELFEXT SIMULATION

H. Cravis and T.V. Crater evaluated the expression for Far-End Crosstalk between two pairs when one considers two pairs of propagation constant, $\gamma(f)$, in a cable section of length *l*[2]. Their expression for the incremental crosstalk current *dI* on the disturbed pair at the receiving end, due to the incremental length of cable *dx* at some distance *x*, is given by

$$\frac{dI}{I_0} = \left(\frac{Z_0 Y}{16} - \frac{Z}{4 Z_0} \right) e^{-gl} dx \quad [3]$$

where *Z* is defined as the mutual impedance unbalance between pairs per unit length at a distance x from the signal source, Z_0 is the characteristic impedance of both pairs – assumed to be equivalent, and *Y* is the unbalance admittance between pairs per unit length. The bracketed expression above, when *Z,* Z_0, and *Y* are independent of frequency, is the unbalance per unit length, commonly called the crosstalk coupling function $C_r(x)$. A more exact expression for the above can be developed when one considers different propagation constants for the send and receive pairs. If we let γ_1 be the propagation constant for the send pair and γ_2 be the constant for the receive pair, then the above equation can be rewritten as follows:

$$\frac{dI}{I_0} = \left(\frac{Z_0 Y}{16} - \frac{Z}{4 Z_0} \right) e^{-g_1 x} e^{-g_2 (l-x)} dx$$

The final equation for the equal level Far-End crosstalk (ELFEXT), *E(f)*, is found by integrating the ratio *dI/Ir* in x, where I_r is the current on the disturbing pair at the receiving end of the cabled pairs, and being similar to the equation provided by the before-mentioned authors[4], is given by:

$$E(f) = i2pf \int_0^l C_r(x) e^{-(g_1 - g_2)x} dx$$

The above equation is pivotal in modeling the ELFEXT between two arbitrary pairs in a cable. With appropriate assumptions made for the propagation constants, I let $C_r(x)$ be normally distributed in amplitude as a function of x, with zero mean, and with a variance to drive the resultant *E(f)* toward some desired level as a function of frequency.

In order to model the ELFEXT of a channel, one must include the contributions of different cabling segments as well as connecting hardware in the channel. This is accomplished by using piece-wise integration; whereby, the contributions of previous segments are appropriately phased and attenuated as a function of x before being added to other expressions further along in the channel. A simple model for each connecting hardware contribution is developed and is provided for completeness, as follows:

$$E(f) = i2pfC_c(x_0) e^{-g_c dx} dx$$

where γ_c is the propagation constant for a connector, *dx* is the incremental length (set to the span of a single connector in a channel), and where $C_c(x_0)$ is the coupling function between pairs in the connecting hardware at some arbitrary distance, x_0, in the channel and over an incremental span *dx*.

BIOGRAPHIES

Christopher T. Di Minico: With Cable Design Technologies (CDT) Corporation, Director of Network Systems Technology. Member of IEEE, TIA TR41.8.1, and the US advisory group for international cabling standards development. B.S.E.E. at Northeastern University with over 30 years experience in the cabling industry both in design and installation.

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Chairman of the TIA Telecommunication Standard Subcommittee for User Premises Cabling.

AKNOWLEGEMENT

Dave Hawkins, Lucent Technologies, provided the ELFEXT simulation analysis in the development of the connector and cable ELFEXT contribution to the cabling as well as the simulation description in Annex C.

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[2] THE BELL LABS SYSTEM TECHNICAL JOURNAL, MARCH 1963, page 476, APPENDIX B.

[3] THE BELL LABS SYSTEM TECHNICAL JOURNAL, MARCH 1963, page 476, APPENDIX B, EQUATION (35)

[4] THE BELL LABS SYSTEM TECHNICAL JOURNAL, MARCH 1963, page 476, APPENDIX B, EQUATION (36)