THE INTER-STANDARD GAP

Fanny I. Mlinarsky

Scope Communications, Inc., Northboro, Massachusetts

ABSTRACT

In an ideal world the networking and the cabling standards would be inter-operable. The IEEE, ANSI and The ATM-Forum standards committees developing new networking standards could simply specify a cable plant compliant with TIA-568-A[1] or ISO11801[2].

This kind of cooperative arrangement among the standards organizations could eliminate the redundancy of standardization effort and the duplication of work. But when dealing with the enormous complexity of data communications, can we honestly believe that a jump from 10 to 100 Mb/s will happen flawlessly and quickly, just as the standards dictate? Has any significant advancement in networking technology ever occurred without inter-operability issues?

This paper provides an overview of the emerging 100 Mb/s Local Area Networking (LAN) applications – their physical layer needs and specifications. It examines how well the generic cabling standards such as TIA-568-A[1] and ISO11801[2] address the requirements of the emerging high speed LANs and demonstrates some gaps between the ideal world and the reality today.

How close are we to our goal of standards inter-operability? Can the industry standards ever catch up with the accelerating pace of advancements in the data communications industry? Before we attempt to answer these questions, let's examine the facts.

INTRODUCTION

The Physical Medium Dependent (PMD) layer of a network encompasses the signaling methodology and the physical medium used to transmit digital information. PMD specifications typically define the modulation, the data rate, the maximum acceptable Bit Error Rate (BER) and the medium. When specifying the medium, or the signaling channel, the networking standards developed by IEEE, ANSI, The ATM Forum and other organizations, typically reference the cabling standards, such as TIA-568-A[1] and ISO11801[2].

Cabling standards are application independent. They form the core of the medium specifications common to all the networking applications but they do not fully address the specific requirements of each network.

So, in addition to referencing a generic cabling standard, the PMD standards typically define unique channel characteristics required to achieve the specified BER performance using the specified modulation scheme. These unique channel requirements, which might include ambient noise, propagation delay, delay skew and other parameters, are often not covered by the generic cabling standards.

The problem is, the cable installer is only required to certify cabling installations to a generic category or class of cabling as defined by TIA-568-A[1] or ISO11801[2] and is not required to verify any network specific channel specifications. And if the installer does nothing more than observe the industry field testing standards, many crucial network-specific channel requirements are not verified because they fall into the inter-standard gap.

This paper examines the implications of incomplete or unspecified PMD channel requirements. Let us begin by reviewing the key cable specifications and their effect on the performance of data communications systems.

PERFORMANCE OF THE PHYSICAL LAYER

A robust physical layer operates at a low BER in the presence of noise, distortion and other hostile conditions in the communications channel. A low BER means a low rate of re-transmissions of corrupted data and, therefore, a high rate of real data throughput. Data re-transmissions impair throughput efficiency because network bandwidth is unnecessarily consumed while transmitting the same information more than once. Throughput is further impaired when the upper networking layers get involved in detecting and re-generating the corrupted information.

Minimizing the BER of the physical layer is the key to optimizing the rate of data throughput.

SYSTEM ROBUSTNESS

In order to minimize the BER of a communications channel, it is necessary to maximize the data signal's immunity to bit errors in the presence of noise and distortion. The data signal's immunity to bit errors is often gauged by examining its eye pattern.

The Eye Pattern

In qualitative terms, the degree to which a data signal is immune to bit errors is a function of how constricted its eye pattern is. The more constricted the eye pattern the higher the probability of bit errors. The opening in the eye pattern determines the amount of noise that must be added to the signal to cause bit errors.

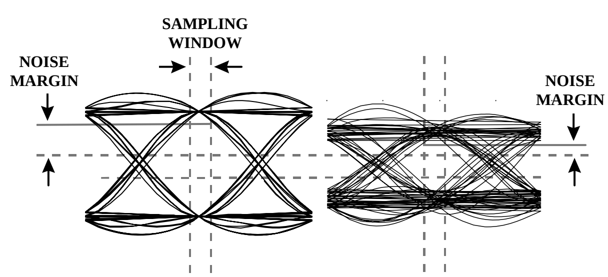

Figure 1

Left -- eye pattern of a good quality signal with a wide noise margin in the sampling window; right -- eye pattern of a poor quality signal with a narrow noise margin

The more constricted the eye pattern, the less noise is required to induce bit errors. The less noise the system can tolerate at a given BER, the less robust the system is.

DISTORTION AND NOISE

Signal distortion contracts the eye pattern opening and thus reduces the transmission system's immunity to noise. Noise, when added to the data signal, also contracts the eye pattern. Therefore, both noise and distortion, each, contribute to the contraction of the eye pattern. The less distorted the signal, the more noise can be tolerated by the system before bit errors occur. The reverse is also true. The less noise is present in the communications channel, the more distortion can be tolerated.

Distortion

In a twisted pair communications channel, signal distortion is primarily caused by channel attenuation.[1] As the simulation in *Figure 2* shows, the high frequency contents of a data signal are attenuated by the channel more than the low frequency contents. The sloping response of channel attenuation distorts the data waveform to such a degree that the eye pattern at the end of a worst case category 5 channel is completely closed. Therefore, before the data can be recovered, it must be equalized to restore the high frequency content of the signal.

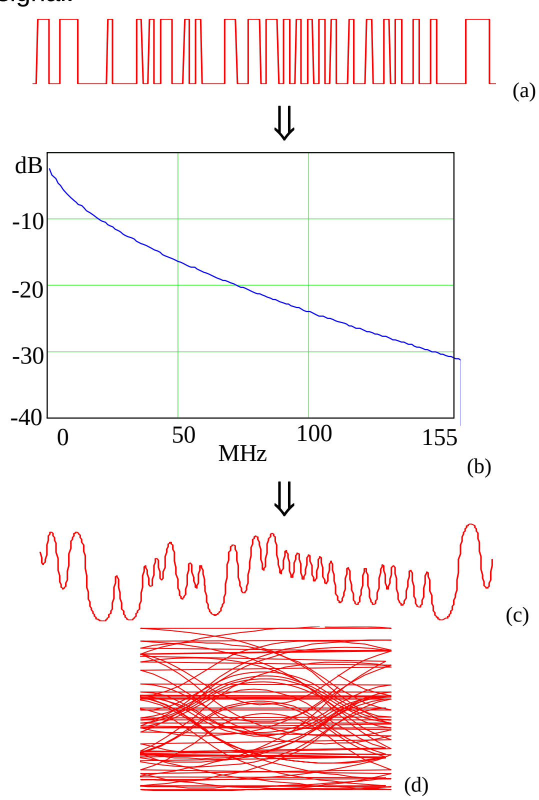

Figure 2

Simulation of a 155 Mb/s NRZ data signal subject to maximum allowable TIA-568-A[1] channel attenuation; (a) ideal, unfiltered 155 Mb/s NRZ data signal; (b) TIA-568-A worst case channel attenuation extended to 155 MHz (Appendix A); (c) simulation of the data signal distortion due *to the attenuation; (d) closed eye pattern of the distorted signal*

A typical twisted pair receiver includes an equalizer. The receive equalizer has a transfer function designed to cancel the attenuation response, resulting in a signal loss that is uniform over frequency.

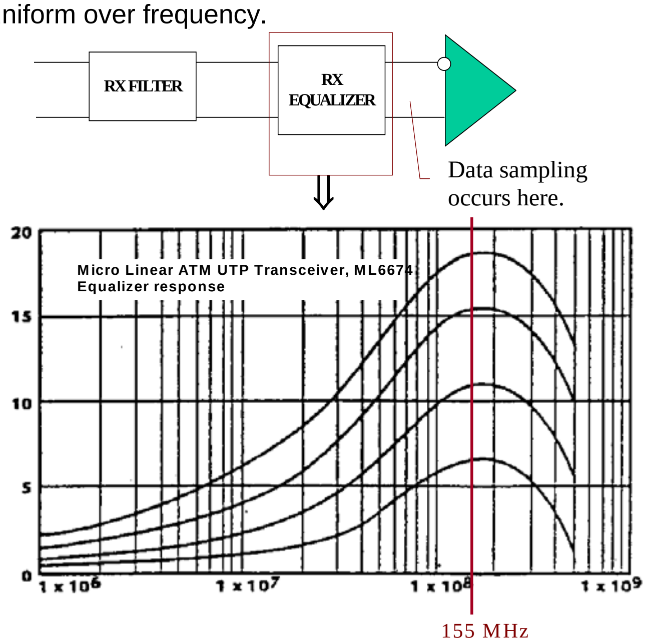

Figure 3

Equalizer curves from the specification of the Micro Linear ATM UTP transceiver, ML667, used in some 155 Mb/s ATM and 100 Base-TX products

The response of the equalizer shown in *Figure 3* slopes upward with frequency, compensating for channel attenuation up to 155 MHz. This is a very common adaptive equalizer that sets the slope of its response based on the measured signal power.

A typical equalizer cancels out the cable attenuation imprecisely and leaves the equalized signal somewhat distorted, as shown below.

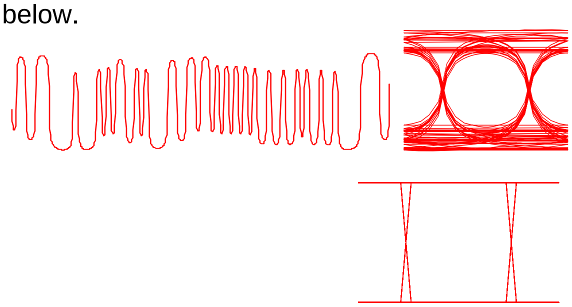

Figure 4

Simulation of a somewhat imperfect (i.e. realistic) equalization of the distorted signal. The eye pattern of the attenuated and subsequently equalized signal (top) is somewhat rounded and more constricted than the transmitted eye pattern (bottom)

Although there are many causes[1] of signal distortion, the distortion in a twisted pair communications channel is primarily due to the imperfect equalization of the channel attenuation response.

Noise

The primary source of noise in a twisted pair channel is the crosstalk between the different pairs in a cable[3]. Depending on the network topology, the crosstalk coupling onto the received signal could be either at the near end of the cable or at the far end.

A physical layer utilizing two pairs typically transmits on one pair and receives on the other simultaneously. Most of the noise on the receive pair is coupled from the near end transmitter and is known as the near end crosstalk or NEXT. The examples of high speed two pair twisted pair LANs sensitive to NEXT noise are 100 Base-TX[5] and ATM[6,7,8].

Networks such as 100Base-T4[5] and 100VG-AnyLAN[4] transmit on multiple pairs simultaneously. In these multi-pair PMD topologies, the receive signal is subject to far end crosstalk or FEXT. FEXT is the crosstalk coupling from one transmit pair to another as the signal propagates from the transmit end of the cable, the far end with respect to the receiver.

The noise spectrum at a communications receiver is a function of the transmit spectrum and of the cable crosstalk response. In the case of two pair networks, the spectral shape of the noise is a function of the transmit spectrum and of the NEXT response of the cable. In the case of multi-pair topologies, the spectral shape of the noise is a function of the transmit spectrum and of Equal Level FEXT[2] or ELFEXT [10].

Although noise in a twisted pair communication channel can come from different ambient sources[3], it is typically dominated by the crosstalk response of the cable.

Signal To Noise Ratio (SNR)

In a communications channel, the power of the noise is only meaningful when compared to the power of the data signal.

SNR is a measure of the strength of the desired data signal with respect to the interfering noise signal. A low SNR results in bit errors as the data signal at the station's receiver becomes indistinguishable from noise.

BER is a statistical function of SNR. Feher[9] defines the probability of error function (which is equivalent to BER) for NRZ modulation as

$$BER = P_e = Q(y) = \int_y^{\infty} \frac{1}{\sqrt{2 \cdot \pi}} \cdot e^{\frac{-w^2}{2}} dw \qquad (1)$$

where y is the ratio of the peak signal value at the sampling instant to the root-mean-square (rms) voltage of the noise power at the sampling point in the receiver. The noise is assumed to be white Gaussian[4].

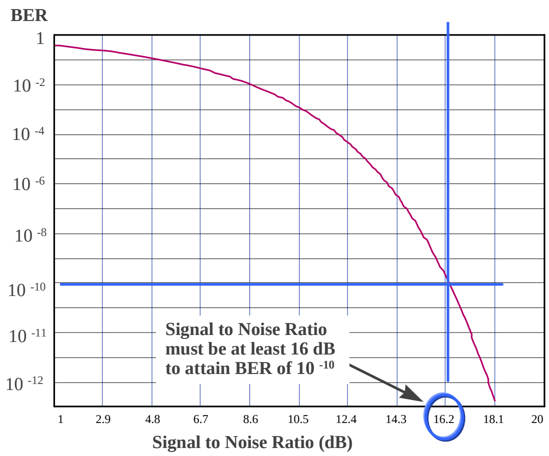

Figure 5

BER vs. SNR function expressed in equation 1 for and NRZ-based communications channel; this function describes the behavior of networks such as 155 Mb/s ATM, which use NRZ modulation

Per *Figure 5,* for a network such as the NRZ based 155 Mb/s ATM to attain the required BER of 10^{-10}, the SNR would have to be better than 16 dB. The shape of the BER vs. SNR curve is unique for each network topology and signaling scheme but, in all cases, the BER increases with decreasing SNR.

THE INTER-STANDARD GAP BETWEEN THE 155 MB/S ATM STANDARD AND TIA-568-A

The 155 Mb/s twisted pair ATM interface[6] employs two pair full duplex NRZ signaling. At the receiver, the noise spectrum is dominated by the transmit spectrum and by the NEXT response of the cable. The amount of signal distortion is determined by the attenuation response of the cable.
The transmit spectrum of the 155 Mb/s NRZ data signal is shown in *Figure 6.* The entire first lobe of the spectrum, extending to 155 MHz, is needed for proper data recovery [11].

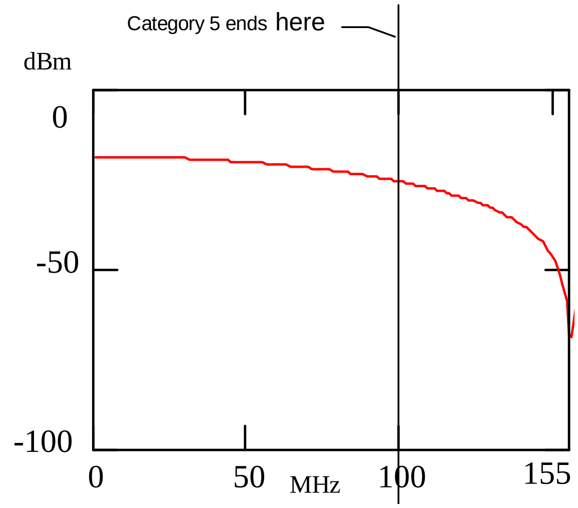

Figure 6

The portion of the 155 Mb/s NRZ signal spectrum needed for proper data recovery

Self NEXT Noise

In specifying the acceptable noise power in the communications channel, the ATM Forum standard AF-PHY-0015.000[6] defines the maximum Self NEXT Channel Noise (Section 5.3.1). The self NEXT noise, composed of the channel near end crosstalk and of ambient noise sources, is not to exceed 20 mV ptp.

To compute the worst case noise power at an ATM receiver, we need to compute the NEXT noise spectrum as a function of channel NEXT and of the useful signal spectrum (*Figure 6*).

The problem is, TIA-568-A[1] only specifies cabling to 100 MHz and the ATM network uses the category 5 channel beyond this specification.

However, we can easily extend the channel NEXT limit, defined in TSB67[3] beyond 100 MHz (see *Appendix A*) so as to account for the useful transmit spectrum of the ATM signal.

If the ATM signal is transmitted at the maximum allowable power over a TSB67[3] channel exhibiting the worst case NEXT response

(*Figure 7)*, the NEXT noise spectrum at an ATM receiver would be as shown in *Figure 8*.

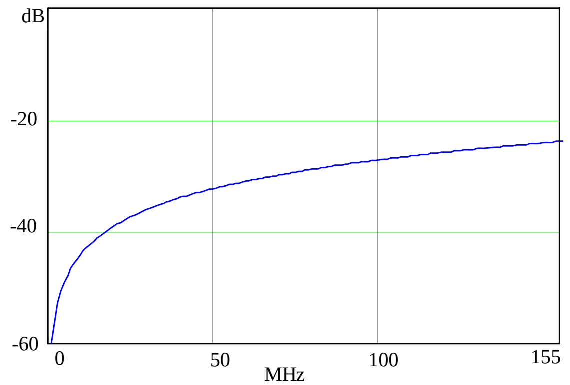

Figure 7

Worst case TSB67[3] channel NEXT response extended to 155 MHz as described in Appendix A

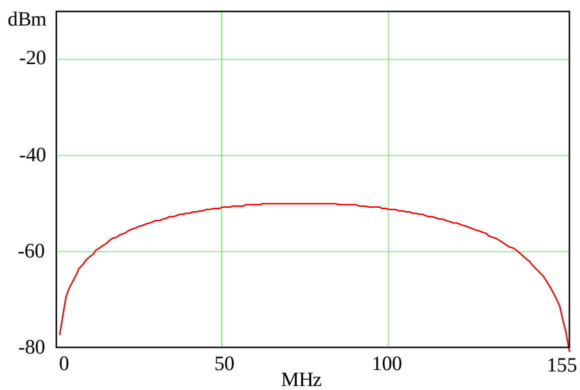

Figure 8

Noise power spectrum at an ATM receiver. This power spectrum is based on the maximum allowable transmit signal of 1060 mV ptp and the worst case TSB67[3] channel NEXT response shown in Figure 7.

Integrating the noise power spectrum results in total noise power of 8.2×10^{-4} mW. Converting total noise power to noise voltage, yields 26 mV ptp. This noise voltage violates the 20 mV limit specified for the Self NEXT Channel Noise (Section 5.3.1).

Based on the Self NEXT noise analysis, the 155 Mb/s ATM physical layer is not likely to achieve the required BER when operating over a worst case category 5 channel.

Signal Distortion

The amount of signal distortion at the end of a worst case TSB67[3] channel is determined primarily by cable attenuation. It is important that attenuation maintain a consistent slope over the entire frequency band of 155 MHz and meet the extended frequency attenuation limit derived in *Appendix A*. The signal spectrum between 100 and 155 MHz significantly affects the eye pattern opening in the presence of distortion and time domain jitter. This subject is extensively treated in the ATM Forum contribution #96-0444[11].

Discussion

Although the ATM Forum standard[6] states that category 5 satisfies its channel requirements, the above analysis exposes two inconsistencies between the TIA-568-A[1] and the AF-PHY-0015.000[6] standards:

1. The needed signal spectrum extends beyond the category 5 frequency range [11,12].
2. The noise voltage created by the worst case category 5 NEXT response violates the 20 mV ptp limit.

The existing 155 Mb/s twisted pair ATM products compliant with the ATM Forum AF-PHY-0015.000[6] standard use category 5 cabling systems beyond specification. The only reason these products work is that most category 5 installations exhibit substantial margin with respect to the worst case NEXT and attenuation levels and thus deliver the needed performance in the required frequency band of 155 MHz.

However, just because most ATM installations work, does not mean that they are guaranteed to operate at the specified BER and data throughput. The only way to guarantee that a given system will function at the required performance level is to design this system to operate with some degree of performance margin in the worst case environment.

Using components beyond their specification is a poor design practice – it leaves the system vulnerable to products which might create worst case operating conditions and to various installation flaws which might be outside the specified frequency range and thus not detectable by standard field test equipment.

But is The ATM Forum's 155 Mb/s interface the only high speed networking standard exhibiting inconsistencies of definition with the cabling standard upon which it relies for its channel specification?

OTHER EXAMPLES OF INTER-STANDARD GAPS

The gap between The ATM Forum standard[6] and its companion TIA-568-A[1] cabling standard is only one example of a general trend: the cabling standards tend to lag behind the networking standards in addressing the medium dependent specifications required by the new networks.

Often, networking standards introduce their own unique physical layer specifications, not addressed by cabling standards. These specifications include delay skew and ELFEXT. Let us look at a few examples.

Delay Skew

One example of how the cabling standards are often struggling to catch up to the networking standards is the case of the delay skew specification.

Delay skew is the worst case difference in propagation delay among the four pairs in a twisted pair cable.

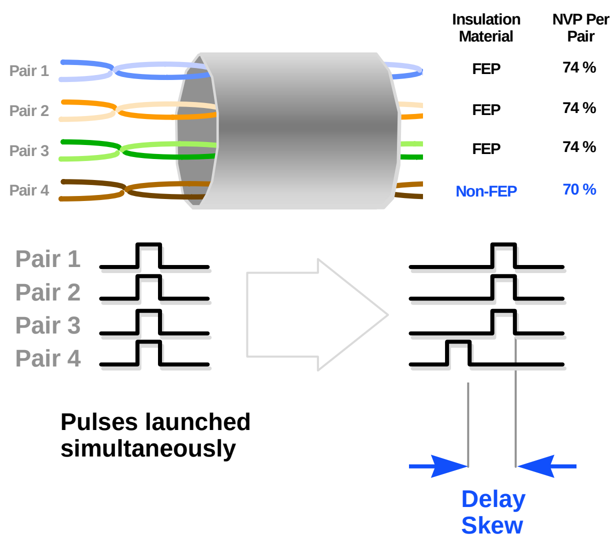

Figure 11

Propagation delay skew among the four pairs in a cable

The LAN standards, such as 100Base-T4[5] and 100VG-AnyLAN[4], which specify transmission over multiple pairs simultaneously, require guaranteed limits on the delay skew among the pairs. The 100VG-AnyLAN[4] standard limits the maximum allowable delay skew to 67 ns (Section 16.9.1.3) and the 100Base-T4[5] standard limits the maximum delay skew to 50 ns.

Although these multi-pair networking standards have been released since 1995, the delay skew parameter has, until recently, been trapped in the inter-standard gap.

The recent development that has attracted attention to the delay skew issue is the shortage of Flourinated Ethylene Propylene (FEP) – the material used as insulation in category 5 plenum cables. Because of the FEP shortage, cable manufacturers have introduced cables using a mix of FEP and polyolyfin based insulation. As a result of having pairs with different insulation material in the same cable assembly, the delay skew among the pairs has been significantly affected and in some cases has violated the requirements of the multi-pair networks.

The delay skew issue demonstrates the potential perils of using cabling systems beyond explicit specifications. As of this writing (August, 1996), the delay skew specification is being belatedly added to the soon to be released TIA-568-A addendum.

Equal Level Far End Crosstalk (ELFEXT)

ELFEXT is another cabling specification trapped in the inter-standard gap. This parameter is important for proper operation of multi-pair networks since it is the major source of noise for these topologies. As of this writing, TIA-568-A[1] does not specify ELFEXT, while 100VG-AnyLAN[4] places limits on this parameter (Section 23.6.2.3.3).

Although most cabling systems appear to support VG-AnyLAN today, this situation is not guaranteed to last. Currently, the IEEE 802.12 committee is working on the specification for 400 Mb/s 400VG-AnyLAN[5], which may be more sensitive to the ELFEXT parameter than 100VG-AnyLAN.

Frequency Bandwidth

Channel frequency specifications occupy a prominent place in the inter-standard gap. The committees developing new networking standards are trying to specify cabling requirements so as to assure operation over the widest possible installed base of cabling. For this reason, both category 3 and category 5 networks tend to stretch the specified channel bandwidth limit.

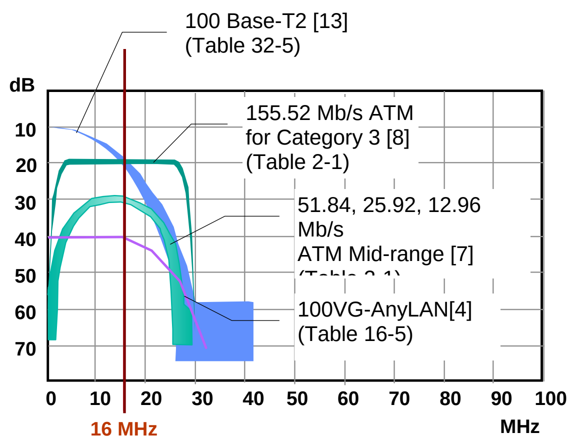

Figure 12

Transmit spectra of several category 3 LANs; these spectra extend beyond the 16 MHz category 3 limits

Figure 12 shows spectra of several high speed networks that specify category 3 cabling. It is easy to see that these networks significantly exceed the 16 MHz frequency limit. *Figure 13* shows the spectra of two category 5 LANs, both exceeding the category 5 frequency limit of 100 MHz.

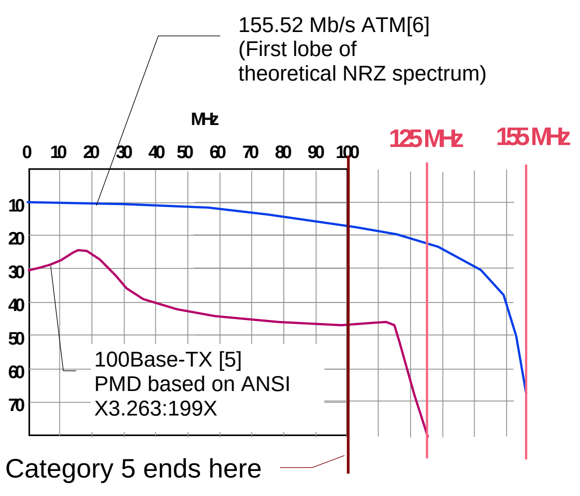

Figure 13

Transmit spectra of category 5 LANs

As already mentioned, the 155 Mb/s NRZ based ATM network has a spectrum extending to 155 MHz. Although it is very easy to show that most ATM products do not filter the first spectral lobe that extends to 155 MHz [11,15], there has been a considerable amount of controversy regarding the importance of the spectral energy between 100 and 155 MHz.

A recently published Bit Error Rate experiment [12] confirms the dependence of the 155 Mb/s ATM network on channel characteristics above 100 MHz.

This experiment demonstrates that a field installation flaw, such as a bridge tap, which disturbs the channel response beyond 100 MHz (*Figure 14)* could cause major performance degradation (*Table 1*) and could substantially deteriorate the BER, causing the link to violate the required BER of 10^{-10}.

Table 1

TEST CONDITION	TIME (min)	# OF ERRORS	BER
no fault	30	6	2.1×10^{-11}
13.8" stub, representing a bridge tap	30	3560	1.2×10^{-8}

Partial summary of BER test results on the same channel with and without an installation flaw – the bridge tap; the bridge tap effected the channel response as shown in Figure 14

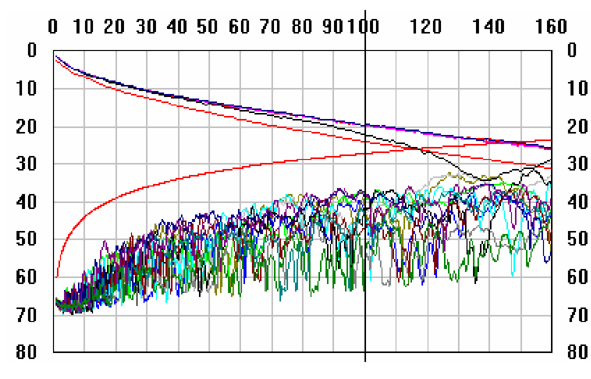

Figure 14

NEXT and attenuation response of a faulty channel with a 13.8" open bridge tap on one of the ATM signal pairs; such a fault is not detectable with a standard 100 MHz field test but significantly effects the performance of the ATM link (Table 1)

This BER experiment reinforces the importance of properly specifying the required channel performance. Since category 5 specification does not extend beyond 100 MHz, most standard field testers would not uncover the installation flaw shown in Figure 14. However, this experiment shows that such a flaw can cause an ATM link to violate the required BER performance by three orders of magnitude – a very noticeable degradation in data throughput.

SUMMARY

This paper has examined how the specifications of twisted pair cabling affect the noise and distortion environment in a communications channel, thereby affecting the data throughput performance of the channel. We have demonstrated that although the networking standards reference the generic cabling standards for most of their physical layer specifications, the cabling standards tend to lag behind the networking standards in specifying key performance parameters.

Therefore it is not safe to assume that a fully certified category 5 installation will support all the existing and emerging networks. And when field testing twisted pair installations, it may not be sufficient to verify compliance to a cabling standard, such as TIA-568-A[1]. It is important to verify that the network specific requirements are also satisfied.

It is important to remember that the 100 Mb/s networks of tomorrow are considerably more vulnerable to imperfections in the physical layer than are the 10 Mb/s networks of yesterday. And as the LAN industry tries to extract every last bit of performance from category 5 systems, it is important to eliminate the inter-standard gap and to explicitly test the cabling parameters that affect the real rate of data throughput.

FOOTNOTES

[1] Other causes of distortion in a twisted pair channel include imperfections in the Structural Return Loss (SRL) and in the phase response non-linearity of the channel. In a good quality category 5 twisted pair channel, these disturbances typically have far less effect on the quality of the data signal than does the cable attenuation response and, for this reason, are not treated here.

[2] In qualitative terms, ELFEXT is the far end coupling as seen by the receiver – the attenuated FEXT.

[3] Other sources of noise include impulse noise and RF interference. Impulse noise is generally induced by office and building equipment and could be the result of mechanical switching transients. RF interference is typically generated by TV, radio and other signal transmissions in the air.

[4] In a twisted pair channel, the noise may not be Gaussian. It is typically dominated by the cable crosstalk and resembles the data signal qualified by the channel crosstalk response.

[5] As of this writing, it appears that the IEEE 802.12 committee is ready to adapt the 400VG-AnyLAN twisted pair PMD scheme requiring simultaneous transmission on 3 pairs while receiving on the fourth pair. In this case the receive pair might be subject to power sum NEXT from all three transmit pairs.

APPENDIX A

EXTENDING TSB67 NEXT AND ATTENUATION LIMITS BEYOND 100 MHz

TSB67, "Transmission Performance Specifications for Field Testing of Unshielded Twisted-Pair Cabling Systems"[3], defines category 5 field certification limits for Near End Crosstalk (NEXT) and attenuation. The limits are defined for two configurations – Basic Link and Channel.

TSB67 CHANNEL CONFIGURATION

The channel configuration represents a complete link including the patch cables connected to the user device in the work area and to the network equipment in the telecom closet.

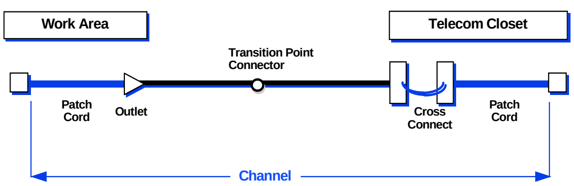

FIGURE A-1

TSB67 channel configuration

TSB67 CHANNEL ATTENUATION

Attenuation is a measure of signal loss. Attenuation response of a category 5 channel is the sum of the attenuation of the cabling and of the connecting hardware comprising the channel.

The attenuation per 100 meters of category 5 horizontal cable is defined in TIA/EIA-568-A[1] Section 10.2.4.6 as follows:

$$AttenCable(f) \le 1.967 \cdot \sqrt{f} + 0.023 \cdot f + \frac{0.05}{\sqrt{f}} \qquad \text{(A-1)}$$

The attenuation per 100 meters of category 5 patch cord cable is defined in TIA/EIA-568-A[1] Section 10.5.4.1 as follows:

$$AttenPatch(f) \le 1.2 \cdot AttenCable(f) \qquad \text{(A-2)}$$

The attenuation of category 5 connecting hardware is defined in TIA/EIA-568-A [1] Table 10-8 and can be interpolated as a function of frequency by the following equation:

$$AttenConnect(f) \le 0.1 + 0.003 \cdot f \qquad \text{(A-3)}$$

The category 5 attenuation certification limit for a channel containing 4 connections, 90 meters of horizontal cable and 10 meters of patch cord cable is defined in TSB67 [3] as the sum of the attenuation limits of the cabling and of the connecting hardware comprising the channel:

$$AttenChannel(f) = 1.02 \cdot AttenCable(f) + 4 \cdot AttenConnect(f) \qquad \text{(A-4)}$$

The factor of 0.02 is obtained for 10 meters of patch cordage, assuming 20% higher attenuation for the patch cord cable than for the horizontal cable, as 0.2*10/100.

The certification limit for channel attenuation is based on the physical properties of the cabling and of the connecting hardware. These physical properties are expected to behave consistently above the 100 MHz band defined by the category 5 specification.

Because the physical properties of category 5 installations remain consistent over frequency, the maximum allowable attenuation of a 100 meter category 5 channel can be extended beyond 100 MHz, as shown in *Figure A-2*.

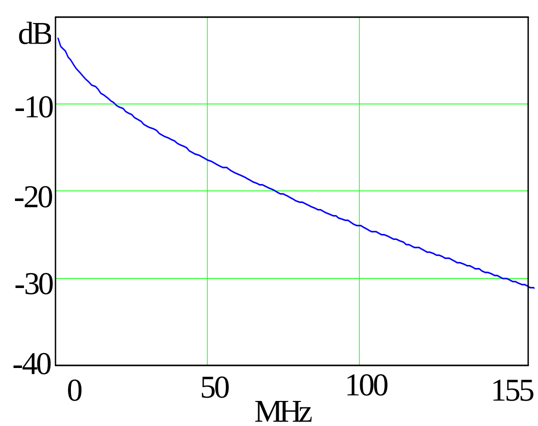

FIGURE A-2

TSB67 channel attenuation limit extended to 155 MHz per Equation A-4

TSB67 CHANNEL NEXT

Near End Crosstalk (NEXT) is a measure of signal coupling from one pair to another. The NEXT response of a category 5 channel is the sum of the NEXT responses of the cabling and of the connecting hardware comprising the channel.

The NEXT of category 5 horizontal cable is defined in TIA/EIA-568-A[1] Section 10.2.4.7 as follows:

$$NEXTcable(f) \geq NEXT(0.772) - 15 \cdot \log(\frac{f}{0.772}) \qquad \text{(A-5)}$$

The NEXT at 0.772 MHz is 64 dB for category 5 cable.

The NEXT of category 5 connecting hardware is defined in TIA/EIA-568-A[1] Section 10.4.4.2 as follows:

$$NEXTconnect(f) \geq NEXT(16) - 20 \cdot \log(\frac{f}{16}) \qquad \text{(A-6)}$$

The NEXT at 16 MHz for a category 5 connector is 56 dB.

The NEXT certification limit of a category 5 channel is the sum of the NEXT limits of the cabling and of the connecting hardware comprising the channel and is computed as follows:

$$NEXTconnLin(f) = 10^{\frac{-56+20\cdot\log(\frac{f}{16})}{20}} \qquad \text{(A-7)}$$

$$NEXTcableLin(f) = 10^{\frac{-64+15\cdot\log(\frac{f}{0.772})}{20}} \qquad \text{(A-8)}$$

$$NEXTchannel(f) = 20 \cdot \log(2 \cdot NEXTconnLin(f) + NEXTcableLin(f)) \qquad \text{(A-9)}$$

Equation A-9 defines the NEXT certification limit of a category 5 channel containing 2 near end connections. This equation is based on the physical properties of the cabling and of connecting hardware, which are expected to behave consistently above the 100 MHz band covered by TSB67[3].

Because the physical properties of category 5 installations remain consistent over frequency, the certification limits for NEXT of a category 5 channel can be extended beyond 100 MHz, as shown in the following figure:

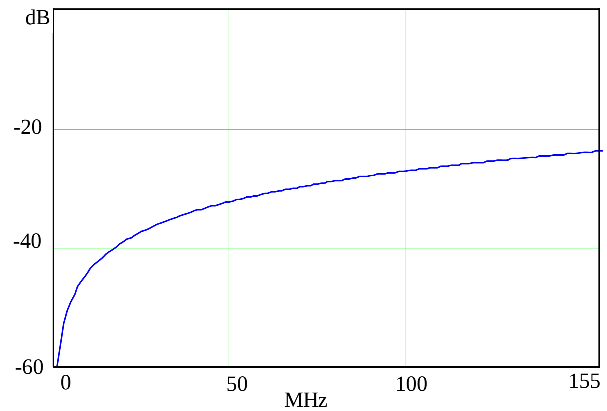

FIGURE A-2

TSB67 channel NEXT limit extended to 155 MHz per Equation A-9

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Fanny I. Mlinarsky
Scope Communications, Inc.
753 Forest Street
Marlborough, Massachusetts 01752

Fanny Mlinarsky has held a number of Engineering and Engineering Management positions at leading communications and test equipment companies including Chipcom, Concord Communications and Teradyne. She has been with Scope Communications since 1993 and is responsible for the development of hand held test tools used by cable installers and network maintenance technicians. Mlinarsky holds a BA in Computer Science and a BS in Electrical Engineering from Columbia University. In her 13 years of experience in the data communications industry, she has actively participated in the development of networking and cabling standards under the auspices of IEEE, ANSI and TIA.