Gigabit Ethernet over Category 5

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Introduction

The twisted pair gigabit Ethernet standard – 1000Base-T – is under development by the IEEE P802.3ab task force and is expected to be ratified in the first half of 1999. The work on this standard started in the latter half of 1996. In September 1997, after a year of debate, the IEEE P802.3ab task force selected the Enhanced TX/T2 line code for implementing 1000Base-T. The name – Enhanced TX/T2 – was chosen because this signaling scheme has inherited the symbol rate and spectrum of 100Base-TX and is based on the line code used by 100Base-T2[1].

1000Base-T achieves the full duplex throughput of 1000 Mb/s by transporting data over four pairs from both ends of each pair simultaneously. Each pair carries a full duplex 250 Mb/s data signal encoded as 5-level Pulse Amplitude Modulation (PAM-5).

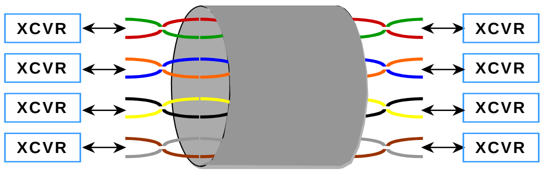

Figure 1: A 1000Base-T device transmits on all four pairs from both directions of each pair simultaneously

A 1000Base-T physical layer device consists of four identical transceiver sections – each with its own transmitter and receiver. Each transceiver section operates at 250 Mb/s – 2 bits per symbol with a symbol rate of 125 Msymbols/s. The total throughput is 250 Mb/s x 4 pairs = 1000 Mb/s = 1 Gb/s. [2]

1000Base-T Data Signal

The 1000Base-T signal was made compatible with the 100Base-TX signal so as to facilitate the development of a dual data rate 100/1000Base-T transceiver. The symbol rate of 1000Base-T is 125 Msymbols/s – the same as that of 100Base-TX.

When implementing a 100/1000Base-T system, one advantage of having equal symbol rates for 100 and 1000 Mb/s operation is that common clocking circuitry can be used for both data rates. Another advantage is that the spectra of both signals are similar with a null at 125 MHz[3] (figure 2), allowing for the use of common magnetics and emissions control circuitry.

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[1] 100Base-TX is the IEEE standard for implementing 100 Mb/s Ethernet over 2 pairs of category 5. 100Base-T2 is the IEEE standard for implementing 100 Mb/s Ethernet over 2 pairs of category 3.

[2] Msymbols = Mega-symbols = Million symbols; Mb = Mega-bits = Million bits; Mb/s = Mega-bits per second; Gb/s = Giga-bits per second

[3] The null in the spectrum of a baseband signal occurs at the frequency equal to the symbol rate. 1000Base-T and 100Base-TX signals exhibit similar spectral shapes because these baseband networks both operate at the same symbol rate. The spectrum of 1000Base-T was shaped, through filtering, to match the spectrum of 100Base-TX.

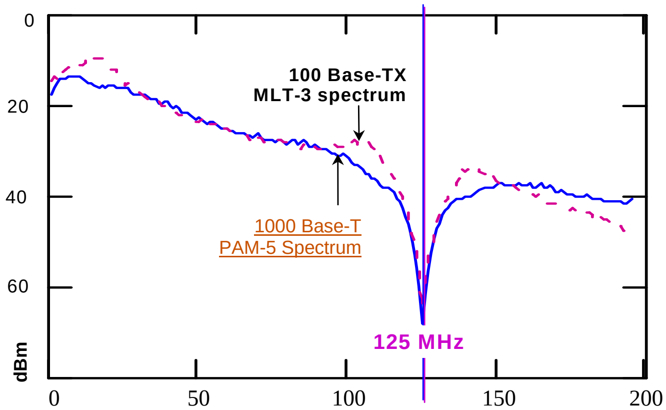

Figure 2: The spectrum of 1000Base-T is shaped to match the spectrum of 100Base-TX. The spectra and the symbol rates of the two networks were matched in order to facilitate the development of a 100/1000Base-T transceiver.

A PAM-5 eye pattern[4] is shown in figure 3. The eye pattern of the Enhanced TX/T2 signal deviates from this classical 5-level eye pattern because the waveform of the Enhanced TX/T2 signal has been shaped so as to make the spectrum of 1000Base-T match the spectrum of 100Base-TX.

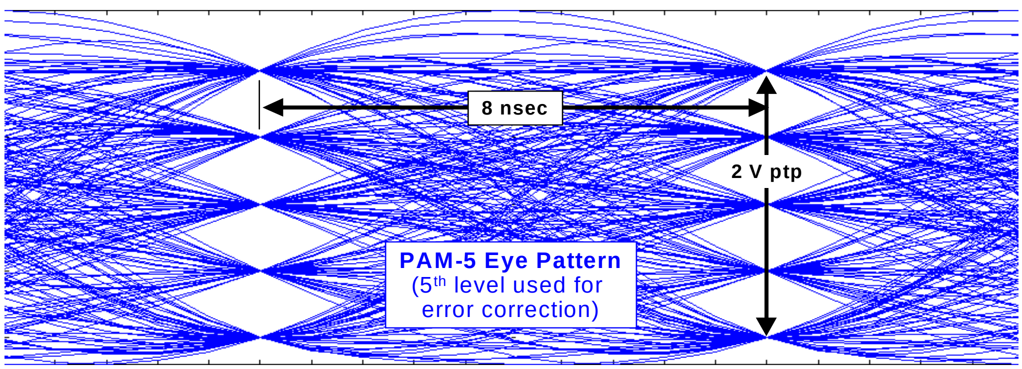

Figure 3: PAM-5 Eye Pattern. 1000Base-T generates a 5-level 2V peak to peak data signal with the symbol period of 8 nsec.

Why 5 Levels?

Typically, only 4 voltage levels are needed to generate 2 bits/symbol because there are only 4 possible combinations of 2 bits – 00, 01, 10, 11. The transmitter can send 4 combinations of 2 bits as 4 distinct voltages and the receiver can decode each voltage level into the corresponding 2-bit combination.

[4] An eye pattern is a trace produced by a modulated random data waveform, with each symbol period tracing from left to right and starting in the same place on the left. An eye pattern appears on an oscilloscope if the modulated random data signal is viewed while triggering the oscilloscope on the data clock.

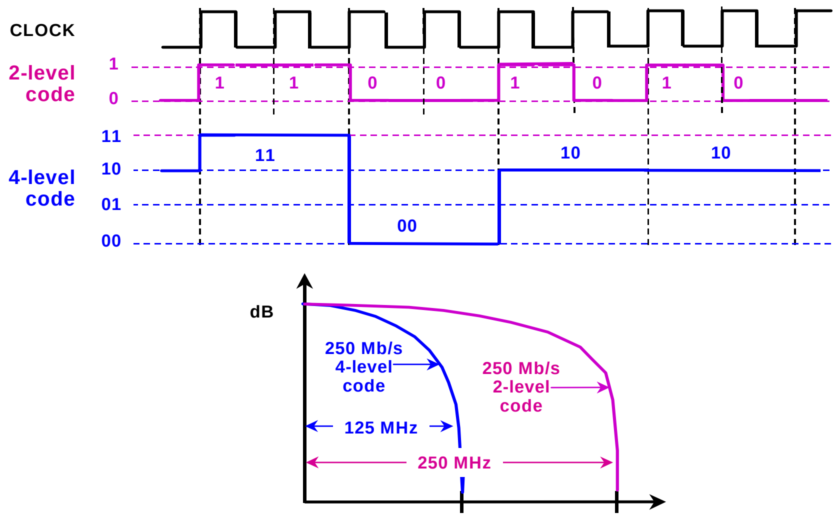

Figure 4: 2- and 4-Level Data Signals. A 4-level data signal generates 2 bits per symbol consuming half the bandwidth of a 2-level signal. Using 4-levels, it is possible to send 250 Mb/s over a 125 MHz channel.

A 4-level signal has voltage transitions every 2 bit periods while a 2-level signal could have voltage transitions every bit period. Therefore, the rate of transitions, or symbol rate, of a 4-level signal is half the frequency of a 2-level signal. Thus, a 250 Mb/s data signal can be transmitted at a rate of 125 Msymbols/sec using 125 MHz of channel bandwidth with only 4 voltage levels

The 5th level in the Enhanced TX/T2 system allows for redundant symbol states that are used for error-correction encoding. The error correction method consists of Trellis coding [9] in combination with Viterbi decoding. The error correction logic is expected to enhance the system's Signal to Noise Ratio (SNR) margin by about 6 dB. The extra 6 dB of SNR margin gives the 5 level Enhanced TX/T2 signal the noise immunity of a 3 level signal.

The following section explains the concept of noise immunity and SNR margin.

SNR Margin

SNR margin is a measure of a communications system's immunity to noise. SNR margin is expressed in dB and represents the level of additional noise that the system can tolerate before violating the required Bit Error Rate (BER). For example, an SNR margin of 3 dB means that if the noise level is increased by 3 dB, the system would be subject to excessive errors.

The higher the SNR margin, the more robust the system. If network A has an SNR margin of 3 dB and network B has an SNR margin of 10 dB, then network B can tolerate 7 dB more noise than network A without violating the required BER.

Figure 5 demonstrates that increasing the number of signal levels while maintaining the same transmit voltage results in a degradation of the SNR margin. The reason for this is that as the vertical opening of the eye gets smaller, the system can tolerate less noise before bit errors begin to occur. For example, increasing the number of voltage levels from 2 to 3 cuts the difference between adjacent voltage levels in half, reducing the vertical eye opening by a factor of 2. The noise voltage required to cause a symbol error on a 3-level signal is half (or 6 dB lower) than the voltage required to cause a symbol error on a binary signal. So a 3-level signal has 6 dB less SNR margin than a 2-level signal, assuming both signals operate at the same peak to peak voltage.

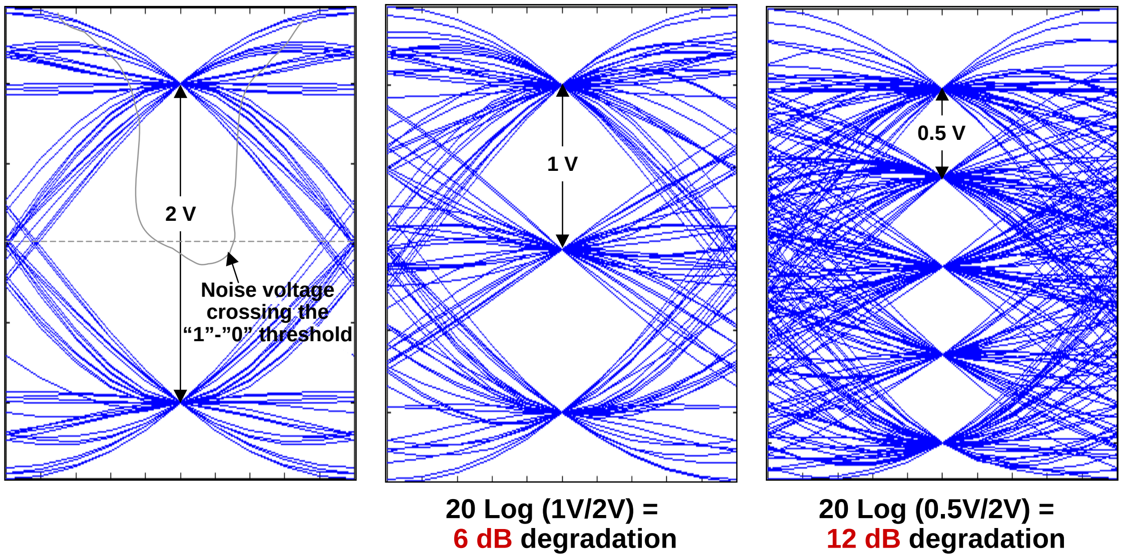

Figure 5: Eye patterns of 2-, 3- and 5-level Signals. Increasing the number of levels while maintaining the same transmit voltage reduces the SNR margin of the system. If the noise voltage is sufficiently high to force the data signal to the wrong voltage level (e.g. to the wrong side of the "1"-"0" threshold as shown on the left) the affected symbol can be misinterpreted by the receiver resulting in bit errors.

Simply put, SNR margin is a measure, in dB, of how much additional noise a system can tolerate or how far the system is from not working properly. The rest of this paper analyzes the SNR margin of 1000Base-T. We will begin with an overview of the noise and crosstalk coupling at each receiver.

Noise Environment in a Category 5 Channel

The noise at each of the 4 receivers in a 1000Base-T device consists of Near End Crosstalk (NEXT) from 3 adjacent pairs, Far End Crosstalk (FEXT) from 3 adjacent pairs, transmit echo and ambient noise.

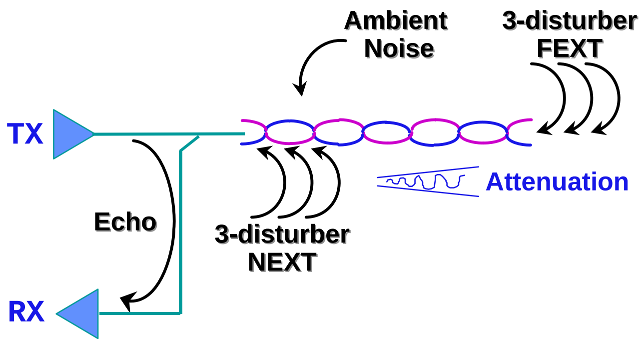

Figure 6: Noise at each receiver is the sum of NEXT from 3 adjacent pairs, FEXT from 3 adjacent pairs, transmit echo and ambient noise. All four sources of noise add onto the attenuated receive data signal.

The SNR margin of 1000Base-T can be computed by adding up the noise from all the sources shown in figure 6 and taking a ratio of the noise with respect to the attenuated signal. When the SNR margin is thus computed for a worst case category 5 channel, it can be shown that a conventional transceiver implementation would yield a system with a negative SNR margin. What this means is that on the wire, the noise power could be so high that the specified Bit Error Rate (BER) of 10^{-10} would not be achievable without the use of sophisticated signal processing technology.

In order to prove the feasibility of the Enhanced TX/T2 technology, the transceiver design was simulated in software using the worst case category 5 models for NEXT, FEXT, attenuation and return loss. Following is an overview of how the category 5 models are defined.

Return Loss Models

The source of noise known as the echo is a direct function of the channel return loss. To implement bi-directional transmission over each pair the transmitter and receiver are connected to each pair through a directional coupler circuit, known as a hybrid (figure 6). The hybrid separates the outbound transmit signal from the inbound receive signal. Echo interference occurs when the outbound transmit signal reflects off the channel due to imperfect return loss and passes back through the hybrid into the receiver. The magnitude of the reflection, or echo, is proportional to the return loss of the channel.

The worst case category 5 return loss was modeled for use in the design simulations. Since the return loss limit for category 5 was not standardized at the time IEEE was evaluating the channel characteristics, the return loss models are based on a couple of representative channel measurements. Figure 7 shows the return loss models along with the draft [4] TIA limits for return loss.

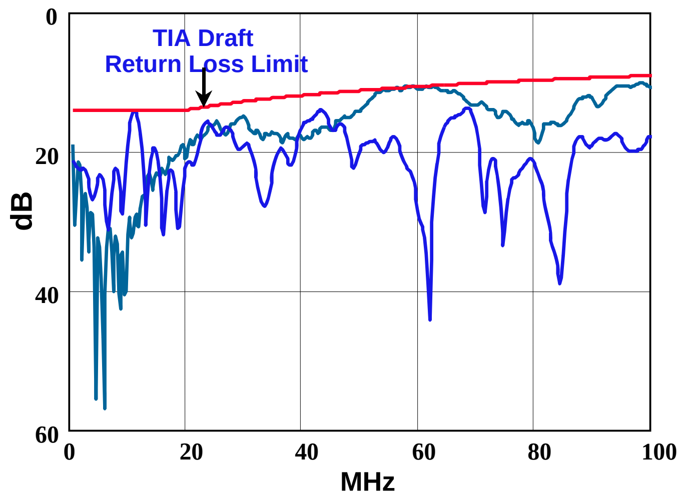

Figure 7: Return Loss models used in design simulations are based on measured data.

Attenuation Model

The amplitude of the receive data signal is a function of channel attenuation. The worst-case category 5 attenuation model is based a measurement of a channel having the attenuation at the TSB67 [1] channel limit.

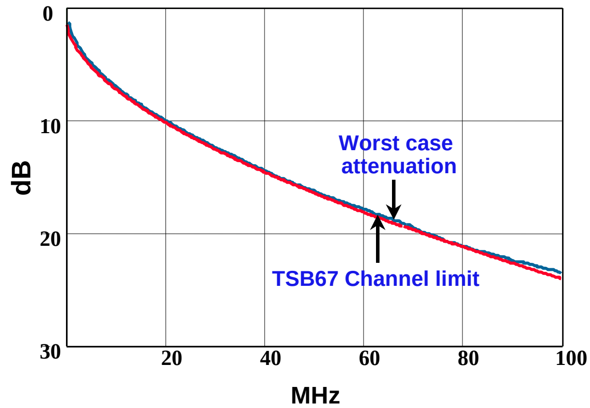

Figure 8: Worst case category 5 attenuation model is represented by an attenuation measurement that has practically no margin with respect to the TSB67 [1] channel attenuation limit.

NEXT Models

Each receive signal is subject to the Near End Crosstalk (NEXT) coupling from three adjacent pairs transmitting simultaneously. The NEXT models shown in figure 9 are based on NEXT measurements of a category 5 channel. To make the measurements appear worst case, an offset was added to the measured NEXT curves so as to shift the peak of the NEXT response up to the TSB67 [1] channel limit.

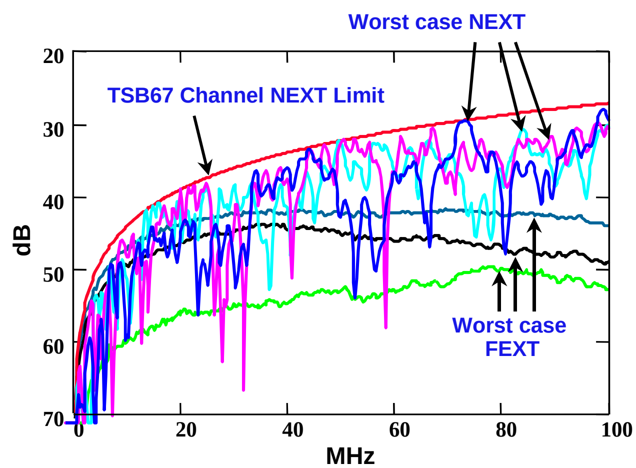

Figure 9: NEXT and FEXT models used in the design simulations. The models are based on measurements offset in the direction of the channel limit so that the peak of each curve touches the limit. The FEXT models are included on this plot to demonstrate that the FEXT noise is comparable in magnitude to the NEXT noise[5].

[5] The FEXT models are based on the *power sum* of the pair-to-pair measurements while the NEXT models are based on the pair-to-pair measurements.

FEXT Models

FEXT (Far End Crosstalk) is the coupling between two or more transmitting pairs as the signal propagates from the transmit end of the pair to the receive end. Far end crosstalk coupling can be expressed as FEXT or ELFEXT (Equal Level Far End Crosstalk) - both measured in dB. FEXT and ELFEXT are the same coupling but measured with respect to two different references (figure 10). FEXT is measured with respect to the disturbing signal. ELFEXT is measured with respect to the attenuated disturbing signal. If FEXT is mathematically subtracted from ELFEXT the result is the attenuation of the channel.

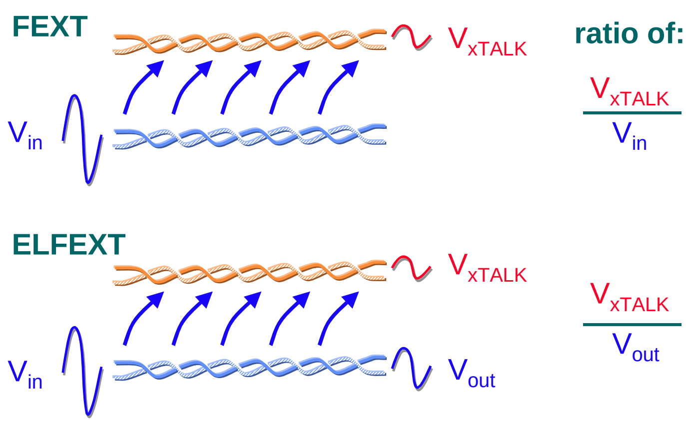

Figure 10: Explanation of FEXT and ELFEXT Coupling. FEXT and ELFEXT are the same coupling but measured with respect to two different references. FEXT is measured with respect to the full power transmit signal while ELFEXT is measured with respect to the attenuated transmit signal.

The limit for FEXT was not standardized at the time IEEE was developing their worst case cable models and the IEEE committee had to make an educated guess about the future TIA limit for FEXT. The method of modeling worst case FEXT is similar to the method of modeling worst case NEXT – by shifting the measured FEXT response up to the assumed FEXT channel limit.

The current TIA draft [4] specifies the limit for channel **EL**FEXT while the IEEE models are based on channel FEXT. This is not an issue since FEXT can be computed from ELFEXT and attenuation. The ELFEXT limit for installed category 5 is still under debate at TIA. The current TIA draft [4] defines the ELFEXT limit approximately 2 dB[6] higher than the limit originally assumed by the IEEE committee. Therefore, the "worst case" FEXT models are 2 dB too optimistic and this means that the original IEEE estimate of worst case SNR margin is also too optimistic (see table 1 below).

[6] The current draft (7B) of the TIA TSB [4] for installed category 5 specifies ELFEXT limit as $ELFEXT_{channel, link} \geq 17-20*\log(f/100)$. The IEEE ELFEXT models were based on the worst pair limit of 19-20*log (f/100).

Ambient Noise

Ambient noise typically includes background white noise, impulse noise generated by power lines and telephone voltages. Ambient noise can also include interfering wireless signals and alien crosstalk. Due to its random nature, the ambient noise cannot be cancelled in the receiver and so directly detracts from the SNR margin of the system.

Total Noise

To summarize, each pair in a 1000Base-T channel is subject to four major sources of noise, two of which can be cancelled by the signal processing circuitry in the receiver and two of which cannot be cancelled. The noise contributed by NEXT and echo undergoes cancellation but does not disappear entirely. The noise contributed by the ambient sources and by FEXT cannot be cancelled and directly affects the Bit Error Rate (BER) performance of the system.

An important consideration regarding FEXT is that the FEXT performance of currently installed systems is not well qualified, but recent studies [6][7] suggest that FEXT might be more significant than originally expected by TIA.

The Position of IEEE 802.3

Considering that two major sources of noise in 1000Base-T system are produced by non-standard and poorly characterized cabling parameters – return loss and FEXT – how can the IEEE 802.3 committee assume that 1000Base-T will operate over existing category 5 cabling?

The IEEE 802.3 committee expects that the TIA and ISO cabling standards will have specifications for the missing cabling parameters by the time the 1000Base-T standard is released. The installed category 5 will have to be re-certified to verify that the requirements of 1000Base-T are met. Following is a quote from a letter written by Geoff Thompson, Chairman of IEEE 802.3, to SC25/WG3 and TR-41.8.1 regarding the cabling requirements of 1000Base-T:

"We expect that it may be an integral part of our standard to require the pre-qualification of an installed link with a hand-held tester that tests to TSB-67. We hope that by the time our standard is approved that TSB-67 and testers in the field will have coverage for the added parameters."

Earlier in his letter, Mr. Thompson identifies the missing parameters as FEXT, return loss, propagation delay and skew.

1000Base-T Signal Processing Technology

The worst case cable models - attenuation, NEXT, FEXT and return loss - were needed in order to select the best signaling scheme and to architect a 1000Base-T transceiver. The transceiver signal processing logic is based on these cable models.

A simplified block diagram of a typical 1000Base-T transceiver is shown in figure 11. The signal processing consists of error correction encoding/decoding, 3 NEXT cancellers (one for each adjacent pair) and an echo canceller.

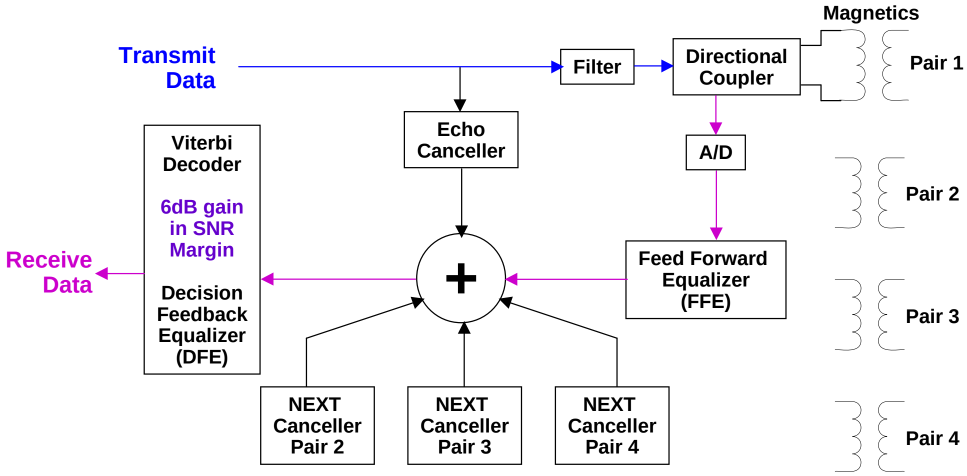

Figure 11: Simplified block diagram of 1000Base-T transceiver. This circuitry will appear at each pair. The NEXT and echo cancellers are designed to minimize the NEXT and echo coupling.

The transceiver architecture shown in figure 11 was modeled and simulated to compute the SNR margin based on the worst case cable models described above.

The simulation takes into account the effects of quantization, error correction, NEXT and echo cancellation, equalization, etc. and produces the SNR margin of the system. The IEEE P802.3ab group has analyzed two designs – one targeting 3 dB of SNR margin on a channel represented by the worst case category 5 models and the other targeting 10 dB of SNR margin on the same channel. The extra SNR margin available in the 10 dB design is achieved at the cost of roughly doubling the complexity of the silicon.

Originally, the 3 dB and the 10 dB designs were simulated using the worst case NEXT, attenuation and return loss models but without including the effects of FEXT. Without FEXT, the SNR margins for the 3 and the 10 dB designs were computed as 3.3 and 10.0 dB respectively. When the optimistic FEXT models (see section called *FEXT Models* above) were added to the simulation, the margins dropped to 2.4 and 6.6 dB respectively. But if the FEXT models are shifted up by 2 dB to the current TIA draft [4] limit, the simulated margins deteriorate to 2.0 and 5.5 dB respectively.

	3 dB	**10 dB**
Margin at cat 5 limits without FEXT	3.3 dB	10.0 dB
Margin with optimistic cat 5 FEXT limit	2.4 dB	6.6 dB
Margin with TIA draft [4] cat 5 FEXT limit	2.0 dB	5.5 dB

Table 1: Summary of SNR margin figures resulting from simulations of the 3 dB and the 10 dB designs. The simulations are based on the Matlab code published in the IEEE 1000Base-T Bluebook.

Can Better Cabling Help?

Since most of the noise in a category 5 channel is due to the crosstalk and return loss properties of the cable, improving the performance of these parameters improves the SNR margin of gigabit Ethernet. TIA is currently in the process of developing a specification for enhanced cabling - category 5E. Category 5E offers 2 dB of improvement in the return loss and ELFEXT performance and 4 dB of improvement in the

NEXT performance (figure 12) over category 5. Category 5E is specified by an addendum to TIA-568-A [5], which is under ballot as of this writing.

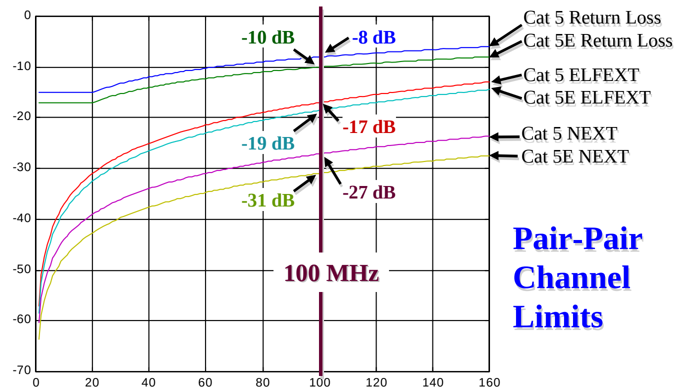

Figure 12: Comparison of category 5 to category 5E channel limits for return loss, NEXT and ELFEXT. The attenuation of category 5E is the same as that of category 5.

Because of the improvements in category 5E, the worst case SNR margin of a typical (3-dB) gigabit Ethernet implementation increases from 2.0 dB to 3.3 dB – a 65% improvement.

	3 dB	**10 dB**
Margin per TIA draft [4] cat 5	2.0 dB	5.5 dB
Margin per TIA draft [5] cat 5E	*3.3 dB*	6.7 dB

Table 2: SNR margins computed based on the TIA specifications for installed category 5 [4] and enhanced category 5E [5]. These computed SNR margins take into account cable models of attenuation, NEXT, FEXT and return loss first shifted up to the cat 5 limits and then shifted to the cat 5E limits.

Summary

Gigabit Ethernet will definitely stretch the limits of category 5. And with good reason – this amazing technology will pump more data through twisted pair Local Area Networks than anyone thought possible back when category 5 was first defined.

Due to the high cost of silicon, most 1000Base-T transceiver implementations will probably have slim SNR margins by design. And because the SNR margins might be slim and performance of installed cabling poorly characterized, existing installations will have to be re-tested to verify that adequate SNR margins are available to support 1000Base-T systems.

Will installed category 5 cabling support 1000Base-T? The answer is "probably". Many category 5 installations with less than maximum allowable attenuation will likely have sufficient margins to form robust gigabit Ethernet channels. The only way to know for sure is through re-certifying the existing category 5 cabling.

In new installations, it would be prudent to use category 5E cabling to ensure sufficient headroom for the emerging 1000Base-T technology.

References

[1] TIA/EIA Telecommunications Systems Bulletin, TSB67, “Transmission Performance Specifications for Field Testing of Unshielded Twisted-Pair Cabling Systems”, October 1995

[2] ANSI/TIA/EIA-568-A, "Commercial Building Telecommunications Cabling Standard", October 6, 1995

[3] ISO/IEC 11801, "Generic Cabling for Customer Premises", 1995

[4] TIA TSB XX (draft) “Additional Transmission Performance Specifications for 100 Ω 4-Pair Category 5Cabling”, 5/98

[5] TIA-568-A Addendum 5 (presently under ballot) "Additional Transmission Performance Specifications for 4-Pair 100 Ω Enhanced Category 5 Cabling" , February 26, 1998

[6] Contribution to TIA TR41.8.1 UTP Systems Task Group, “Far End Crosstalk of Cat 5 Connecting Hardware”, 6/97, by Sterling Vaden of Superior Modular Products

[7] Contribution to TIA TR41.8.1-97-08-46, “Relationship [Between] Near End and Far End Crosstalk in Modular RJ-45 Connectors”, 8/97, by Henriecus Koeman & Andrew Bennett of Fluke

[8] ASTM D 4566-94, “Standard Test Methods for Electrical Performance Properties of Insulations and Jackets for Telecommunications Wire and Cable”, 8/94, Section 24

[9] G. Ungerboeck, "Trellis-Coded Modulation with Redundant Signal Sets, Part I and II", IEEE Communications Magazine, vol.25, no.2, 2/87

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